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Making connections: Elementary students' ideas about electricity and energy resources

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ABSTRACT

The development of energy literacy for all citizens is critical as we face climate change and rapid depletion of existing energy resources. This study explores energy literacy development in fourth grade classrooms. Our team developed a curriculum on energy resources aligned with the Next Generation Science Standards. We then trained teachers how to implement the program and support their students' engagement in a service-learning project related to energy conservation. We used qualitative methods to analyze students' open-ended responses from an energy literacy assessment. Students were familiar with solar, hydropower and wind energy, and suggested that solar energy should be used more in the future. Students were more easily able to explain energy transfer in wind turbines and solar panels than in other electricity production systems. Students learned important energy and natural resource concepts in the context of an environmental service-learning program. Discussion focuses on the importance of integrated science instruction that helps students see how their electricity use impacts the environment, and provides them with opportunities to take action. We also suggest important ways that renewable energy companies can contribute to energy and climate literacy initiatives.

1. Introduction

The development of energy literacy for all citizens is critical now as we face global climate change and rapid depletion of existing energy resources. Scientists and engineers have generated the knowledge and technologies needed to harness renewable resources for energy. Electricity production from renewables benefits society, our economy and the environment. However, in the United States, most people have low levels of energy literacy, and do not understand the benefits or importance of shifting toward renewable energy (e.g. Refs. [1–3]. For example, most people do not understand where electricity comes from or what energy sources are used to generate electricity [1]. Energy literacy programs are critical, so that citizens have the knowledge and skills necessary to make more informed and sustainable decisions about energy use (United States Department of Energy, [4].

Most U.S. students get information about energy sources in school, suggesting the importance of integrating energy literacy into the curriculum [5,6]. The framework for K-12 science education in the U.S. outlined ambitious goals for energy education in the elementary years; students in elementary school should understand the connection between energy and natural resources (National Research Council, [7]. If students start learning these concepts early, they will be ready to make important decisions needed for our society in the future. Many states have started the challenging work of implementing these new standards via professional development for teachers and curricular supports (e.g. Refs. [8,9].

Although students learn most of what they know about energy sources in school, the content is often geared toward passing an assessment. Traditional instruction on these topics may provide information, but rarely excites students to use their knowledge to produce change. Science sparks student interest when the concepts are personally relevant to them [10–12]. Youth have described the importance of science that "matters to our community and to our Earth" [13]; p. 820). Service-learning experiences provide students with opportunities to explore scientific ideas and identify problems. In doing so, students see science as relevant to their own lives and become motivated to apply energy conservation ideas to their community. This present study is conducted within the context of a

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service-learning program, Connect Science, designed to foster fourth grade students' energy literacy as they plan and enact a service-learning project that promotes energy conservation. We use open-ended questions to assess fourth graders' knowledge about energy systems and beliefs about energy sources at the end of the unit.

1.1. Energy literacy

Energy literacy is "an understanding of the nature and role of energy in the universe and in our lives" and "the ability to apply this understanding to answer questions and solve problems" [4]. Energy literacy is multi-disciplinary, includes cognitive, affective and behavioral components, and encompasses a variety of skills and concepts [4,14]. Energy literacy goals for each grade level are included in *A Framework for K-12 Science Education* [7]. For example, students in grades 3–5, should learn to observe and understand different energy forms, sources and transformations [7,15]. Fourth grade students are expected to learn that energy and fuels that humans use are derived from natural sources, and their use affects the environment. Also, some resources are renewable over time, while others are not. Scientific and engineering practices are used in the process of learning these concepts. For example, developing and using models is useful in helping students understand energy systems. Thus, fourth grade is a critical juncture for energy literacy development, since the NGSS explicitly focus on the connection between energy and natural resources, setting the stage for more complex energy concepts in middle school. Students will need to know about energy sources and systems, and the impacts of energy use in order to solve energy problems in the future.

1.1.1. Knowledge about energy sources

Students of all ages have difficulty distinguishing between renewable and nonrenewable energy resources [1,16,17]. For example, most eighth grade students in the U.S. do not understand which energy sources we use in the United States, where fossil fuels come from, or which resources are nonrenewable [1]. Similarly, only half of nine and ten-year old students in New Zealand could name an energy source [18]. Students have many inaccurate conceptions about energy and fossil fuels. Rule [3] found that most elementary students did not know how fossil fuels are extracted or where they are found; believed that natural gas is the same thing as gasoline; that oil does not cause many problems in the world other than oil spills; and that fossil fuels can form in a short time.

