Learning Science and Engineering by Designing Sustainable Houses

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Abstract

In the wake of climate change, we need to find ways to maintain the thermal comfort of our homes without compromising the environment. This article introduces the Energy-Plus House Design Project, an NGSS-aligned curriculum unit developed to inspire and prepare high school students for tackling this pressing challenge. In this project, students learn and practice science and engineering by designing a house that generates more renewable energy than it consumes over the course of a year (hence known as an energy-plus house). Students will use a free, Web-based computer-aided design tool called *Aladdin* to create realistic-looking 3D house models, simulate their energy generation and consumption, and analyze the results to evaluate their energy performance. The unit covers design specifications, passive and active heating and cooling design strategies, and the interdependencies of design variables within a system. Students will collect quantitative evidence from simulation results, make trade-off decisions among multiple criteria and constraints, and explain their design solutions in a final presentation.

Introduction

The increasing heating and cooling costs due to climate change impact low-income communities disproportionately (Root, 2021). Science education can play a role in mitigating this inequity by inspiring and preparing students with knowledge needed to build a sustainable and just future. The energy cost for maintaining the thermal comfort of our homes is dictated largely by science. For example, insulation reduces conduction, airtightness prevents convection, and low-emissivity windows decrease radiation. These three mechanisms of heat transfer collectively drive the thermodynamics of a house. Challenging students to find ways to improve the energy efficiency of a house provides them opportunities to learn science more deeply through solving real-world problems, which also addresses the Next Generation Science Standards (NGSS). For example, MS-PS3-3 requires students to “apply scientific principles to design, construct, and test a device that either minimizes or maximizes thermal energy transfer,” and HS-ETS1-4 requires students to “use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.”

Improving building energy efficiency is crucial to slowing down climate change, as the operations of buildings account for 30% of global energy consumption and 26% of global carbon emissions according to the International Energy Agency. It is also important that educators help students develop career interest in this field. The U.S. needs a strong workforce at this frontier as the American Jobs Plan promises to invest $213 billion to improve the energy efficiency of buildings.

For more than two decades, the U.S. Department of Energy (DOE) organizes the Solar Decathlon, a green building design challenge for college students (see “On the web”). The DOE vision has the potential to reach out to millions of pre-college students as well. The problem is that high school students do not have the privileges and resources to tackle the DOE challenge. To address this problem, we have developed a free Web-based computer-aided design (CAD) tool called Aladdin (see “On the web”) that supports K-12 students to design virtual buildings and simulate their energy performance. While there have been many tools for virtual construction of buildings such as Bloxburg and Minecraft that are popular among children, most lack numerical simulation and analysis capabilities needed for authentic engineering design. To this end, Aladdin provides students with both architectural design and energy modeling capabilities in a single platform, allowing them to freely explore the design of green buildings with a computer. As a result, students with diverse socioeconomic backgrounds are given equal opportunities to benefit from the ideas behind the Solar Decathlon. In this article, we introduce the Energy-Plus House Design Project, an NGSS-aligned curriculum unit developed to realize the above vision. In this unit, students first conduct inquiry-based investigations to learn the effects of various design variables and the underlying science concepts. Equipped with this knowledge, they then follow the engineering design cycle to create a realistic-looking 3D house, with the goal to generate more renewable energy than it consumes over the course of a year. We briefly report findings from a classroom study to conclude this article.

