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# Learnscapes for renewable energy education: An exploration of elementary student understanding of solar energy systems

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**ABSTRACT**

Integrating the built environment of the school is one avenue to deliver place-based energy education connecting abstract ideas with the physical environment. This study examined how and if an outdoor classroom (learnscape) with solar panels together with a six-week renewable energy unit supported students in developing conceptual knowledge of energy systems. Fourth grade classrooms from two schools, one with a learnscape and one without, within the same district enacted the unit. Student learning gains (n=97) were measured through model-based reasoning at four time points before, during, and after the unit. Students (n=12) were interviewed about their models. Students in both schools identified the main system components and sequences. However, learnscape students exhibited a more nuanced understanding of solar energy systems and explicitly cited the learnscape as a "teaching tool" for energy education. Findings suggest that the presence of sustainability features on the school campus can enhance student learning outcomes.

**Keywords:** renewable energy education, place-based learning, outdoor classroom, model-based reasoning

## INTRODUCTION

Understanding how energy is essential to our daily lives is a global focus across K-12 schooling (UN, 2015). Yet connections between energy usage within natural systems (such as ecosystems) and human use are rarely a focus in the science classroom (Kandpal & Broman, 2014). Without these connections, US citizens who hold little energy-related knowledge are likely to make emotionally driven, rather than knowledge-driven, decisions related to human energy consumption (Bang et al., 2000). However, it is critical that their decisions be knowledge driven and consider energy flow across human and natural systems given the importance of addressing global carbon emissions, which directly relates to human energy consumption (IPCC, 2021). Buildings, in particular, drive energy consumption and global carbon emissions (US DOE, 2015). Over one-third of global energy use and nearly 40% of global carbon dioxide emissions come from building construction and operation (GABC, 2018). To reduce these outputs, there is an increasing global trend to construct environmentally friendly buildings. These buildings typically include recycled-content materials, energy efficient design, renewable energy production, non-toxic finishes, and water conservation among other sustainable features.

Eco-friendly school buildings and practices are part of the green building movement, where US Green Building Council (USGBC) contains the "Center for Green Schools" (USGBC, n. d.) and integrates school design into the latest guidelines for green building design (Elkhapery et al., 2021). Green buildings and conventional buildings alike provide a potential setting for place-based sustainability education. Previous work refers to school buildings as "hidden curriculum" (Orr, 1997), "3D textbooks" (Taylor, 1993), or "teaching green buildings" (Cole, 2018). When the building itself becomes connected to learning, students are provided opportunities to build a rich place-based understanding about relationships between human and natural systems.

A challenge to teaching with green buildings is that facility upgrades are costly for school districts. However, in the absence of a green school building, evidence shows the potential for schoolyards to enhance environmental education efforts (e.g., Malone & Tranter, 2003; Ozguner et al., 2011). Schoolyard interventions can facilitate direct connections between human-built infrastructure and nearby nature. "Learnscape" is one term employed to describe outdoor classrooms that transform the schoolground itself into a learning environment (Tyas-Tunggal, 1997). Learnscapes typically have features such as edible gardens, wildlife habitat,

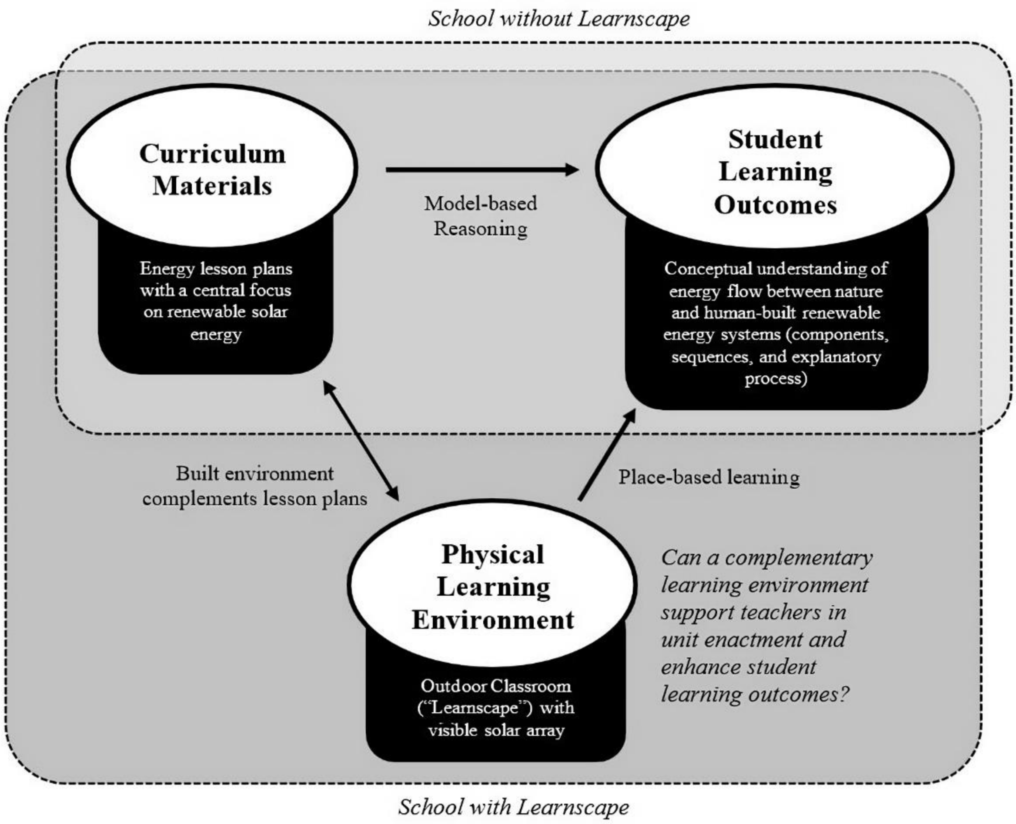



**Figure 1.** Theoretical framework linking physical learning environment, curriculum materials, and student learning outcomes (Source, Authors, adapted for the current study from Cleveland, 2009)

rainwater management, and sustainable energy. These features assist with the goal of encouraging student interactions with their local built and natural environments.

This study explores the possibility that an on-campus learnscape supports and enhances the development of conceptual knowledge about solar energy systems for elementary students. Fourth grade students (ages 9-10) developed and used models as reasoning tools (model-based reasoning [MBR]) to convey their understandings about the flow of energy between human and natural systems. We compared fourth grade classrooms in two different schools in one school district near a Midwestern US urban center. One school featured access to a learnscape on the school campus and the other school had a schoolyard with no learnscape. Both schools used the same unit focused on renewable energy, but the school with the learnscape had access to full-scale solar panels visibly connected to electrical outlets. The goal was to examine student development of conceptual energy knowledge, and the ways in which student models and MBR differed on solar energy systems.

## THEORETICAL FRAMING AND BACKGROUND LITERATURE

Elementary educators have few tools to teach energy systems qualitatively as a cross-cutting theme that conceptually links human and natural systems (Jorgenson et al., 2019). The topic of green building design, and specifically the subtopic of renewable energy systems, is well positioned to make these connections. The current study examines the potential for a learnscape, together with renewable-energy-focused lesson plans, to enhance elementary student conceptual understanding of energy systems with an emphasis on solar energy.

Our theoretical framework is informed by the Cleveland (2009) provocation to consider the "power of space and the influence it has over … learning" (Cleveland, 2009, p. 386). Cleveland's work contributed to the 'spatial turn' in educational research and provided a theoretical model for further development. In the Cleveland (2009) model, the influence of the physical space interrelates with other teaching tools used by teachers to augment and/or support their teaching actions. Within our theoretical framework, these tools serve as "vital artifacts" that support teachers in student learning goal achievement (Brown, 2011, p. 19). Therefore, our adapted teaching tools model includes: the *physical learning environment* and the *curriculum materials* as influences on *student learning outcomes* (**Figure 1**).

In the current study, the *physical learning environment* is the "learnscape" with eco-friendly features (where the solar array is the focus of the current study). The *curriculum materials* (i.e., "resources and guides used by teachers" [Remillard, 2005, p. 213]) were adapted by the research team and the teachers from existing materials to emphasize solar energy themes and integrate MBR. Finally, the *student learning outcome* of greatest interest was increased conceptual understanding of solar energy systems.

Using **Figure 1** as our guiding framework, we thus develop our theoretical frame from three bodies of theory and research. First, we review challenges and contemporary approaches to delivering energy education to enhance youth energy understanding. Second, we explore how MBR supports students to articulate their understanding about energy flow across human and natural systems. Third, we examine the potential for the built environment, specifically the outdoor classroom, to support place-based science education.

## Student Learning Outcomes: Energy Learning in Science Classrooms

In the current study, the student learning outcome of interest is the understanding of solar energy systems, which requires systems thinking. To understand how energy moves between human and natural systems, students must be able to trace energy flow. Yet, the challenges students have in tracing energy flow has been researched extensively (Chen et al., 2014). Prior work on students' energy ideas suggests that students struggle to understand energy concepts and are often unable to translate energy learning from the science classroom to their everyday lives (Duit, 2014). These findings may be because traditional models of energy instruction assumed that students develop energy ideas in a linear fashion. However, more recently, learning progression research suggests that students' ideas about energy and energy flow are woven together in "a complex networks of ideas" (Hermann-Abell & Deboer, 2018, p. 3) in which interrelated energy ideas are co-developed (Fortus et al., 2019; Tobin et al., 2018). Rather than testing students on isolated energy concepts, outcomes may focus instead on students' abilities to integrate and apply their energy ideas in increasingly complex ways over time (Jin & Anderson, 2012; Lacy et al., 2014).

To integrate and apply energy ideas, students benefit from opportunities to use their energy ideas within real world contexts. For example, Tobin et al. (2018) developed an energy unit where fourth-grade students used complex energy ideas about energy transfer and transformation to power a toy car with a solar cell. We extend this work for students to consider what and why of solar panels as a renewable energy technology, including the importance of solar panels to lessening the environmental impact of human energy consumption (Fallahhosseini, 2020; Liu & Park, 2014; NGSS, 2013). This involves learning energy ideas across different domains of science while also making connections to human systems. Students have opportunities to consider how and why societies harness and use non-renewable and renewable energy, what effects this may have on natural systems, and what options are available to individuals and societies for energy use (Hermann-Abell & DeBoer, 2018; Lacy et al., 2014; Liu & Park, 2014; NGSS, 2013). These concepts can then be localized to the student's own school building to consider how a solar panel can impact larger systems (e.g., energy grids and Earth's atmosphere) beyond the school building.

### *Renewable energy education*

Renewable energy systems comprise one knowledge domain within the vast possibilities for teaching energy systems to youth. Examination of conceptual knowledge of energy systems across human and natural systems has not been a strong focus in energy education research (Bodzin, 2011); the same is true of renewable energy systems. However, given the cross between human and natural systems, the concept of renewable energy systems (e.g., solar, wind, biofuels, hydropower, etc.) is a natural fit for teaching about energy in the integrated way promoted by the NGSS. Renewable energy education (REE) has the potential to deliver 3D learning at the heart of the US Next Generation Science Standards (NGSS, 2013) that includes disciplinary core ideas that cut across domains of science (e.g., across earth science, energy & matter, and engineering design). REE has fundamental aims to increase both knowledge and awareness of renewable energy systems, with the hopeful outcomes of supporting sustainable energy infrastructure projects and promoting future green workforce development.

