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Sustainability in Mechanical Engineering Undergraduate Courses at 100 Universities

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Mechanical engineers have an important role in contributing to a more sustainable future. However, the extent that sustainability is currently being integrated into mechanical engineering (ME) curricula is unclear. This research characterized sustainability integration in undergraduate ME courses at 100 universities. Criterion-based selection resulted in a range of institution types and geographic locations (including institutions outside the United States); 93 of the 100 programs were accredited by the Engineering Accreditation Commission (EAC) of ABET. For 90 institutions, the data came from the Association for the Advancement of Sustainability for Higher Education (AASHE) Sustainability Tracking, Assessment & Rating System (STARS). Course catalog information was used for ten additional schools, in addition to comparing catalog data to STARS for ten institutions. Overall, sustainability topics were found in at least one elective or required undergraduate ME course at 83 institutions; only 43 institutions included sustainability in at least one required ME course; 16 institutions offered ten or more ME courses that integrated sustainability topics. Courses with sustainability integration at the greatest number of institutions were thermodynamics, engineering design, introduction to engineering, and heat transfer. Few of these courses appeared to integrate all three sustainability pillars (environmental, social, and economic). Leading institutions for sustainability integrations across the curriculum were identified. This work offers a picture of sustainability incorporation in undergraduate mechanical engineering programs, with the hope of catalyzing greater and more visible sustainability integration in the future. [DOI: 10.1115/1.4063387]

Keywords: engineering education, curriculum, courses, sustainable development, environmental, social, economic, design education, environmental effects, sustainable design, sustainable engineering

1 Introduction

Mechanical engineers have an important role to play in working toward a sustainable future. The American Society of Mechanical Engineers (ASME) has increasingly promoted Engineering for Sustainable Development and recently "encourage[d] engineering educational institutions to develop clear pathways for the next generation of the engineering workforce to support sustainable development efforts" [1]. This joins earlier efforts such as the ASME position on climate change [2] and other calls for sustainability inclusion in the mechanical engineering (ME) curriculum [3]. While many publications describe individual mechanical engineering courses that have integrated sustainability concepts (e.g., [4–7]) and sustainability integration more broadly in the curriculum at individual institutions (e.g., [8–12]), what is lacking is a more comprehensive analysis of the extent to which mechanical engineering curricula integrate sustainability topics. This research aimed to fill that gap by characterizing the extent of sustainability inclusion in 100 undergraduate mechanical engineering programs.

2 Background

Sustainability is a complex concept. A classic definition is meeting the needs of the present without compromising the ability of future generations to meet their own needs [13]. The 17 United Nations (UN) Sustainable Development Goals (SDGs) [14] attend to both current quality of life issues, including health, education, and economic growth, and concern with intergenerational equity (e.g., combating climate change). The UN has identified Education for Sustainable Development [15] as important to meeting these goals.

Seay [16] proposed a taxonomy of sustainable engineering and sustainable process design, which included professional sustainability, environmental sustainability, social sustainability, economic sustainability, and sustainability methods and metrics. The Institution of Mechanical Engineers [17] noted: "Sustainable engineering principles, when considered at an early stage, can make a huge impact on the society, but also save time, money, and future proof businesses' value chain by minimizing the threats and maximizing the opportunities of this new changing world. The key is finding a balance between the three dimensions of sustainability: the economic, the social and the environmental."

The accreditation criteria for engineering education programs reflect the importance of preparing engineers to contribute to

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sustainable development. The International Engineering Alliance includes sustainability issues in multiple outcomes in its Graduate Attributes and Professional Competences (2021) [18], such as: "knowledge of the role of engineering in society… such as the professional responsibility of an engineer to public safety and sustainable development" (WK7); "analyze complex engineering problems… with holistic considerations for sustainable development" (WA2); and "seek to achieve sustainable outcomes" (EC6). ABET (which accredits engineering programs in the United States and an increasing number of international programs) has less definitive outcome statements with respect to sustainability [19]. In its definition of engineering design, sustainability is listed as an example of a possible constraint, and the term does not appear within the student outcomes. However, sustainability is implied within the outcome statements on design (i.e., "… design … with consideration of… global, cultural, social, environmental, and economic factors") and ethics (i.e., "consider the impact of engineering solutions in global, economic, environmental, and societal contexts").

While each engineering discipline has an important role to play in contributing to sustainable development, their commitment and level of sustainability integration in engineering education vary. Under the ABET program–level criteria [19], the disciplines of civil, environmental, and architectural engineering have long required specific integration of sustainability topics, filling perceived gaps in the ABET general criteria. The codes of ethics from different engineering professional societies also have varying levels of commitment to sustainability [20,21], and the percentages of engineering faculty teaching sustainability in different disciplines vary [22]. In addition, a recent comprehensive literature review identified a number of sustainability implementation case reports in general, civil, and environmental engineering, but none in mechanical [23].

ME was selected as the focus of this research because it is a particularly high-impact discipline with room for improvement. For over 15 years, the number of bachelor's graduates in the United States has been the highest in ME [24,25]. However, studies have found that sustainability integration in ME courses and curricula lags disciplines such as civil engineering [26–28].

Within higher education, the Association for the Advancement of Sustainability for Higher Education (AASHE) created the Sustainability Tracking, Assessment & Rating System (STARS) [29]. STARS is a free, self-reporting framework for institutions of higher education to measure their sustainability efforts. Institutions can earn a STARS rating of Bronze, Silver, Gold, or Platinum or earn the STARS Reporter designation. There are 1153 institutions that have registered with STARS, of which 596 have earned a STARS rating [30]. There are five categories of STARS credits: academics (curriculum and research), engagement (campus and public engagement), operations (air & climate, buildings, energy, food and dining, transportation, waste, water), planning & administration, and innovation & leadership. The total number of points available is 100, with a maximum score of 40 points under academics (including a maximum of 14 points that can be earned based on academic courses). AASHE publishes the STARS reports from institutions online.