1.1.2. Connecting energy and natural resources

In order to care about reducing energy consumption, students need to understand where energy comes from (energy sources), but also how energy use impacts the environment, other people, and/or the economy. Students in Turkey had limited knowledge about renewable energy sources, but understood a few economic and environmental benefits of renewable energy [16,17]. Elementary students in New Zealand were aware that electricity costs money, but not were aware of environmental issues associated with electricity production [18]. Fell & Chiu [19] found that most children in the United Kingdom did not see the connection between saving electricity and protecting the environment; none mentioned climate change or saving money as reasons for using less electricity. While reducing electricity consumption is a primary focus of many energy conservation programs, energy use in production and transportation are emerging areas of emphasis [20].

1.1.3. Student understanding of energy systems

Most students (and adults) are unaware of how electricity is produced at a power plant [1,18]. Energy is a challenging topic with nuanced vocabulary that is difficult to understand [21,22]. Neumann and others conceptualized a learning progression for energy concepts, which suggested teaching about forms and sources first, followed by transfer and then transformation [23]. They explored learning progressions for energy using a multiple choice survey, and found that most sixth grade students were able to understand ideas about energy forms and sources, and a few could understand more complex concepts such as energy transfer. Other studies have found that key ideas about energy do not necessarily progress in a distinct sequence or at specific ages [22,45] and that elementary children are capable of complex understandings [45]. The K-12 Framework outlines a progression for learning about energy topics based on prior research, recognizing that younger students are likely to use the words "producing energy" when they are talking about electricity generation at a power plant [7].

One thing that makes energy systems challenging to understanding is that students often conflate processes with objects [24]. Conceptually, energy transfer includes objects like coal, turbines, generators, and wires. However, energy transfer is a process, not an object–nor can it be reduced to a property of these objects. Energy transfer is a relational process among those objects. When students encounter new processes, they often miscategorize that process as an object. For example, many students "believe gravity to be in the earth" [25]; p 32) rather than it being a relational process between the earth and other objects. Chi [26] posits that robust misconceptions in science are often held because student categorically misunderstand these processes as objects. As children navigate their own understanding of sources and energy forms, they stumble as they move to processes like transfer and transformation-not only because those topics are complex, but also because those concepts are processes and not objects. Since we know that processes are difficult for students and that students build knowledge through learning experiences [27], we believe there is a need to look closely at conceptions that children form in the midst of learning about energy. This type of fine-grained analysis can expand on existing research that relies more on multiple choice assessments, to demonstrate student thinking in the midst of making sense of energy transfer.

1.2. Energy literacy initiatives

Given that levels of energy literacy are low, and that schools are places where students get a lot of their knowledge, K-8 energy literacy initiatives in U.S. schools are emerging. For example, urban eighth-grade students participated in an 8-week geospatial curriculum, and made positive gains on energy content knowledge, attitudes and conservation behaviors [1]. Third-grade students who participated in a green school competition gained new knowledge about electricity use and consumption, and reduced energy consumption at home and school [28].

Some after school programs also focus on energy literacy. A program called GET City engaged youth in investigating local energy and environmental problems, and provided supports for communicating their ideas to the community. Youth investigated the energy crisis in their city, then planned and implemented an energy carnival. They wanted to inform community members about their important role in energy-related problems and solutions and motivate them to care and act [29]. A program for Girl Scouts encouraged girls to earn a series of patches related to energy and conservation [30]. Girl scouts improved their understanding of the connection between their own energy use and climate change, and also reported increase in energy conservation behaviors after completing patch activities [30]. Many recent educational initiatives have been focused more on *impacts* of climate change, and less on the process of electricity generation or many uses of energy resources [1,28,30].

1.2.1. Service-learning

The pedagogy of service-learning requires students to discover a variety of problems as they learn concepts, and then choose a problem and work on a solution later in the unit [31]. Some solutions involve educating others, necessitating an understanding of what people can do to save energy, and what might motivate them to change. Youth voice is a key element of service-learning that focuses on giving students autonomy to identify problems, decide on, and enact solutions to problems they discover [32]. Service-learning has been shown to be effective in fostering environmental literacy (e.g. Refs. [33–35], and holds promise for energy literacy, as well [44].

