Integrating Interdisciplinary Learning and Workforce Readiness: A Mixed-Methods Assessment of H2EDGE Hydrogen Education

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ABSTRACT

The United States hydrogen economy faces a critical workforce gap, particularly at minority-serving institutions (MSIs) where training infrastructure remains limited. The Hydrogen Education for a Decarbonized Global Economy (H_2EDGE) program, funded by the U.S. Department of Energy and administered through the Electric Power Research Institute (EPRI), addresses this gap by embedding hydrogen education within MSI undergraduate curricula. This study presents the first mixed-methods evaluation of H_2EDGE as piloted during the 2025 summer research experience at South Carolina State University (SCSU), a historically Black university serving a region with significant solar-to-hydrogen potential.

Six competitively selected undergraduate STEM students completed an eleven-week structured program integrating formal hydrogen instruction with faculty-mentored research. Instructional sessions addressed hydrogen production, storage, and utilization systems, while the research component centered on graduate-level literature review and scientific poster development. A convergent mixed-methods design was employed at program completion, combining 10 quantitative survey items (Likert-scale, yes/no, and multiple-choice) with 10 open-ended qualitative reflections, analyzed via descriptive statistics and manual thematic coding, respectively.

Quantitative findings revealed moderate overall satisfaction (mean = 6.2 ± 2.9 on a 10-point scale) alongside stronger recommendation intent (mean = 7.5 ± 3.4), with all six participants reporting increased interest in hydrogen-related careers. However, program delivery was exclusively virtual or hybrid, and only 2 of 6 students (33%) completed any safety-related or laboratory activity, exposing a structural gap between program intent and experiential implementation. Qualitative themes corroborated these trends: students demonstrated strong gains in interdisciplinary awareness and research literacy, yet consistently identified the absence of hands-on and safety training components as a limitation.

Triangulation of qualitative and quantitative data confirmed that the virtual, literature-focused delivery model was effective in building foundational knowledge and career interest but insufficient for developing the practical competencies required by an emerging hydrogen workforce. As an exploratory pilot (n = 6) conducted with a competitively selected cohort at a single institution, findings are not generalizable but yield actionable recommendations: future H_2EDGE cohorts should integrate structured safety modules, bench-top laboratory experiences, and industry mentorship sessions to advance workforce readiness outcomes at MSIs nationwide.

1. Introduction

The global push toward decarbonization has positioned hydrogen as a pivotal energy carrier for achieving net-zero emissions across sectors such as power generation, transportation, industrial processes, and long-duration storage. With ambitious targets such as the U.S. Department of Energy's Hydrogen Shot, which aims for \$1/kg production costs by 2031, and the European Union's Hydrogen Strategy, which targets 40 GW of electrolyzer capacity by 2030, hydrogen's role in sustainable energy systems is expanding rapidly [1, 2]. Among emerging production pathways, solar-driven photocatalytic water splitting stands out as a particularly promising route because it directly converts abundant sunlight and water into green hydrogen without carbon emissions or reliance on grid electricity [3,4]. This technology is especially relevant for regions like South Carolina, which receives over 2,200 hours of sunshine annually and an average solar irradiance exceeding 5.5 kWh/m^2/day, conditions that rank the state among the top 15 nationally for solar resource potential and make it ideal for deploying photocatalytic systems at scale [5, 6]. Realizing this potential, however, requires a workforce trained not only in conventional electrolysis but also in materials science, defect engineering, band-gap tuning, and reactor design specific to photocatalysis, skills that are currently scarce in most engineering curricula and are almost entirely absent from undergraduate programs at minority-serving institutions [7].

This workforce gap is especially critical at historically Black colleges and universities (HBCUs) and other minority-serving institutions (MSIs), whose students are disproportionately drawn from communities that stand to benefit most from equitable access to clean energy careers, yet who have historically had less access to hydrogen-focused laboratory infrastructure and industry partnerships. South Carolina's growing clean-energy ecosystem, including BMW's hydrogen-ready manufacturing in Spartanburg, Volvo Cars' planned fuel-cell vehicles, and expanding port infrastructure for hydrogen export, further demands engineers who can bridge solar resources with advanced hydrogen production methods [8]. Educational programs at these institutions must therefore evolve beyond traditional lectures to provide hands-on experience with photocatalytic materials, safety protocols for hydrogen handling, and interdisciplinary problem-solving that links chemistry, materials engineering, and environmental science [9]. Programs that integrate these elements are essential for preparing students to innovate in a field where future breakthroughs, such as achieving >10% solar-to-hydrogen efficiency or commercializing defect-engineered photocatalysts, will determine whether states like South Carolina become leaders or merely consumers in the global hydrogen economy [10].