To earn STARS credits under the curriculum category within academics, universities self-report the courses they consider sustainability-focused and sustainability-inclusive. "Sustainability-focused" courses have a primary and explicit focus on sustainability. If the course does not unequivocally indicate a focus on sustainability or ecological, social, and economic issues and concepts, but does contain aspects of these, then the course may be considered "sustainability-inclusive." The STARS report identifies these courses by academic department and as either undergraduate or graduate level. The AASHE STARS website links to spreadsheets of sustainability-inclusive courses for each university [29]. The institution typically indicates the methods that they used to identify the sustainability-inclusive and sustainability-focused courses, as well as the year that they classified the courses. Often a course description was included. Some institutions used the AASHE STARS course classification template [31], which also indicates which of the UN SDGs are covered in the course.

This work utilized information from the STARS databases and course catalogs to explore sustainability inclusions in undergraduate ME courses and if/how sustainability is being interwoven throughout the curriculum. This broader knowledge can help catalyze enhanced sustainability incorporation into mechanical engineering courses and curricula.

The specific research questions explored in this study are:

- What is the total number of undergraduate ME courses at each institution that include sustainability, including in required, core, and elective courses?
- Do ME programs at institutions with the highest AASHE STARS ratings offer more courses with sustainability?
- What specific ME courses most commonly include sustainability?
- To what extent are the three sustainability pillars of environment, economics, and social represented in ME courses?
- Where is sustainability inclusion commonly located in a typical 4-year ME curriculum?

3 Methods

There were two sources of data used to evaluate the research questions: course information available through AASHE STARS and institutional undergraduate catalogs. Both of these data sources are freely available online. After approximately ten catalogs were explored, it was found that most included very short and/or technically focused descriptions for engineering courses, which led to the decision that the majority of the course benchmarking (90 of 100 programs) would be based on STARS reports.

3.1 Criterion-Based Selection of Institutions. The 100 institutions included in the study were selected using a range of criteria. A list of ABET-accredited mechanical engineering programs [32] was accessed on March 5, 2022, including 343 programs in the United States and 82 programs outside the United States. Cross-referencing the ABET list with institutions in STARS found 168 U.S. institutions and three international institutions meeting both of the primary criteria for inclusion in this study (however, it was later found that some of these institutions had expired STARS information). Because this group lacked significant representation of programs outside the United States, additional selections were made among the 43 international institutions that had participated in STARS and offered ME degrees.

It was desired to have at least ten institutions representing each of the STARS rating levels, including reporter and institutions not participating in STARS; however, there were only nine platinum-level schools that offered ME bachelor's degrees and only seven reporter institutions that included course data within the last 8 years and offered ME bachelor's degrees. Undergraduate mechanical engineering programs highly ranked by the U.S. News and World Report (USNWR) in 2022 were included: all of the top 12 at doctoral institutions [33] and six of the nine top ranked at nondoctoral institutions (military academies were not included) [34]. Note that this resulted in the inclusion of institutions with ABET EAC-accredited programs not under the mechanical engineering program criteria (i.e., Harvey Mudd engineering degree and MIT degree in mechanical engineering accredited under the general criteria). Institutions awarding the most bachelor's degrees in ME [24] were preferentially selected, as these programs will have an outsized impact on the skills and attitudes of ME graduates entering the workforce; seven of the ten programs awarding the most degrees were included. Colleges with sustainability minors and/or certificates, published papers on sustainability integration into ME, minority-serving institutions (Historically Black Colleges and Universities, Hispanic Serving Institutions), and institutions graduating the most female, Black, and Hispanic students were also intentionally selected. Institutions meeting multiple inclusion criteria (e.g., STARS, top ranked by USNWR, a large number of degrees awarded, a large percentage of degrees awarded to women, etc.) were preferentially selected. Ten institutions outside the United States were selected.

Details on the characteristics of the 100 institutions included in the study are provided in the Supplemental Materials on the ASME Digital Collection. The number of institutions per STARS rating category was 9 platinum, 33 gold, 28 silver, 13 bronze, 7 reporter, and 10 institutions not participating in STARS. Overall, there were 64 public and 36 private institutions. The Carnegie basic classifications of the institutions were: very high research 55, high research 19, doctoral 3, master's 10, baccalaureate 2, and special focus 2 (9 international programs not classified). The institutions also represent all 8 Carnegie geographic regions and 37 of 50 states. The number of bachelor's degrees in ME awarded at each institution in 2019–2020 ranged from 4 to 572 (median 126, mean 155, standard deviation 117) [24,35]. The demographics of the ME bachelor's degree recipients at each institution were percentage of BS degrees awarded to females 7–49 (median 20); percentage awarded to Hispanic students 0–94 (median 9); percentage awarded to Black students 0–100 (median 2) [24,35]. A list of the 100 institutions is provided in Ref. [36].

3.2 STARS Data. STARS data for 90 institutions were acquired via the AASHE website [29] from January to September 2022. While the majority of the institutions ($n = 59$) used STARS version 2.2, some were still rated under STARS version 2.1 ($n = 26$) and version 2.0 ($n = 5$). Across the institutions in the dataset, the total STARS scores ranged from 26.1 to 88.59 (median 65.2), the curriculum scores from 11.95 to 40 (median 26.39), and the academic courses scores from 1.74 to 14 (median 8.65). The scores represent 83 institutions because STARS scores are not available for reporter institutions.