Empirical evaluation of REE programs is scarce, with very little occurring prior to the year 2000, and much of the work situated in the Middle Eastern, Eastern European, and Australian contexts. Researchers over the last two decades have primarily identified themes and best practices for teaching renewable energy to adult learners in the university setting (Jennings, 2009; Jennings & Lund, 2001; Nowotny et al., 2018; Thomas et al., 2008). Studies in the K-12 setting show general awareness of renewable energy technologies, but an overall lack of in-depth understanding (Altuntas & Turan, 2018; Guven & Sulun, 2017; Zyadin et al., 2012). Most relevant to the current work, a mixed-methods study of 60 Turkish middle school students examined REE in a nature-based program (Buldur et al., 2020). The intervention in the Buldur et al. (2020) study was a nature education camp that was predominantly taught outdoors. It had an interdisciplinary focus that utilized the built environment with a variety of field trips to renewable energy power plants. The curriculum also included a few hands-on activities to learn about renewable and non-renewable energy sources. The dependent variable in the study was "renewable energy perceptions" (REP) using an adapted instrument from studies with adults. Buldur et al. (2020) found that the educational program increased awareness and positive perceptions of renewable energy projects, indicating that place-based, experiential learning that utilizes the built environment might have positive affective outcomes.

The current study builds on the Buldur et al. (2020) work by shifting the focus to knowledge-based outcomes. Our team has done preliminary studies examining energy literacy in the upper elementary and middle school contexts, where learners struggle to understand energy transfer or make distinctions between the various concepts of energy, electricity, power, and fuel (Cole et al., 2022; Duit, 2014; Liu & McKeough, 2005). Related to REE specifically, we have identified common misconceptions that students have about solar panels, including misunderstandings such as belief that solar panels do not work at night, they "save electrical energy," or they only power lights (Cole et al., 2022; Kishore & Kisiel, 2013).

## Curriculum Materials: An Emphasis on Model-Based Reasoning

The use of modeling in science education is an important way to support student learning of complex systems such as energy. Both models and modeling are important aspects of learning science, but they serve different functions. Models are representations that map onto reality; they are depictions of a "real thing" (Gouvea & Passmore, 2017). Modeling is the process of externalizing a mental model, which serves as a conceptual window into the ways in which students understand how and why the world works (Coll & Lajium, 2011). This cognitive tool then serves as a support for reasoning about the phenomenon (Tobin et al., 2018; Zangori & Cole, 2019). These externalized mental models support articulation of existing knowledge and forming links to new knowledge, while each completed model serves as a historical artifact of learning (Ainsworth et al., 2011; Nersessian, 2002; Tytler et al., 2020; Windschitl et al., 2008).

When students develop and use their own models to reason with, they are shifting into MBR as they are constructing, manipulating, and conjecturing causal accounts about phenomenon (Nersessian, 2002; Windschitl et al., 2008). This occurs through the act of drawing and writing about their drawings. We use modeling in the form of drawings because of the multiple affordances present within the act of drawing in science, such as considering how their drawings correspond to and are coherent with the scientific phenomenon (Ainsworth et al., 2011; Tytler et al., 2020).

Within MBR, students draw an initial model in response to a question or problem that links to scientific phenomenon (Schwarz et al., 2009). This model is developed using prior knowledge, which demonstrates their conceptual understanding of the interrelationships of the elements involved in the system, process, or phenomenon at that moment in time. We operationalize these interrelationships within three features that we call components (elements), sequences (connections between elements), and explanatory process (how and why it works this way) that are found in students' drawn models and writings (Minshew et al., 2022; Zangori & Cole, 2019). Students' *components* are the elements included in the model, which can be represented by words, numbers, drawn objects, or other symbols. Students then make connections between the components, where they may articulate the relationships that exist, which we term *sequences*. Finally, students identify the cause-and-effect occurrences with the underlying mechanisms through their articulated *explanatory processes* (Bechtel & Abrahamsen, 2005; Gilbert et al., 2000). Together these three features–*components, sequences*, and *explanatory process*–comprise the sense-making (i.e., MBR) that students are doing about key concepts and issues related to the phenomenon (Minshew et al., 2022; Zangori & Cole, 2019). Students iterate their models throughout lessons, and as their understanding about the hidden elements within the phenomena grows, they are able to develop models with increased explanatory power, so that their MBR grows in complexity (Bechtel & Abrahamsen, 2005; Schwarz et al., 2009; Zangori & Cole, 2019).

The term "curriculum materials" in our conceptual model (**Figure 1**) encompasses both the didactic and curricular dimensions of unit enactment. The term simultaneously invokes the curricular unit and the way in which a teacher chooses to enact that unit, acknowledging that many factors (internal and external to the teacher) potentially impact unit implementation (e.g., Brown, 2009; Remillard & Heck, 2014; Remillard, 2005). We further acknowledge that the participatory nature between the curriculum materials and the teachers' enactments are not easily untangled when examining student learning outcomes related to an intervention. However, our goal is not to untangle this relationship, but to see how augmenting this relationship with the additional tool of the physical space supports student learning outcomes. Learnscape is thus conceptualized here as a didactic tool that supports teacher enactment.

### Physical Learning Environment: Place-Based Outdoor Education in Learnscapes

Place-based education "focuses on using the local community as an integrating context for learning at all levels" (Powers, 2004, p. 17). Place is a broad construct that variously refers to social contexts (e.g., political, cultural, etc.), ecological contexts (e.g., climatic zone, nearby nature), and the physical built environments that sit at the intersection of people and nature (e.g., buildings and cities). Place-based education often focuses on breaking down the barriers between the school and the broader community to increase civic engagement for students and promote connections to local place (Powers, 2004). This latter outcome is often referred to 'sense of place' that can be cultivated in youth as a portal toward environmental stewardship later in life (Kudryavtsev et al., 2012; Sobel, 1997). Strong connections to local place have been shown to shift student attitudes, motivation, and engagement in the learning process (Powers, 2004). Place-based learning in the current study is localized to built infrastructure in the schoolyard where the schoolyard itself was designed to promote rich thematic connections between socio-technical and ecological systems.

#### *Learnscape as third teacher*

"Learnscape" is a term to describe schoolyards that promote human-nature interactions (Tyas-Tunggal, 1997). The school garden is the subject most emphasized in the literature, where school gardens have been shown to positively impact science achievement and food behaviors (e.g., Blair, 2009; Skelton et al., 2020). Built features, such as energy systems, have received less attention. These features, however, relate well to the emergent area of scholarship on green buildings as teaching tools for sustainability education.

The idea of the "environment as third teacher" has existed for decades as a feature of Reggio Emilia early childhood education (Hall, 2017), but only recently has been the subject of empirical work across grade levels (e.g., Cole & Hamilton, 2020; Fallahhosseini, 2020; Hamilton, 2020; Kong et al., 2014). Work to date suggests that the physical environment can indeed be a third teacher, but not without the teacher social dynamics that support a building occupant's consciousness of the physical environment (e.g., constructivist philosophies and engaged instructors) (Barr, 2011). Recent studies have found that the presence of visible green building features can engender basic awareness of green building practices, but not deep or lasting green building knowledge (Cole & Hamilton, 2020). These findings suggest that green building features will be best understood when used as educational tools for place-based learning that is orchestrated by educators.

Learning activities that are outdoors and/or off-site can present challenges to educators. Obstacles to outdoor learning beyond the school building include liability concerns for

**Figure 2.** Learnscape outdoor classroom images at Sunshine Elementary School (Source: Authors)

student health and safety, lack of funding, transportation, and a range of additional burdens on teachers. Utilizing the schoolyard for outdoor education reduces some of these obstacles given the ease of access and elimination of transit and unpredictable safety concerns. Despite potential challenges, the importance of taking students outside may be worth the effort, as the cognitive benefits of outdoor learning are well documented (e.g., Alexander et al., 1995; Mabie & Baker, 1996; Moore & Wong, 1997; Rahm, 2002; Rickinson et al., 2003; Sabet, 2018). Notably for the current study, outdoor learning has been connected to both science achievement and environmental sensitivity (e.g., Rios & Brewer, 2014). Connection between renewable energy systems in schoolyard and energy learning outcomes for youth is a novel contribution to this area of scholarship on place-based outdoor education.

### Summary

Elementary school educators have few tools to use to teach energy flow as a cross-cutting concept that conceptually links human and natural systems (Tsurusaki & Anderson, 2010). Overall, few curriculum materials are NGSS aligned and connected to the everyday environment (NAESEM, 2018). While the topic of green building design, and specifically the subtopic of renewable energy systems, is well positioned to make these connections, there is a general lack of research-based curriculum. The current study examines the potential for an on-campus learnscape, together with renewable-energy-focused lesson plans, to enhance Elementary student understanding of solar energy systems.

**Figure 1** depicts the conceptual framework for this study adapted from Cleveland (2009), showing the intertwined influences of the learning environment and a teacher-enacted curricular unit on student learning outcomes. Here we acknowledge the power of well-crafted curricular units and excellence in teaching and go the next step to question how and if a complementary built environment (e.g., learnscape) offers teachers yet another tool to enhance student understanding.

## MATERIALS AND METHODS

The research question guiding this study was: In what ways did students in schools with and without a learnscape differ in their conceptual understanding, i.e., their ability to use MBR about solar energy systems? Given the focus on conceptual understanding about energy flow in systems as a learning outcome, MBR served as an analytical tool to examine student learning outcomes about the interconnections between elements of natural and human systems. In the current study, natural systems include the sun, energy resources, and impacts to climate; human systems refer to human-built environments and human energy consumption. We use the term "solar energy systems" to describe the interconnected human-nature systems that include the processes of capturing sunlight (natural systems) to provide electrical power to buildings (built systems). Our hypothesis for this exploratory study was that the physical learning environment, the learnscape, would increase conceptual understanding of solar energy systems for students experiencing the fueling our future (FoF) unit.

### Study Design

This study is a pretest–post-test quasi-experimental study design (Reichardt, 2009) where the settings were non-equivalent. At one public elementary school, the fourth-grade students participating in this study had access to a newly constructed learnscape, while fourth-grade students at the other public elementary school who were enrolled in this study, did not. However, across both public elementary schools, the fourth-grade teachers taught the same curriculum materials over the same period. Data analysis followed an explanatory sequential mixed methods analytical process (Creswell & PlanoClark, 2011) to answer our driving research question. In the first phase of the study, we developed rubrics that used the dimensions of *components*, *sequences*, and *explanatory process* to score student models (n=97), and then used these scores as the basis for statistical analysis. In the second phase of the sequential study, we used qualitative analysis of student interview data (n=12) to enhance our interpretation of trends that emerged from quantitative data. We qualitatively analyzed students' models together with student interviews to generate richer explanations of the observed trends discovered in the quantitative analyses.

### Research Participants

This study takes place in two public elementary schools from the same school district in a town with a population of 55,000 on the metropolitan outskirts of a Midwestern urban center. The district was chosen because of the recent construction at Sunshine Elementary of a "learnscape" that was designed with numerous sustainable features such as native plantings, garden boxes, rainwater collection, and solar PV panels atop the main structure (**Figure 2**).

