Learning Science and Engineering by Designing Sustainable Houses

ELENA SEREIVIENE, XIAOTONG DING, RUNDONG JIANG, DYLAN BULSECO, AND CHARLES XIE

ABSTRACT

Science and engineering offer ways to maintain the thermal comfort of our homes while minimizing impacts on 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 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 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 and find clues for improvements. The unit covers design specifications, passive and active heating and cooling design strategies, and the interdependencies of design variables within the house as a system. Students collect quantitative evidence from simulation results, make trade-off decisions among multiple criteria and constraints, and explain their design solutions in a final presentation.

Keywords: Science education; engineering education; STEM education; engineering design; computer-aided design; computer simulation; net-zero buildings; sustainability

Increases in heating and cooling costs impact low-income communities disproportionately (Root 2021). The energy costs for maintaining the thermal comfort of our homes are 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.

Science education can play a role in mitigating this inequity by inspiring and preparing students to build more energy-efficient houses to lower the costs. 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 energy efficiency of buildings is crucial to the sustainability of civilization, as they account for 30% of global energy consumption according to the International Energy Agency. For more than two decades, the U.S. Department of Energy (DOE) has organized the Solar Decathlon, a green building design challenge for college students (see "On the web"). The idea behind this DOE challenge can benefit millions of high school students as well. The problem is that high school students do not have the privileges and resources needed to tackle the challenge. To address this problem, we have developed a free, Web-based computer-aided design (CAD) tool called Aladdin (see "On the web") that allows high school students to design 3D virtual buildings and analyze their energy performance through physics-based simulation.

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. Aladdin provides students with both architectural design and energy modeling capabilities in a single platform, allowing them to freely explore the energy ramifications of various design options. This capability can thereby help students develop an understanding of the relationship between structure and function, an NGSS crosscutting concept.

In this article, we introduce the Energy-Plus House Design Project, an NGSS-aligned curriculum unit developed for high schools. 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 of generating more renewable energy than it consumes over the course of a year. We briefly report findings from a classroom study to conclude this article.

Design concepts and specifications

The minimum goal is to design a net zero energy building–one that generates as much renewable energy as it consumes throughout the 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 "off-grid"; i.e., it may not be 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 has energy implications. For instance, different styles may have different surface-area-to-volume ratios – a house with a larger building envelope (external surface area) consumes more energy than a house with the same volume but a smaller external surface area (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).

Educational technology

To support engineering education, Aladdin integrates 3D modeling and energy modeling in a single system (Xie et al. 2018; Xie, Ding, and 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.

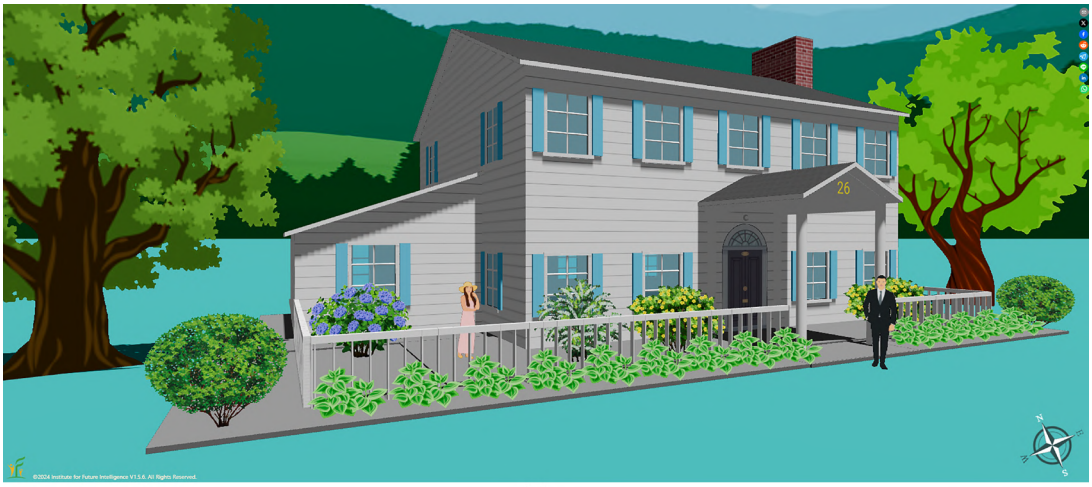
After constructing a house, students can then analyze its daily and yearly energy use.