For each institution, both general engineering and mechanical engineering courses identified as sustainability-focused or sustainability-inclusive in STARS were recorded and summed (termed ME^+). General engineering courses such as first-year engineering, general engineering statics, and CAD are often a required part of mechanical engineering curricula, and in some institutions, these courses are taught by ME professors. Courses offered by other disciplines were not recorded, regardless of whether they were required in ME (e.g., circuits taught by electrical engineering). The university catalogs and/or websites were utilized to determine if each course was required in the undergraduate mechanical engineering curriculum (based on the 2019–2020 academic year, which was the average year represented by the STARS data). It was also noted whether the courses with sustainability content were part of a "typical" mechanical engineering core curriculum, as defined in Sprouse et al. [37]. Note that while there is significant overlap between the required and core course counts, they are not synonymous since the required course list for each university is unique (e.g., a university could opt to require a course on renewable energy, for example). The course descriptions in STARS often appeared to be the standard catalog description of the course, although in some instances, a rationale for inclusion or mapping to the SDGs was provided.

3.3 Data From Catalogs. To obtain data on sustainability-focused ME courses for universities without AASHE STARS information, we explored the course catalog. This included identifying mechanical engineering and general engineering undergraduate courses, reading through each course description, and identifying potential sustainability courses based on descriptive words. This approach appeared similar to that used by many institutions for STARS [38] and keywords used in Paterson and Fuchs [39]. General sustainability descriptive words included energy conservation, holistic solutions, photovoltaic, process efficiency, renewable energy, solar, sustainability, sustainable, and wind engineering. Environmental pillar–related descriptive words included clean energy, climate, eco-design, ecological, ecosystem, environment*, impact on the planet, life cycle, pollut(ant/ion), and recycl(ed/ing). Societal pillar–related descriptive words included culture, health, inequalities, public responsibility, safety, social, and society. Economic pillar–related keywords included economic, energy efficiency, and globalization. The word "ethics" alone or "cost" alone was not determined sufficient to assume that sustainability was included in the course. However, if other terms led to the course being classified as including sustainability, ethics was tallied under the societal pillar and cost under the economic pillar. Context was also utilized to determine if the word was being applied in a sustainability sense.

We included courses with a 400/4000 level and below unless their undergraduate course plan included courses with higher numbered levels. The course catalog year selection was based on availability, synchronization with the year of STARS data (if applicable), and the fact that 2019–2020 was the most common year for STARS data. To validate our data collection from two distinct sources, we tabulated sustainability inclusion for ten universities both from STARS and catalog information. The ten institutions for comparison were selected to encompass the range of sustainability course counts of both total and required courses from STARS.

3.4 Data Analysis. Nonparametric statistics were used because the data were not normally distributed, and this did not presume linear relationships. To investigate potential differences in course counts across the multiple STARS rating categories, we conducted a Kruskal–Wallis test using IBM SPSS version 26. When statistically significant differences were found, we performed post hoc pairwise tests. SPSS calculated both standard pairwise difference significance and adjusted significance value using the Bonferroni correction for multiple tests; the Bonferroni correction can be overly conservative [40]. In addition to these tests, we used Mann–Whitney U tests for direct pairwise comparisons between categories and calculated the nonparametric effect size eta squared (η^2). For paired samples (such as comparing the course counts from STARS and catalogs), the Wilcoxon signed-rank test was used. Spearman's rho was used to test for potential correlations between STARS scores and the course counts.

3.5 Limitations. This work has several limitations, mainly due to the quality of the data sources. The STARS data rely on each university's criteria for identifying sustainability courses, which may differ from one institution to another. The threshold for counting a course may vary between institutions and among instructors. Furthermore, the data may not capture all relevant courses, as some sections or instructors of the same course may include sustainability content while others do not. Similarly, the course catalog method is subject to interpretation, as identifying sustainability keywords in course descriptions is not a standardized process. At many institutions, the course catalog descriptions are very short (median 52 words among the 20 institutions in this study), so small integrations of sustainability topics may not be reflected in the catalog descriptions. Moreover, the data span different years, ranging from 2016 to 2022, and may not reflect recent changes in course offerings. Mechanical engineering students will have access to elective courses outside ME and, in some cases, sustainability minors or certificates at the institution that may include significant sustainability opportunities; these were not characterized in this research. The majority of the 100 institutions selected participated in STARS, so there is a potential for institutions that place greater value on sustainability to be emphasized in the data set. All of the U.S. institutions represent ABET-accredited engineering programs. Finally, only a small number of institutions outside the United States were included (either due to having an ABET-accredited ME program or participation in STARS); thus, the data should not be considered representative of mechanical engineering education globally.

4 Results and Discussion

4.1 Catalog and Stars Comparison. A comparison of the counts of ME courses with sustainability integration between the STARS and catalog methods across ten institutions is shown in Table 1. The counts were not significantly different based on a two-tailed Wilcoxon signed-rank test ($p = 0.13$).

