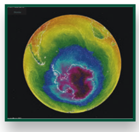
Solarize Your World: Addressing Climate Change Through Renewable Energy Engineering



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Physics teachers often teach solar energy as an alternative energy source to mitigate climate change. However, applications of solar energy are typically limited to solar cookers. Students need a tool to design solar energy solutions at any scale, and teachers need curriculum materials for solar energy engineering. In this article, we introduce Aladdin, an engineering design platform for sustainable energy solutions. We also present *Solarize Your World*, a set of curriculum modules that help students apply their physics knowledge to design real-world solutions to climate change.

Solar energy is a favorite topic in the physics classroom. For over four decades, *The Physics Teacher* has published teaching materials related to solar energy, including solar astronomy,[1–3] solar radiation,[1,4] the inner workings of solar panels,[5–9] and the efficiency of photovoltaic (PV) systems.[10]

However, there is a disconnect between what students learn about solar energy and what they can do with that knowledge. For example, the *Next Generation Science Standards*,[11] which is adopted by many states across the U.S., describes a performance expectation that high school students can "design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy." But the most common solar energy project remains solar cookers.[12–14] Compared with the rich literature on how PV works, little has been said about the engineering design of residential and commercial PV systems and the role of physics in their design, despite their growing popularity and importance in the global energy landscape.[15]

Furthermore, recent examples of successful student-led solar school projects[16,17] prove that students are more than capable of initiating, designing, and driving solar energy solutions at the megawatt level. But for the majority of the other schools and students looking to follow suit, publicly available resources have mixed quality and appropriateness. For example, professional software is needed to design both rooftop and ground-mount PV systems. However, commercial PV design software tends to be prohibitively expensive, and while free solar calculators such as Project Sunroof[18] or PVWatts Calculator[19] allow students to estimate the total energy production on a given lot, they do not provide any detailed layout or the ability to design one. Without a visualization of the proposed PV system, students will not know exactly where to put the solar panels. On the other hand, guidelines and best practices for PV system design are widely available on the internet, but they are often too technical, rendering them unsuitable for students, for whom learning is often more important than business considerations.

A recent article in *The Physics Teacher* described modeling and designing concentrated solar power with Aladdin, a free educational tool for sustainable energy engineering developed by the Institute for Future Intelligence.[20] Here, we describe its PV design capabilities. We also present *Solarize Your World*, a curricular framework based on a suite of engineering design projects addressing the design of various PV systems. Students will learn the basic science of solar energy, explore the design requirements of different PV systems, create multiple iterations of PV design, and use physics concepts to explain the reasoning behind their final designs.

Technology

Aladdin is an open-source web-based computer-aided design (CAD) and computer-aided engineering platform for designing solar power systems and energy-efficient buildings.[20,21] Specifically, Aladdin allows students to create 3D models of built environments that include homes, buildings, infrastructure, vegetation, and so on (Fig. 1). Google Maps is integrated into Aladdin, such that students can display a map of any address as the ground image and create CAD models on top of the map. Not only do the building models and environment imagery add a degree of authenticity to engineering design projects, but they also serve as the constraints for engi-