By default, the house is controlled by a thermostat set to 20 °C (68 °F) that drives heating and air conditioning systems to maintain the indoor temperature. But users can select a programmable thermostat and use different setpoints for heating and cooling in different periods of the day. 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 in each period 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

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.



(a)

(b)

(c)

FIGURE 2

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

(a)

(b)

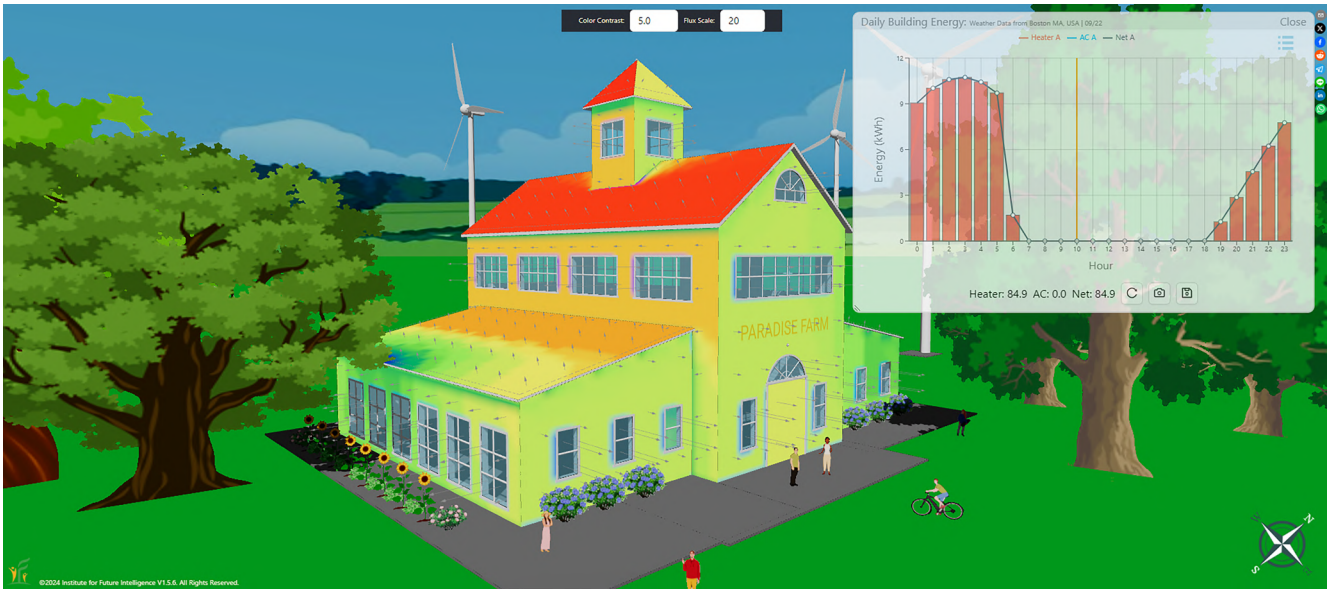
negative (i.e., the design achieves an energy surplus). For example, students may discover that the heat flux arrows sticking out of the windows are much longer than those of the walls, which may prompt them to increase the insulation value of the windows and/or decrease the emissivity property of the windows to reduce the heat transfer through them.

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

FIGURE 3

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



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 of 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 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 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 most AC cost (Figure 4b).

After studying a design variable through an investigation, students can apply the knowledge to their own designs. For example, knowing that trees can save energy for a house (in addition to adding aesthetic value to the living environment), students can add trees to their 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.