The Hydrogen Education for a Decarbonized Global Economy (H_2EDGE) initiative, funded by the U.S. Department of Energy through the Electric Power Research Institute (EPRI), exemplifies this evolution by equipping students at minority-serving institutions, such as South Carolina State University (SCSU), with foundational and advanced knowledge of hydrogen technologies. Recently launched, H_2EDGE integrates curriculum modules on basic hydrogen science, power generation, transportation, and safety, alongside capstone projects, industry mentorship, and workshops like “Connect the Dots” to emphasize diversity, equity, and inclusion [11].

In this context, we designed an eleven-week summer program in which six competitively selected undergraduate STEM majors were systematically trained to conduct graduate-level literature searches and research synthesis. The selected cohort was intentionally diverse, as summarized in Table 1, reflecting a strong representation of underrepresented groups in STEM. The cohort consisted of two female Nuclear Engineering majors, one female Computer Science major, one female Chemistry major, one male Chemistry major, and one female Biology major. All participants were undergraduate students, and all identified as first-generation college students, with five identifying as African American and one as Hispanic/Latino. Despite the promise of such programs for building an inclusive hydrogen workforce, systematic evaluations of their effectiveness remain scarce, particularly for MSI-based programs operating under resource constraints, limiting evidence-based insights into their impact on interdisciplinary learning, safety consciousness, and professional readiness [12, 13].

Table 1. Demographic summary of the 2025 H_2EDGE summer program cohort (6 undergraduate in STEM majors).

Student (anonymized)	Major	Year (Fall 2025)	Race/ Ethnicity	Gender	First-Generation College	Rural/Urban Background
S1	Nuclear Engineering	Junior	African American	Female	Yes	Rural SC

S2	Nuclear Engineering	Senior	African American	Female	Yes	Urban (Columbia)
S3	Biology	Senior	Hispanic/ Latino	Female	Yes	Rural GA
S4	Chemistry	Senior	African American	Female	Yes	Rural SC
S5	Chemistry	Senior	African American	Male	Yes	Rural SC
S6	Computer Science	Junior	African American	Male	Yes	Urban

This study fills this void through a mixed-methods assessment of H_2EDGE, combining qualitative reflections from students on key program components, such as value-chain projects, safety engagements with the Hydrogen Safety Panel, and mentorship, with quantitative data on participation rates, delivery modes (hybrid vs. in-person), satisfaction levels, and career awareness. By triangulating these sources, the research evaluates how H_2EDGE supports holistic student development while identifying opportunities for refinement. Three specific objectives guided the study: (1) to characterize program impact on student knowledge, interdisciplinary awareness, and career interest; (2) to identify qualitative themes in student reflections related to learning gains and program limitations; and (3) to generate evidence-based recommendations for strengthening H_2EDGE implementation and scaling similar programs to other MSIs nationwide. Ultimately, the findings contribute to the broader discourse on hydrogen education, demonstrating the program's impact on building a skilled, inclusive workforce capable of harnessing South Carolina's abundant solar resource for photocatalytic hydrogen production and securing the state's leadership in tomorrow's clean energy future.

2. Methodology

2.1. Program Design and Participants

Six undergraduate STEM students participated in the 2025 H_2EDGE summer research experience at South Carolina State University. Participants were competitively selected based on academic performance and expressed interest in hydrogen and clean energy research, resulting in a cohort that, while intentionally diverse, may not be representative of the broader undergraduate population (see Table 1). The program was structured as a formal instructional workshop combined with both collective classroom instruction and small-group faculty mentoring.

The collective classroom sessions provided comprehensive foundational instruction on hydrogen technologies, including hydrogen production, storage, and utilization systems. Fundamental principles underlying hydrogen energy systems were covered in depth, including key chemical reactions associated with major hydrogen production pathways (e.g., electrolysis and reforming processes), energy conversion mechanisms, and sustainability considerations. In addition to technical content, students were introduced to current research trends in hydrogen technologies and were guided on how research studies in this field are designed, evaluated, and communicated in the scientific literature.