At three institutions, the catalog method identified eight or more fewer ME courses with sustainability than STARS. At Carnegie Mellon, for example, STARS reported 38 courses, with 26 courses having a combination of solely SDG 4 quality education, SDG 8 decent work and economic growth, SDG 9 industry, innovation, and infrastructure, and/or SDG 17 partnerships for the goals. Many of these topics might be included in many traditional engineering courses, and their linkage to the promotion of sustainable development could be tenuous. Carnegie Mellon used a sophisticated method to identify the 17 SDGs from its course catalog descriptions, using a custom list of 250 words for each SDG. Our simpler list of sustainability-related keywords, including the sustainability pillars of environment, society/social, and/or economic, did not identify those courses as sustainability-inclusive based on their catalog descriptions. For example, the *Introduction to Computer Aided Design* course was listed in STARS as a sustainability-focused course including SDGs 4, 8, and 9, but the course description from the catalog was not clearly indicative of sustainability topics; i.e., "This course expands upon the knowledge of basic model, assembly, and drawing generation using SolidWorks 3D CAD software. Topics include structural analysis, flow analysis, motion analysis, global variables, equations, 3D visualization, and GD&T through guided activities. 1-unit mini (7-weeks)." The "global variables" in this course description was likely meant in a technical rather than holistic manner that implies sustainability content. Thus, the counting methodology used at each institution is a critically important variable. Using its method of mapping to the SDGs, Carnegie Mellon found that 48% of all of its courses were sustainability related, which seems unusually high.

Another example where our catalog counts were significantly below the institution-reported STARS information was Santa Clara. Santa Clara reported using a combination of flagging courses using algorithms similar to keywords with catalog descriptions, followed by faculty review. Faculty clearly have knowledge of their course content that extends well beyond the brief descriptions typical in the catalogs at most institutions (e.g., the three courses at Santa Clara identified in the catalog with sustainability integration were 28 to 108 words). The STARS spreadsheet reported the rationale for including the courses; for example, the note with thermodynamics from the course instructor stated, "In class I discuss societal and economic considerations to motivate the importance of this science. For example, should power plants be located in Antarctica?"

At Berkeley, the ME courses reported in STARS and our own counts based on the catalog were in close agreement. Berkeley described its method of identifying sustainability-related courses for STARS as starting with keywords and its catalog, with results flagged by keywords then reviewed by a student fellow. Our own keyword list was likely a close match to that from Berkeley. In addition, the Berkeley course descriptions were quite extensive, averaging around 457 words. These longer course descriptions allowed more detailed descriptions of course content, which may partially account for the high number of ME courses with sustainability identified at Berkeley.

In contrast, there were significantly higher catalog counts from Georgia Tech. The courses identified in STARS (based on fall 2017 to fall 2020) included the required courses thermodynamics and capstone design; only capstone design was found using the catalog analysis from 2022. Three 4000-numbered elective courses identified in STARS were confirmed by the catalog examination in 2022. The additional courses found in the catalog analysis may have been new upper-division elective courses (e.g., ME3700 Introduction to Energy Systems Engineering) or courses with recently added sustainability content (e.g., ME4763 Pulping and Chemical Recovery, "air and water pollution minimization"). Sometimes, electives will appear in the catalog that are not routinely taught, so these courses might not have been offered in the years Georgia Tech compiled its STARS information. Alternatively, our keyword list may have been more extensive than that used by Georgia Tech in its own STARS process.

In subsequent sections of the paper, the higher count between STARS and catalogs was used for these ten institutions when analyzing trends across the 100 institutions.

Table 1 Comparison of the number of ME courses with sustainability based on STARS and catalogs at 10 institutions

University	ME courses with sustainability, *n*	
	STARS data	Course catalog
Carnegie Mellon University	38	8
University of California, Berkeley	26	24
Santa Clara University	16	3
Olin College of Engineering	12	9
University of Michigan	10	2
Iowa State University	9	6
Georgia Tech University	6	11
Boston University	3	3
University of Texas, El Paso	0	1
Auburn University	0	0

4.2 Counts of Courses. Across the 100 institutions, it was found that 83 have sustainability in one or more elective or required undergraduate mechanical engineering courses (including required engineering courses taken by ME students); 43 have sustainability in at least one required course, and 16 institutions have ten or more ME^+ courses with sustainability. Figure 1 demonstrates the frequency of institutions with sustainability with each of the specified number of courses for both the undergraduate ME^+ courses (Fig. 1(*a*)) and number of required courses (Fig. 1(*b*)). A broad range of the number of courses in the undergraduate ME curriculum including sustainability across the 100 institutions is evident, but the majority of the institutions tend to have a low number.

If the general engineering courses are excluded from the counts, the median number of undergraduate ME courses at the 100 institutions that were found to integrate sustainability topics was 2 (compared to a median of 4 when the general engineering courses required for mechanical engineering students like first-year design were included); the mean was 4.2, and the standard deviation was 6.1. The differences between the number of required courses in the undergraduate ME curriculum at each institution and the common set of "core" courses listed in Sprouse et al. [37] were negligible (mean 1.2 required versus 1.1 core, standard deviation 2.4 and 2.3, median 0 for both).

4.3 Stars Ratings Versus Course Counts. The box-and-whisker plot in Fig. 2 shows the total and required number of undergraduate ME^+ courses with sustainability at institutions with different STARS ratings. Differences were statistically significant among STARS rating levels for both the number of total courses with sustainability integration available to undergraduate ME students and required ME courses (Kruskal–Wallis independent-samples asymptotic significance in a two-sided test of <0.001 and 0.012, respectively). The pairwise analysis results are shown in Table 2.

The results roughly follow expected trends where institutions with higher STARS ratings included sustainability in more ME courses available to and required of ME students. For the total ME^+ counts, five of the paired comparisons initially met the typical 95% confidence of significant difference, but this dropped to only two pairs when the Bonferroni correction was applied.