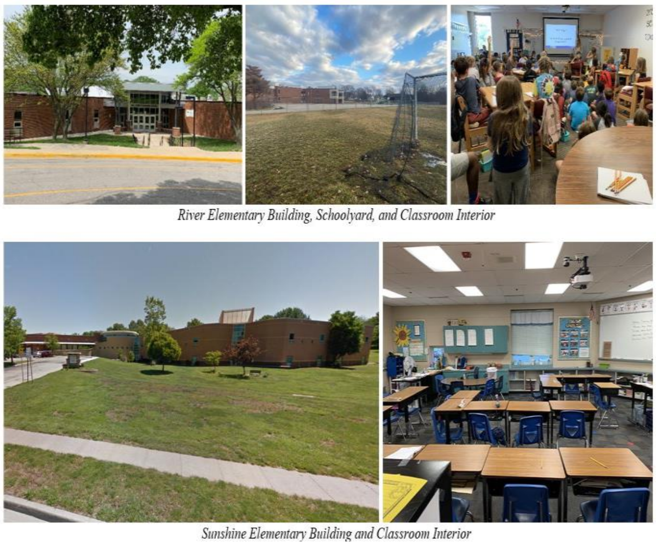



**Figure 3.** Exterior & interior images of participating elementary schools (Source: Authors)

The PV panels were designed in such a way that the components of the system were visible including the panels, battery storage, and a connected outlet. The staff at the district level recommended the second elementary school, River Elementary, identifying it as an equivocal match to Sunshine Elementary as determined by student achievement. In the year of this study, the Sunshine Elementary student population was 65% White, 13% Hispanic, and 9% Black with 7% of students as English language learners (ELL). The student population at River Elementary was 76% White, 8% Hispanic, and 5% Black with 7% ELL. The percentage of students with free and reduced lunch is 30% at Sunshine Elementary compared to 20% at River Elementary. The two schools are approximately 2.5 miles from each other. The school building design of both elementary schools followed district standards with comparable architecture and interiors (**Figure 3**). The key difference between the two contexts was the availability of learnscape at Sunshine Elementary, an outdoor classroom that was detached from main school building.

At the time of this study, the district had a sustainability coordinator, but no formal sustainability education program at the elementary (K-5) level. The district scope and sequence of content did not include renewable energy system instruction. The district science coordinator stated that no one in the district had received formal instruction on renewable energy systems at the time of this study. Learning about the sun in the context of plant and animal life was the closest connection to renewable energy that fourth grade students in the district would have experienced in their prior science instruction. Further, the learnscape was a new construction project where the design and construction were donated by a local architecture firm and community partners. Given the newness of the learnscape at the time of this study, teachers at Sunshine Elementary had not yet used the outdoor classroom in a formal way. Implementing unit for this study was their first experience in incorporating learnscape into science lessons.

## Curricular Context

This study took place over a six-week period and focused on the implementation of a curricular unit titled "FoF: Grades 3-5" (USGBC, 2020) in the two participating schools. The unit was implemented in all fourth-grade classrooms at both schools. Lessons were taught three-four days a week for about 40 minutes per class period, which totaled to approximately 20-22 days across six weeks (Banilower et al., 2018). Prior to unit selection, the research team evaluated available units for suitability and alignment with the NGSS and presented available options to the teachers. Of the three units presented, the teachers selected FoF. FoF was developed by Western Washington University to focus on biofuels (Facing the Future, 2015), where lessons emphasize hands-on learning over lecture-based learning.

We modified the unit to make specific place-based connections to the learnscape at Sunshine Elementary, and place-based connections at River Elementary where no learnscape was available. The final curricular unit with lesson sequence and activities is shown in **Figure 4**.

The key modifications included the insertion of place-based learning activities in weeks three-four that included:

(1) a school building tour with a behind-the-scenes look at energy systems,

(2) lesson 4 on renewable versus nonrenewable energy sources, and

(3) lesson 5 on solar power, where student teams learned about both passive and active solar energy systems, eventually constructing their own small solar-powered houses (**Appendix A**).

Another activity added to the unit was the solar energy guest speaker. This speaker was a solar panel installer who visited each school separately and taught about solar panels from residential to commercial scale applications and showed images and demonstrations.

The practice of scientific modeling (MBR) provided a window into students' development of conceptual energy systems understanding over the unit implementation. The purpose of this study was not to assess students' development of MBR, but rather to use MBR to assess their understanding of the link between the sun, solar panels, and energy. The team developed supplemental modeling lessons (Scientific Practices Research Group, n. d.; Zangori & Cole, 2019) to introduce students to using the 2-D diagrammatic modeling techniques. The supplemental modeling lessons were embedded within the unit at four time points as shown in **Figure 4** and the data collection process is detailed in the next section. The modeling packet instructions given to teachers emphasized that students were not to receive teacher support for how to approach their drawings nor given expectations of what the drawings should contain. The modeling packet teacher instructions also included a reminder for students that the modeling exercise was an ungraded activity.

Teachers attended a four-hour professional development (PD) session to provide feedback to the lesson modifications and discuss implementation. The final seven-lesson unit (**Figure 4**) was provided to all participating teachers. Each teacher was given a binder with lesson plan materials (with

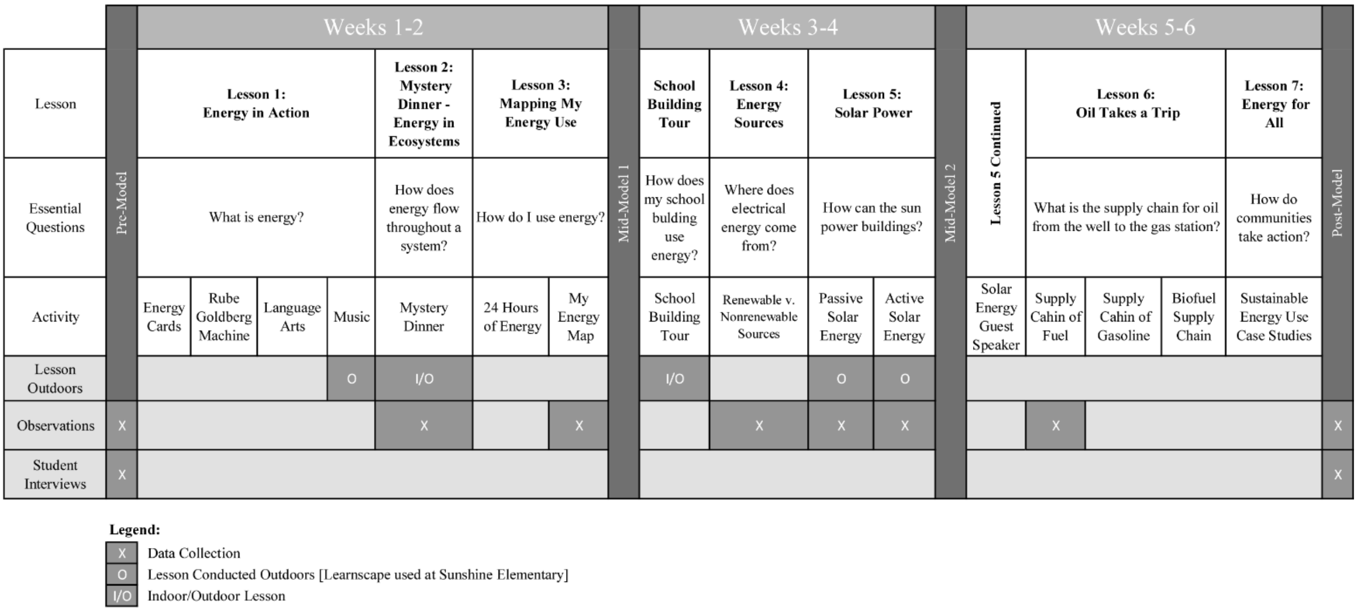



**Figure 4.** FoF unit outline (Source: Authors)

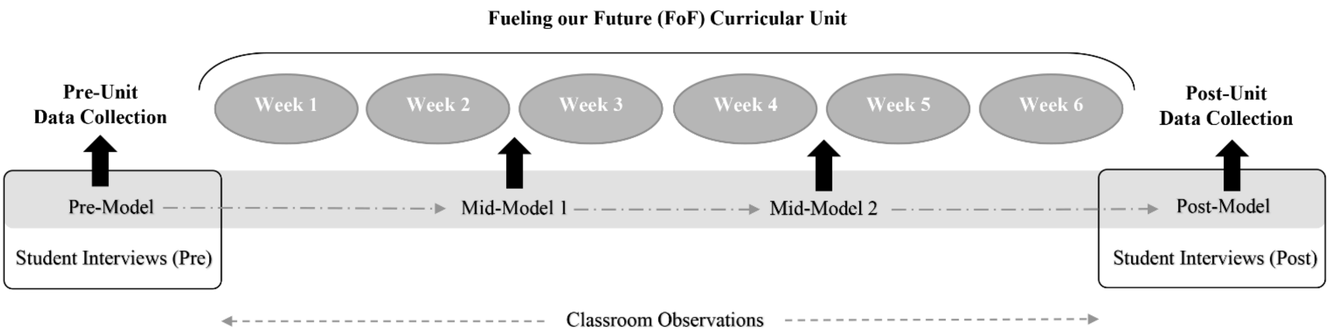



**Figure 5.** Data collection timeline (Source: Authors)

access to electronic files online) and a kit of materials for hands-on lessons. The same lessons were taught at both schools over the same six-week period. Across the two schools, the key implementation differences occurred during "Lesson 5: Solar power" when Sunshine Elementary teachers could take students outside to the learnscape. The learnscape outdoor classroom was used continuously throughout weeks one-four for the activities that occurred outdoors (**Figure 4**) and the learnscape is adjacent to the playground that students use daily, which meant that the solar panels were ever-present for students during the FoF unit. At River Elementary, where no solar panels existed, students were able to use the schoolyard for parts of lesson 5 and make observations about the location of the sun relative to their models. However, students at River Elementary did not have a 3D sample of solar panel installation on a real structure.

## Data Collection

The data collection process is diagrammed in **Figure 5**. Each school had three fourth-grade classrooms and thus six teachers total who participated in the study. Class size, and thus the number of participating students, was larger at River Elementary (n=58) compared to Sunshine Elementary (n=39). Various sources of student data were collected for this study. First, student artifacts created throughout the unit were collected, which included the student model drawings and writings. Second, we interviewed two students from each classroom for a total of 12 students for semi-structured interviews immediately following their completion of their pre- and post-models (24 interviews total).

The research team also observed teacher enactments across eight different days over the unit, dividing our time and team across schools and classrooms. Class periods were observed during each week of the unit, which resulted in four-seven observations per teacher and 32 total observations across the unit, where each observation led to one-two pages of field notes. The researchers met weekly to discuss classroom observations. When comparing memos during these meetings, the members of the research team detected no substantial differences among teachers. In addition to observations, our team did pre- and post-unit focus groups with teachers (n=6) and asked teachers to fill out a weekly online survey for the lessons taught. These data sources were used as important secondary data sources for understanding enactment differences. From these data sources, we found that lesson goals were maintained at both schools.

### *Student model drawings and writing*

The focus of analysis in this study is the packet of four modeling artifacts (pre-model, mid-model 1, mid-model 2, and post-model) from participating fourth grade students (n=97, 385 models). The prompt for student models was: *How does the sun power a building?* Students were instructed to: "Use the box on the following page to draw a model that shows your understanding of how sunlight can be used by humans to create power in buildings. Think of everything you have learned about in your classroom that helps you understand solar energy." Students were then prompted to

(1) include the most important parts of the system in their drawings and

(2) label their drawings with words.