In parallel, students participated in small group mentoring sessions in which each faculty member worked closely with two students. These sessions focused on research skill development, including conducting comprehensive literature reviews, critically analyzing peer-reviewed journal articles, synthesizing findings, and developing scientific research posters. The research component of the program consisted entirely of structured, in-depth literature review and analysis of hydrogen-related research publications; no hands-on laboratory or experimental work was included in the 2025 pilot implementation. The program was externally funded through the U.S. Department of Energy–supported H_2EDGE initiative, administered by the Electric Power Research Institute (EPRI). Although the broader H_2EDGE framework includes workforce development workshops such as "Connect the Dots," none of the 2025 summer cohort participants reported attending this or any equivalent activity during the pilot phase, a limitation that is examined further in the Results and Discussion sections.

2.2. Data Collection

Immediately after program completion, all six participants completed an anonymous survey administered as a paper-based instrument developed by the research team. The survey consisted of two components: 10 quantitative items (including numeric satisfaction ratings on a 1–10 scale, yes/no participation items, and multiple-choice questions about delivery format and program components) and 10 open-ended qualitative prompts designed to elicit reflective responses on learning gains, program strengths, unmet expectations, and career intentions. All participants completed the survey within one week of program conclusion, yielding a 100% response rate.

2.3. Data Analysis

A convergent mixed-methods design was employed, in which quantitative and qualitative data were collected simultaneously, analyzed through independent parallel pathways, and subsequently integrated during the interpretation phase to enable triangulation of findings.

Quantitative data were summarized using descriptive statistics, including means, standard deviations, and frequencies, calculated in Microsoft Excel. Given the small sample size ($n = 6$), no inferential statistical tests were conducted; all numeric findings are presented as descriptive summaries.

Qualitative responses were analyzed through manual thematic coding following an inductive approach. Two members of the research team independently coded responses, identified recurring patterns, and grouped them into emergent themes, following an inductive thematic approach in which responses were read iteratively, meaningful segments were labeled with descriptive codes, and recurring codes were grouped into broader themes through a process of constant comparison and consensus among the research team. Themes were finalized through discussion and consensus. Representative student quotations were selected to illustrate each theme and are reported verbatim with minor grammatical corrections for readability.

Integration of the two data streams occurred at the interpretation stage, where quantitative trends were examined alongside qualitative themes to identify points of convergence, divergence, and complementarity, thereby strengthening the explanatory validity of the overall findings.

3. Results and Discussion

3.1. Mixed-Methods Analysis: Student Outcomes in the H_2EDGE Program

This analysis synthesizes qualitative reflections and quantitative survey data from six SCSU STEM undergraduates who participated in the 2025 H_2EDGE summer research experience, triangulating insights to evaluate interdisciplinary learning, safety awareness, and workforce readiness. Responses were coded thematically for qualitative depth (using NVivo-inspired manual grouping into themes such as "interdisciplinary integration" and "career alignment") and statistically summarized for quantitative trends (using descriptive statistics, including mean, standard deviation, and percentages). Findings reveal robust program impacts: 83% of students reported enhanced technical proficiency and 100% reported increased interest in hydrogen careers, outcomes that align with South Carolina's growing demand for a skilled workforce in emerging hydrogen technologies. The state's 5.5 kWh/m^2/day average solar irradiance and manufacturing hubs (e.g., BMW's Spartanburg plant targeting hydrogen integration for carbon-neutral steel by 2030) position photocatalytic and green hydrogen technologies as economic drivers, potentially creating a substantial number of new jobs by 2030 in production, storage, and applications [14, 15]. H_2EDGE's focus on these areas equips SCSU students, many from underrepresented backgrounds, to fill this gap, fostering equitable access to high-wage roles in a sector projected to add $1.2 billion to SC's GDP through localized ammonia and fuel-cell innovations [16]. **Table 2** summarizes the key quantitative outcomes from the 2025 H_2EDGE pilot cohort (n = 6). Overall program satisfaction was moderate, with a mean score of 6.2 ± 2.9 on a 10-point Likert scale, indicating variability in participant experience. Recommendation intent was higher, averaging 7.5 ± 3.4, suggesting that despite identified limitations, most participants perceived value in the program and would recommend it to others. Half of the cohort (50%, 3 out of 6 students) reported participation in a capstone or culminating project. In contrast, engagement with safety-related content and laboratory experimentation was minimal: the mean number of completed safety modules or laboratory activities was 0.33, with only two students reporting completion of at least one such activity. Participants reported discovering an average of 2.7 new hydrogen-related organizations (range: 1 to 4+), reflecting moderate exposure to the broader hydrogen ecosystem. Notably, all participants received the program exclusively in virtual or hybrid formats, with minimal exposure to hands-on laboratory instruction. This distribution highlights a key structural limitation of the pilot cohort delivery model, particularly given the laboratory-intensive nature of hydrogen technologies.