Guided by the belief that elementary students care about their environment and want to learn about topics that matter to our world, our team developed Connect Science. Connect Science includes professional development and curricular materials to support teachers in the implementation of environmental service-learning projects. Students learned about energy and natural resources as they discovered problems and chose a solution to try together. The work extends beyond existing work by using open-ended questions instead of multiple choice surveys to assess students' energy literacy. Our research questions were: 1a) Which renewable energy sources can fourth graders identify? 1b) Which renewable resources do fourth graders think we should use more, and why? 2) To what extent were students able to understand the connection between purchasing local foods and energy use? 3) What conceptions about energy emerge as students explain and model the process of electricity production?

2. Methods

The data from this study came from a three-year development project funded by the Institute of Education Sciences. We conducted a qualitative study of responses from an end-of-unit assessment about energy to understand fourth graders' conceptions after participation in Connect Science. Qualitative research complements and informs quantitative research [36]. Often small qualitative studies such as this one lead to or are embedded within larger quantitative studies, and can answer questions about mechanisms [37].

2.1. Participants

Teachers were recruited in spring, 2016 by flyers to district coordinators to attend a summer PD and pilot a new curriculum – Connect Science. Six teachers (all females with master's degrees, and an average of 17 years of experience), provided data to us from the end of unit student assessment. Five teachers were fourth-grade public school teachers at two different public schools in Virginia and Massachusetts, and one teacher taught grades 4–6 at a Montessori School in Massachusetts. Student participants included 101 students from these six classrooms. Teachers reported demographic data at the classroom level. Students were 53% Caucasian, 18% Hispanic, 8% African American, 10% Asian American and 9% of other race/ethnicity. Also, 8% of students were English Language learners, and 16% were students with disabilities.

2.2. Program description

Connect Science professional development and curricular materials support teachers in implementing a service-learning project related to energy conservation. The curriculum integrates social and emotional learning (e.g. skills such as respecting multiple perspectives and perseverance), NGSS aligned science lessons, and lessons that teach skills for implementing service-learning. The ten science lessons addressed fourth-grade concepts related to energy and natural resources. In one lesson, students conducted research on how electricity is produced from a specific energy source. The teacher showed students a video clip and diagram of a hydroelectric power plant and had students discuss the process of electricity production. Next, small groups of students were given a list of web links with different modes of representation (text, videos and diagrams) to learn about an energy source that they selected. They read and learned about that energy source, drew models of the energy system and presented their ideas to classmates (see Fig. 1). In another lesson, students sorted flash cards into groups of renewable vs. nonrenewable sources, and read about pros and cons of different sources. They had a discussion where they deliberated on various sources, and discussed which sources should be used more in the future. They also learned about food miles in a lesson about fruits and vegetables. Students generated a list of energy problems that they discovered along the way. After learning key science concepts, students chose a problem to work on, and were guided to consider various solutions, and then plan and implement a project. For example, one class chose the problem, "the world uses too much non-renewable energy."

Teacher professional development consisted of a four-day summer institute and a coaching session in the fall with a service-learning expert. Teachers implemented the curriculum in ways that matched the background and skills of their students, adding lessons as needed to align with their state or district standards. Teachers provided feedback on the curriculum and assessments.

2.3. Data sources

Students completed a survey at the end of the service-learning unit. The survey was developed and reviewed by a team of scientists and educators. We explored existing measures, and adapted items that aligned with our learning goals. In this study, we analyzed responses to the following questions:

1a) List three types of sources for renewable energy.
1b) Which renewable energy source do you think we should use more in the future and why?
2) Sarah told her friend that she wants to buy an apple from a local farm instead of one from California. She said her food choice will help the environment. Her friend disagreed and

Fig. 1. Students give a presentation to their classmates about wind energy.

said it doesn't matter which apple she picks. Who do you agree with and why?
3) How is electricity produced from an energy source? Choose one energy source (e.g. water, coal, wind, etc.). Then, draw a diagram, and explain how it produces electricity.

2.4. Data analysis

The first two authors systematically reviewed qualitative data. We used three strategies to strengthen validity of our study: peer debriefing, rich descriptions, and reporting of disconfirming evidence [38]. The third author and other members of the research team served as peer debriefers as we conducted analyses, asking clarifying questions and suggesting alternate interpretations. We also wrote rich descriptions of our results to provide transparency, and presented disconfirming evidence (e.g. data that shows when students did not understand concepts) along with evidence of student understanding.