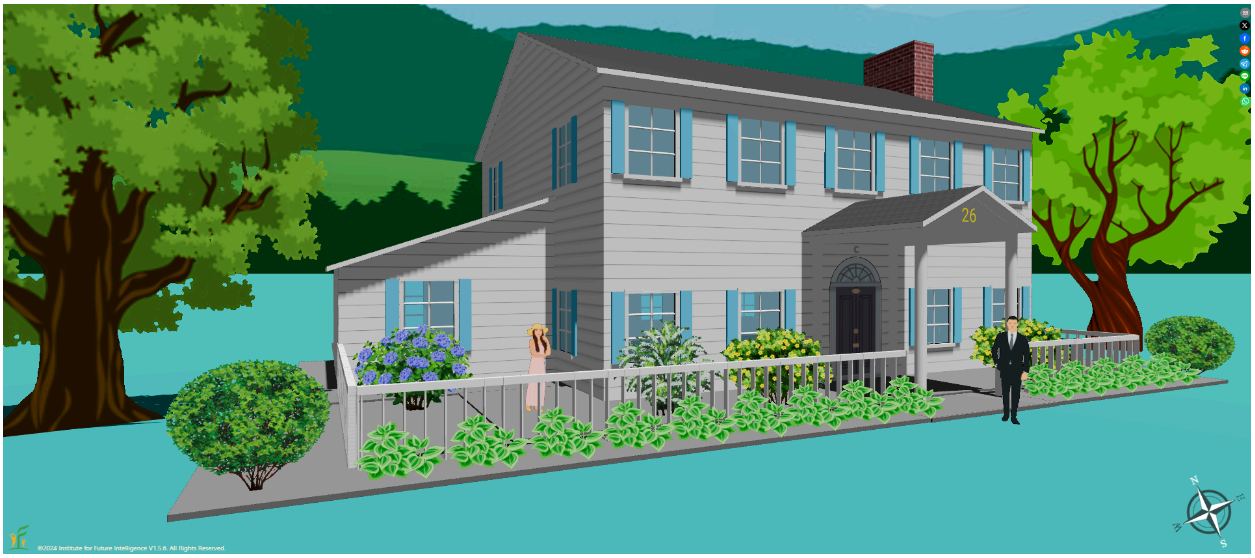
The Curriculum Unit

Design Concepts and Specifications

Students are challenged to design a house that needs as little external energy as possible while maintaining the thermal comfort inside the house year round. The goal is to realize the concept of the zero-energy building that generates enough renewable energy onsite to achieve net zero energy consumption throughout a year. If such a house generates more energy than it needs, it is called an energy-plus building. Note that a zero-energy or energy-plus house is not necessarily an “off-grid” one capable of generating renewable energy sufficient to heat or cool itself on any single day of the year such that it can be disconnected from the power grid completely.

Students are encouraged to design multiple houses in different architectural styles. In this article, we choose three styles common in northeastern United States, colonial, Cape Cod and ranch (Figure 1), as examples. The style of a house may have energy implications. For instance, different styles may have different surface-area-to-volume ratios – a house with a larger external surface (i.e., building envelope) consumes more energy than a house with the same volume but a smaller external surface (e.g., a one-story ranch house vs. a two-story colonial house). This is because the heat exchange between the inside and the outside of the house is proportional to the area of the external surface.

Challenging students to design multiple houses also serves as an instructional strategy that drives students to consider alternatives and practice divergent thinking, which is critically important in fostering their design thinking (Dym et al., 2005).



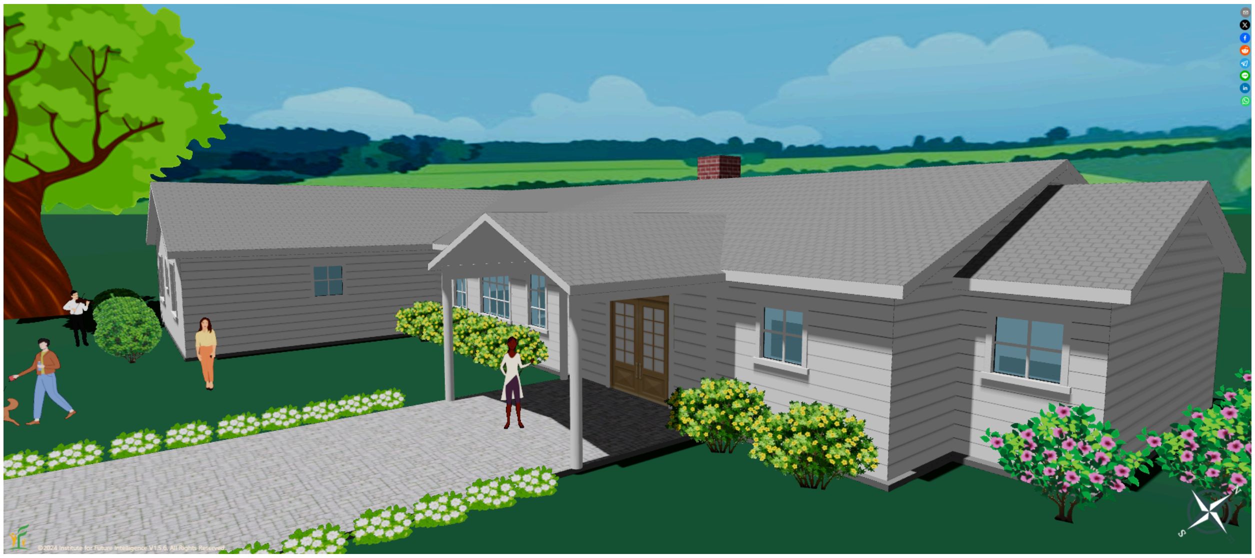


Figure 1. 3D models of (a) a colonial house with two stories of living space, (b) a Cape Cod house with a smaller second story, and (c) a one-story ranch house, created with Aladdin.