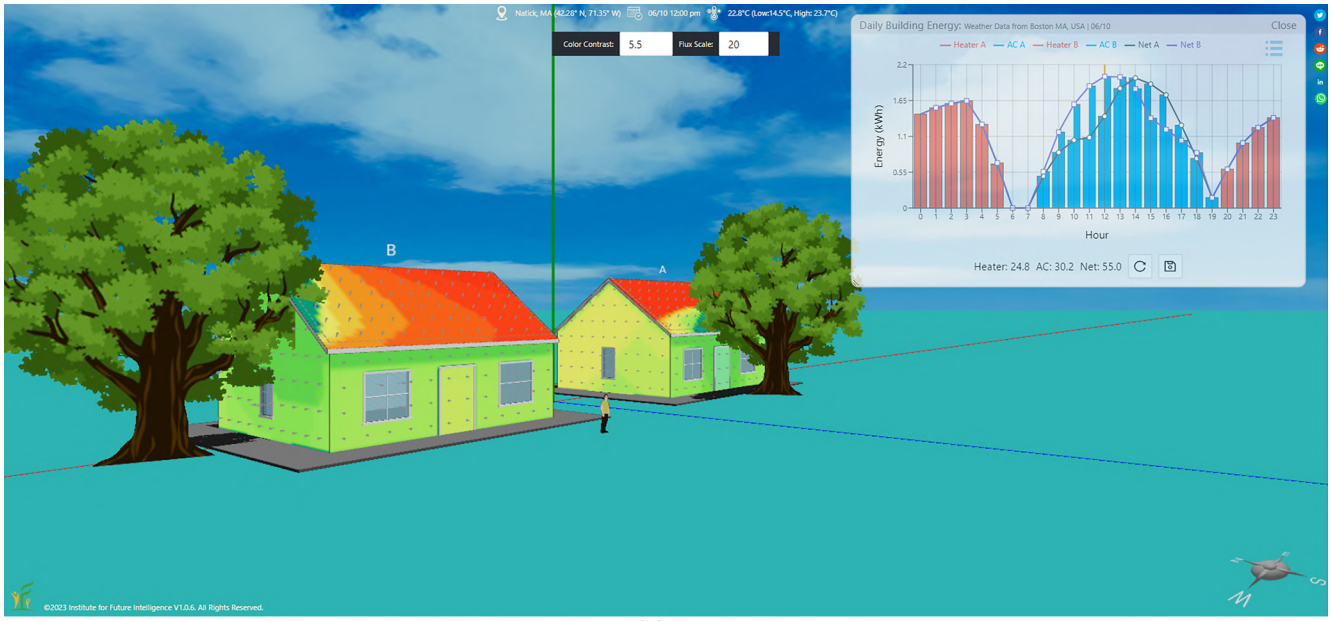
Building as a system

The Energy-Plus House Design Project also highlights the concept of "Systems and System Models," a crosscutting concept of *NGSS* (in addition to energy and matter as well as structure and function). 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 interdependence of different design variables to develop and practice systems thinking.

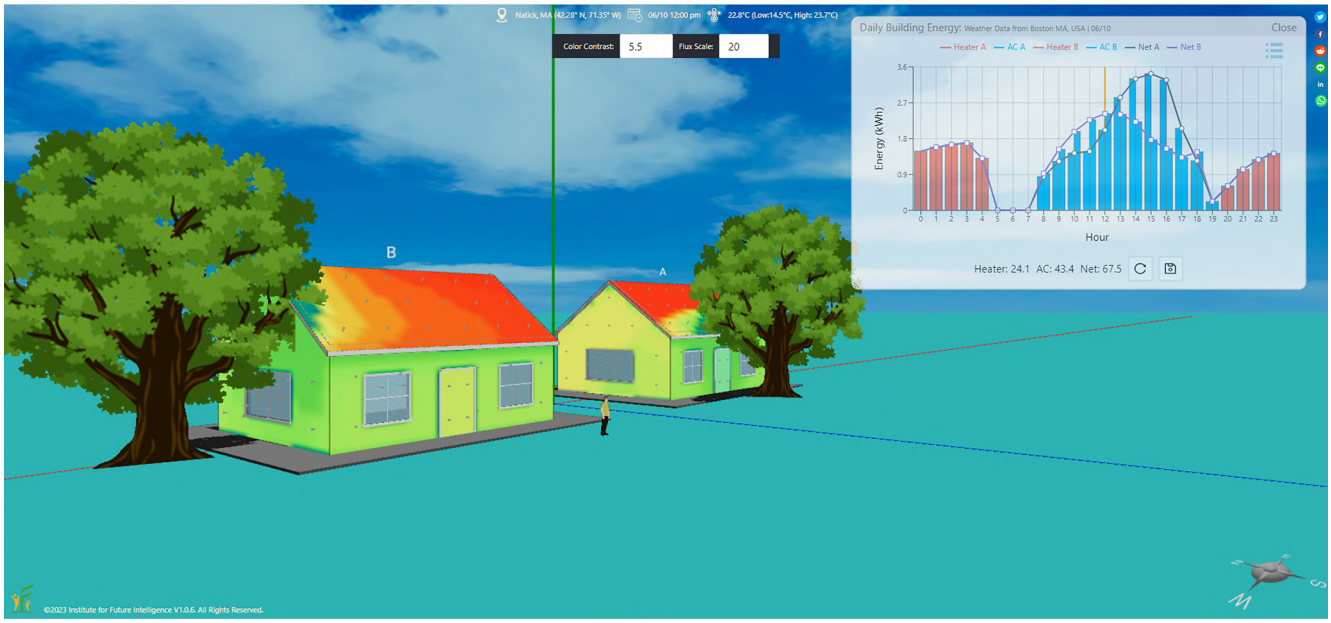
This ability is crucial in engineering design as students need to take multiple criteria and constraints into account to find balances and tradeoffs among competing objectives. One example illustrating the coupling of science concepts and engineering