Students drew to the same instructions and prompt at each modeling time-point. After students drew their models, they answered four reflective prompts about their models: what their model showed, how their representation worked, why what they represented mattered for the environment, and what their drawing helped them think about relative to sun and buildings. Data collection of the scientific models is informed by prior work using students' 2D diagrammatic models (e.g., Samarapungavan et al., 2017; Schwarz et al., 2009; Tytler et al., 2020; Zangori & Cole, 2019), and was incorporated here to focus on student conceptual understanding of solar energy systems. For each modeling lesson, students were given approximately 20 minutes to model and write. The modeling packets were collected and scanned by the researchers at the conclusion of the unit.

### *Student interviews*

Interviews were conducted with two students in each classroom (a total of six students in each school, n=12). The students were selected in consultation with teachers, who were asked to select two students who are expected to vary on academic performance from average to above average (avoiding outliers on both ends of the achievement spectrum) and provide gender diversity. Ultimately, the students selected were dominantly female (n=8) versus male (n=4). The same students were interviewed prior to the beginning of the lessons (pre) and then immediately following the six-week unit (post). The interviews contained questions about student energy understanding and energy behaviors at home (see the pre and post interview protocols in **Appendix B**). The interview main focus was the model drawings created by the student. The researchers walked through the drawing elements encouraging students to verbalize their understanding about elements in the drawings, links between elements, explanations of how the system works, and why it matters.

## Data Analysis

In keeping with the exploratory sequential-mixed methods analytical process, data analysis began with a quantitative analysis of the full set of student drawing data followed by in-depth qualitative analysis of models and student interviews.

### *Rubric development*

The research team met weekly to construct three holistic scoring rubrics to capture students' MBR. The rubrics were built for each feature of MBR: c*omponents, sequences, and explanatory processes*. The rubrics were informed by precedent literature:

(1) prior work examining students' MBR (Minshew et al., 2021; Scientific Practices Research Group, n. d.; Zangori & Cole, 2019),

(2) learning progression work on energy conceptual development (Hermann-Abell & Deboer, 2018; Jin & Anderson, 2012; Lacy et al., 2014), and

(3) standards related to energy flow and human impacts on Earth systems (NGSS Lead States, 2013; US DOE, 2017).

First, we determined the target explanation as the starting point for examining student understanding about the relationship between the sun and solar panels through modeling. The target explanation was defined, as follows:

> Solar panels are a source of renewable energy that do not require non-renewable fossil fuels. Renewable energy sources can reduce air pollution that contributes to climate change. Solar panels work best when oriented toward the sun. When sunlight comes into contact with the solar panel, energy is transferred from the sun to the solar panel. The energy is transformed by the solar panel into electrical energy. The electrical energy can be used to power anything that plugs into an outlet and requires electricity.

Second, we unpacked the target explanation for fit into *components*, *sequences*, and *explanatory processes* and defined target levels for each feature. For example, to support students in meeting the target explanation, they would need the following components: the sun with rays, a solar panel, wiring from the solar panel to an electric outlet, an electrical object plugged into the outlet, and the object working in some manner. Finally, we broke each rubric into levels that ranged from zero (lowest level) to the highest level of the characteristics necessary for students' understanding about solar energy systems to meet the target explanation. The lower levels were built considering the aspects of the sun to solar panel relationship that students would need to build to obtain the highest rubric level. Each rubric began at zero, where a score of zero indicated the construct dimension (component, sequence, explanatory process) was not present. The highest level for each rubric indicated that the dimension was well represented in the drawing and/or writing. It is additionally important to note that the three levels of the rubric are tiered as conceptualized in previous studies (Zangori & Forbes, 2016), where components are the base onto which sequences are mapped and explanatory processes are then articulated.

Once the rubrics were established, the team compared rubric scores across time points to explore potential progression of MBR over the implementation of the FoF unit. After data collection, we tested the rubrics by having two members of the research team individually score twenty-four students' drawings (four students from each class) as a pilot for the scoring process. Results were discussed with the team, which led to qualitative adjustments to the rubrics to better ground the analytical process for the collected data. We repeated the scoring process on the subset of drawings. Interrater reliability was then calculated with Cohen's kappa

**Table 1.** Rubric for scoring student model drawings and writings

| Description | Scoring levels |
|---|---|
| *Components:* A count of each element of the solar energy process that was shown in the drawing (or written about in the text). Sample components include the sun, sun rays, solar panels, wires, converter, battery, power box, and end use for electricity such as lights or electronics. Each unique component received one point up to 12 potential total points. | 0–0 components<br>1–1 component<br>2–2 components<br>3–3 components<br>…<br>12–12 components |
| *Sequences:* Assessment of students' demonstrated understanding of the links between components. The idealized relationships were (1) sun rays to the solar panel, (2) solar panel to the storage, (3) storage to the inverter, (4) inverter to the outlet, and (5) outlet to end-use inside a building. | 0–No links<br>1–One link<br>2–Two links<br>3–Three links<br>4–Four links<br>5–Five links |
| *Explanatory processes:* A holistic assessment across drawing and writing of students' demonstrated understanding of how and why the solar energy process works. We counted each unique reason the student mentioned about why solar power matters (e.g., pollution, climate change, saving non-renewable resources, etc.) | 0–No explanatory process<br>1–One reason and not accurate<br>2–One+ reason(s) & somewhat accurate<br>3–One+ reason(s) & well explained |

**Table 2.** Sample scoring for explanatory process

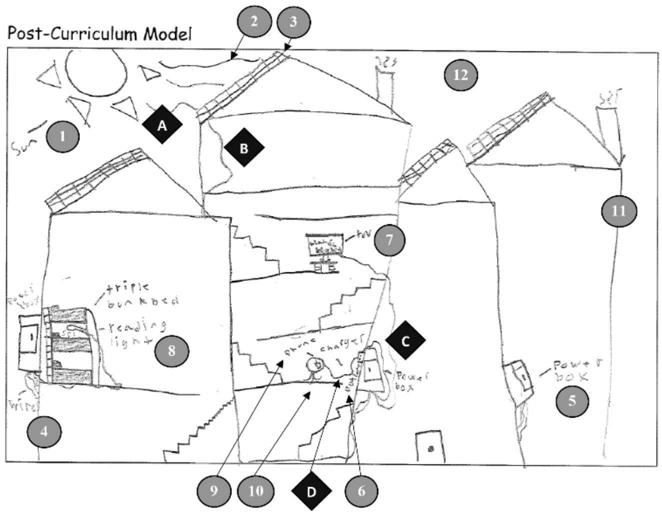
| Scores | Student explanatory process: Sample student responses to the question posed on model drawing worksheet: "This solar energy process helps the environment because …" | School |
|---|---|---|
| 0 | It (sun) helps the world be bright not dark and people can see things when there driving from the sun. | Sunshine |
| | We save time. | Sunshine |
| | It helps the house and that helps the house and the house and … | Sunshine |
| | We can have a lot of power. | River |
| | It helps you see. | River |
| | It's making more energy. | River |
| 1 | It gives us energy. | Sunshine |
| | It helps save energy. | Sunshine |
| | The solar panil (sic) make energy for many houses/buildings. | Sunshine |
| | It does not need wood. | River |
| | It can bring in light and that way we do not have to use are electricity so we can save it. | River |
| | We are using the sun to power a building. | River |
| 2 | It does not take fossil fuels. | Sunshine |
| | Instead of using a bunch of stuff to make electricity you are just using the sun wich is your natrel (sic) resources. | Sunshine |
| | We do not need to use other bas sorses (sic) of energy. | Sunshine |
| | It saves your money, there's less trash, and solar panels can last up many years, so it's reusable. | River |
| | It uses clean energy. | River |
| | It does not use gas. | River |
| 3 | The solar powered cars can use les gas/fuel and not pollot (sic) the environment as much as normal cars. | Sunshine |
| | It uses a renable resoure wich (sic) is the sun instead of using a nonrenoble resoure (sic). | Sunshine |
| | It doesn't polut the are or water (sic). | Sunshine |
| | Because what makes the energy is sunlight, water flow, and wind, and they are a renewable recorces. | River |
| | The suns power is renewabul (sic). | River |
| | If you use green energy it saves nonrenewbele enrg sorses (sic). | River |

coefficient to examine covariance between raters (0.900, p⩽0.001) and showed substantial agreement (Landis & Koch, 1977). The final rubrics are presented in **Table 1**.

### *Scoring analysis*

Each student drawing, with its written narrative, constituted one unit of analysis. Using the developed rubrics, frequencies of elements were counted and used for quantitative analysis (Kalvaitis & Monhardt, 2012). Models were scored manually, and scores were input into Excel as the researchers progressed through the drawing packets.

**Table 2** shows how samples of student writing were scored for explanatory process for each score 0-3 and **Figure 6** shows an example of how the rubric was applied to a student model. All scores were imported into RStudio: Integrated development environment (RStudio Team, n. d.) for analysis, the normality of the data was examined, and appropriate tests were chosen in consultation with a statistician. To explore the hypothesis that Sunshine Elementary students perform better at modeling solar energy systems over time, the 'lmer' function in the 'lmerTest' library (Kuznetsova et al., 2017) was used to develop linear mixed-effects regression (LMER) models with each rubric dimension (components, sequences, explanatory process). School and time points were input as predictors in each model to examine if predicts model drawing scores. Given that the rubric dimensions of components, sequences, and explanatory process are understood as a progression of complexity (where components demonstrate the most basic understanding and explanatory scores provide more complex thinking) (Zangori & Forbes, 2016), the rubric dimensions were included as predictors in the LMER models accordingly. Thus, component scores were input as a predictor




**Components score = 12**

1) sun, 2) sunray, 3) solar panel, 4) wire, 5) power box, 6) outlet (plug), 7) TV, 8) reading light, 9) phone, 10) charger, 11) house, 12) Neighborhood

**Sequences score = 4**

A) sun to solar panel, B) solar panel to power box (via wire), C) power box to outlet (plug), D) outlet to end use.

**Figure 6.** Sample rubric application to a student model drawing (Sunshine Elementary, Student: Will) (Source: Authors)

of sequences and components and sequence scores were input as an additional predictors of explanatory process scores. The LMER models were run with random intercepts and slopes, which allowed schools and time to interact to predict student intercepts and slopes. LMER models are useful when the data include violations of independence, such as the repeated measure design in this study (Bates et al., 2015; Kuznetsova et al., 2017). While testing assumptions, we found that the residuals for each model (components, sequences, and explanatory process) were not normally distributed; however, LMER models are robust to violations of distributional assumptions (Schielzeth et al., 2020). No other violations of assumptions were found. Given the potential variation across teachers, means were compared across teachers and rubric dimensions (components, sequences, explanatory) and no outliers were found.

### *Visible in learnscape*

We additionally isolated and quantified the types of features that were visible in the learnscape to examine the possibility that access to the outdoor classroom inspired the content in student drawings. The following components were considered as "visible in learnscape":

(1) battery storage,

(2) power box,

(3) outlet (plug), and

(4) converter as the components.

For sequences, we identified each of the following links a student could have drawn:

(1) solar panel to battery storage,

(2) battery to converter,

(3) converter to outlet, and

(4) outlet to end-use (e.g., lamp).

All student drawings were coded for the themes above and the scores of the components and sequences "visible in learnscape" were then totaled for each student at each point in time. This analysis was used to triangulate other findings in the qualitative and quantitative results.