Educational Technology

To support engineering education, Aladdin integrates 3D modeling and energy modeling in a single system (Xie, et al., 2018; Xie, Ding, & Jiang., 2023). This integration is necessary as it allows students to switch seamlessly between design and analysis to get just-in-time feedback for each design decision. With its 3D modeling capabilities, students can sketch up a simple house by adding a foundation, walls, roofs, doors, windows, solar panels, and even wind turbines. As shown in Figure 2, once a simple house is completed, students can continue to enrich it with more architectural features.

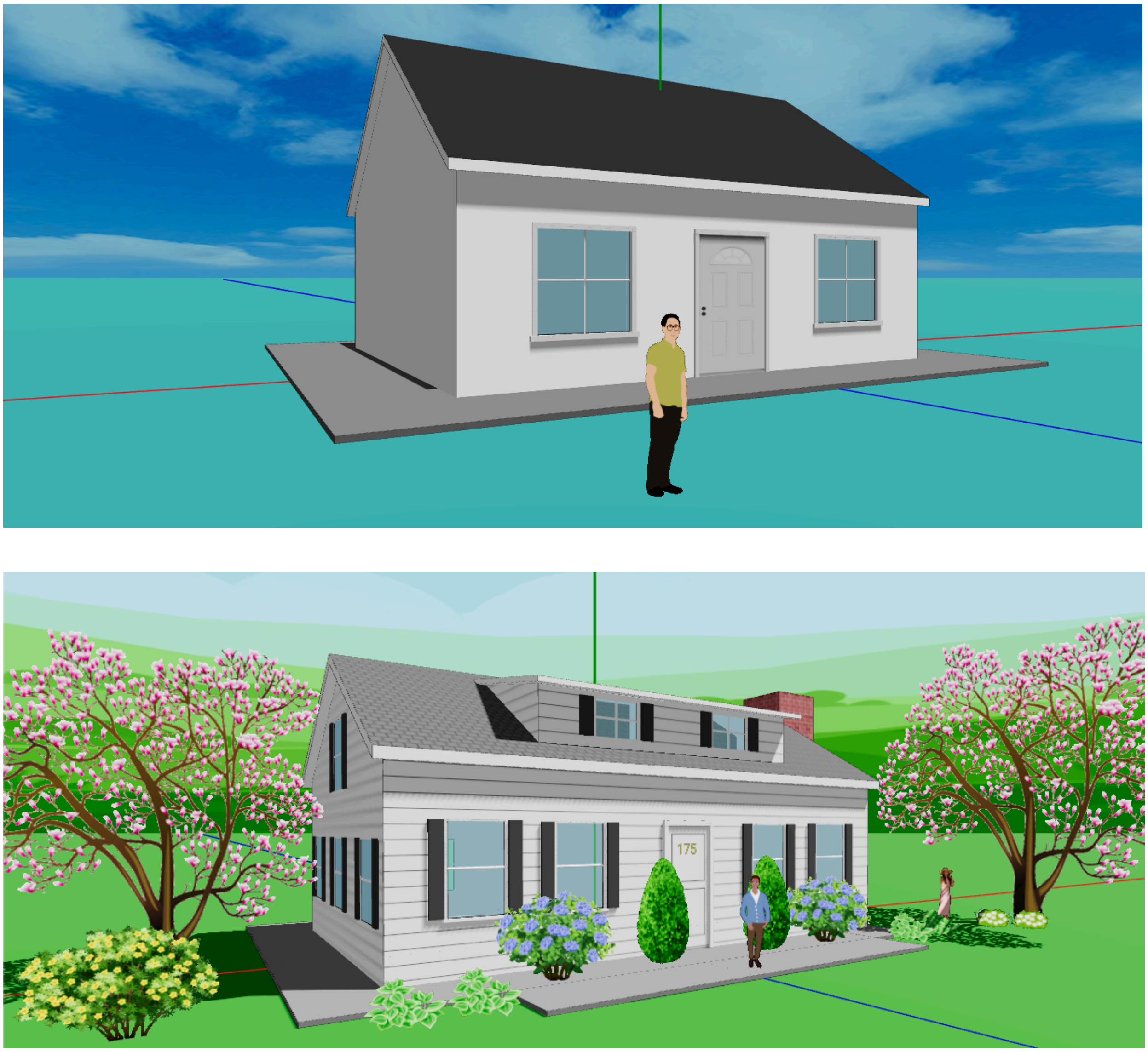


Figure 2. (a) A simple house and (b) a decorated house created using the 3D design capabilities of Aladdin.