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.



(a)

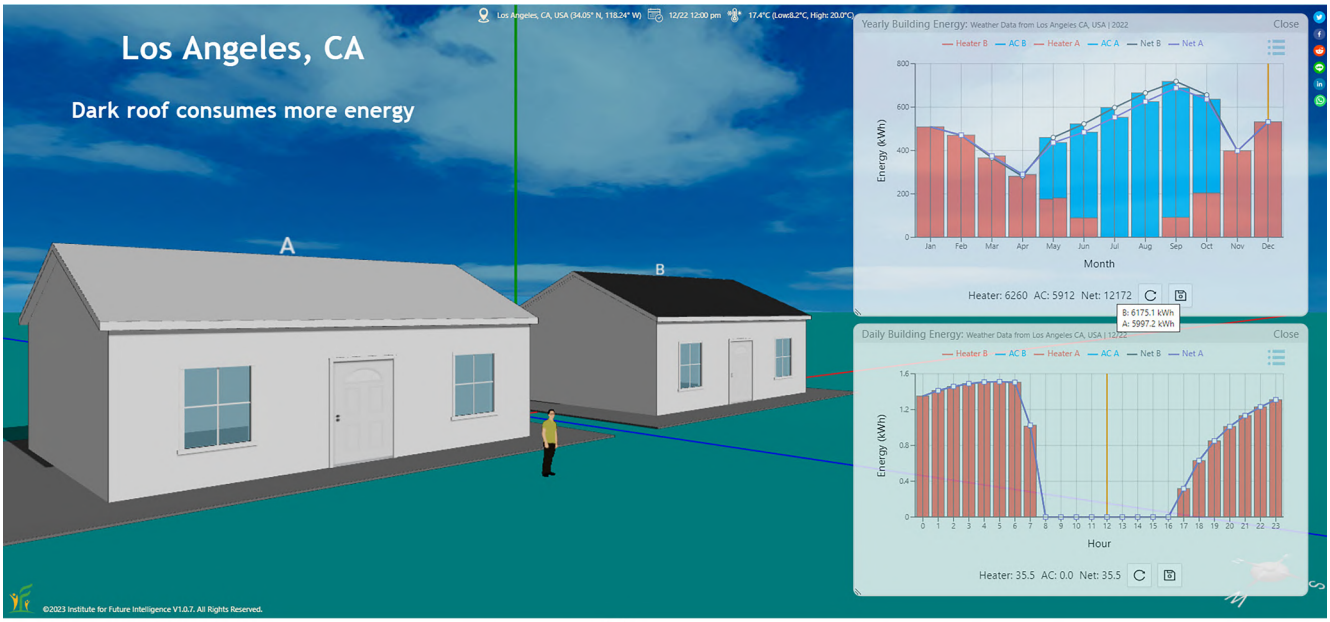


(b)