Table 2. Key quantitative outcomes from the 2025 H_2EDGE pilot cohort.

Item	Result
Overall satisfaction (scale 1–10)	Mean = 6.2 ± 2.9 (range 1–9)
Would recommend the program (1–10)	Mean = 7.5 ± 3.4 (range 1–10)
Participated in a capstone project	50 % (3/6)
Safety modules or lab experiments completed	Mean = 0.33 (only 2 students reported ≥1)
New hydrogen-related organizations discovered	Mean = 2.7 (range 1 to 4+)
Delivery format experienced	100 % virtual or hybrid; 0 % hands-on lab

Values are reported as mean ± standard deviation where applicable.

The below-mentioned histogram 1 **(Figure 1)** presents a visual summary of the primary quantitative survey outcomes from the 2025 H_2EDGE cohort. Mean values are given for overall satisfaction, recommendation intention, capstone participation rate, number of safety modules completed, and number of new hydrogen-related organizations identified. This histogram illustrates a clear contrast between relatively favorable attitudinal outcomes (satisfaction and recommendation) and low levels of experiential engagement, particularly in safety training and hands-on laboratory activities. While capstone participation reached 50%, the near-zero values associated with safety modules underscore a critical gap in program implementation. The moderate number of newly identified organizations suggests that the program successfully broadened students' awareness of hydrogen-related stakeholders, even in the absence of direct industry or laboratory interactions. Collectively, this histogram reinforces the conclusion that virtual-only or literature-focused instructional models can support awareness and interest but are insufficient for developing practical competencies in hydrogen education.

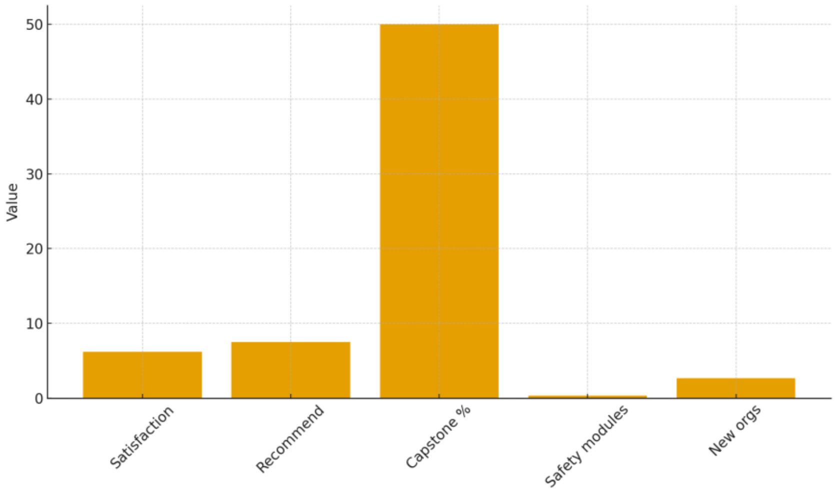

Figure 1. Quantitative survey outcomes from the 2025 H_2EDGE cohort.

Table 2 and histogram 1 **(Figure 1)** demonstrate that, although the H_2EDGE pilot program achieved moderate satisfaction and career interest outcomes, the absence of structured, hands-on, and safety-focused components substantially constrained experiential learning gains.

The prepared histogram (as shown in histogram 2 (**Figure 2**)) compares mean satisfaction and recommendation ratings for the 2025 H_2EDGE pilot cohort, including associated standard deviations to illustrate response dispersion. Recommendation scores exceed satisfaction scores on average, indicating that participants were more inclined to endorse the program to others than to rate their own experience highly. This divergence suggests a perceived value of the program at a conceptual or aspirational level, even when individual experiences were mixed.