After constructing a house, students can then analyze its daily and yearly energy use. By default, the house is controlled by a thermostat set to 20ºC (68ºF) that drives heating and AC systems to maintain the indoor temperature. Aladdin uses numerical simulation based on physics to calculate the solar radiation on the building envelope and the heat fluxes through it, from which the energy needed to maintain a constant room temperature throughout a day is computed. The results are shown as a heat map overlaid on the building envelope and as an interactive graph in a floating window (Figure 3). Based on the analysis results, students can evaluate the energy efficiency of the house, revise the design, and redo the analysis, until the yearly net energy consumption becomes negative (i.e., the design achieves an energy surplus). For example, students may discover that the heat flux arrows sticking out of the windows are much longer than those of the walls, which may prompt them to increase the insulation value of the windows and/or decrease the emissivity property of the windows to reduce the heat transfer through them.

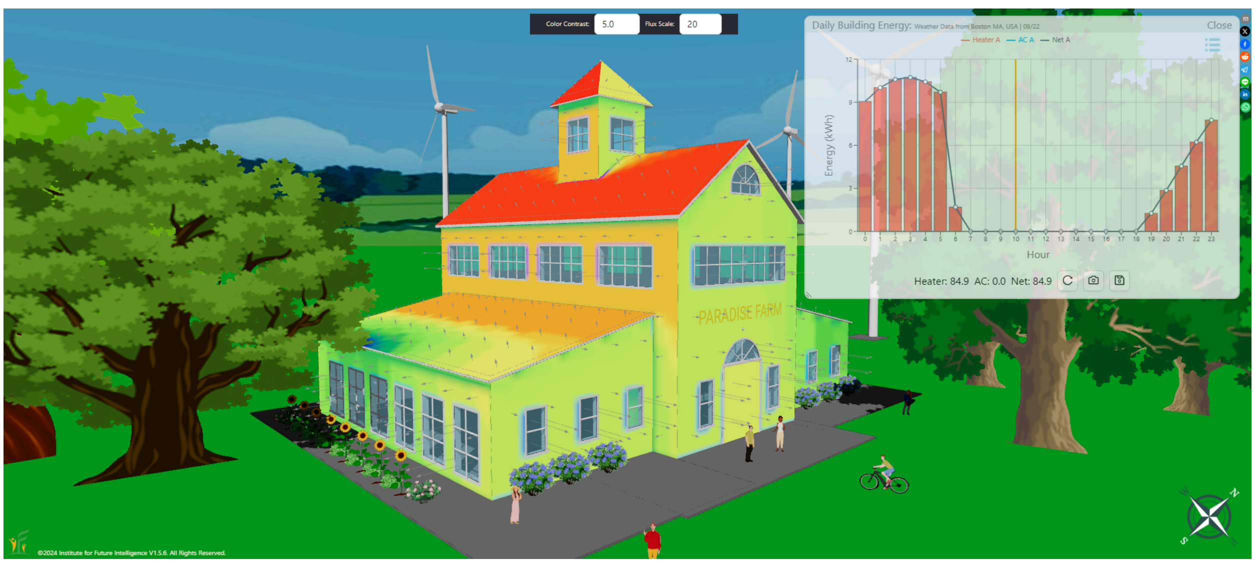


Figure 3. Building energy simulation and analysis built in Aladdin allows students to immediately examine the energy performance of a house with rich visualization.

Design Variables

The NGSS performance expectation HS-PS1-3 requires students to “design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.” One way for students to attain this performance expectation through the Energy-Plus House Design Project is to explore various design variables that may affect the energy efficiency of the building as a system and derive their design strategies from their findings. The curriculum unit provides a comprehensive list of design variables, categorized as either passive (e.g., insulation and landscaping that require no external energy inputs) or active (e.g., solar panels that generate energy for the house). A supplemental Web page (see “On the web”) offers teachers additional explanations of the science underlying each design variable. As an option, students can also conduct one or more self-directed investigations into these design variables to explore how they affect the energy performance of a house.