### *Qualitative interview and focus group analyses*

Pre-post student interviews (n=12) and teacher focus groups (n=6) were transcribed and imported into Dedoose web-based qualitative analysis software. The student data underwent a two-phase coding process with extensive memoing. In the first round of open coding, the interview transcripts were coded line-by-line (Bernard et al., 2017) by a single researcher, a grounded analysis process that captured both expected topics and those not previously anticipated. The process of coding line-by-line ensures that the researcher remains close to the data without forcing findings prematurely into a preconceived framework (Charmaz, 2006). In this round, each student was treated as a unit of analysis, whereby the researcher examined the model drawings side-by-side with interview transcripts, allowing for a rich view of verbal, visual, and written student data. The process of coding was complimented with in-depth memoing that resulted in an extensive summary of each unique learner. Teacher focus group transcripts were content analyzed for themes that were similar across and unique to each school. Teacher insights were integrated into research memos and treated as secondary data supporting emerging student results. The student and teacher memos, grounded in the data, were the basis for the reporting of qualitative results (Charmaz, 2006). While this process generated numerous robust themes, the current study focuses on the interview analyses relevant to understanding the quantitative results based on rubric scoring.

After quantitatively scoring the drawings, the research team returned to the interview data and completed a second round of coding that employed the a priori three-part rubric framework that focused on components, sequences, and explanatory process related to solar energy systems. Student interviews were comprehensively coded for content that fell into and across these three categories and passages of text were coded accordingly. The first round of open coding had also generated a theme on student perceptions of outdoor learning, which was extracted for further analysis in the second phase of coding given the insights it provided on lessons that occurred outdoors (in the learnscape at sunshine and the open schoolyard at River). We collaboratively compared students within and across schools for reoccurrences and similarities in the ways in which they discussed their model drawings. The interpretations presented here were the result of a discussion-based consensus process amongst a four-person interdisciplinary research team (e.g., Harry et al., 2005). Interview data and student profiles were presented, discussed, and debated as the team triangulated interview results with researcher memos, classroom observations, and quantitative model scores.

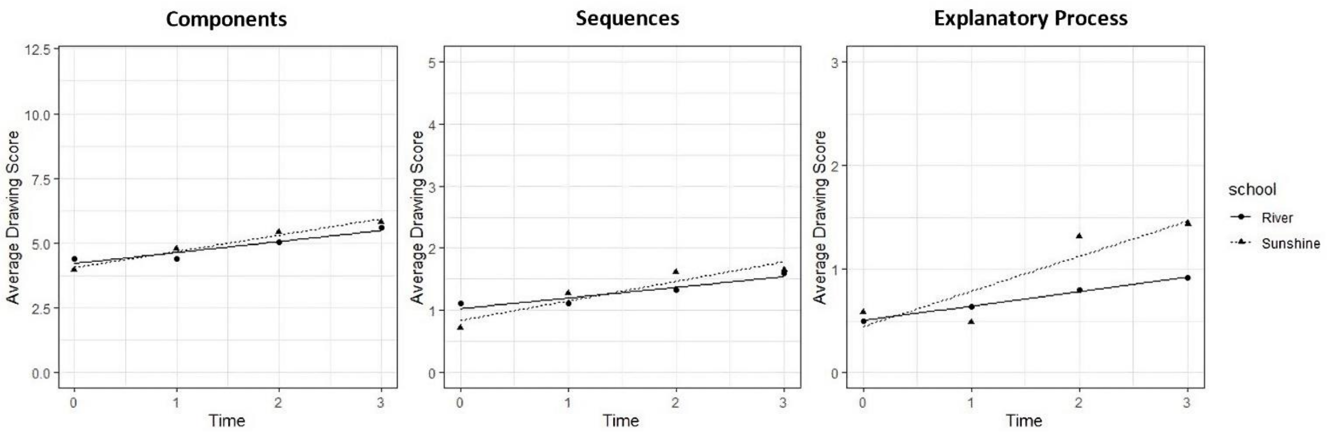



**Figure 7.** Average drawing scores for each rubric dimension by school (Source: Authors)

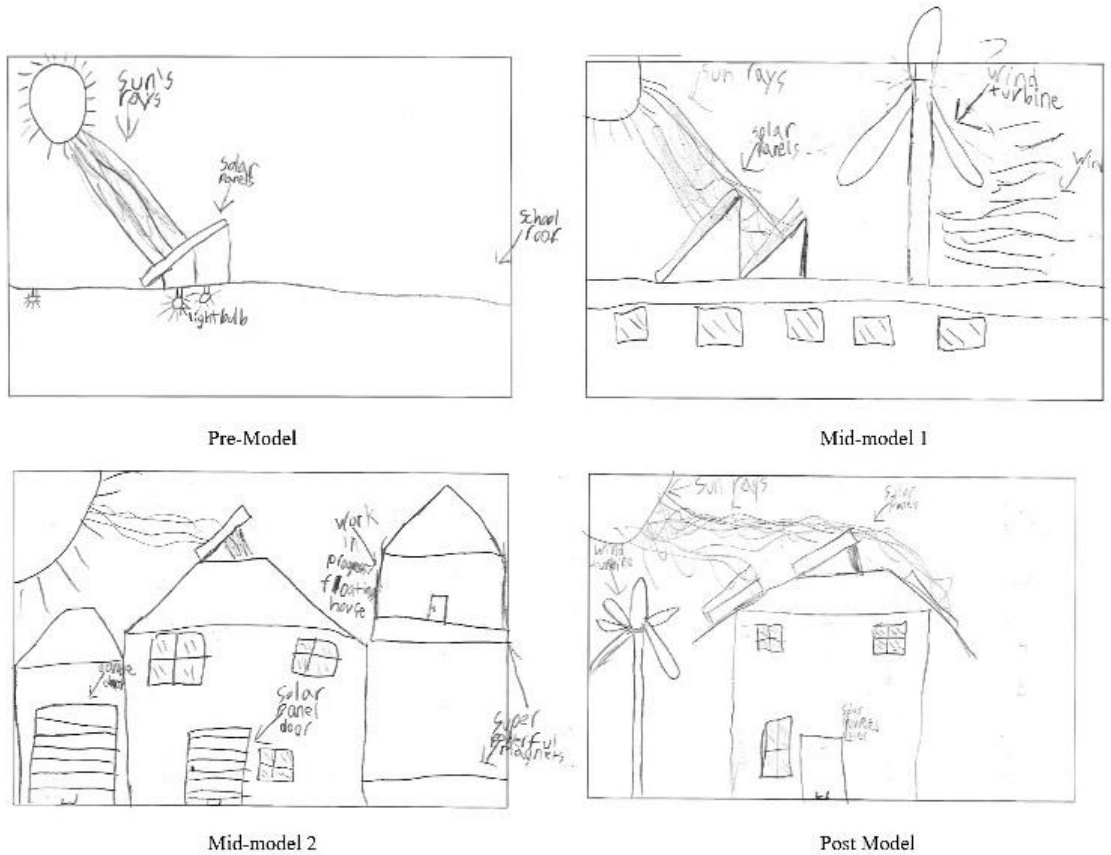



**Figure 8.** Model drawings for River Elementary student (Abeo) (Source: Authors)

# RESULTS

The analysis of student data illuminates the ways in which student conceptual knowledge about solar energy systems increased over the six-week unit and the qualitatively different ways in which the learnscape supported student learning. Given the sequential nature of our analysis, we begin with the trends in the quantitative findings that provided focus for the qualitative data analyses that followed.

## Did the Learnscape Make a Difference?

The first phase of analysis employed quantitative analyses using rubrics to uncover patterns across the sample of students (n=97, 385 models). **Figure 6** shows the average drawing scores for each dimension of the rubric (components, sequences, and explanatory process) by school and the changes across four models.

There was an upward trajectory of rubric scores for students at both schools (**Figure 7**).

The four model drawings from Abeo (River Elementary) demonstrate increasing model complexity across the unit (**Figure 8**).

The category of *components* is dominating the overall model scores, with categories of *sequences* and *explanatory process* scoring much lower (**Figure 9**).

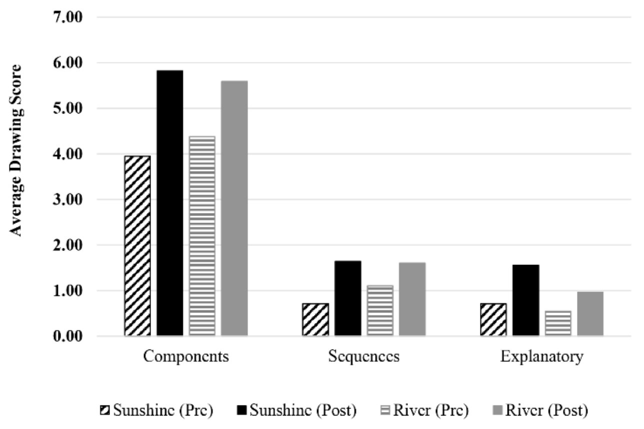



**Figure 9.** Average drawing scores by rubric dimension, school, & pre vs. post (Source: Authors)

However, this is expected given the rubric in **Table 1** that allowed up to 12 points for the inclusion of components within the model. Further note that the rubric scoring (**Table 1**) included "0", and that student average scores for sequences and explanatory processes were between zero and one in the pre-unit model (as seen in **Figure 7** and **Figure 9**) indicating that students struggled to demonstrate sequences and explanatory process prior to instruction.

### *Components scores*

**Table 3** shows the LMER model predicting student model drawing scores for components. **Table 3** shows a statistically significant increase in student component scores over time, where all students increased the number of solar energy system components in their drawings across the unit (also shown in **Figure 6**). For students at both schools, there was a statistically significant increase (p<0.001) of 0.42 points in the average component score every two weeks. There is a statistically insignificant (p>.05) difference of -0.2 in the mean scores over time for Sunshine students, which means that school setting was not a predictor of component scores.

### *Sequences scores*

**Table 4** shows the LMER model predicting student model drawing scores for sequences. **Table 4** shows that higher component scores predicted higher sequence scores, a finding that is in keeping with the tiered nature of the rubric dimensions. For each component students added to their model, the sequence score showed a statistically significant (p<0.001) increase of 0.38. For students at both schools, there was not a statistically significant change (p>0.05) of the average sequence score every 2 weeks when controlling for the number of components. There is a statistically insignificant (p>.05) difference of -0.13 in the mean scores for Sunshine students, which means that school setting was not a predictor of sequence scores.

### *Explanatory process scores*

**Table 5** shows the LMER model predicting student model drawing scores for explanatory process. In keeping with the tiered nature of the rubric dimensions, sequence scores predicted explanatory process scores. For an increase of one in student's sequence scores, there is a statistically significant increase of 0.27 of student's explanation scores (p<0.001). For students at River Elementary there was not a statistically significant change (p<0.05) in their average explanation score every two weeks.