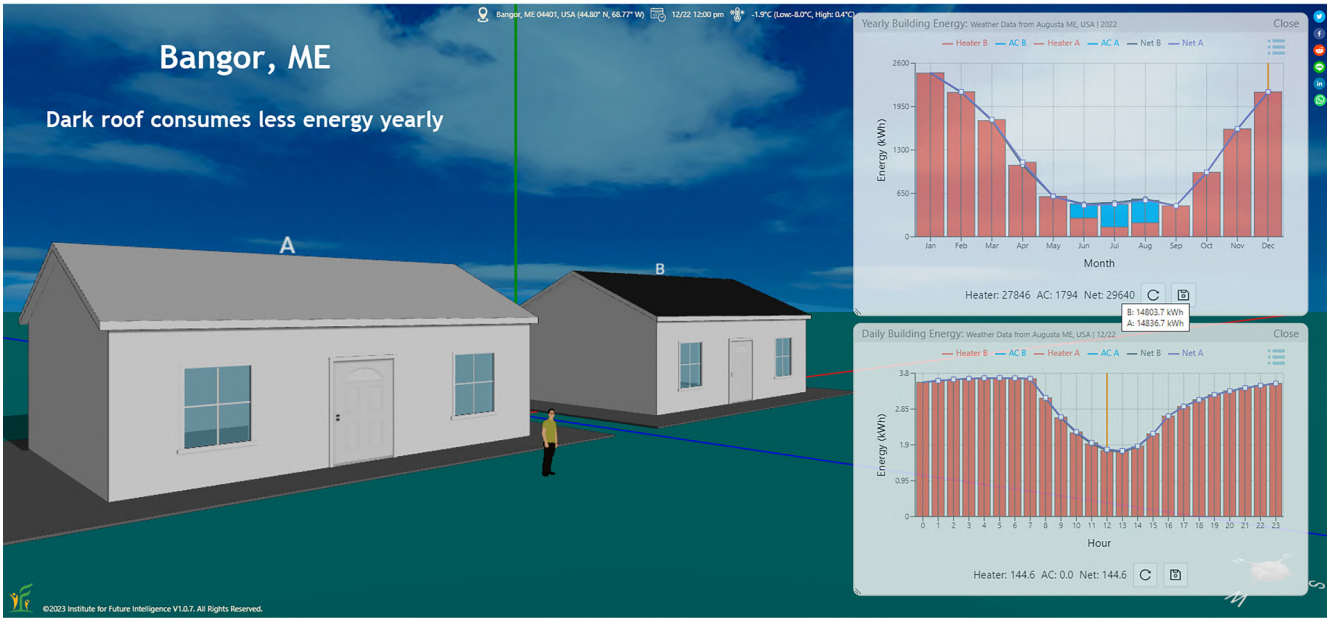
design involves the ability of the roof material to absorb solar radiation and conduct thermal energy. If a roof absorbs a lot of solar energy and passes the energy into the house, it will drive up the cooling cost in the summer. This heat transfer pathway can be impeded by using either a reflective 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).

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.



(a)



(b)

But the story may be different if students are designing a house in a cold climate. While a lighter roof color helps reduce 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 to 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 different if the house is 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.

Design presentation and checklist

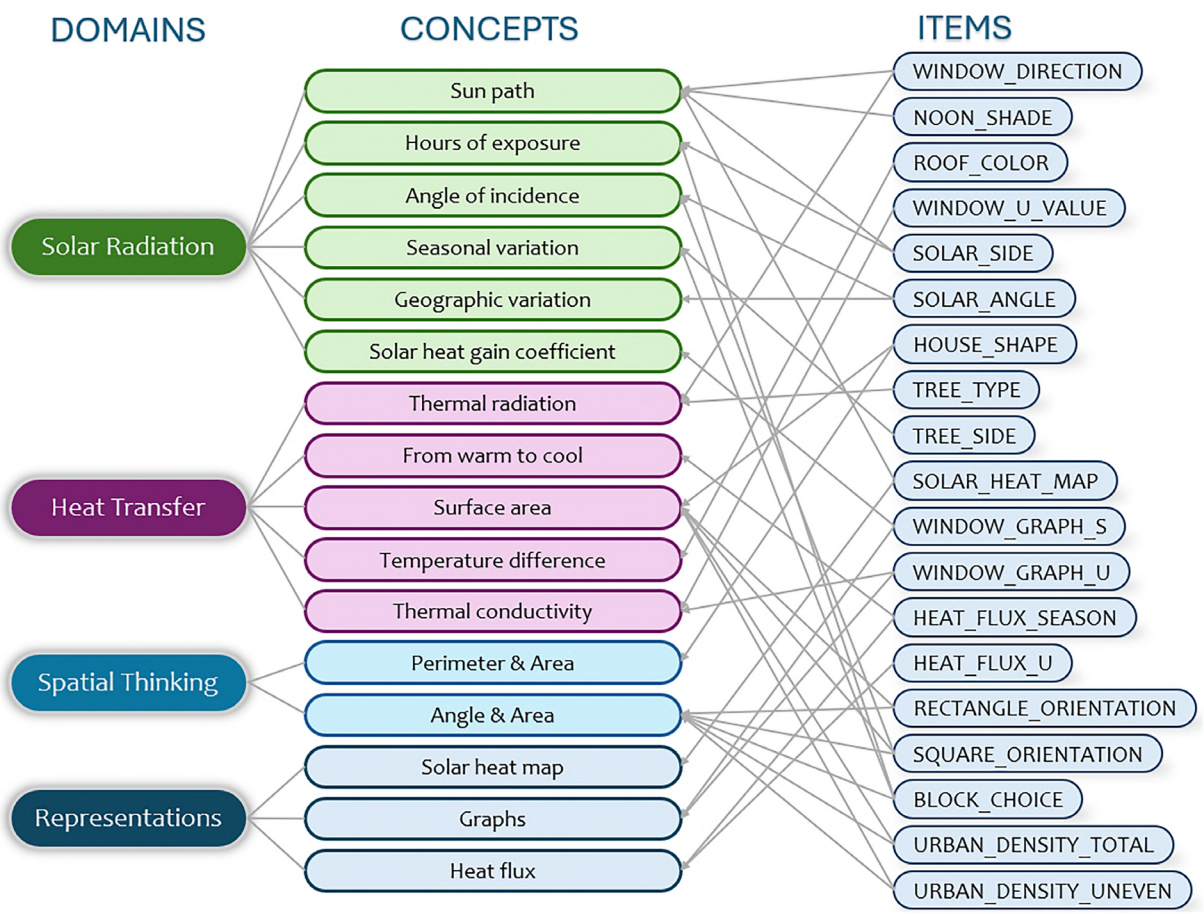
In the final stage of the project, students will present their designs to their teacher and peers. They will highlight the energy-efficient features of their designs, explain their design choices, and back them up with their simulation results. The presentation also serves as an opportunity for students to discuss the challenges and lessons learned during this project. 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. Starting with these factors before others such as insulation may ignite student interest at the beginning of the