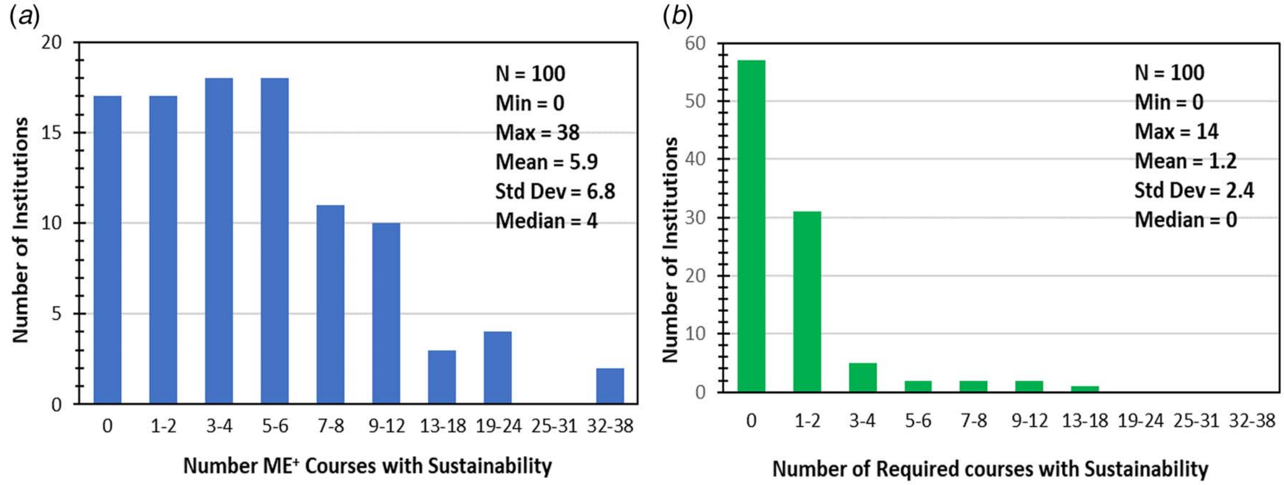

Fig. 1 Frequency of institutions with different numbers of courses with sustainability: (*a*) total ME^+ courses and (*b*) required ME^+ courses

Looking at a combination of effect size and significance that balances type I and type II errors, it appears that institutions at the reporter and bronze STARS ratings differ from institutions at the silver, gold, and platinum levels. For the number of required ME courses with sustainability, there were fewer differences among pairs of the STARS rating categories. Using a typical 95% confidence, only four pairs differ, and with Bonferroni correction, only one pair differs (bronze–platinum). Adding evidence from the effect size to balance type II errors, there is evidence that institutions with bronze ratings differ from those with silver, gold, and platinum STARS ratings. Overall, it appears that an institutional culture supportive of sustainability, as indicated by the STARS rating level achieved, fosters sustainability integration into more ME courses, with a cluster of "lower" ratings (reporter and bronze) and "higher" ratings (silver, gold, and platinum).

Potential correlations were investigated for the STARS scores (total score out of 100, curriculum score out of 40, and academic courses score out of 14) in relation to the counts of sustainability in the total ME^+ courses and ME required courses. Results are summarized in Table 3. Statistically significant, moderately strong correlations were found between all categories. For the number of required ME courses with sustainability, the strongest correlation was with the STARS academic courses score. This is logical, given that the institutional commitment to sustainability integration into courses campuswide is reflected in the score. By comparison, the overall curriculum score includes other attributes such as learning outcomes and a sustainability literacy assessment, while the total STARS score includes university operations, planning and administration, and other sustainability accomplishments. Institutions may intentionally elect to emphasize sustainability in their curriculum and educational mission, which would support sustainability integration into ME courses.

4.4 Core Courses With Sustainability. Out of the 100 universities examined, 41 institutions have at least one core ME course with sustainability, and 43 institutions have at least one required ME course with sustainability. A breakdown of the core

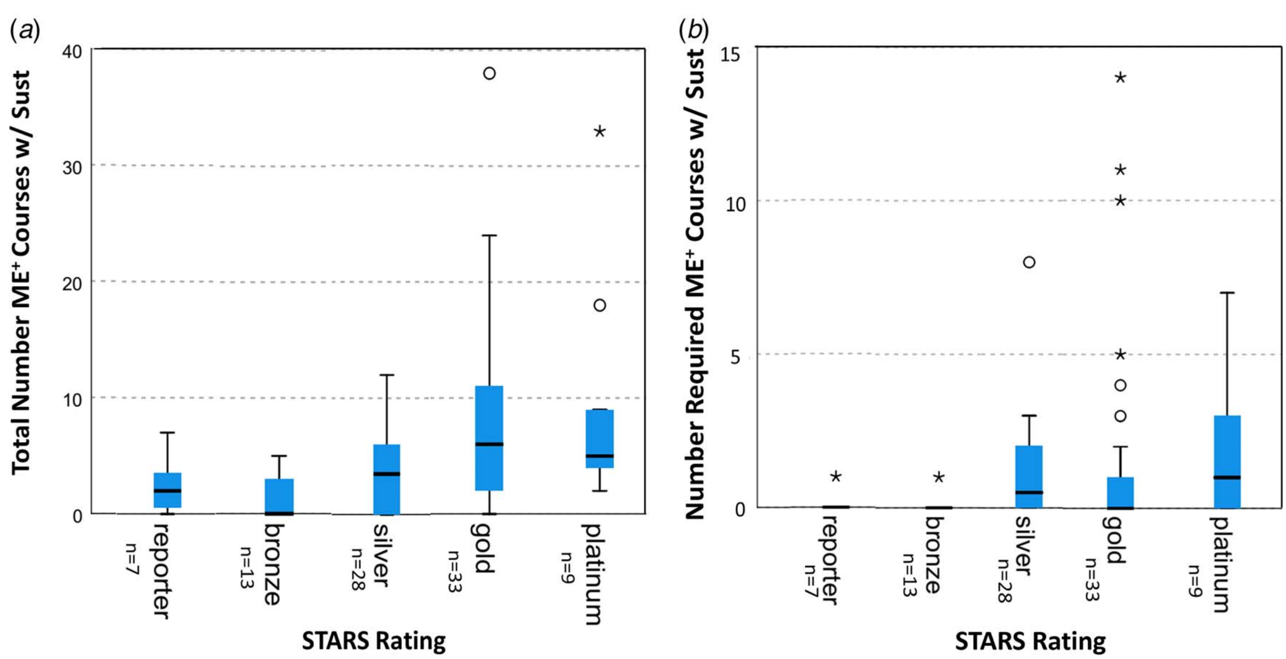

Fig. 2 Number of ME^+ courses integrating sustainability at institutions with different STARS ratings: (*a*) total and (*b*) required