Each investigation is driven by a question. For example, when examining the effect of trees, students are asked on which side of the house they would plant trees to minimize the AC usage in the summer. They can move the tree around the house, analyze the building energy use in each case, and use the shadow tool and the solar radiation heatmap to visualize the shading effect. Each investigation also includes formative assessments to help students self-regulate their learning (Zheng, et. al, 2020). For example, once students find out that trees reduce the AC usage the most when planted to the south of a house in Massachusetts (Figure 4a), they are prompted to think about whether the trees would block sunlight in the winter and prevent solar heating through the south-facing windows (deciduous trees do not because they shed leaves in the winter). This relationship may change if there is a large west-facing window, in which case trees planned to the west of the house can save the AC cost the most (Figure 4b).

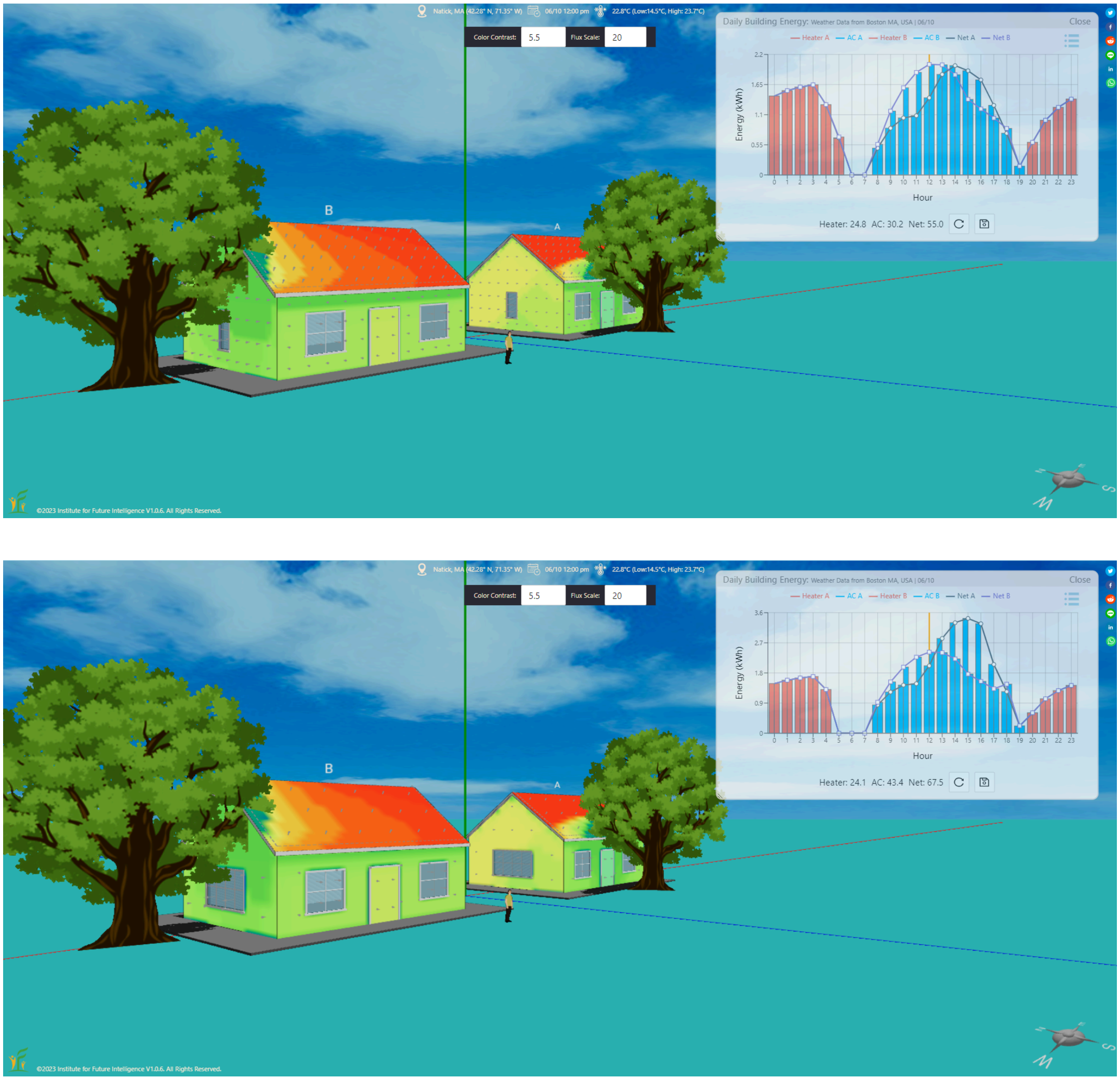


Figure 4. An activity to investigate how trees may affect building energy use on a summer day. (a) Two identical houses with a tree to their south and west with a small

west-facing window; (b) The same houses and trees, but with a large west-facing window.