For question 1a, the student responses were compiled into an excel spreadsheet. Frequencies of each source were computed and reported in a table. Thematic analysis was used to analyze student responses to questions 1b and 2 [39]. For question 1b, data were reviewed, and categories for student rationales for their choices were generated. Some of these categories were expected based on prior literature (e.g. economic, environmental), and others emerged from students' responses (e.g. availability) [40]. Responses were sorted into these groups, verified for accuracy, and a table was generated that reported frequencies of each code, assigned codes. Then, we selected excerpts that illustrated student responses in each area. We used a similar approach to coding student data for RQ 2. We grouped student responses based on similar themes (e.g. students who made the connection between use of fuel and food transportation), and then described students' responses from each group.

Question 3 required multiple levels of analyses because of the complexity of the ideas and the addition of student drawings. All student responses to question 2 were printed, and data from two classes were reviewed first. Each student response was examined to look for evidence that they understood the key concepts of evidence of energy and energy transfer. The second author analyzed student work, and evaluated each response for accuracy related to NGSS core ideas:

1) source of energy (source selected by students to explain);
2) evidence of energy (ability to identify evidence of energy in the system, such as light, motion, sound or heat); and
3) energy transfer (ability to explain or draw the process of energy being transferred from one part of the system to another).

We also identified emergent understandings-ideas that represented naïve conceptions. After agreement on code definitions (e.g. what counts as energy transfer), the first two authors reviewed all student data and came to agreement on reported results. Energy transfer was credited when students clearly described evidence of energy, and a process that showed a relationship or action between one form of energy and another component of the power plant system. Next, we counted responses in each category, selected text excerpts, and categorized conceptions where students seemed to be making sense of concepts.

3. Results

Students demonstrated a lot of knowledge about renewable energy sources, and chose mostly renewable sources when asked to explain power plant systems. Many understood some complex ideas, such as economic and environmental factors to consider when selecting an energy source, and energy transfer within a power plant system. Some students had naïve conceptions, which are described in detail in section 3.6. below.

3.1. Knowledge about energy sources

Of the 101 students who responded to the question "List three types of sources for renewable energy", 89 (88%) accurately listed three renewable energy sources. Fig. 2 categorizes student responses. The most common sources listed, in order, were solar, water and wind followed by biomass and geothermal energy (see Table 1). Inaccurate responses listed by 1–3 students include (in order of frequency): gas, oil, coal, circuit, chemical, electrical, led, wires, battery, air conditioner.

3.2. Connecting energy and natural resources

The majority of students (57%) chose solar as the energy source that should be used more in the future. The next most prevalent response was hydropower (24%). Some students also chose wind (8%), biomass (7%), nuclear and geothermal (2%).

3.3. Reasons for choosing a specific source

Most of the 101 students were able to articulate a valid reason for their choice. Students listed availability, environmental and economic reasons for their decisions.

3.3.1. Availability of the energy source

Sixty-four students described the availability of the resource as a reason to use it. For example, students said, "we should use solar energy more because the sun is always there", and "solar cause the sun will never go away." (Note that although scientists have

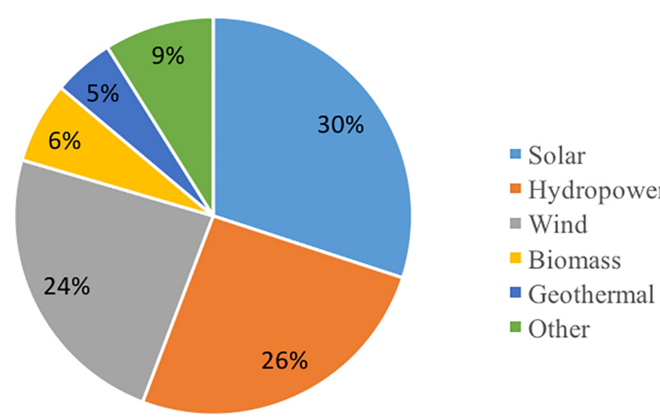

Fig. 2. Sources of renewable energy listed by students. Each student named up to 3 sources.

Table 1
Energy sources selected and reasons for choices.