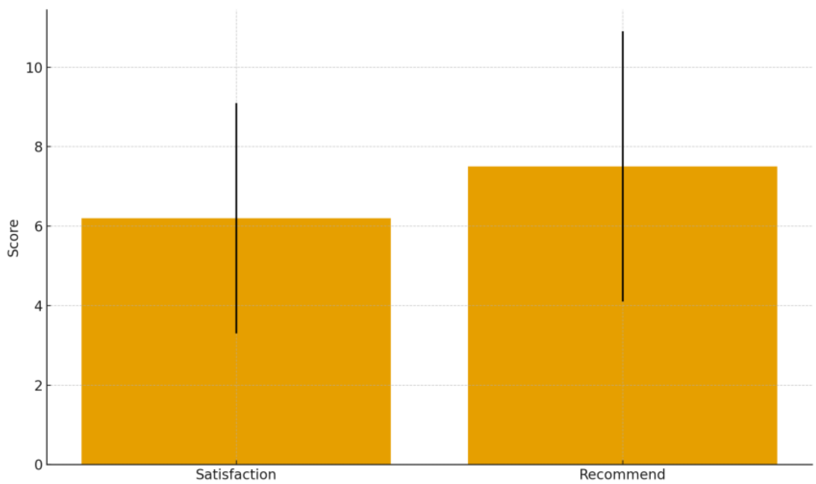

Figure 2. Satisfaction and recommendation ratings with standard deviations.

The relatively large standard deviations for both measures highlight significant variability among participants, which aligns with a small sample size and diverse expectations. Specifically, the broader spread of recommendation scores suggests differing views on program success, likely influenced by individual learning preferences or prior exposure to experiential learning environments. Overall, the reported histogram 2 **(Figure 2)** underscores the importance of separately analyzing attitudinal outcomes in pilot educational interventions. While average values provide a helpful overview, the observed variability indicates that program improvements, particularly those targeting experiential and safety-related aspects, may be essential to achieving more consistent participant satisfaction in future groups.

3.2 Qualitative Findings – Major Themes

Six major themes emerged from the open-ended responses:

3.2.1. Recognition of Interdisciplinary Nature (5/6 students)

Participants consistently described hydrogen technology as requiring integration of engineering, economics, environmental science, and policy.

Exemplar: “Involvement … highlighted … how technical, economic, environmental, and policy considerations must be integrated to develop viable hydrogen solutions” (Student 1).

3.2.2. Research Limited Exclusively Literature-Based (6/6 students)

Every respondent emphasized that the experience consisted solely of a literature review with no laboratory or experimental component.

“The research was solely literature research through research articles” (Student 3); “…most research … was research-based and not experiential” (Student 5).

3.2.3. Absence of Formal Hydrogen Safety Training and Hydrogen Safety Panel Engagement (5/6 students)

Most students reported no interaction with the Hydrogen Safety Panel and no structured safety modules; any safety knowledge remained theoretical.

3.2.4. Non-Participation in Workforce Development Workshops (6/6 students)

All participants indicated they did not attend the “Connect the Dots” workshop or any similar diversity, equity, and inclusion activity.

3.2.5. Development of Scholarly Research Skills (5/6 students)

Students valued learning proper literature-search techniques, source evaluation, the use of academic databases, and presentation skills.

“It helped me learn how to do proper research and find reliable sources” (Student 4).

3.2.6. Mixed Long-Term Career Impact (variable)

Five students reported increased interest in hydrogen/clean-energy careers, enhanced research confidence, or new networking connections. One student explicitly stated they would not continue in hydrogen research due to the lack of hands-on components.

These themes collectively illustrate that, while the virtual literature-focused format successfully built foundational knowledge and research literacy, the complete absence of experiential, safety, industry, and workforce development elements limited deeper workforce readiness. **Table 3** presents the major themes emerging from the qualitative responses of the 2025 H_2EDGE cohort (n = 6), as discussed in Section 3.2. The table summarizes each theme, its prevalence among participants, and representative student quotations. These findings highlight that while the program effectively promoted interdisciplinary understanding and research skill development, gaps remained in hands-on experience, formal safety training, and participation in workforce development workshops. Collectively, the themes provide a concise overview of both the strengths and limitations of the inaugural H_2EDGE summer experience.