Table 2 Paired comparisons between institutions with different STARS ratings and the total ME+ and required courses with sustainability (only pairs with some evidence of difference are shown)

Count	Pair	n–n	Sig.	Adj. sig.	η^2 and effect size
Total ME+	Reporter–Gold	7–33	**.021**	.213	.06 intermediate
Total ME+	Reporter–Platinum	7–9	**.029**	.293	**.24 large**
Total ME+	Bronze–Silver	13–28	.057	.570	.129 intermediate
Total ME+	Bronze–Gold	13–33	**<.001**	**.002**	.108 intermediate
Total ME+	Bronze–Platinum	13–9	**.002**	**.016**	**.270 large**
Total ME+	Silver–Gold	28–33	**.022**	.218	.001 no effect
Total ME+	Silver–Platinum	28–9	.057	.570	.028 small
Required ME	Reporter–Platinum	7–9	**.022**	.220	.093 intermediate
Required ME	Bronze–Silver	13–28	**.011**	.107	.130 intermediate
Required ME	Bronze–Gold	13–33	**.012**	.118	**.420 large**
Required ME	Bronze–Platinum	13–9	**.004**	**.039**	.098 intermediate

Note: Values in bold have strong statistical evidence of differences between the paired categories.

Table 3 Nonparametric correlations between number of ME+ courses with sustainability and STARS scores

Courses	Total STARS score	STARS curriculum score	STARS academic courses score	Strength of correlations [19]
Total ME+	.451**	.472**	.471**	Moderate
Required ME+	.325*	.364**	.503**	Moderate

**Sig. (2-tailed) <.001; *Sig. (2-tailed) <.01.

Table 4 Number of ME core courses with sustainability across the 100 institutions and percentage including specific sustainability pillars

Core course	No. of institutions	% Environment	% Social	% Economic	% With all 3	% With word "sustainability"	% None
Thermodynamics	20	20	0	10	0	5	70
ME senior design	15	33	47	40	0	40	33
Introduction to engineering/ profession	13	23	62	15	15	15	23
Heat transfer	12	17	0	0	0	0	83
1st year design	12	25	25	8	8	17	33
Fluid mechanics	7	14	0	0	0	0	86

courses and frequencies encountered is shown in Table 4. Thermodynamics is the core course with sustainability inclusion at most schools (20), followed by ME senior capstone design (15), courses introducing students to the field of engineering (13), heat transfer (12), and a first-year design course (12). Other core courses and the number of institutions where these courses integrated sustainability were fluid mechanics (7), materials properties and processing/materials science (5), mechanics of materials (4), system dynamics and controls (4), machine design and analysis (4), computer programming for engineers (3), CAD (2), mechanics/statics (2), dynamics (2), circuits (1), and probability and statistics (0).

It was then investigated which sustainability pillars (environmental, social, and economic) are included in core courses, with sustainability inclusion at seven or more institutions. Table 5 provides examples of course descriptions from STARS. The wording around sustainability pillars is in bold. Economic issues were the least evident in the course descriptions. Several course descriptions did not include any sustainability information, as shown in the last column. The descriptions for engineering science courses (fluids, heat transfer, and thermodynamics) contain the least sustainability information. For example, in the fluids courses, "conservation of energy" was often included, but that is meant in a technical rather than broader sense (design to use less energy).

4.5 Elective ME Courses With Sustainability. Universities demonstrated sustainability inclusion in a wide variety of undergraduate elective ME+ courses; the most common are shown in Table 6. While these courses were typically electives, in a few institutions, they were required. For example, manufacturing was not listed in Sprouse et al. [37] as a core course for ME, but it was required in the undergraduate ME curriculum at four of the 11 institutions in this dataset.

Half of the universities offered an undergraduate ME+ course on renewable or sustainable energy. There were also several institutions that offer undergraduate ME+ courses in specific types of renewable energy. Some institutions offer either or both. Many of the specific renewable energy courses (e.g., solar, wind) did not provide any tangible indicators that sustainability issues were included; these courses might be fully focused on the design of the technology, so the assumption that sustainability topics (e.g., life cycle assessment) are inherent in these courses could be challenged. When evidence was provided, the environmental pillar was most common. An example where sustainability topics were clearly evident is the University of Dayton's *Renewable Energy Systems* course: "Introduction to the impact of energy on the economy and environment…."

