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Student-designed greenhouse for sustainability competencies

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Abstract: This case study describes a student-led campus sustainability initiative to design and implement a power-generating greenhouse at Allegheny College. The design of the greenhouse was carried out by students in collaboration with professionals in a variety of learning settings including research seminars, independent studies, paid internships, and senior thesis projects. By providing a detailed account of the student-driven design process and structuring the analysis around a framework of documented sustainability competencies, this paper identifies challenges and opportunities for utilizing living labs for sustainability education. Researchers observed that students who contributed to greenhouse development in multiple capacities developed several sustainable competencies. The project also demonstrates the difficulty of engaging students in both the planning and implementation stages of multi-year efforts. While the student-led design process introduced new logistical challenges, deep levels of student commitment and unique student backgrounds were critical to the greenhouse project's success.

Keywords: Campus sustainability, sustainability competencies, education for sustainable development, luminescent solar concentrator, living learning laboratories.

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Introduction

Experts agree that education is critical to the creation of a more sustainable society (Cortese, 2003; Lockhart, 2018; Sterling, 2001; United Nations Educational, Scientific, and Cultural Organization, 1997), but a growing number of educators and professionals argue that conventional classroom settings may not adequately prepare students for real-world problem solving (Ciriminna, Meneguzzo, Pecoraino, & Pagliaro, 2016; Rittel and Webber, 1973; Frisk and Larson, 2011; Mertens, 2015). Critiques echo a call from Debra Rowe (2008) to move beyond the teaching of critical thinking and to help students develop "change-agent skills" (p. 323). As a result, education institutions around the world are exploring new, applied, and interdisciplinary education models while also developing language to describe the best forms, practices, and goals of education for sustainable development (ESD) (Lockhart, 2018; Leal Filho, Manolas, & Pace, 2015; Glover, Peters, & Haslett, 2011).

As David Orr (1997) pointed out, "the curriculum embedded in any building instructs as fully and as powerfully as any course taught in it" (p. 597), and campus infrastructure can serve as a valuable educational tool. Colleges and universities contain the human and physical resources needed to put new systems and infrastructure into practice. More importantly, they host communities that can achieve deep cultural shifts in systems, ideas, and behaviors. When these shifts occur, campus cultures can influence other institutions and facilitate the spread of ideas into local and regional communities (Cortese, 2003).

A framework for harnessing the higher education campus as a learning tool is provided by the living learning laboratory model (American Association of Community Colleges' SEED Center & the US Green Building Council's Center for Green Schools, 2014; Evans, 2015; König, 2013; Zen, 2017). In a living learning laboratory (or living lab for short) interventions are staged in real-world settings to develop and test new systems and behaviours (Ballon, Pierson, & Delaere, 2005; Ballon & Schuurman, 2015; Eriksson, Niitamo, & Kulkki, 2005; Leminen, Niitamo, Westerlund, 2017; Leminen, Westerlund, & Nyström, 2012). Projects often address physical infrastructure, but past efforts have also used this approach to address social systems and influence human behavior (Hossain, Leminen, & Westerlund, 2019; Mohamad et al., 2018).

Allegheny College, located in Meadville, PA, has successfully engaged students in several living lab experiences for education and campus sustainability (Pallant, Boulton, & McInally, 2012). Recent efforts include the student-aided renovation of a LEED-certified academic building, a successful behavioral change campaign that is led annually by students (Boulton, Pallant, Bradshaw-Wilson, Choate, & Carbone, 2017), and the development and implementation of a mobile food market (Erwin, 2016).

This case study will introduce a living lab initiative that developed and implemented a power-generating greenhouse at Allegheny College. The student-led project resulted in a new structure that impacted food and energy systems on campus while providing a variety of real-world learning experiences for undergraduates. This article will describe the design process and the learning experiences provided by the greenhouse and then reflect on the educational benefits and challenges of a student-led project of this scale and complexity.

Living Labs

Westerlund and Leminen (2011) define living labs as "physical regions or virtual realities where stakeholders form public-private-people partnerships (4Ps) of firms, public agencies, universities, institutes, and users all collaborating for creation, prototyping, validating, and testing of new technologies, services, products, and systems in real-life contexts" (p. 20). The vast majority of living lab examples emphasize the co-creation of systems and knowledge with stakeholders in a given territory (Bergvall-Kareborn & Stahlbrost, 2009; Følstad, 2008; Hossain et al., 2019; Leminen & Westerlund, 2016; Mulder, Velthausz, & Kriens, 2008; Voytenko, McCormick, Evans, & Schliwa, 2016). As these characteristics suggest, living labs can exist in a variety of settings for a range of research applications. Nevertheless, living labs have a long history of being employed in academic settings (Leminen et al., 2017) and focusing on systems for sustainable development (Bakıci, Almirall, & Wareham, 2013; Hossain et al., 2019; Nevens, Frantzeskaki, Gorissen, & Loorbach, 2013; Nystrom, Leminen, Westerlund, & Kortelainen, 2014; Leminen & Westerlund, 2016; Rodrigues & Franco, 2018).