After understanding a design variable through an investigation, students can apply the knowledge to design. For example, knowing that trees can save energy for a house (in addition to adding the aesthetic value to the living environment), students can add trees to their own designs, and determine how many trees are needed through multiple iterations. Students are encouraged to keep a design journal in the built-in note area in Aladdin, where they can document their design decisions and the performance changes at each step.

Building as a System

The Energy-Plus House Design Project also highlights the concept of "Systems and System Models," a crosscutting concept of NGSS (in addition to energy). The unit guides students to view a house as a complex system consisting of various components that interact with one another to drive the energy exchange with the environment. As they work towards the design goal, they consider the interdependencies among different design variables to practice and develop systems thinking. This ability is crucial in engineering design as students need to take multiple criteria and constraints into account to find balances and tradeoffs among competing objectives. One example to illustrate the coupling of science concepts and engineering design involves the ability of the roof material to absorb solar radiation and the ability to conduct thermal energy. If a roof absorbs a lot of solar energy and passes the energy into the house, it will drive up the cooling cost in the summer. This heat transfer pathway can be impeded by using either a reflective coating on the surface to bounce sunlight back or an insulative material underneath the roof to block the energy from entering the house (or a combination of both).

But the story may be different if students are designing a house in a cold climate. While a lighter roof color helps reduce the AC usage, the same mechanism may also lead to more heating usage in the winter. Aladdin allows students to not only discover this phenomenon, but also make quantitative evaluations. For example, a yearly building energy analysis confirms that a white roof is indeed more energy efficient than a black roof in sunny California due to reduced AC usage in the summer, and a daily building energy analysis in the winter further explains why the heating usage does not increase as much: Most of the heating occurs at night, when the roof color does not matter (Figure 5a). The story is dramatically different if the house is located in northern Maine (Figure 5b), in which case a darker roof color may actually result in energy saving. This systems-thinking approach, supported by Aladdin, allows students to develop a holistic understanding of how different factors collectively affect building energy efficiency and make evidence-based design decisions.