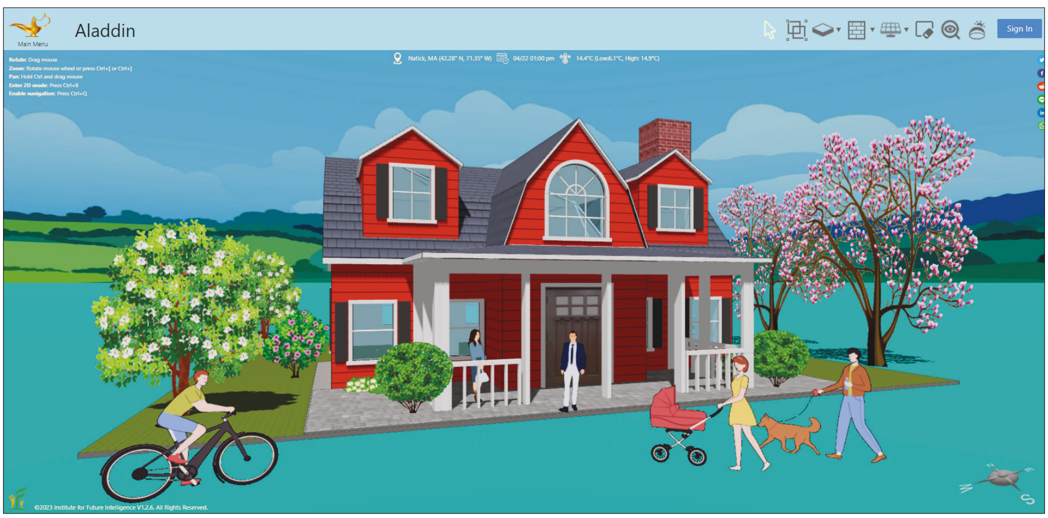

Fig. 1. A screenshot of an Aladdin model of a Dutch colonial house. Aladdin allows students to model buildings and environments, design solar power systems, and calculate their outputs based on numerical simulations.

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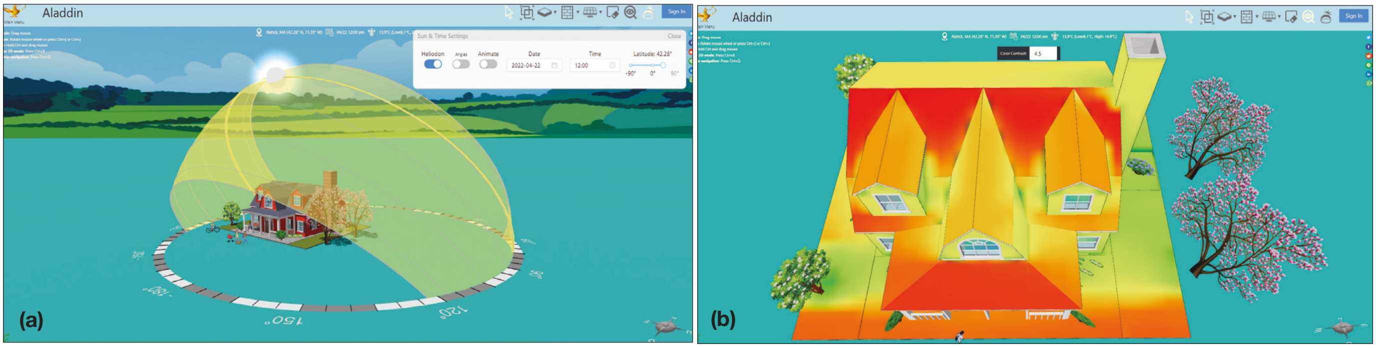

Fig. 2. (a) The same Dutch colonial house with the heliodon visualization showing the Sun's position at 12 p.m. on April 22 at a latitude of 42° N. (b) Heat-map visualization of the same house reveals the rooftop distribution of solar radiation on April 22. The red areas receive more solar radiation than the green areas and are considered better locations for installing solar panels.

neering design. For example, one key attribute of PV systems is their significant land use due to the low energy density of solar radiation, which has inspired many creative solutions that promote dual use of space (e.g., solar canopy parking lots, agrivoltaics, and floatovoltaics). This enables students to use their living environments as laboratories[22] to examine how human–environment interactions are governed by the laws of physics.

Though activities for designing solar power systems have existed for decades,[23] they are often limited to theoretical principles, whereas Aladdin allows students to design and visualize various solar power systems in different built environments in realistic settings. It uses weather data and physics-based simulation to analyze the daily and yearly energy outputs of solar power systems, which not only enables students to test different designs and explore the effects of different design variables, but also allows them to apply physics knowledge to guide their iterative design process. To illustrate this, the following sections will describe a variety of PV design projects that students can do with Aladdin.

Solarize your home

Residential solar installations totaled 1.36 GW in just a single quarter in 2022.[24] Many parents may be thinking about going solar too, but they may have lots of questions about it, such as, does our house get enough sunlight for solar to make sense? Instead of putting their trust entirely in solar salespersons, parents can turn to their children, who are looking for motivation to learn science and engineering knowledge at school, to play an active role in the decision-making of their families. In the *Solarize Your Home* (SYH) project, students will use Aladdin to create a 3D model of their homes, assess the rooftop solar potential, and recommend an optimal PV design and plan to their parents.