When implemented on college and university campuses, living lab projects are often horizontally coordinated, where multiple students and/or courses contribute to the effort in complementary ways (Evans, 2015). They may also be vertically coordinated so that portions of the project are handed off to new groups of students over multiple semesters (Evans, 2015). Living labs often partner students and researchers with external stakeholders, and when utilized in sustainability programs, these partnerships can address environmental challenges in sustained and holistic ways (Evans, 2015; König, 2013; Zen, 2017).

The applied and experimental nature of living lab research could be used to provide a number of unique learning opportunities for students. Most notably, the approach is compatible with problem- and project-based pedagogies, where students collaboratively solve applied challenges, shape their own discovery processes, and engage in focused reflection (Carlson & Sullivan, 1999; Herselman, Marais, & Pitse-Boshoman, 2010; Justice & Do, 2012). These active learning approaches have been shown to develop skills for problem-solving, collaboration, and self directed-learning (Blumenfeld et al., 1991; Hmelo-Silver, 2004; Kokotsaki, Menzies, & Wiggins, 2016; Mills & Treagust, 2003). Living labs also provide real-world experience for students entering the job market (Evans, 2015).

For these reasons, a number of higher education institutions are opening up campuses to living lab interventions. Students in Malaysia restored a polluted campus lake and developed a water management plan (Mohamad et al., 2018). Students in Barcelona Spain designed and constructed a solar-powered residence that was used to explore green lifestyles (Masseck, 2017). A living lab in Finland developed software to reduce food and water consumption on their campus (Palacin-Silva, Seffah, & Porras, 2018), and the British University in Egypt opened up its campus for students to design a low cost and low impact refugee camp (Dabaieh, Mahdy, & Maguid, 2018).

In the United States, several institutions including Carleton, Middlebury, Pomona, Williams, and Amherst Colleges used student labs to evaluate and develop renewable energy technologies on campus (Cleveland, Müller, Tranovich, Mazaroli, & Hinson, 2014; Finley-Brook, Zanella-Litke, Ragan, & Coleman, 2012; Savanick, Strong, & Manning, 2008). Students at the University of Minnesota and George Mason University designed and implemented wetland restoration programs on their campus grounds (Savanick, 2004; Ahn, 2016). Projects at North Carolina State, Greensboro, and the University of California, Santa Barbara were instrumental in developing local food systems for their college communities (Andreatta, 2005; Cleveland et al., 2014). These are just a handful of examples that demonstrate a variety of student-driven campus interventions.

While projects such as these have been well documented, more literature is needed to assess the learning benefits of such programs. Most literature emphasizes the research process and the novel systems developed by living labs, and relatively few have detailed the student experience or connected living labs to specific ESD learning outcomes (Beecroft, 2018; Krutli, Pohl, & Stauffacher, 2018; Schapke et al., 2018). Moreover, campus initiatives are often presented in the literature as one-off experiences with self-contained contexts, challenges, and learning outcomes, making it difficult to use these project inform larger programs of study (Beecroft, 2018). Documented sustainability competencies provide one set of analytical tools that can be used to assess living lab experiences and design new programs that contribute to sustainability education in more sustained and reproducible ways.

Sustainability Competencies

The last two decades have seen the development of sustainability competencies that attempt to organize the varied concepts, skills, and experiences required for real-world sustainability work. While these categories may be more abstract than specific learning outcomes, they generate a framework from which we can understand and assess sustainability education using a common language. For the purposes of the discussion in this article, we employ the following definition of a sustainability competence derived from the ideas of Baartman et al. (2007), Barth et al. (2007), and Wiek et al. (2011):

> *A collection of knowledge, skills, experiences, and perspectives that empower individuals to address real-world sustainability challenges.*

One notable list of sustainability competencies that will be central to the discussion in this case study was compiled by Wiek, Withycombe, and Redman (2011), who identified recurring themes in ESD literature. The result was a set of five key sustainability competencies that are listed and briefly described below:

1. Systems-thinking competence - One defining characteristic of 21st-century sustainability challenges is that they often involve complex and interconnected human and environmental systems. In order to address these challenges, problem solvers need to be able to identify points of intervention and predict the consequences of disruptions to these systems. As a result, many education programs provide experience thinking across temporal and spatial scales as well as navigating different organizational structures and system types. Systems-thinking competence encompasses the specific knowledge, skills, and perspectives that support this understanding of systems. Wiek et al. (2011) define it as "the ability to collectively analyze complex systems across different domains (society, environment, economy, etc.) and across different scales (local to global), thereby considering cascading effects, inertia, feedback loops, and other systemic features related to sustainability issues and sustainability problem-solving frameworks" (p. 207).