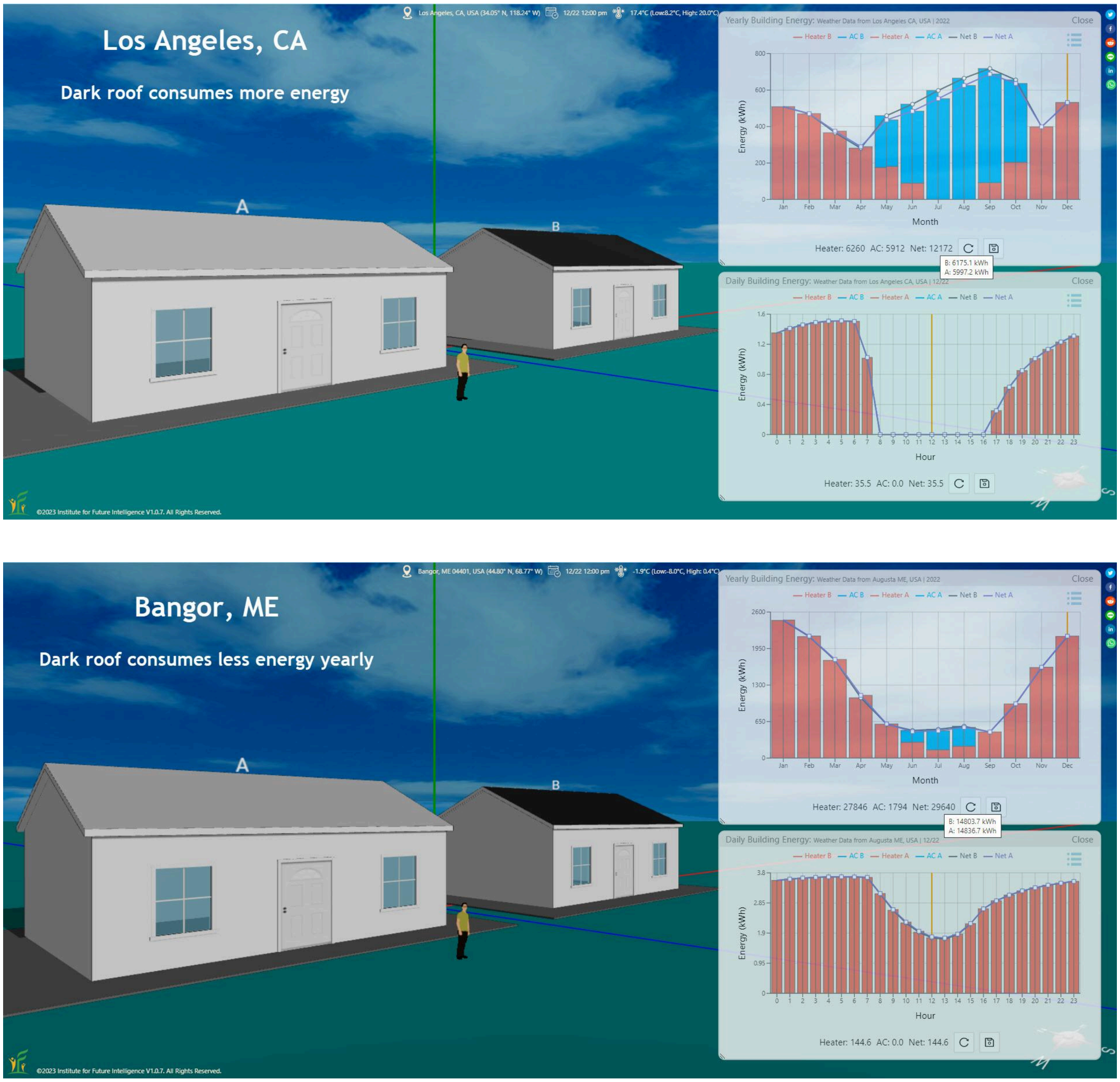


Figure 5. An activity to investigate how the roof color may affect building energy use in two different locations. In each image, the top right graph shows the yearly building energy analysis result, and the bottom right graph shows the daily building energy analysis result in the winter. (a) The results for Los Angeles, CA show that the house with the dark-colored roof consumes about 178 kWh more than an identical house with

the light-colored roof. (b) In Bangor, ME, the same house with the dark-colored roof consumes 33 kWh less than an identical house with the light-colored roof.

Design Presentation and Checklist

In the final stage of the project, students will present their designs to their teacher and peers. They will highlight the energy-efficient features of their designs, explain their design choices, and back them up with their simulation results. The presentation also serves as an opportunity for students to discuss the challenges and lessons learned during this project and reflect on the importance of sustainable engineering in addressing climate change, energy equity, and social justice. In lieu of a presentation, students can also choose to complete a design checklist, where they document their investigations of each design variable. Students write down their final design choices, compare them with the default values, and document their reasoning.

Adaptations and Recommendations

If time is limited, teachers can direct students to focus on design variables that are more visual, such as building orientation, roof color, and so on.These factors are also suitable for stimulating student interest, before they explore other factors such as insulation. Students can work either individually or in teams, and teachers are encouraged to offer guidance and feedback to students as they develop and refine their designs.

Results

We conducted a study in a suburban high school in northeastern America, involving 111 9th-grade students from five physical science classes. The valid sample size was determined to be 83 (40 girls and 43 boys). We developed the 18-item Green Building Science Test (see "On the web") and used it in the pre/post-tests to measure student learning as a result of completing the Energy-Plus House Design Project. Each item combines a multiple choice question about a design decision and a free response area for justifying the respondent's selection. These items were reviewed by a panel of experts including building physicists, engineering professors, learning scientists, and science teachers to ensure their content validity and developmental appropriateness.