FIGURE 6

Concepts underlying the Green Building Science Test items.



project. Students can work individually or in a team, and teachers are encouraged to offer guidance 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 following completion of 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.

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 five-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).

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

FUNDING

This work was supported by the National Science Foundation (NSF) under grant numbers 2105695, 2131097, and 2301164. Any opinions, findings, and conclusions or recommendations expressed in this paper, however, are those of the authors and do not necessarily reflect the views of the NSF.

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 was created or analyzed.

SUPPLEMENTARY MATERIAL

Supplemental data for this article can be accessed online at https://doi.org/10.1080/00368555.2025.2469120

REFERENCES

Chao, J., C. Xie, S. Nourian, G. Chen, S. Bailey, M. H. Goldstein, S. Purzer, R. S. Adams, and M. S. Tutwiler. 2017. "Bridging the Design-Science Gap with Tools: Science Learning and Design Behaviors in a Simulated Environment for Engineering Design." *Journal of Research in Science Teaching* 54 (8): 1049–1096. https://doi.org/10.1002/tea.21398.

Dym, C. L., A. M. Agogino, O. Eris, D. D. Frey, and L. J. Leifer. 2005. "Engineering Design Thinking, Teaching, and Learning." *Journal of Engineering Education* 94 (1): 103–120. https://doi.org/10.1002/j.2168-9830.2005.tb00832.x.

Root, T. 2021. Heat and smog hit low-income communities and people of color hardest, scientists say. *The Washington Post*, https://www.washingtonpost.com/climate-environment/2021/05/25/heat-inequality-climat e-change/

Xie, Charles, Xiaotong Ding, Rundong Jiang, Beatriz Sousa Santos, Alejandra J. Magana, and Jiri Zara. 2023. "Using Computer Graphics to Make Science Visible in Engineering Education." *IEEE Computer Graphics and Applications* 43 (5): 99–106. https://doi.org/10.1109/MCG.2023.3298386.

Xie, C., C. Schimpf, J. Chao, S. Nourian, and J. Massicotte. 2018. "Learning and Teaching Engineering Design through Modeling and Simulation on a CAD Platform." *Computer Applications in Engineering Education* 26 (4): 824–840. https://doi.org/10.1002/cae.21920.

Zheng, J., W. Xing, G. Zhu, G. Chen, H. Zhao, and C. Xie. 2020. "Profiling Self-Regulation Behaviors in STEM Learning of Engineering Design." *Computers & Education* 143: 103669. https://doi.org/10.1016/j.compedu.2019.103669.

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