1. Anticipatory competence - Sustainability efforts require the ability to envision future scenarios created by different interventions. Planning documents, modeling, narratives, imagery, mapping, and a variety of other tools can be essential to compare the approaches and efficacy of future actions. Even when projects do not require the development of original future models, sustainability actors still need to interpret available information in order to articulate clear interventions, understand context, and identify key determinants of success. Wiek et al. (2011) group these skills and experiences under anticipatory competence and formally define it as "the ability to collectively analyze, evaluate, and craft rich 'pictures' of the future related to sustainability issues and sustainability problem-solving frameworks" (p. 207).

2. Normative competence - Interventions on behalf of sustainability almost inevitably require compromise due to competing social, environmental, and economic interests. Sustainable solutions therefore require value-driven judgment calls that rely on normative notions of justice, equity, and ethics. Educators may train students to identify these judgments, understand multiple stakeholder perspectives, and navigate situations that require negotiations and trade-offs. Experiences like these develop what Wiek et al. (2011) call normative competence, or "the ability to collectively map, specify, apply, reconcile, and negotiate sustainability values, principles, goals, and targets" (p. 209).

3. Strategic competence - The concept of strategic competence stems from the need to put knowledge into action. When sustainability interventions are implemented, actors require an understanding of the barriers, opportunities, organizational structures, and logistical

considerations involved. Once the process is in motion, it also requires adapting, recognizing setbacks, and incorporating lessons learned for long-term project success. Wiek et al. (2011) define strategic competence as "the ability to collectively design and implement interventions, transitions, and transformative governance towards sustainability" (p. 210).

4. Interpersonal competence - Finally, we have the strategies and experiences necessary to navigate the interpersonal demands of sustainability work. Disruptions to existing systems will inevitably impact multiple stakeholders with different histories, concerns, and goals. Collaborations require leadership, team building, and interdisciplinary coordination. All of these demands require clear and respectful communication as well as the ability to understand the many perspectives contributing to challenges and solutions. According to Wiek et al. (2011), interpersonal competence is "the ability to motivate, enable, and facilitate collaborative and participatory sustainability research and problem-solving" (p. 211).

These competencies provide a framework for constructing and evaluating sustainability programs using a common language, and this can help to identify avenues for program improvement. As Wiek et al. (2011) have pointed out, one challenge for educators is to move beyond the teaching of individual competencies and towards the teaching of multiple competencies that all support a particular end goal. One benefit of living learning laboratories is that they provide an opportunity to link multiple competencies together in cohesive learning experiences.

In the following sections, this article will introduce the greenhouse design project carried out by students at Allegheny College and employ the above sustainability competencies as a framework to discuss the learning opportunities that were supported by the living lab research process.

Greenhouse Description

To develop a local food economy in a northwest Pennsylvania climate, it is necessary to explore season extension through the use of energy-intensive greenhouses. With funding from Constellation, an energy provider based out of Baltimore, MD, students and researchers at Allegheny College designed a small-scale demonstration greenhouse featuring innovative technologies for the production and utilization of renewable energy sources. The roof of the greenhouse is composed of semi-transparent solar panels called luminescent solar concentrators (LSCs). These devices are able to generate electricity without negatively impacting the amount of photosynthetically active light reaching the plants below (Corrado et al., 2016). LSCs represent a unique tool that transforms what is typically an energy-intensive greenhouse operation into an energy-generating system. Students and faculty can monitor the electricity production of the panels through a real-time monitoring dashboard and develop production practices and goals that fit within this energy budget. Pelletized switchgrass, a native perennial that is locally cultivated on land unsuitable for food production, fuels a pellet stove to provide biomass space heating in the greenhouse. By combining LSCs, monitoring, and heating systems with a well-insulated building design, the Allegheny greenhouse demonstrates a new tool for food production that operates on underutilized energy sources in a completely carbon neutral manner. The completed "Carrden greenhouse," which is named after its proximity to Carr Hall, is depicted in Figure 1.