	Environment	Economic	Availability	Other	% of Students
Solar	8	10	35	5	57%
Hydropower	4		18	2	24%
Wind	3		5		8%
Biomass	1		6		7%
Geothermal	1		1		2%
	16%	10%	64%	6%	

established that the sun will not last forever, this is a reasonable statement from a fourth grader given their understanding of time.) Another said, "We should use hydroelectricity because we have a lot of water in the world and that would be easy to renew."

3.3.2. Environmental reasons

Sixteen students listed environmental reasons for selecting their chosen source. Some had simple reasons, such as "I would use wind energy because it causes less pollution", or "it is good for the environment".

3.3.3. Economic reasons

Ten students cited economic reasons for their choice, and all of those students chose solar energy. For example, one student said, "I think we should use solar energy in the future because solar panels can make you money". Another said, I think we could use solar energy because solar energy can save the town money, [and it is good for the environment]."

3.3.4. More complex responses

As students explained their energy sources and rationales, eight students included a potential drawback to their source along with the benefit, and seven described limitations of other sources. One student said, "geothermal because it doesn't hurt animals. The only con is it is not everywhere." This student response was coded as environmental, since their choice was likely referring to the potential for wind turbines to harm animals. The student also recognized that geothermal is not available everywhere. Another student wrote that solar energy was widely available, but expensive when he/she said, "solar energy because the sun is always shining but solar panels cost a lot. There is a lot of it why not use it?" Her response was complex because more than one reason to use solar energy, and also recognized a limitation of solar energy. Seventeen students listed more than one reason for their choice. For example, a student said, "I think we should use solar energy because it easy, clean and it can save money and get money. And best of all it is renewable."

3.4. Impacts of food choices

To explore whether students understood the connection between foods that they purchase and energy use, we asked them to explain whether they thought buying an apple from a local farm helped the environment. Overall, out of 101 students who took this assessment, 55 understood the connection between resource use and local food purchase, 23 thought that a local apple was better for a variety of other reasons, and 19 did not think it mattered where the apple was purchased.

Fifty-five students (55%) explained that purchasing a local apple would save energy, or use less energy for transportation. Typical responses include: "I agree with Sarah because when they carry food long distances the thing that they travel in pollutes the air." and "It's saving energy and it doesn't make trucks drive and get more gas."

Twenty-three students (23%) agreed with Sarah, but for reasons that were not related to the amount of energy used in transportation. Eleven of the twenty-three students thought that the quality of apple would be better at a local farm, with reasons ranging from the potential use of pesticides from the other apple, to the use of chemicals to keep the apples fresh. One of these students said, "I agree with Sarah because if you buy an apple from California, it'll rot on the way." Seven of the twenty-three students described environmental reasons, but did not explain the link between energy or resources used and the apple from California. Two students gave financial reasons. One said, "I agree with Sarah because if you go to a local farm it will support the local area and give money to the area so they can use it to make the farm better."

Nineteen students explained that it does not matter where the apple comes from. One said, "I agree with her friend because it's just an apple." Another student noted that having an apple is good, regardless of where it came from, saying, "I agree with Sarah's friend because it doesn't matter what apple or veggie (fruit), at least you get one."

3.5. Making sense of electricity production

Students used diagrams and words to try to explain how electricity is produced from an energy source that they selected. Fig. 3 shows representations of two different student responses, along with an explanation of how they were analyzed based on our coding approach described in section 2.4. Thirty-eight percent of students chose wind turbines to describe, 24% chose solar panels, 14% chose hydropower, 6% chose biomass and 4% chose coal. Of the 101 responses, eight students did not respond, one identified a battery as a source, two described water wheels that grinded grain rather than hydropower plants, and two others had answers that did not identify an energy source.

3.5.1. Evidence of energy

The first step in tracing energy through a system is recognizing evidence of energy. Seventy-four percent of students who drew models of wind turbines identified energy of motion or wind as evidence of energy. They made it clear that wind moved the blades or caused the turbine to spin. Seventy-five percent of students who wrote about solar energy described the sun's light or pictures of the sun's rays as evidence of energy. Example responses included: "The suns energy goes into the solar panels by the light" and "solar energy is produced by the solar panels by the light". Seventy-one percent of students who discussed hydropower were able to show that the movement of water provided energy to the power plant system. A typical response that showed evidence of energy in the system was "the water turns a generator". For biomass, a few students identified heat or motion as evidence of energy in the system. None of the students who chose coal clearly identified evidence of energy (chemical/stored or heat) in the system.