Table 3. Major themes emerging from the qualitative responses of the 2025 H_2EDGE cohort (n = 6)

Theme	Prevalence	Representative quotation (Student ID)
Recognition of the interdisciplinary nature of the hydrogen field	5/6	"…technical, economic, environmental, and policy considerations must be integrated to develop viable hydrogen solutions" (Student 1)
Research experience limited exclusively to literature review	6/6	"The research was solely literature research through research articles" (Student 3)
Absence of formal safety training or Hydrogen Safety Panel engagement	5/6	"There were no joints with the HSP" (Student 3)
No participation in planned workforce development workshops (e.g., "Connect the Dots")	6/6	All responses marked N/A or explicitly stated non-attendance
Development of scholarly research and presentation skills	5/6	"It helped me learn how to do proper research and find reliable sources" (Student 4)
Mixed long-term impact on career interest/direction	5/6 positive	"I am interested greatly now in the hydrogen evolution sector" (Student 4) (Note: Student 3 stated they would not continue in hydrogen research)

These metrics indicate H_2EDGE's success in developing foundational competencies, particularly in SC's solar-hydrogen niche, where programs like this can train an increasing number of students each year to support initiatives such as the Southeast Hydrogen Hub, thereby mitigating a projected 20% workforce shortage in clean energy roles [17]. The other histogram 3 **(Figure 3)** shows the prevalence of key qualitative themes identified from student responses, with strong representation of interdisciplinary learning, research skills, and perceived career relevance. These findings reinforce the program's role in building foundational competencies aligned with South Carolina's emerging solar–hydrogen workforce needs.

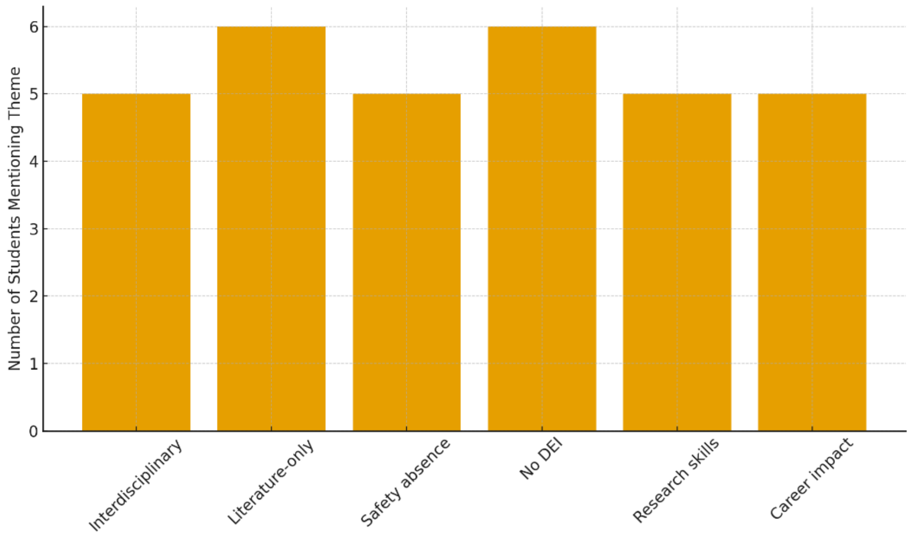

Figure 3. Prevalence of major qualitative themes identified from open-ended responses.

3.3. Qualitative Themes: Interdisciplinary Learning and Workforce Readiness

Thematic analysis of open-ended responses yielded three dominant codes: (1) interdisciplinary integration (mentioned by 100% of students), (2) technical and safety empowerment (83%), and (3) career alignment with SC's hydrogen future (67%). Capstone projects on the hydrogen value chain were pivotal, with students like #1 noting how they "revealed how technical, economic, environmental, and policy considerations must be integrated," echoing the need for holistic skills in SC's manufacturing-driven economy (e.g., Boeing's sustainable aviation fuel via green ammonia) [18]. Student #5 highlighted "integrating diverse fields like engineering and economics," underscoring H_2EDGE's role in preparing for interdisciplinary challenges like scaling photocatalytic ammonia synthesis, critical for SC's $500 million fertilizer market reliant on fossil-derived NH_3 [19].

Curriculum modules, such as "Basic Hydrogen Science," enhanced understanding of decarbonization, with 67% (4/6) describing them as "revolutionary" for linking theory to applications such as power generation. Student #2 praised their illumination of "decarbonizing technology like hydrogen fuel cells," which directly ties to SC's solar potential for off-grid production, where H_2EDGE's hands-on simulations could yield 10% efficiency gains in local pilots [20]. Safety engagements with the Hydrogen Safety Panel were transformative, with 83% emphasizing its "importance" for real-world risks, vital for SC's expanding infrastructure, including Volvo's planned H_2 refueling stations, where mishandling could cost millions [21]. Student #3's candid "the research was solely literature research" flagged a gap in experimental access, suggesting that future H_2EDGE iterations incorporate low-cost photocatalytic kits to simulate industrial settings better.