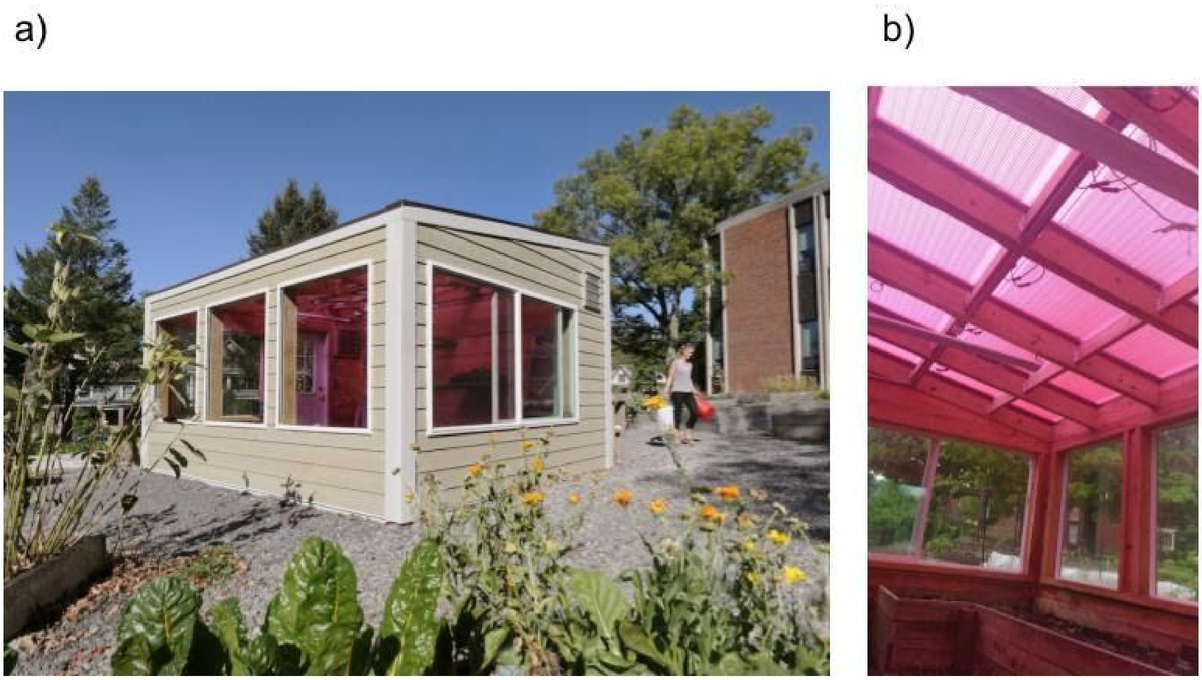

Figure 1. Exterior (a) and interior (b) views of the Allegheny Carrden greenhouse. The LSC panels convert green light into electricity and generate additional red light to be utilized by the plants underneath. The resulting spectrum gives the structure a pink glow.

The greenhouse project has produced a number of positive benefits for the Allegheny community. The structure serves as a stop on college admissions and campus sustainability tours. The daily operation of the greenhouse has allowed the campus garden to extend its growing season and increase food production for campus dining halls. Most notably, several Environmental Science and Sustainability courses have begun utilizing the greenhouse as an instructional tool for topics including photosynthesis, optics, solar-energy systems, season extension, and local food systems.

Researchers partnered with several organizations throughout this project and introduced companies and individuals to new technologies and collaborators. The installation of a switchgrass pellet stove means that Allegheny will continue to purchase locally grown and manufactured switchgrass pellets from Ernst Conservation Seeds, a native seed producer and supplier. Firth Maple Products, a local maple syrup and sustainable logging company, donated scrap lumber for the construction of raised beds and shelving units in the greenhouse interior. The greenhouse team worked closely with Soliculture, a California-based LSC start-up, to design and manufacture an LSC array specifically for the Allegheny greenhouse. Lucid, a building energy analytics company, and Allegheny's Information Technology Services staff collaborated to develop a real-time monitoring system for tracking energy production and consumption. Most significantly, researchers collaborated with Ceres Greenhouse Solutions to design a structure compatible with the LSC roof. Ceres had never encountered LSC panels before this project but has since explored future designs that utilize the technology.

Student Involvement

Like many campus infrastructure projects, the Allegheny greenhouse came about iteratively. The idea was first proposed in one of the Environmental Science and Sustainability Department's *Junior Seminar* courses, where instructors and students work collaboratively on applied environmental projects. In the spring of 2015, seven students and one instructor participated in a seminar section that explored applications of LSCs. After developing a basic understanding of the technology and interviewing stakeholders who operated and managed campus grounds, it was decided that the college would benefit from a greenhouse to support local food and electricity production. The class investigated Allegheny's food and energy systems in greater detail and began addressing the details of a proposed greenhouse structure. By the end of the semester, the research team produced a site assessment, budget, and proposal for the college administration to consider.

After the development of the initial proposal, a subsequent *Junior Seminar* course was vertically coordinated to study the greenhouse LSC technologies in greater depth. In the fall of 2016, a group of 12 students constructed prototype LSCs to explore the feasibility of fabricating the greenhouse panels in-house. While the final greenhouse LSC panels were purchased from a commercial manufacturer, the research carried out in this seminar informed the final design choices and provided students with an intimate understanding of LSC technologies.