3.5.2. Energy transfer

Thirty-seven percent of students explained energy transfer accurately. Other students either did not attempt to describe

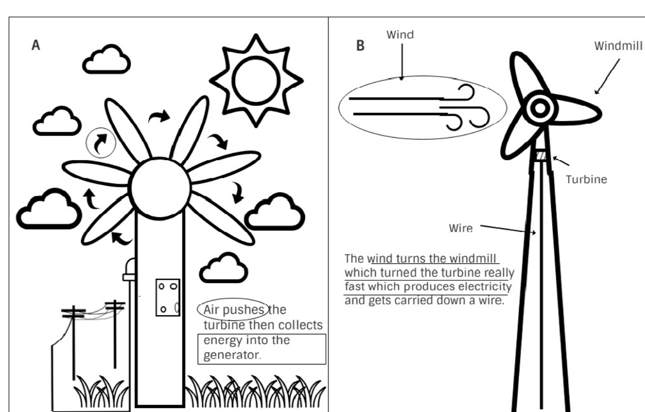

Fig. 3. Data analysis procedure for research question 3. Circled sections indicate where authors credit student work (drawing or writing) for evidence of energy. Underlined sections indicate where authors credit student work for energy transfer. Boxed sections indicate where a naïve conception is identified.

energy transfer or were still making sense of energy transfer.

3.5.2.1. Wind turbines. Eighteen students described energy transfer in their wind diagrams or written responses. For example, one student said "The wind causes the turbine to move then it produces electricity to the house". This student did not understand all of the components of a wind energy system, but understood energy transfer. Another said, "Wind spins the 'arms' of the wind turbine. The turbine then converts the spinning motion into energy. Finally, the energy is sent to the homes and other people."

3.5.2.2. Solar panels. Thirteen students could explain the transfer of energy in solar panels. Students said "the light is converted into electricity", "solar panel converts sunlight to DC current", and "solar panels use the sun to generate electricity".

3.5.2.3. Hydropower plants. Five students included energy transfer in their explanations of hydropower plants. The most sophisticated explanation was this student's: "Water from a river comes through an intake of a dam. Then it flows through a penstock ad turns a turbine. The turbine turns a generator which makes electricity with the flow of copper electrons." A few students clearly understood that energy of motion was transferred to the generator, which produced/made/created electricity. One student said, "the generator spins and creates electricity." Students who did not understand the system very well said things like: "hydro gets electricity and goes to an energy pole to give us energy".

3.5.2.4. Biomass. A few students who chose biomass could explain that biomass is heated in the system. One said, "Biomass can use trash or cow dung. It works by starting a fire, putting in trash, making bubbles, pushing a turbine, going in a machine, and then making energy." Another student could explain transfer of energy in one part of the system, "the steam spins the turbine and powers the generator" (see Fig. 1). Overall, students who tried to explain the coal and biomass systems had less clear ideas about evidence of energy and energy transfer.

3.5.2.5. Coal. Of the four students who chose coal, none identified coal as the evidence or source of energy in the system. None of them were able to accurately depict energy transfer in the system. For example, one student said, "coal is picked up from coal mines and then made energy."

3.6. Still making sense of energy in complex systems

Students demonstrated in a variety of ways that they did not yet understand energy forms and energy transfer**.** Examples of naïve conceptions are described below.

3.6.1. Creating energy

Across all of the sources, many students communicated the idea that energy was *created*, *made or produced* in the power plant system. Example statements include: "solar energy shines on solar panels to create energy in a house"; "the turbine then converts the spinning motion into energy", and "biomass is when waste things and other materials are used to create energy."

3.6.2. The role of the generator

Some students (mostly those who described wind energy) did not know what happens to energy in the generator. One student said "wind pushes the turbine then collects energy into the generator". Another said, "when the wind blows energy is trapped into the generator."

3.6.3. Generators and solar panels as energy sources or storage devices

A few students described a solar panel or a generator as energy sources. One student said "wind produces energy by a giant windmill powered by a power source that basically is just like a big battery that makes is spin pushing wind through a clear field." Another student said, "my power source is a solar panel collecting energy from the sun to have light in the house." Finally, one student said, "the sun shines down on the solar panels. Some of the energy is transferred to the house and the rest to a generator to store the energy." Another said, "its rays hit the solar panel, and it turns it into electricity by storing energy from the sun."