Another common elective ME+ course integrating sustainability was a global engineering type course. All of the ME+ global engineering courses at the institutions in this study had at least one sustainability pillar mentioned in the course descriptions, and 93% included societal components. An example is from the University of California Berkeley in their course *Global Engineering: The Challenges of Globalization and Disruptive Innovation*: "The course examines the challenges of innovation beyond new technology development: from the challenges of global expansion to the issues of unintended consequences of technology and the ability

Table 5 Examples of core ME course descriptions including evidence of sustainability

Course	Institution	Course description
Introduction to engineering	McGill University	Introduction to engineering practice; rights and code of conduct for students; professional conduct and ethics; engineer's duty to **society and the environment; sustainable development**; occupational health and safety; overview of the engineering disciplines taught at McGill
Introduction to mechanical design	South Dakota State	Introduction to the design process, statement of problem, modeling, research, interaction of system components. **Economic, social, and environmental limitations**; and manufacturing processes and constraints. Factors of safety, reliability, utilization of engineering software for graphics and vector methods in mechanical design. Design project.
Thermodynamics	Cornell University	Presents the definitions, concepts, and laws of thermodynamics. Topics include the first and second laws, thermodynamic property relationships, and applications to vapor and gas power systems, refrigeration, and heat pump systems. Examples and problems are Inclusive to contemporary aspects of energy and power generation and to **broader environmental issues**.
Heat transfer	University of Colorado Boulder	Studies fundamentals of heat transfer by conduction, convection, and radiation. Emphasizes problem formulation and selection of appropriate solution techniques. Provides applications to modern engineering systems, which may include energy, biological, **environmental**, and materials engineering problems
Senior capstone design	Texas A&M University	MEEN 402 is the second of the two-semester capstone design that addresses the engineering product design and development process from need definition to embodiment, and the development of innovative solutions to real-world, industry-provided design challenges. Students who successfully complete this course should be able to design a system, component, or process to meet desired performance requirements within realistic constraints that include **economic, social**, political, **environmental**, ethical, health and safety, as well as manufacturability and **sustainability**.

Note: The wording around sustainability pillars is in bold.

Table 6 Noncore and/or elective ME$^+$ courses with sustainability integration and evidence included particular sustainability pillars

Noncore/elective course	No. of institutions (required)	% With environment	% With social	% With economic	% Sustainability pillars not included in description
Renewable/sustainable energy (general)	50 (2)	47	12	41	41
Specific renewable energy (e.g., solar, wind)	23 (0)	27	9	23	55
Global engineering	14 (0)	50	93	29	0
Manufacturing (all types)	11 (4)	45	36	36	45

of technology to support or hinder social justice…" Another example is from Virginia Tech's course description of *Global Engineering Practice*: "…Learn about the impact of different political, technological, social, cultural, educational and environmental systems on engineering…"

Manufacturing course descriptions most commonly included the environmental pillar. For example, the University of Connecticut's *Manufacturing 4P: People, Planet, Process and Profit* course stated "…environmental concerns to minimize pollution and reduce material use and increase recycling…" and MIT's *Energy, Materials, and Manufacturing* course included "how to support economic development while protecting the environment…."

4.6 Curriculum Integration. The placement of the courses with sustainability integration throughout a typical 4-year ME curriculum is illustrated in Fig. 3, with the number of institutions integrating sustainability into the core ME courses represented. The figure illustrates the potential to integrate sustainability into one or more required courses each semester. Note that the exact courses and semester placement in ME curricula vary by institution; here the University of Colorado Boulder [41] and the University of Dayton [42] were used as models. Sustainability integrated throughout the 4-year curriculum has led to broader, deeper, and more connected sustainability knowledge [5]. Thus, it is desirable for students to encounter sustainability consistently throughout their studies. Courses with sustainability integration at ten or more universities are primarily located at the beginning and end of the students' undergraduate ME studies. This includes opportunities to take ME elective courses with sustainability integration (43 schools offered three or more ME electives with sustainability).

4.7 Leading Programs. Leading programs with significant sustainability inclusion in ME were further characterized. Institutions with 15 or more undergraduate ME$^+$ courses with sustainability or five or more required courses with sustainability are shown in Table 7, along with the sustainability pillars evident in the course descriptions. There are multiple patterns of sustainability integration visible. Both international universities, Universidad San Francisco de Quito and the University of Queensland, have very high numbers of total courses, required courses, and core courses with sustainability. In contrast, the University of Pittsburgh and Iowa State University have 15 ME$^+$ courses with sustainability, but none of them are required. Some of these elective courses with sustainability are specialty courses that are cross-listed as upper-division undergraduate and graduate level (e.g., at Iowa State University 20% of the courses with sustainability fit this description). Larger institutions with graduate programs and/or more faculty are more likely to have the resources to offer more elective courses.

The lack of sustainability presence in required courses can send a message to students that the topic is not of core importance in ME. This aligns with a theory of hidden curriculum, more specifically, the null curriculum [20,43]. If sustainability elements are integrated into core and/or required ME courses but not present in the catalog descriptions, this signals that these sustainability topics are less

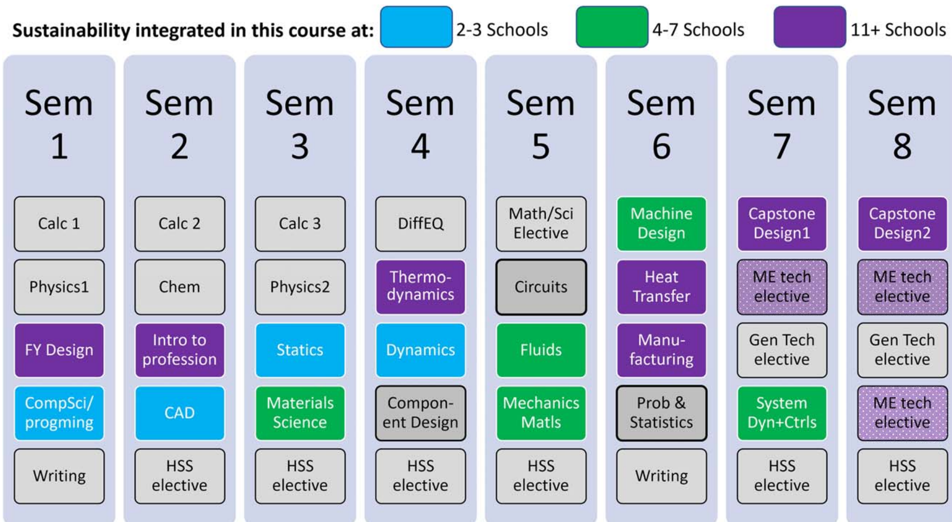

Fig. 3 Typical 4-year ME curriculum showing courses with sustainability integration