After the development of the initial greenhouse proposal, several students who participated in the research seminars sought out opportunities to move the project forward. Even though the college curriculum did not afford more formal classroom experiences organized around the greenhouse, these students were able to stay involved by taking advantage of independent studies, paid internships, and senior projects that were coordinated horizontally and vertically with one another. As the project developed organically and built momentum, these students inevitably contributed to the project in new ways and developed skills that were not emphasized in their research seminars. The result was a scaffolded educational experience with several points of attachment to the project. To facilitate a discussion of the learning benefits afforded by this unique learning structure, it is worth describing the experiences of a few students in greater detail. For clarity and anonymity, we will refer to these students as Students A, B, and C in the text below.

Student A was introduced to the greenhouse project in their 2015 *Junior Seminar* course that developed the initial building concept. Like all members of this course, this student met informally with project stakeholders, researched greenhouse designs, and helped to prepare a budget and proposal. When it became necessary to form subgroups addressing specific design questions, Student A worked with a partner to assess possible locations and orientations for the greenhouse. To do this, Student A and their partner calculated sunlight availabilities using GIS tools that they developed in a previous course. By adding new skills to their established toolset, the two were able to generate a map of solar irradiance that covered the northwest section of campus containing the Environmental Science and Sustainability Department and campus garden. The seminar used this information to propose a location and orientation for the greenhouse, estimate annual power production, and develop a proposal for the college administration. Two site assessment maps generated in collaboration with Student A are presented in Figure 2.

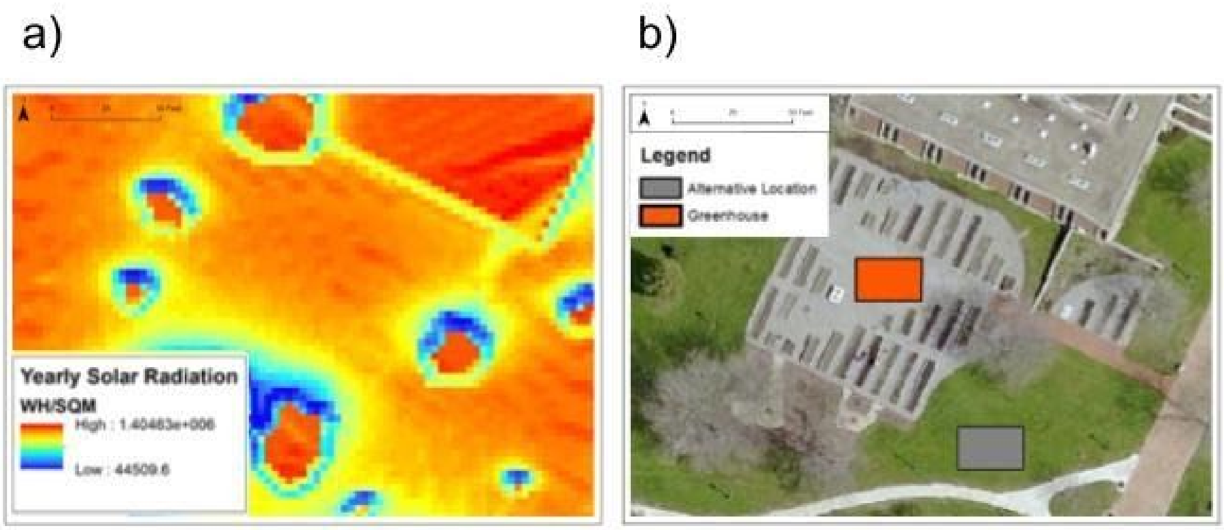

Figure 2. Sunlight availability map (a) and proposed greenhouse locations and orientations (b) created by Student A in the Spring 2015 *Junior Seminar*. The greenhouse was eventually constructed in the red region indicated in Figure 2b.

After the spring 2015 *Junior Seminar*, Student A applied for and received funds from the College administration to continue developing the greenhouse concept as a summer research project. The summer collaboration was spent working with a local architect and Allegheny's Physical Plant Department to put together a design and budget for a structure that met the sustainability goals of the original proposal as well as the college's aesthetic and maintenance requirements. After 10 weeks of summer research, the collaboration yielded blueprints and a budget for a design that incorporated the LSC system, insulated walls, and site proposed in the 2015 Junior seminar. This research provided a foundation for a successful grant proposal that would end up funding the rest of the project. Figure 3 contains an excerpt from the architectural plans developed in collaboration with Student A.