However, students at Sunshine saw a statistically significant (p<.05) increase of 0.24 in the average explanatory process score every two weeks when controlling for components and sequences scores (**Figure 6**). While school did not emerge as a statistically significant predictor in the model,

**Table 3.** Linear mixed-effects models predicting drawing scores for components

| **Sequences** | **Model (random intercepts & slopes)** | | | **Random effects** | | | |
|---|---|---|---|---|---|---|---|
| **Predictors** | **Estimates** | **CI** | **p-value** | | | | |
| (Intercept) | 4.21 | 3.84-4.58 | **<0.001** | $\sigma^2$ | 0.94 | ICC | 0.63 |
| School [Sunshine] | -0.20 | -0.79-0.39 | 0.505 | $\tau_{00}$ | 1.41 $_{id}$ | N | 97 $_{id}$ |
| Time | 0.42 | 0.26-0.59 | **<0.001** | $\tau_{11}$ | 0.21 $_{id.time}$ | Observations | 385 |
| School [Sunshine]*Time | 0.22 | -0.04-0.48 | 0.099 | $\rho_{01}$ | -0.35 $_{id}$ | Conditional $R^2$ | 0.672 |

**Table 4.** Linear mixed-effects models predicting drawing scores for sequences

| **Components** | **Model (random intercepts & slopes)** | | | **Random effects** | | | |
|---|---|---|---|---|---|---|---|
| **Predictors** | **Estimates** | **CI** | **p-value** | | | | |
| (Intercept) | -0.58 | -0.81-0.35 | **<0.001** | $\sigma^2$ | 0.19 | ICC | 0.49 |
| School [Sunshine] | -0.13 | -0.37-0.11 | 0.281 | $\tau_{00}$ | 0.20 $_{id}$ | N | 97 $_{id}$ |
| Component | 0.38 | 0.34-0.42 | **<0.001** | $\tau_{11}$ | 0.03 $_{id.time}$ | Observations | 385 |
| Time | 0.01 | -0.06-0.08 | 0.758 | $\rho_{01}$ | -0.49 $_{id}$ | Conditional $R^2$ | 0.763 |
| School [Sunshine]*Time | 0.07 | -0.04-0.17 | 0.224 | | | | |

**Table 5.** Linear mixed-effects models predicting drawing scores for explanatory process

| **Explanatory process** | **Model (random intercepts & slopes)** | | | **Random effects** | | | |
|---|---|---|---|---|---|---|---|
| **Predictors** | **Estimates** | **CI** | **p-value** | | | | |
| (Intercept) | 0.16 | -0.16-0.47 | 0.333 | $\sigma^2$ | 0.35 | ICC | 0.65 |
| School [Sunshine] | 0.00 | -0.30-0.30 | 0.995 | $\tau_{00}$ | 0.28 $_{id}$ | N | 97 $_{id}$ |
| Component | 0.02 | -0.06-0.09 | 0.673 | $\tau_{11}$ | 0.06 $_{id.time}$ | Observations | 385 |
| Sequence | 0.27 | 0.13-0.41 | **<0.001** | $\rho_{01}$ | 0.43 $_{id}$ | Conditional $R^2$ | 0.699 |
| Time | 0.09 | -0.01-0.18 | 0.080 | | | | |
| School [Sunshine]*Time | 0.16 | 0.01-0.31 | **0.036** | | | | |

the interaction of school and time was a statistically significant predictor in the model (p=0.036).

In summary, the quantitative analyses of models revealed that all students experiencing the FoF unit demonstrated similar performance on components and sequences portions of the model drawing. Sunshine Elementary students however, performed better over time on the explanatory process dimension of the models. The quantitative data, however, was insufficient to explain why explanatory processes would have increased for Sunshine Elementary students. Our mixed-methods data collection process allowed us to approach our qualitative data in a targeted way to elucidate this difference within our quantitative findings.

### How Did Explanatory Process Increase at the Learnscape?

The second phase of analysis involved the treatment of student pre- and post-interviews (n=12) and teacher focus groups (n=6) to examine the ways in which explanatory process surfaced in the conversations about the drawings. The scoring of drawings, as presented above, showed that students understood the natural and human-made components of solar energy systems (e.g., sun rays, solar panels, electrical wires, uses of electricity inside buildings). Explanatory process, however, is harder to ascertain from the drawings alone. The student interviews, together with teacher focus group insights, show a clearer picture of the role the learnscape played in student learning. In the sections to follow we elaborate on the themes that were collaboratively developed in our multi-phase qualitative analysis.

#### *Similarities in energy literacy across schools*

To begin, post-curriculum interviews reveal sophisticated understandings from students at both schools, where each school had one or more students who seemed to be an outlier in terms of previous knowledge. Both schools also had students who felt less confident about their energy knowledge and demonstrated fewer conceptual linkages in conversation. Every student interviewed understood the basic idea of renewable versus non-renewable energy sources, even if their descriptions were at times disjointed and lacking clear terminology.

By the end of the unit, students at River Elementary demonstrated understanding of energy sources and why different sources matter. For example, Mia said that the lessons helped her learn "how you can stop global warming, because I do not know if anybody wants global warming." Emma noted the superiority of solar panels by concluding that "the sun's not going to really go anywhere" suggesting a clear understanding of renewable energy sources. Skylar made connections between energy infrastructure and impacts on nearby nature and then correctly compared solar energy to fossil fuel energy sources:

> But now that I think about it with the wires, and the oil, and the gas, and stuff that's not good for nature, I feel like solar panels would be the best option because it does not include oil or gas or anything like that (Skylar).

Skyler's comment shows how she is differentiating between different kinds of energy sources used by humans (oil, gas, and solar panels) and how these different kinds of sources may have different effects on natural systems.

Sunshine Elementary students displayed similar strong understandings in post interviews. When asked about ways to conserve energy, Lily mentioned that "you can use solar panels instead of burning coal. It saves the environment because when you burn coal it also pollutes," demonstrating that she was linking concepts without prompting. Some students, like Charlotte, understood the finite nature of nonrenewable resources, noting that "it was like a nonrenewable resource, then we would not have it for a million years or so and that would not be good." Other students understood this basic idea but did not articulate the difference between fossil fuel energy sources specifically and the broader concept of "energy."

Teachers at both schools commented on the growth their students experienced in better understanding energy, though they also commented that "I still do not think we really got as deep as we thought" (Krista, River Elementary) and "I'm not sure they gained a total understanding" (Nancy, Sunshine Elementary). However, all six teachers discussed the high levels of engagement and interest that students demonstrated, which was particularly the case with hands-on activities across the unit.

#### *A nuanced understanding of solar panel installation at Sunshine Elementary*

The research team extracted all interview passages that had been coded as "explanatory" and then examined patterns by school. Much of the explanatory process gained by students at both schools came from the FoF curriculum itself, which contained numerous engaging lessons about energy sources. However, one finding in the explanatory process excerpts was unique to Sunshine Elementary students. A review of the Sunshine Elementary student excerpts revealed that students at this school were integrating a higher level of understanding about the positioning of solar panels and/or overall design of a solar energy system. Several model drawings that sparked these conversations are shown in **Figure 10**.

Serenity, for example, tried to explain why she chose to draw the solar panel on the roof instead of the ground: "Cause the solar panel that's on the ground [the sun] might not actually hit it, sometimes, the sunlight might not actually hit it, but up high it might hit it." Serenity's consideration of where the solar panel should be (on the ground or on top of something) reveals her knowledge of the necessary relationship between the sun's rays and the solar panel for the solar panel to be effective. In mid-model 2, Serenity created a clear representation of the learnscape that shows the outdoor structure–and the way her teacher plugged a lamp into it–within her model drawing (**Figure 11**). One of the teachers who facilitated that activity said, "even several days later [they] were still talking about the lightbulb that we plugged in … [saying] 'that's so cool' and I'm like 'Yes! Yes!'" (Mary, Sunshine Elementary).

Several other Sunshine Elementary students discussed their choices to draw solar panels in a certain way in their model drawings. Alex noted: "I chose to draw it [the solar panel] in the backyard to show the different ways that you can put or arrange solar panels." Amelia also demonstrated her systems thinking when she commented:

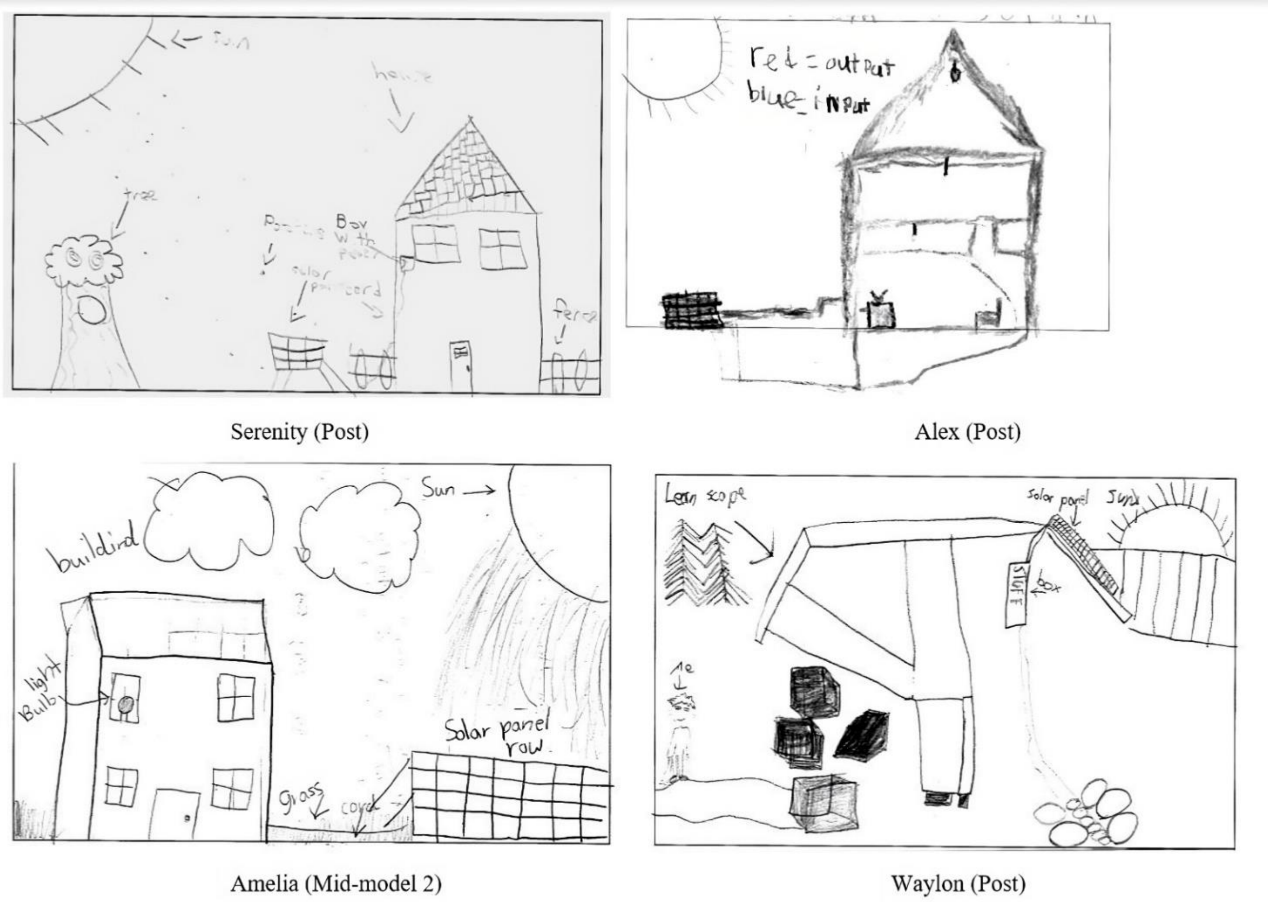



**Figure 10.** Learnscape student models that prompted conversations about solar panel design options (Source: Authors)

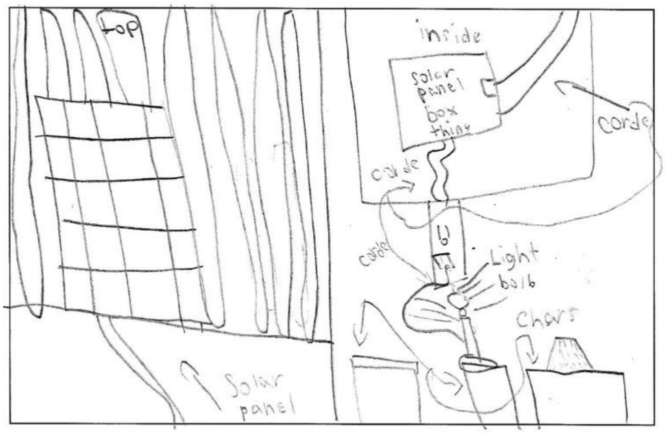



**Figure 11.** Mid-model 2 drawing of solar panel components at learnscape (Serenity) (Source: Authors)

> I thought maybe because most houses, if you're going to be powered by a solar panel, usually it's going to power the whole neighborhood by having a solar panel row instead of it on just one house. I mean you can see a couple houses with solar panels on it, but it's showing how it can power a bunch of houses (Amelia).