Table 7 Top institutions for number of ME+ undergraduate courses with sustainability

University	Total ME+	Core	Required ME+	Environment in total/required	Social in total/required	Economic in total/required
Carnegie Mellon	38	11	11	4/0	4/2	1/0
U California Berkeley	33	5	5	6/2	6/1	3/0
U San Francisco de Quito	24	14	14	3/1	1/0	1/0
U Queensland	24	9	8	1/0	5/2	3/1
U Dayton	24	4	4	10/1	8/2	5/2
Santa Clara U	21	8	10	5/2	10/6	3/1
U California Irvine	18	4	7	5/3	6/2	2/1
U Pittsburgh	15	0	0	13/NA	12/NA	8/NA
Iowa State U	15	0	0	5/NA	8/NA	4/NA
U Michigan	11	5	5	5/2	2/1	3/1

important compared to what is listed in the course description in the catalog (often focused on specific technical topics).

Among the ten institutions in Table 7, Santa Clara stands out with the greatest inclusion of the social pillar in required courses. As previously described, Carnegie Mellon had 38 ME courses declared in the STARS reporting system to have sustainability incorporation, but for the majority of these courses, the nature of sustainability integration was unclear, and thus, the pillars were not evident.

4.8 Future Work. Additional research could be conducted to include more universities. Of particular interest are international schools, where accreditation requirements and national culture around sustainability differ from the United States. One could also try to acquire syllabi from course instructors in order to gain an expanded view of sustainability inclusion. Faculty surveys or interviews could confirm sustainability inclusion or absence in particular courses, as well as perceptions of best practices for teaching sustainability. This more in-depth information might help spur expanded sustainability integration in ME courses and curricula.

4.9 Recommendations. A first recommendation is for mechanical engineering professors and programs to incorporate sustainability throughout the undergraduate curriculum. This is being done in universities both in the United States and abroad. The top programs described above could serve as model institutions, and there are likely more exemplary institutions beyond the 100 programs explored in this study. Even if a university does not take an across-the-curriculum approach, each should commit to substantive integration of sustainability in at least one required course. Placing sustainability early in the curriculum can attune students to this important issue, and then later courses could briefly return to the topic. Sustainability integration into capstone design also seems imperative to ensure that students graduating with degrees in ME understand that their work should consider sustainability.

Second, there is room for growth in course catalog descriptions. If sustainability is included in the course, then the addition of even one word, "sustainability," could more accurately represent the course. This would send a message to students that sustainability is considered an important topic in the course (countering the message of a null curriculum with respect to sustainability). If a single pillar or concept is included, then the addition of even a small number of descriptive words around that could increase the accuracy of the catalog description without significantly increasing the word count. When the course catalog descriptions are expanded to include sustainability keywords associated with course content, then the keyword approaches used to identify sustainability courses would be more accurate. The University of California Davis, McGill University, and the University of Southern California provided a keyword list utilized in their search for sustainability in their courses in their AASHE STARS course spreadsheet; these are models that others could consider emulating.

Another recommendation relates to sustainability reporting. For the full benefit of the STARS program, accurate descriptions of courses with sustainability are important. Currently, institutions take varied approaches to identifying courses with sustainability. Some institutions seek information from instructors and faculty, others utilize course catalogs, and others utilize syllabi. If an institution has not taken the approach to course descriptions in the catalog recommended above, we would suggest utilizing a thorough keyword list cross-referenced with course syllabi.

5 Conclusions

Engineering for a sustainable future is of utmost importance, and mechanical engineers hold a vital role [44], particularly across the product life cycle and the impacts on societies, the environment, and economics. The current state of undergraduate mechanical engineering programs' inclusion of sustainability was explored at 100 universities, based on AASHE STARS and course catalog data. We found that 83 of the schools had sustainability present in one or more elective or required courses for ME students. However, less than half of the ME programs included at least one required ME^+ course with sustainability.

Sustainability integration throughout the curriculum has known benefits [45], and sustainability has been included in courses throughout the mechanical engineering 4-year plan at some universities, including the University of California Berkeley and the University of Dayton. Among the one hundred institutions studied, seven institutions had at least five required ME^+ courses with sustainability. Core courses with the greatest frequency of sustainability integration were thermodynamics, engineering design (capstone and first year), introduction to the field of mechanical engineering, heat transfer, and fluid mechanics. While the short course descriptions hindered a complete understanding of the type of sustainability integration, the environmental and social pillars were the most prevalent in ME core courses. Elective courses that commonly integrate sustainability include renewable energy (in a variety of forms), global engineering, and manufacturing.

The study revealed challenges and limitations with the approaches taken to characterize if and how sustainability is being included in ME undergraduate courses. The lack of sustainability evidence in the course descriptions in the catalog may be sending a message to ME students that sustainability is not a critically important topic. On the other hand, seven universities have already integrated sustainability into at least five required courses and at least ten overall undergraduate courses in the mechanical engineering curriculum. It is likely that these students who have encountered sustainability consistently throughout their degree program will perceive that sustainability is a necessary part of the mechanical engineering profession.

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Conflict of Interest

There are no conflicts of interest. This article does not include research in which human participants were involved. Informed consent not applicable. This article does not include any research in which animal participants were involved.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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