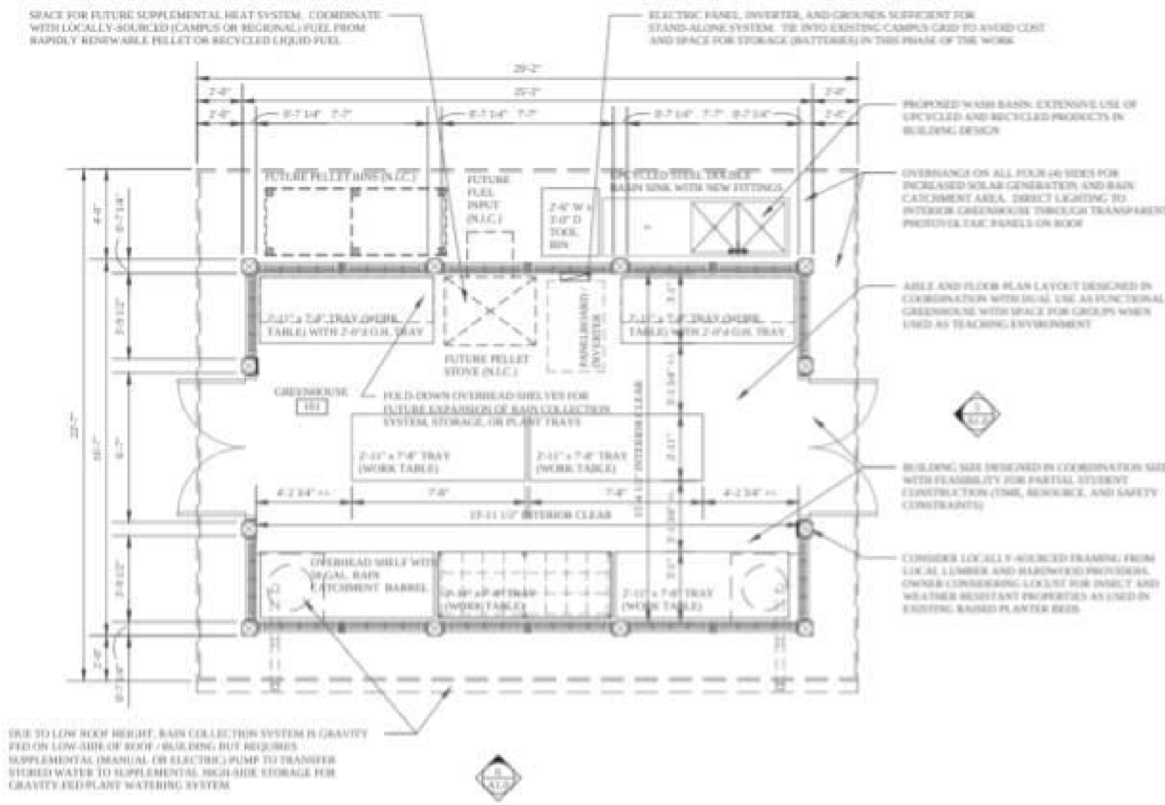

Figure 3. Architectural plan excerpt depicting proposed greenhouse interior. Student A worked in collaboration with a professional architect to develop detailed plans and a rough budget for a funding proposal.

Students B and C were also introduced to the greenhouse concept in a *Junior Seminar* course, but the research in their 2016 section was more narrowly focused on the LSC technologies that were eventually incorporated into the greenhouse roof. The two worked in a team of 12 to mix luminescent materials, characterize small-scale devices, and articulate a set of best practices for device fabrication. In the end, the class concluded that fabricating large-scale panels in-house was not practical, but the research process provided students with an intimate understanding of the technology and the characterization steps required to understand performance.

In the fall of 2017, the college received the E^2 Energy to Educate grant from Constellation to implement the greenhouse and to hire students to help lead the process. With these funds, the faculty member and the sustainability coordinator who were advising the project were able to recruit Students B and C to oversee the final design and implementation stages of the project. The students were employed as paid interns for 10 weeks during the summer of 2017.

Student B was hired to facilitate the construction process by working alongside paid contractors. This involved finalizing the details of the switchgrass heating system, introducing contractors to the roof technology and mounting system, and designing and constructing the interior gardening space. Student B was selected for this role, in part, due to their past experience building a house, blacksmithing, and working for Firth Maple Products, a local logging company specializing in sustainable harvesting practices. In a remarkable development, Student B was able to glean discarded lumber from Firth Maple Products in order to construct raised beds and shelving units inside the greenhouse. A few of these upcycled interior furnishings are depicted in Figure 4.

Figure 4. Interior of the greenhouse including raised beds and collapsible shelving units designed and constructed by Student B. Shelves and beds were constructed with reclaimed wood donated by Firth Maple Products.

Due to their past participation in garden education programs initiated by the college, Student C was hired to develop outreach materials so that the greenhouse could be promoted and incorporated into educational programming. This student-designed signage for campus visitors and created materials to train campus tour leaders. Student C also developed several lessons on food and energy systems that have been used to introduce students to the major environmental concepts explored by the greenhouse. In addition to several Allegheny courses, these materials have been used in activities with gardening groups and a horticultural course from a local vocational school. Figure 5 provides an example of signage prepared by Student C.

Figure 5. Example of signage located in, on, around the completed greenhouse. The structure is now a stop on campus sustainability tours and has been incorporated into Allegheny courses and community programming on energy and food systems.