Comments such as these showed that students were thinking about the spatial relationships between the sun and solar technologies, including ideas about the installation of panels for one or more buildings. Sunshine Elementary teacher data supported this finding. When asked about teaching outside, Charlotte said, "it made it easier to teach about solar because we could point to, you know, the solar panels" and Melissa followed up with: "Well, yeah … they could trace with their finger … well it goes here and then here and then here."

These types of comments with details about installation considerations for the solar panels were not found in the River Elementary student interviews. While River Elementary models showed promising upward trends from pre to post unit in all rubric dimensions (components, sequences, and explanatory process), the conversations with River students did not feature in-depth discussions of solar panel installation. These students were able to articulate some of the broad reasons why solar panels matter (e.g., they "help the environment"), but were less likely to make connections between solar energy systems components at a more granular level or make connections between solar panels and the reduction of greenhouse gases.

### *Perceptions of outdoor education: The learnscape helped me learn*

In the post-interviews, students at both schools were asked directly about their experiences in outdoor learning during the FoF curriculum. River Elementary students tended to talk about the benefit of being outdoors and the hands-on nature of lesson 5:

> It was really cool because you could see the sun and … because there's a power thing that connected to the LED light. And it was really cool that it actually lit it up

> and it was so cool because I covered my hand and then it went off and I put it down and it went (Mia).

> Because when we do it inside, we did not do any experiment-type stuff inside, and I thought the experiments were really cool that we did (Ava).

These quotes from River Elementary show that going outdoors was memorable and potentially impactful for students who did not have the supportive learnscape outdoor classroom environment. However, when River Elementary teachers were asked about their experiences teaching outdoors, the responses were neutral or negative toward this aspect of the unit. They recognized that going outdoors was necessary to enhance student learning, but noted that the oppressive heat, distractions from other students at recess, and logistics of getting outdoors detracted from the learning experience.

While students at both schools were generally positive about learning outdoors, students at Sunshine Elementary tended to cite the learnscape as a learning tool in the curriculum.

> Researcher: Was it helpful to go outside to learn that lesson?

> Lily: It was better outside because we could really see how solar panels really work. It transfers all that energy to the little light bulb. It's really cool.

> Researcher: And what did you notice about that?

> Lily: I noticed that when it's facing … I think it's the south that has to face for the sun to get it. If it's facing a different direction, even when there's a lot of sun in this area, it does not mean that most of the day there's going to be sun there. So that's why you always need a face it south.

Lily continued on to mention how her teacher used the learnscape: "It was really helpful and [my teacher] brought out a lamp she had, because the solar panels on the learnscape … She plugged it in, and it turned on. So, I think that was really helpful." Amelia echoed that sentiment when asked:

> Researcher: What did you think about using that outdoor classroom?

> Amelia: I thought it was a lot better than doing it inside because our teacher got to a point to a real solar panel, and it was more fun than doing it inside because you got to actually be outside and see. Instead of doing it like inside, maybe under a light you do it under the actual sun.

> Researcher: Yeah. And was it helpful to you to have the learnscape solar panel there too? Did your teacher talk about it while you were doing the lesson?

> Amelia: She talks kind of how the wires from the solar panel come to this little box battery that connects to the outlet. And she plugged in a lamp and the lamp lit up whenever she plugged it in to show how the solar panel travels from that … travels from the solar panel to the little gray box to the outlet.

Later in the interview when asked about where she learned about battery storage, Amelia mentioned the learnscape again:

> Whenever we were watching a video about how solar panels can power stuff and it was talking about how from the solar panel it goes to … Well actually no, because someone came and talked to us about how solar panels goes to this little gray box, actually outside in the learnscape, and goes to the outlet. So that's where I learned about that (Amelia).

Student data further suggests that the learnscape solar panels aided Sunshine student comprehension. One student went into a high level of detail discussing his drawing with the researcher. As the conversation continued, he indicated that the learnscape features helped him learn about the solar energy components.

> Researcher: The sun hits the panel, then what happens?

> Waylon: And then it absorbs the power, and then it goes into the wires. Then it goes into a box that I could not fit onto the drawing. So that'd be like down here, I think, so they would hold the energy.

> Researcher: So what does the box do? Its main goal is to hold the energy.

> Waylon: Uh-huh. And then it goes to the thing we need to use when we need to use it.

> Researcher: I see. So, why is that box so important, you think?

> Waylon: Because otherwise I do not think we'd have anywhere to store it, and then we'd just have a solar panel with just wires everywhere, and we could not use it because it would not have the box to hold the energy.

> Researcher: Thank you. Where did you learn about the battery or the storage?

> Waylon: Well, when we were in the learnscape doing this stuff we had some extra time, and I saw solar panels and then I saw the box and then the outlets. So, then I realized that the wires go to the box, and then there are just like wires to the outlet from the box in case we need to use the outlet.

Conversations, like this one with Waylon, illuminated the ways in which the learnscape structure catalyzed deeper understanding for Sunshine students. In the example above, the researcher asked Waylon to elucidate his understanding, and, through the course of the conversation, he recalled the features of the learnscape to aid his explanation. When Sunshine teachers were asked about how much their students knew about the solar panel on the learnscape previously, Charlotte noted "some of them knew that there was one on the

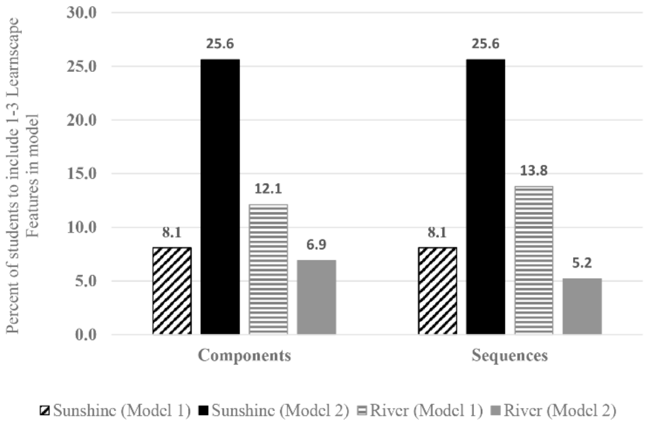



**Figure 12.** Components & sequences visible in learnscape, change from mid-model 1 to mid-model 2 (Source: Authors)

learnscape, but maybe did not understand how it works or what it does. I think they definitely have that understanding now."

The interview data bring life to the ways in which all fourth graders could explain the importance of renewable energy systems like solar panels. The conversations with students and teacher across schools confirmed the quantitative findings that showed high levels of understanding about solar panel components and sequences. The qualitative interview data revealed nuances in Sunshine Elementary student understandings of solar energy sequences that had not been captured by our rubrics of the static drawings over time. These findings emerged as students sat with the research team to discuss their drawings in more depth.

### *Model drawings inspired by the learnscape*

To triangulate these qualitative findings about the learnscape, we used the "visible in the learnscape" analysis to produce descriptive statistics of students' models regarding features of the learnscape. Given that the solar power lesson occurred between mid-model 1 and mid-model 2, this analysis focused on the models immediately before and after the lesson. At both schools, student scores were comparable in mid-model 1. However, Sunshine Elementary students included renewable energy systems elements that were visible in the learnscape at a higher percentage than River Elementary students in mid-model 2 (**Figure 12**).

**Figure 12** shows that Sunshine students increased the number of learnscape elements in their model drawings from 8% to approximately 26% (components and sequences) while River students decreased learnscape drawing elements from 12% to 7% (components) and 14% to 5% (sequences). These findings suggest that access to the solar panels on the learnscape helped students at Sunshine Elementary create their model drawings after lesson 5.

### Summary

When examining the quantitative and qualitative analyses together, the useful role of the learnscape in energy education becomes clearer. First, we found that students in both schools had a comparable spectrum of moderate to high energy literacy with an overall basic command renewable and nonrenewable energy sources and a general understanding about why alternative energy matters. However, Sunshine Elementary students expressed a more sophisticated understanding of the configurational aspects of solar array design. Additionally, Sunshine Elementary students interviewed clearly expressed ways in which the physical learnscape structure assisted with their emergent understanding of solar energy systems. Finally, we saw that Sunshine Elementary students showed a higher frequency of learnscape features in their drawings after lesson 5 (**Figure 12**). Taken together, the various data sources point to the benefits of the outdoor classroom for enhancing REE.

## DISCUSSION

This study examined the potential for an outdoor classroom, the learnscape, to enhance REE. Our guiding question for this study was: In what ways did the learnscape support student ability to model-based reason about solar energy systems (demonstrate conceptual understanding of energy flow) compared to students who did not have access to a learnscape? Direct cause-effect relationships, in this case the impact of the learnscape on student conceptual knowledge about solar energy systems, are difficult to establish in social research conducted in naturalistic settings. Future quantitative research in a larger number of schools, and with a broader range of controls and predictors, would increase confidence in the cause-effect relationship between the learnscape and student outcomes. However, the schools in this study were well matched and no substantial stylistic differences between teachers were identified in mean comparisons or field observation notes. Further, a mixed-methods approach was chosen to address the challenges and opportunities inherent in each quantitative and qualitative approaches. The results of this exploratory study contribute to several bodies of knowledge across science education and architectural studies.

The inclusion of the built environment as a didactic tool for science educators is among the key contributions of the current study. The work here adds to early-stage empirical work on green buildings as teaching tools, where there is much yet to learn about if and how green buildings can play a meaningful role in sustainability education. This body of work has typically examined green building "atmospherics" (Wu et al., 2016) and the broad potential for the static built environment to communicate sustainability messaging (e.g., Cole, 2018; Cranz et al., 2014; Higgs & McMillan, 2006). Work by architectural scholars puts much faith in the building alone as a "teaching tool" without companion curriculum. Early work focused on the building alone has shown that students in green schools exhibit higher green building knowledge than students in non-green school buildings (Cole & Hamilton, 2020). However, results from the qualitative arm of the same study revealed the shallowness of student green building knowledge (Cole & Altenburger, 2019), which echoes findings from REE studies that show knowledge gaps about renewable energy systems in particular (Altuntas & Turan, 2018; Zyadin et al., 2012). Results such as these have led scholars to call for green building curriculum to enhance the educational potential of the built school environment (e.g., Tucker & Izadpanahi, 2017; Zangori & Cole, 2019).

Furthermore, this work contributes to empirical research on REE in the elementary science classroom where little research has occurred in the US context. Buldur et al. (2020) examined awareness and perceptions of renewable energy technologies with middle school students in Turkey. Their results complement our work and suggest that units such as "FoF" may have similarly positive outcomes for elementary student attitudes about renewable energy systems, even though this particular outcome was not measured in the current study. The results here illuminate the "teaching tool" potential of outdoor classrooms, which has not been a feature of prior research.