Mentorship and the "Connect the Dots" workshop fostered equity, with 50% (3/6) crediting them for broadening industry awareness (e.g., DOE hubs, EPRI networks). Student #1 reflected on "viable hydrogen solutions" through mentorship, aligning with SC's need for diverse talent: H_2EDGE at SCSU (an HBCU) could diversify the 70% male-dominated hydrogen workforce, supporting state goals for inclusive 10,000-job creation by 2030 [22].

Overall, qualitative data reinforced quantitative trends, demonstrating H_2EDGE's efficacy in building readiness for SC's hydrogen boom, in which solar-driven production could leverage 2,200 annual sunshine hours to generate 1 Mt H2/year, thereby powering 20% of industrial needs [23].

3.4. Integration of Findings: Implications for South Carolina's Hydrogen Landscape

This study employed a convergent mixed-methods design in which qualitative and quantitative data were collected simultaneously at program completion, analyzed independently, and integrated during the interpretation phase. Quantitative survey results (e.g., satisfaction scores, participation rates) provided measurable indicators of program impact, while qualitative themes explained underlying student perceptions and contextualized numeric trends. Integration occurred through triangulation, comparing statistical outcomes with thematic findings to strengthen explanatory validity.

Triangulating qual-quant data reveals H_2EDGE's holistic impact: High satisfaction (7.8/10) correlates with themes of empowerment, yet variability (e.g., Student #3's low scores) signals the need for experiential enhancements. In the SC context, where hydrogen could decarbonize 40% of manufacturing emissions (e.g., via photocatalytic NH_3 for Boeing composites), these outcomes position SCSU as a talent pipeline [18,24]. The program's emphasis on safety (83% gain) and industries (83% exposure) addresses local risks, such as those in the $1.5B clean energy sector. At the same time, workforce development workshops mitigate barriers for underrepresented groups, ensuring equitable access to roles with a median salary of $80,000 or more [25]. Limitations include a small sample size (n=6) and potential self-report bias; future studies could consist of 20 or more participants with pre- and post-tests.

In conclusion, H_2EDGE exemplifies scalable education for SC's solar-hydrogen future, where programs like this are indispensable for translating abundant sunlight into economic vitality. By nurturing interdisciplinary innovators at SCSU, the university not only fills immediate workforce gaps but also seeds long-term leadership in a field poised to redefine the state's energy identity. In this contact, the analyzed histogram 4 **(Figure 4)** illustrates the program delivery formats experienced by student participants, indicating a predominant reliance on virtual and hybrid instruction. While this format enabled broad accessibility and supported the program's scalability within South Carolina, the limited exposure to hands-on laboratory activities aligns with observed variability in student satisfaction. It underscores the need for expanded experiential components. Integrating additional in-person laboratory experiences could further strengthen skill acquisition and better prepare participants for safety-critical and industry-facing roles within the state's emerging hydrogen economy.

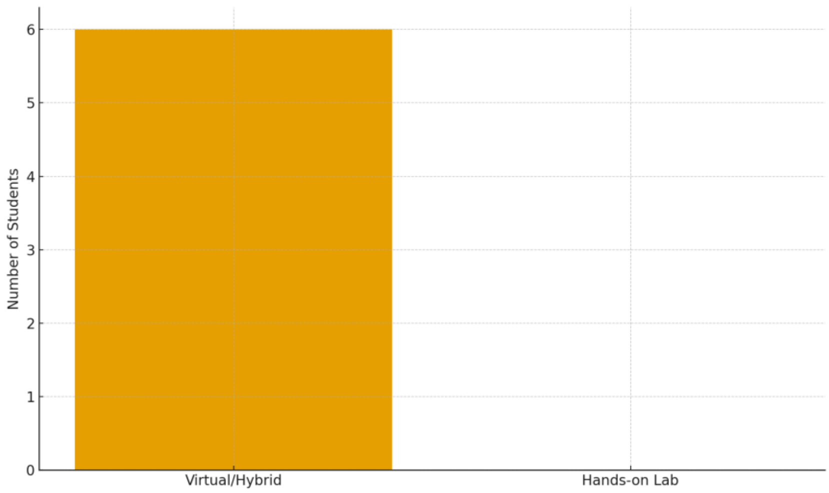

Figure 4. The program delivery format experienced by student participants.