The Carrden Greenhouse was finally completed in October of 2017 as a result of the direct contributions of more than 35 undergraduate students. Efforts were coordinated in both horizontal and vertical ways over the course of two years. It was a bottom-up project that was shaped and guided by student ideas. It was also an organic process with no plan to act on the structure at its original conception. In the next two sections, we will reflect on the ways in which student involvement shaped this campus sustainability initiative and benefitted from their unique learning experiences.

Student Leadership

One defining characteristic of the process outlined above is that the research was driven by student ideas throughout planning and implementation. One strategy that allowed students to be successful in these roles was the pairing of students with administrators, faculty members, suppliers, and contractors who supported them throughout the process. Student A worked alongside a professional architect while Student B worked with construction contractors. Student C collaborated with both the campus Garden Manager and Sustainability Coordinator, and all students were in regular contact with faculty members and physical plant staff. In this manner, students did not have to master all of the design and construction skills required to build a greenhouse themselves, but they did have to develop tools and knowledge to communicate effectively, make educated decisions, and understand the technologies, systems, and processes involved with greenhouse construction.

Student leadership had a number of important consequences for the design process. First, the implementation of the Carrden greenhouse was not as streamlined as many construction projects that are initiated by campus administrations. Rather than relying solely on contractors and professionals, students were tasked with gathering the knowledge and skills necessary to guide each step of the planning process. This facilitated student learning, but it also meant that the team often encountered unanticipated design challenges and had to regularly make significant revisions to greenhouse plans.

There were several examples of student setbacks throughout the greenhouse design process. The 2016 *Junior Seminar* fabricated LSCs before concluding that the final greenhouse would incorporate commercially available LSC panels. One student used their senior thesis project to design a waste vegetable oil space heating system that was eventually deemed too expensive and impractical by campus maintenance staff. Even Student A's architectural plans for the greenhouse were not used to guide construction. Though the drawings were a critical component of the grant application that ended up funding the project, the team ended up modifying a simpler design provided by Ceres Greenhouse Solutions in order to reduce cost. In all of these circumstances, it was critical to frame these setbacks as part of the research process so that students could recognize the value of their contributions to the final product. Informed design choices were enabled because students explored both viable and impractical options.

Despite the challenges mentioned above, student leadership was also one of the project's greatest assets, and the greenhouse benefitted from the unique backgrounds and strengths of the students who carried out the work. Student A was able to use their GIS background in order to produce an initial site analysis. Student B was able to use their construction and logging background to extend the project budget and physically construct furnishings for the interior of the greenhouse. Student C was able to use their previous experience working in the campus garden to frame the greenhouse as an educational tool grounded in the campus food system. The project originated from students who were rooted in the Allegheny College community and aware of its strengths and needs. Without the leadership of these students, the project would have lost this deep connection to local spaces and resources.

Student leadership also provided motivation for students to stay engaged and carry the project through to completion. Evidence suggests that psychological investment is cultivated when students are provided autonomy and ownership over their learning environment (Boud, 2012; Moore, 1973; Stefanou, Perencevich, DiCintio, & Turner, 2004). Students were given almost complete control over the greenhouse project in the initial research seminar courses, and several of these students continued to stay engaged until the greenhouse was completed. Five students stayed involved in the project through their senior years, and two have continued to contribute to this paper after graduation.

Student Competencies

The greenhouse project served as a unique educational tool due to its scale and the variety of learning opportunities it provided. To explore the educational benefits in greater detail, we reflect on the experiences of Students A, B, and C using the framework of sustainability competencies introduced by Wiek et al. (2011). While it could be argued that the learning environments, described above, facilitated growth in most or all of the major sustainability competencies, this analysis will focus on those that were most pronounced in each learning experience.

The *Junior Seminar* courses that developed the early LSC and greenhouse concepts emphasized the systems-thinking, anticipatory, and interpersonal sustainability competencies. During the process of developing project goals and methods, students developed conceptual models of energy, food, and economic systems in order to identify promising intervention strategies. In this manner, the seminars exercised skills for systems-thinking competence. These projects tested skills for anticipatory competence by requiring students to develop sunlight availability maps, device prototypes, budgets, and building plans. In this manner, students modeled local infrastructure, available technologies, and the possible futures that could marry the two. Both seminars also emphasized interpersonal competence by requiring students to work collaboratively with each other, college employees, and experts with knowledge of specific technologies and growing practices.

As the project developed beyond the initial seminars, Students A, B, and C were encouraged to engage with new competencies while still engaging with those that were emphasized in their seminars. When Student A worked closely with an architect to develop a design and budget, they were forced to grapple with the space limitations and budgetary and maintenance realities of implementing an unconventional structure. They also needed to balance food production, energy goals, and finances with the structure’s size, materials choices, and systems design. The summer work regularly required Student A to balance competing interests and to make value-informed design decisions. As a result, this student’s individual work heavily emphasized new skills and experiences for normative competence.