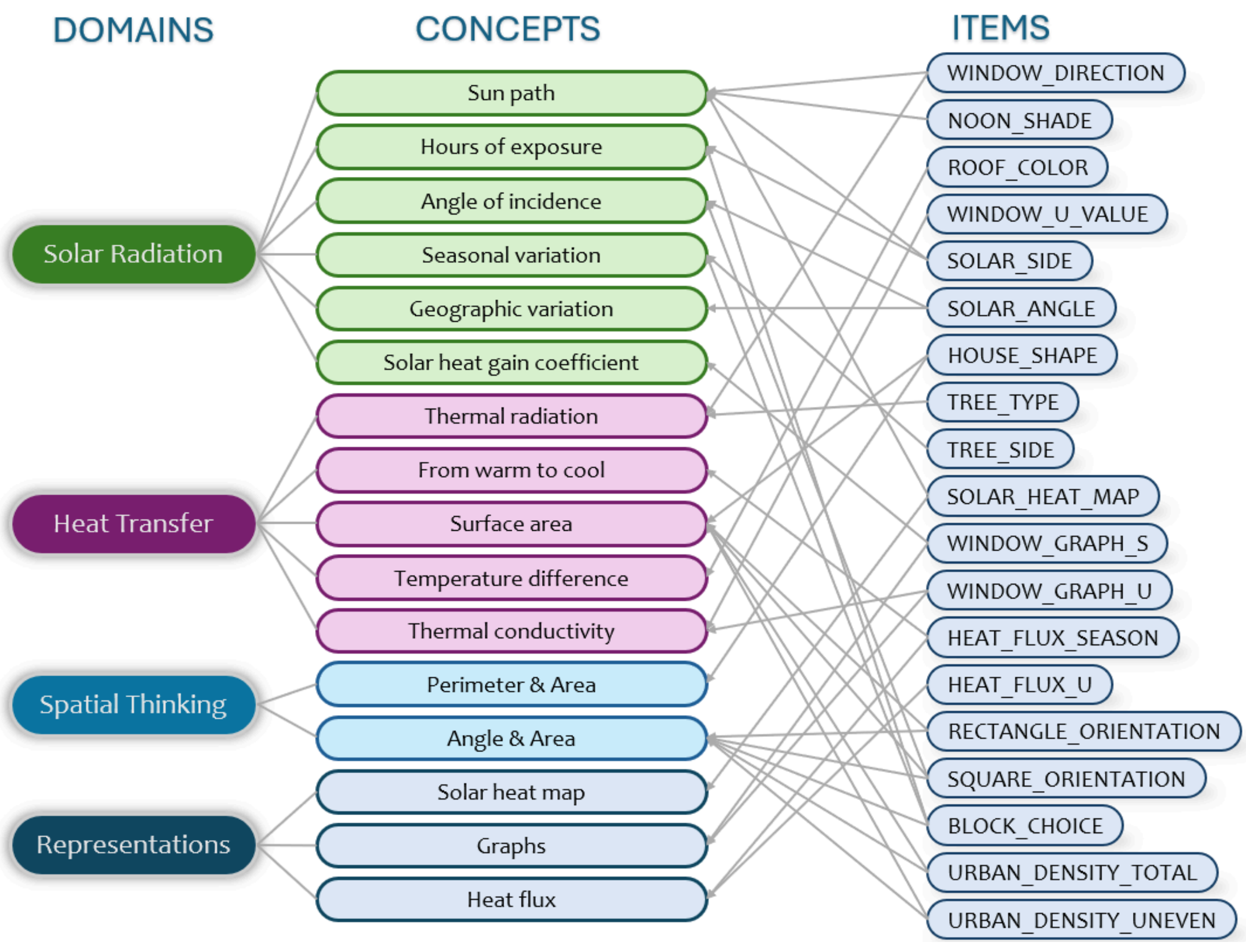


Figure 6: Concepts underlying the Green Building Science Test items.

As shown in Figure 6, each item covers a subset of concepts from the four target domains (solar radiation, heat transfer, spatial thinking, and representations). Students' responses were scored using a 5-level scoring rubric developed to differentiate different levels of design thinking. A paired-samples *t*-test indicated that students' performance significantly improved from pretest (*M*=24.82, SD=8.61) to posttest (*M*=37.81, SD=8.66), *t*=15.08, 1-tailed *p*-level<.001, with a large effect size, Cohen's *d*=1.66. Raw gain scores (*M*=12.99, SD=7.85) were calculated by subtracting the pretest scores from the posttest scores. More details and results about this study can be found in our earlier paper (Chao et al. 2017).

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On the web

The Solar Decathlon: https://www.solardecathlon.gov/

The Aladdin software: https://intofuture.org/aladdin.html

Explaining the design variables: https://intofuture.org/aladdin-building-energy-2.html

The Curriculum Unit for the Energy-Plus House Design Project: http://intofuture.org/aladdin-energy-plus-house-design.html

The Green Building Science Test: https://intofuture.org/papers/green-building-science-test.pdf

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed.

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