3.6.4. Sources instead of energy moving through the system

A couple of students described the energy source itself (e.g. water, biomass) moving through the system. One student said. "the coal goes through the combustion chamber into the turbine shaft then into the generator into the transformer then into the power lines into your house."

3.6.5. Other emerging understandings

One student described the role of heat in making electricity. He/she said, "the turbines spin and it makes heat and the heat makes electricity." A different student added a generator to a solar panel system when he/she said, "solar energy goes from solar panels to power lines, then to an electric generator that makes it into electrical energy."

4. Discussion

Fourth graders in our study were beginning to make sense of NGSS disciplinary core ideas about energy and natural resources at the end of the service-learning program. They were particularly strong at identifying which energy sources were renewable and understanding impacts of energy use.

Many students had a sophisticated understanding of how electricity is produced at a power plant, particularly when describing wind and solar energy. We found that power plants are a useful context to help students grapple with the complexities of energy systems, and for helping students connections electricity use and climate change. Students like learning about things that matter to their communities and the environment [13]. The service-learning framework provided an opportunity for students to learn about electricity and where it comes from as they discovered energy problems, and then designed their own solution. Many classes conducted energy fairs in order to educate others about energy conservation. Environmental service-learning is a form of project-based learning that includes a civic component, allowing students to develop a deeper understanding of science concepts as they apply knowledge learned in class to real-world problems.

To date, there is surprisingly little description of children's understanding of energy literacy. This study extends current knowledge by analyzing students' diagrams and open-ended responses to provide a nuanced understanding of students' beliefs and emerging conceptions. We also provide detailed descriptions of students' naïve conceptions. This information is essential to understand how energy literacy develops in children and youth, and can inform future development of curricula and assessments.

4.1. Knowledge about renewable resources

Eighty-eight percent of fourth grade students were able to list three renewable energy sources after participating in the program. Similar-aged students in Australia were able to categorize resources as renewable or nonrenewable 60–90% of the time (depending on the source) after a school-wide program [41].

4.2. Connecting energy and natural resources

We extend prior work by asking students to explain why they prefer some energy sources more than others, and found that 90% could articulate a clear reason for their choice. Students recognized the availability of renewable sources as important, but also valued environmental and economic factors. Students' ideas aligned with goals of education for sustainability initiatives, which aim to help people understand and evaluate economic, social and environmental impacts of personal and collective decisions [42].

Electricity production and transportation use the majority of energy resources around the world. Students were able to grasp the connection between their food purchases and energy use after one lesson on food miles. Our intention was to make them aware of the concept of food miles as a factor to consider when purchasing foods. The majority of students could explain that purchasing food from far away required more gasoline or energy. They did not have a complex understanding of the issue, but these initial ideas can be expanded on in later years to give them a richer understanding of energy use in food systems.

4.3. Modeling energy systems

The range of student responses to the question about electricity production surprised us; many students were able to grasp energy transfer and describe the process of electricity production, while others were still making sense of energy sources and evidence of energy. Our analyses of students' responses confirmed prior work that students' development of energy conceptions are non-linear and complex [22], and challenged the notion that students are not ready to grapple with complex societal issues related to energy resources before high school [15].

Students found it easier to explain electricity production in wind and solar than in more complex systems. The majority of students chose wind to explain although student groups had researched and learned about a variety of sources. In fact, most students showing an understanding of energy transfer used wind to explain the process. This suggests that some energy sources would be ideal for teaching students about in early years, building toward more complex systems in later schooling. The thermal systems (coal and biomass) proved more difficult to understand for the students in our study with only 10 of 101 choosing these systems and no students able to explain energy transfer in thermal systems. We posit that difficulty in thermal systems may come from a lack of understanding around potential energy in matter and energy transformation, and the fact that heat is added to the already complex process of electricity generation.