Even though our quantitative findings did not reveal statistically significant differences between schools on the sequences scores (**Table 4**), qualitative findings showed that the learnscape provided a bridge for students to determine the sequences between what was occurring and how those sequences resulted in a change in system behavior (they could see the sunlight hitting a panel and a working lamp). They could then use their models to articulate this process, when it would work, and predict when it would not work (e.g., depending on the angle of the panels in relation to the sun). This qualitative finding elucidates a student understanding about sequences that may have supported their success with explanatory process given that an understanding of sequences was predictive of explanatory process scores (**Table 5**). While their models were not mechanistic in the sense of how precisely the solar panels work to convert solar energy into electrical energy, that was also not the goal. Rather, students were predicting and explaining energy flow for what they could observe both through the lamp lighting and the visuospatial experience in the learnscape. As Tobin et al. (2018) emphasize, it is possible to construct "meaningful explanations and predictions about phenomena even when the mechanisms underlying those phenomena are unknown" (p. 22). We speculate that the learnscape provided the necessary connection for the students to conceptualize the relationship between the human system (solar panel) and natural systems (such as sun, energy sources, and air quality).

Finally, the dual intervention of learnscape together with the FoF energy unit further contributes to prospects for place-based sustainability education. In science education specifically, outdoor learning environments have been found to support "contextualization in science lessons at K–12 levels" (Ayotte-Beaudet et al., 2017, p. 5344). This contextualization supports the process of connecting abstract themes like energy with tangible, everyday experiences. To date, much of the work on place-based education has focused on leaving school for off-campus community projects or nature immersion experiences. "Place-conscious education" (Gruenewald, 2003) is an expansive and multi-dimensional concept that includes a range of socio-cultural and physical notions of place. The work here focuses on the physical built environment of the schoolyard, the learnscape, to anchor broader understanding of energy systems in the students' everyday school environment.

The current study joins a sizeable and growing body of literature on the educational impact of schoolyard design, where the dominant focus has been nature access (e.g., Malone & Tranter, 2003; Rickinson, 2004; Sobel, 1997) and the presence of school gardens (e.g., Blair, 2009; Skelton et al., 2020). By contrast, learnscapes, such as the one studied here, are larger-scale investments in the schoolyard compared to garden boxes. Results of the current study show that the built elements of the learnscape, and specifically the solar PV panels, enhanced understanding of energy flow within and across systems for elementary school students.

## CONCLUSION

This study examined the ability of a curricular unit entitled "FoF" together with an outdoor classroom with a solar panel installation to enhance student learning outcomes. This work contributes to the existing body of literature on the use of MBR in science instruction (e.g., Tobin et al., 2018) and further integrates the built environment as a teaching tool for environmental and sustainability education (e.g., Cole, 2018). While the model score analysis did not show statistically significant differences across the two schools on components and sequences, the model score analysis did show that time and school significantly predicted higher explanatory process scores at Sunshine elementary. The qualitative data for explanatory processes elucidated this finding, demonstrating that students who had access to the learnscape exhibited a more nuanced understanding about solar panel installation. The Sunshine elementary students were able to explicitly connect learning about solar panels to the learnscape at their school. In addition, our "visible in the learnscape" drawing analysis showed the rate at which Sunshine Elementary students increased the use of learnscape features within their models as the unit progressed. Overall, our results suggest that the built environment, when combined with curriculum, can support students in connecting the dots between elements in the solar energy system, from the sun to the panel to an outlet.

We note limitations in this study. First, our teacher PD was only four hours. If more time had been devoted to PD, it is possible that we would see enhanced student learning outcomes due to increased teacher understanding of the place-based REE unit. In addition, the study context is a dominantly white suburban public school district in the Midwestern U.S. However, the newly constructed learnscape provided a unique opportunity to examine one curricular intervention at two schools within the same district matched for student achievement and demographics, where only one school had access to the learnscape as a curricular tool. Future research in more diverse school settings is needed to understand if similar dynamics occur across settings.

Despite these limitations, the current study has several implications for both practice and research. To begin, the installation of solar panels on or near the school building is a substantial investment. Future research might explore the possibility that more affordable interventions, such as a smaller scale and portable solar panel demonstration, could yield comparable learning outcomes. The current study featured a solar panel guest speaker who brought a demonstration and images into both schools in the study. This part of the intervention may have been impactful and could have potentially diminished differences in the post-models, but the data in the current study design is insufficient to draw conclusions about the demonstration. We maintain, however, that it would be hard for a solar panel demonstration to compete with the learnscape design, which included a full solar panel array constructed on a south-facing roof. This structure showed a common application of solar panels to roofs without leaving students to connect the dots and imagine what an installation looks like. Compared to a portable demonstration, the outdoor classroom is part of students' everyday environment showing them that renewable energy is integral to their school campus. Given the proximity to the playground, the solar panel on the learnscape provided a daily visual cue of renewable energy systems in action.

Another practical implication of the study is the question of tailoring place-based units to varying contexts. Utilization of the school building or schoolyard will inevitably ground learning in the students' everyday environment and require educators to stitch together science content with their unique locations. Ideally, curricular units will have built-in suggestions for ways in which educators in different contexts can modify content. The results of the current study suggest that place-based units can help teachers leverage the built environment to enhance science education. Other types of built environment lessons could include auditing the school building energy usage, monitoring rainwater collection, improving recycling collection, and the list continues. The creation of evidence-based and widely available green building curriculum will help teachers enact this unique type of place-based education.

This work points to several potential avenues for future empirical investigation. We will highlight a few possibilities below:

1. Create and evaluate renewable energy lessons that engage students in engineering design as aligned with the NGSS to help students see the career potential in renewable energy and increasingly promote development of the future green workforce.
2. Study the topic through a social justice lens that would help under-resourced school districts achieve similar goals with standards-aligned curricula. For example, examine small-scale solar panel demonstrations in isolation to test the viability of more affordable hands-on interventions compared to (or instead of) full-scale solar panel installations.
3. Expand the intersection of science education and building design to topics beyond solar energy, such as water conservation, green roofs, building material sourcing and toxicity, indoor air quality, and eco-friendly behaviors that are supported by buildings.

In conclusion, despite the growing number of green school buildings, the educational potential of these buildings is largely overlooked by both science educators and architects. Architects can build facilities that better support students learning about connections between human and natural energy systems, and science educators can better incorporate green building themes into curriculum. The potential synergy between the physical learning environment, curriculum materials, and student learning comprised the theoretical framework (adapted from Cleveland [2009]) that guided this study. This project focused on curriculum that connects the NGSS with REE, where lesson plans were created to complement the built environment in the schoolyard. Beyond the "FoF" curricular unit itself, we found that the presence of a visible solar PV panel enhanced student understanding of the process of harvesting solar energy for buildings and thinking about energy flow within their everyday experiences. School buildings are important places where students spend most of their early lives and have rich experiences. The results here can inform teachers, science educators, and architects who aspire to use the school buildings as effective tools for sustainability education.

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**Declaration of interest:** No conflict of interest is declared by authors.

**Data sharing statement:** Data supporting the findings and conclusions are available upon request from the corresponding author.

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## APPENDIX A: SOLAR ENERGY LESSONS IN THE LEARNSCAPE


▲ Passive Solar Lesson measuring the temperature of different materials left in the sun ▲ Learnscape with view of work tables

▲ Active Solar Energy Lesson where students built miniature houses and placed solar panels with a small light to test outdoors

(Source: Sepideh Fallahhosseini)

## APPENDIX B: INTERVIEW PROTOCOLS

### Student Interview Protocol (Pre)

Hi, [student name] my name is Ms./Mr./Dr. __________. I am a researcher (graduate student, research assistant) at the University of ________. Thank you very much for agreeing to talk with me! Is it okay if I audio record our interview?

I would like to talk with you about the things you included in your drawing. There are no right or wrong answers for any of the questions we will talk about–I'm in just interested in hearing your ideas. Your answers will not affect your grade in your science class in any way.

1. **Now I have some questions about what you know about energy.**
   - Do feel like you know a lot about energy?
     i. How have you learned about it before? (Inside or outside school?)
   - What is energy?
     i. What is the difference between energy and power?
     ii. Do you know where energy comes from?
     iii. Where do you think most of the energy in the US comes from?
     iv. Do you know the difference between renewable and non-renewable energy? (If yes, please explain)
   - How does energy go from the original source to something that humans can use?
   - Do you know how to conserve energy in your life?
     i. Do you try to conserve energy in your life? How?
     ii. Does your family try to conserve energy at home? How?
     iii. Do you think you can make a difference by doing these things?
   - Does human energy use affect nature? How?
   - Why are these things important?
2. **Why do you think were asked to draw your ideas?**
   - Have you heard of a model?
   - Do you think this picture is model?
   - Why would scientists use models?
3. **Tell me about your drawing** (ask about each element on the drawing).
   - ✓ For each area ask them:
     - **WHAT** do you think happens, **HOW** do you think this happens and **WHY** does this happen?
     - **HOW** does your model show this? *Why* did you choose to draw it that way?
     - **WHAT** experiences have you had that help you think about this?

[Student name], thank you for sharing your ideas. I enjoyed very much hearing your thoughts about energy! Do you have any questions you would like to ask me before we finish?

### Student Interview Protocol (Post)

Hi, [student name] my name is Ms./Mr./Dr. __________. As you may remember, I am a researcher (graduate student, research assistant) at the University of ______. Thank you very much for agreeing to talk with me! **Is it okay if I audio record our interview?**

I would like to talk with you about the things you included in your drawings. There are no right or wrong answers for any of the questions we will talk about–I'm in just interested in hearing your ideas. Your answers will not affect your grade in your science class in any way.

1. **Let's begin with questions about what you know about energy.**
   - **Now that you have finished the energy curriculum with your teacher, do feel like you know a lot about energy?**
   - **What is energy?**
     i. What is the difference between energy and power?
     ii. Do you know where energy comes from?
     iii. Where do you think most of the energy in the US comes from?
     iv. Do you know the difference between renewable and non-renewable energy? (If yes, please explain)
   - **How does energy go from the original source to something that humans can use?**
   - **What did you think about the energy lessons you did with your teacher?**

*If they struggle to think about it or only mention recent lessons…*

i. You had a lot of lessons if you think back to making Rube Goldberg contraptions, a mystery dinner, mapping your own energy use, learning about solar panels, the path of oil, and so on.
   1. Which energy lessons were your favorites?
   2. Were there any energy lessons you did not like?

ii. What did you think about the lessons that happened outside?

- **Do you know how to conserve energy in your life?**

i. Do you try to conserve energy in your life? How?

ii. Does your family try to conserve energy at home? How?

iii. Do you think you can make a difference by doing these things?

- **Does human energy use affect nature? How?**
- **Why are these things important?**

2. **Why do you think were asked to draw your ideas?**
   - Do you understand scientific models better now? What are they for?
3. **Tell me about your drawing** (ask about each element on the drawing).
   - ✓ For each area ask them:
     - **WHAT** do you think happens, **HOW** do you think this happens and **WHY** does this happen?
     - **HOW** does your model show this? *Why* did you choose to draw it that way?
     - **WHAT** experiences have you had that help you think about this?

[Student name], thank you for sharing your ideas. I enjoyed very much hearing your thoughts about energy! Do you have any questions you would like to ask me before we finish?