Student B also developed normative competence when finalizing the greenhouse design. In the early stages of Student B’s paid internship, the research team encountered significant budgetary challenges that threatened the fate of the project. Grant funds received only totaled 75% of what was requested for the project, and physical plant personnel objected to the proposed heating system design. Student B had to adapt the plan so that it could still be implemented and meet the project's food production and energy goals. This required Student B to revise the scale of the project, but it also provided opportunities for creative solutions like sourcing discarded wood to furnish the greenhouse interior.

Unlike most students who contributed to the project, Student B was also directly involved with the physical construction of the greenhouse, and this meant that they had opportunities to gather skills and experience for strategic competence. Student B was positioned in the construction crew in a leadership role. Not only did they put the building together, but they also problem solved on-site when LSC panels arrived broken and contractors prioritized other projects for weeks at a time.

In addition to emphasizing a greater range of competencies, continued project involvement allowed students to reinforce competencies in different capacities. Students A and B further developed systems-thinking and anticipatory competencies after their *Junior Seminars* as they planned for the structure's integration into campus systems and tackled specific design challenges. Most notably, Student C developed new interpersonal tools when they introduced the greenhouse to horticultural students from a local vocational school. In addition to developing the educational tools that were presented, Student C had to learn how to educate with these tools and communicate difficult concepts to those that were unfamiliar with the project.

The examples of Students A, B, and C highlight some of the challenges associated with providing sustained learning experiences rooted in labs. Individual research experiences are time- and resource-intensive. In the end, only six students were able to find opportunities to contribute to greenhouse development beyond their *Junior Seminars*. Among these students, only one individual (Student B) was able to engage in all five competencies in meaningful ways. We found that, despite the involvement of students throughout the project, its long duration and the limited number of learning opportunities surrounding the project made it difficult to engage the same students in both the planning and implementation of the greenhouse. These observations highlight the need to design living lab experiences that are capable of engaging a larger number of students in both the early and late stages of campus initiatives.

Conclusion

This case study describes a living lab research project to develop an innovative greenhouse at Allegheny College. While the student-led research process was less efficient than design work carried out by professionals, it supported deep levels of student commitment that allowed the project to sustain over a two-year planning process. The greenhouse design benefited from the unique strengths and backgrounds of student researchers, and this example demonstrates that students can provide effective leadership in campus projects of significant scale and complexity.

The Carrden greenhouse supported several learning opportunities for students who contributed to the project in leadership roles. Research seminars used to develop the greenhouse concept encouraged the development of systems-thinking, anticipatory, and interpersonal sustainability competencies. Students who continued to contribute to the project beyond their research seminars experienced unique learning environments with multiple attachment points to living lab research. Observations suggest that this scaffolded structure allowed students to explore more sustainability competencies in more varied contexts than they could have in their research seminars alone.

Despite the range of experience supported by the project, advisors struggled to develop opportunities for students to participate in both the planning and implementation stages of greenhouse development, and few students utilized the project to develop strategic competence. Future programs could potentially emphasize smaller projects or expose students to several campus initiatives at different stages of development in order to target a range of desirable sustainability competencies. However, living lab environments structured to meet specific learning objectives must also be careful to preserve student autonomy. Student leadership and deep levels of engagement shaped the Carrden greenhouse research process and benefited the final product. This example highlights the need for living labs to balance student-driven inquiry with specific research goals and educational outcomes. Similarly, future programs must also balance depth and breadth when training for multiple sustainability competencies.

This case study highlights several logistical barriers to student involvement in multi-year sustainability efforts. Even with external funding, the Carrden greenhouse could only support a handful of student experiences with multiple attachment points to the project. Living labs are often time- and resource-intensive and do not necessarily fit easily into program timelines and learning outcomes. These observations support the recommendation of Beecroft (2018) to more formally embed these experiences into sustainability departments and programs to increase access to hands-on sustainability education.

Some institutions are now developing models that successfully bringing living labs into undergraduate curriculum in more formalized ways. Arizona State University's School of Sustainability has developed a real-world teaching philosophy and has structured courses at all levels around applied campus and community sustainability projects (Brundiers, Wiek, & Redman, 2010). A more established model is provided by the Worcester Polytechnic Institute (WPI), which requires all students to carry out a junior level project "at the intersection of science, technology, and culture " (p. 1) and a senior-level project solving "problems typical of those to be encountered in their professional discipline" (p. 1) (Salazar et al., 2013). Several institutions have also dedicated buildings and other campus facilities to support multiple on-going living lab projects (Cianfrani et al., 2018; Evans, 2015; König, 2013; Zen, 2017).

As living labs continue to grow in scale and number, there is an opportunity for more institutions to formally incorporate campus sustainability projects that provide multiple attachment points for students. We must assess them critically while continuing to develop shared goals for ESD. In this manner, we can identify new strategies that better prepare students, improve institutions, and support the work that will make societies more sustainable.

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