Naïve conceptions were identified and described. Students used "making" or "producing" energy to describe processes in power plants, as expected by the learning progression for energy-related concepts in NGSS [7]. We extend the existing literature on students' ideas about energy systems by providing clear examples and a few new emergent understandings that have not been described in prior work. Prior studies focus more on emergent understandings of isolated science concepts (e.g. electricity, energy), and not on energy systems [43]. For example, some students thought of generators or solar panels as energy sources, and were confused about the role of the generator. Hand-cranked generators or flashlights and small solar panels are expensive for typical classrooms, but may be useful in explaining the processes that are difficult to grasp. Teachers and curriculum designers can elicit and address these naïve conceptions as they design lessons to teach about energy systems.

4.3.1. Developing and using models

We found that the process of iterating evolving conceptual models provided a rich opportunity for learning. Working in collaboration with peers to research and model energy systems gave students practice at modeling before they were asked to explain the system independently. Scientists use models to communicate their ideas and build knowledge, and NGSS suggests that teachers and students should do the same [7]. As students' conceptions are forming, they can make them visible for others to see and ask about. In our program, students looked at videos and diagrams of these energy systems, made models and then presented them to others. The pedagogical enactment of class discussions around the models varied widely among teachers, with clear explanations of the phenomena present in some classes and missing in others (authors, under review). The road to sophisticated conceptions about science processes requires dedicated effort in allowing students to work through their conceptions over time as they learn [27].

4.4. Limitations

A few limitations require mention. Connect Science is in an early phase of development and we cannot make causal inferences about its impact based on this small, descriptive study. It is plausible that some students had knowledge of some concepts prior to participation. However, given research showing low levels of energy literacy across ages and contexts, we believe that many of the students' conceptions were informed through participation. Also, individual student sociodemographic information was not collected, and factors such as gender or geographic location are important to consider in future studies.

4.5. Future directions

Our results can inform development of energy curricula and assessments for upper elementary students. We found that it is important to address energy transfer explicitly through modeling (student diagrams), helping students understand and explain the process of transfer rather than focusing on the objects in the system. We also discovered that trying to understand a variety of systems left some students without a deep understanding of a particular system. Our results suggest that wind turbines and solar panel systems are comprehensible to elementary students when they are provided with curricular supports and teacher scaffolding. Thermal power plant systems add a layer of complexity that may be better addressed in middle and high school years.

With the implementation of NGSS in many states, open-ended questions are becoming more widely used to assess student learning about complex concepts such as energy and systems thinking. This question that we asked students yielded particularly interesting responses, which provided insights into students' conceptions: *How is electricity produced from an energy source? Choose one energy source* (e.g. *water, coal, wind, etc.). Then, draw a diagram, and explain how it produces electricity.* Teachers and researchers should consider using this prompt as a formative and/or summative assessment, to elicit naïve conceptions that can be addressed through the use of models and in-class activities.

Students in our program were able to list and distinguish between renewable and nonrenewable energy sources. Our unit consisted of 10 science lessons, along with other lessons on collaborative skills and civic engagement. This combination of lessons allowed students to learn and then apply science concepts to the real world, as they designed and completed a service-learning project. Service-learning projects allow students to take action and focus on solutions rather than just gaining an understanding of energy problems.

Helping students make the connection between electricity and energy use in their daily lives, and the natural environment around them, is a critical part of climate change education. Existing curricula that teaches and assesses electricity as a distinct unit from natural resources should be updated. Standards that focus on topics such as static electricity and series and parallel circuits are not as relevant for energy education in an era of climate change. Teachers need to be more intentional about helping students to see that electricity is not an isolated physical science topic; it is integrally connected to natural systems around us.

The role of renewable energy in our pathway to sustainable development is clear to scientists. We need to be smarter and more proactive in our future energy uses, eventually replacing our nonrenewable resources with renewable, sustainable energy sources. However, today's children and youth will play important roles as citizens, scientists and policy makers in transforming our existing energy infrastructure. Funding in public schools is sparse, and most schools cannot afford equipment such as solar panel and wind turbine models for student investigation. Many energy companies have a stake in fostering energy literacy for citizens. Companies that research and produce renewable energy technology would be wise to consider funding energy literacy curricula, materials and systems in K-12 settings. Renewable energy scientists and engineers can also serve as local experts, providing guidance to service-learning projects or teaching explicitly about energy systems. Funding solar energy panels and wind turbine models or systems at schools would provide real-world examples for students to observe and investigate. These tangible examples may yield benefits of helping students understand better options for powering our future, motivating them toward civic engagement and/or careers in the field of renewable energy.

Declaration of interest

None.

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