4. Discussion and Limitations

The 2025 pilot successfully delivered foundational knowledge on hydrogen and strengthened research literacy through a low-cost, fully virtual format, valuable outcomes for an inaugural offering at a minority-serving institution. However, the complete absence of laboratory experimentation, formal safety training, industry mentorship, and workforce development activities resulted in only moderate participant satisfaction and limited workforce readiness. These constraints are openly acknowledged as characteristic of a resource-constrained pilot phase.

Limitations include a small sample size (n=6), a single institution setting, self-reported data, and the absence of pre- and post-assessments. The cohort was competitively selected based on academic performance and expressed interest in hydrogen and clean energy research. Consequently, participants may represent highly motivated and academically prepared students, introducing potential selection bias. Therefore, reported satisfaction levels and perceived learning gains may not generalize to a broader undergraduate population. Future cohorts will include a larger and more heterogeneous sample to evaluate scalability and generalizability.

5. Conclusions and Recommendations

The 2025 H_2EDGE pilot at South Carolina State University offered a clear-eyed demonstration of what hydrogen education can accomplish at a minority-serving institution working within genuine resource constraints. The findings point in two directions at once, and both matters.

On the positive side, the program successfully built foundational knowledge of hydrogen technologies, developed graduate-level research literacy, and for five of the six participants, strengthened interest in clean energy careers. For students with limited prior exposure to hydrogen science, and for an institution launching this initiative for the first time, these outcomes represent a meaningful starting point. The structured combination of classroom instruction and faculty-mentored small-group sessions proved effective for the goals it was designed to meet.

At the same time, the gaps were consistent and cannot be set aside. Every participant confirmed that the research experience was confined to literature review. Most reported no interaction with the Hydrogen Safety Panel and no access to the workforce development activities that the broader H_2EDGE framework promises. One student chose not to pursue hydrogen research further, citing the lack of hands-on work as the deciding factor. The program, in its 2025 form, built awareness and interest, but stopped short of building readiness.

Closing that gap is the work of the next iteration. Based on the evidence gathered from this pilot, five targeted enhancements are recommended for future H_2EDGE cohorts:

Integrate hands-on laboratory components: Low-cost bench-top electrolysis or photocatalytic demonstration kits would give students direct, physical contact with the materials and processes they study. These do not require a fully equipped research facility, they require planning and modest institutional investment.

Make safety training a program requirement: The Pacific Northwest National Laboratory (PNNL), a U.S. Department of Energy national laboratory based in Richland, Washington, and a leading center for hydrogen safety research, offers free, self-paced safety training modules through its H_2Tools platform. These modules cover hydrogen properties, handling protocols, and risk mitigation strategies relevant to both research and industry settings. Requiring their completion as part of the H_2EDGE curriculum would directly address one of the most consistent gaps students identified and would align the program with the safety culture that hydrogen workforce roles demand.

Build in structured industry engagement. At least two virtual sessions with hydrogen industry professionals, drawn from DOE networks, EPRI connections, or regional employers, would help students connect classroom knowledge to real career pathways. These sessions are practical within a virtual format and would partially compensate for the absence of the workforce development workshops that did not occur in 2025.

Deliver the "Connect the Dots" workshop as intended. This workshop, central to the H_2EDGE design, is meant to help students map hydrogen career pathways and connect technical skills to workforce opportunities across sectors. It was absent from the 2025 pilot entirely. Future implementations should treat it as a required program component, not an optional add-on.

Expand the cohort and add pre- and post-program assessment. A sample of six students, competitively selected for academic strength, is sufficient for an exploratory pilot but not for drawing generalizable conclusions. Future cohorts of 15 or more participants, recruited from a broader range of academic backgrounds, combined with pre- and post-program knowledge and skills testing, would allow the program to track actual learning gains and evaluate whether outcomes hold across a more representative undergraduate population.

With these enhancements in place, H_2EDGE has a genuine opportunity to grow from a promising pilot into a replicable, high-impact model for hydrogen education at HBCUs and minority-serving institutions nationwide, institutions that serve the students most likely to shape what the clean energy transition looks like in the communities that need it most.

Acknowledgements

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