To start, students will first model their own home buildings in Aladdin. The Google Maps embedded in Aladdin allows students to enter their home address and display a satellite image of their house as the ground image in Aladdin. Students can then use a suite of CAD features to add different building components such as foundations, walls, roofs, windows, doors, and so on, directly on top of the satellite image. Since an accurate roof model is critical to rooftop PV design, Aladdin supports a variety of common roof types of different

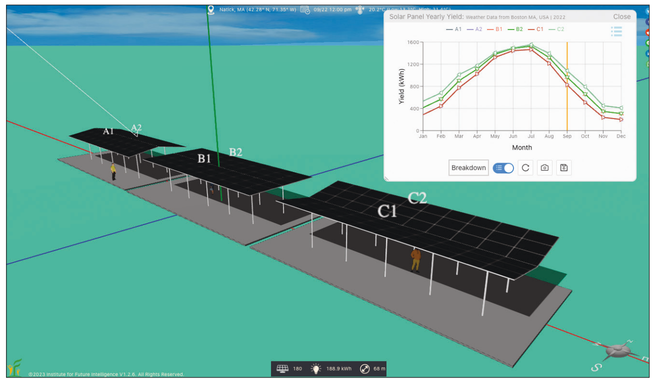

Fig. 3. A comparison of the yearly energy output of three different solar canopy configurations.

architectural styles, so students from different regions and cultures can all create realistic-looking houses. As students view the satellite image, they will notice rooftop structures like dormers and chimneys as well as obstructions like ventilation hatches and HVAC modules. These existing structures act as constraints to rooftop PV design, since they affect solar panel placement. They can also model the vegetation around their houses and evaluate how surrounding trees may affect the energy generation.

After students finish modeling their houses, they can experiment with different design variables. For example, if the parents wonder which side of the roof is the most suitable for installing solar panels, the student can visualize the rooftop distribution of solar radiation on any given day as a heat map and notice that for houses in the northern hemisphere, south-facing sides receive the most solar radiation over the course of a day. If the parents still have doubts about the heat map analysis, the student can also visualize the Sun's path using the built-in heliodon and show how the solar elevation and azimuth angles change throughout a day (Fig. 2). While the rationale for choosing roof sides can be explained with physics, the feasibility of a rooftop PV system remains an engineering problem that can only be answered by students adding solar panels to the roof, estimating the yearly energy output, and comparing that with the electricity bill. To some extent, the SYH project demonstrates the relationship between physics and engineering design: physics provides the scientific reasoning that validates an engineering decision, while the engineering design provides an actual solution that turns abstract concepts into actionable plans.

Solarize your school

As of 2022, only 9% of all K–12 schools in the U.S. use some form of solar power.[25] Students can play a vital role in solarizing their schools. For instance, a solar energy project in a Maine school stemmed from a student-led initiative[16]; and in Minnesota, students helped a school district achieve millions of energy savings through switching to solar power.[17] In the *Solarize Your School* (SYS) project, students assess the solar potential of their school, design a PV system consisting of both rooftop PV and solar canopies, and present their final designs to stakeholders.

As preparation for the SYS project, the teacher may obtain a 12-month electricity bill from the facilities manager of the school. The monthly and yearly electricity usage can serve as a goal for students, as they attempt to offset 100% of the school's electricity consumption with solar energy. The teacher may also create a CAD model of the school campus in Aladdin, or they can motivate students to model their school themselves.

Once students have an Aladdin CAD model of their school, teachers can engage students with a driving question: *Does it make sense for our school to go solar?* To answer this question, students will first explore the design criteria and constraints for designing a PV system for a school. Criteria may include technical objectives like the yearly energy output, financial objectives like the payback period, and the aesthetic considerations of the PV design. Constraints may include existing structures and fire code compliance, which limit where solar panels can be installed. Students have two main options of PV design: rooftop solar panel arrays and solar canopies. The angles of rooftop solar panel arrays are restricted by the roof pitch, and the shape of solar canopies is also restricted by the layout of the parking lots. Therefore, the optimal designs are specific to each individual school.

While the design considerations for rooftop solar panels are similar to the SYH project, solar canopies may have different configurations: 1) L-shaped, which is commonly used on single-row parking spaces near the parking lot perimeter; 2) T-shaped, which is commonly used on double-row parking spaces near drive aisles in the west–east direction; or 3) Y-shaped, which is commonly used on double-row parking spaces near drive aisles in the north–south direction (Fig. 3). Rather than giving students these directions, the teacher can encourage students to investigate why solar canopies have different shapes by comparing their energy outputs in different sections of a parking lot and using solar angles to explain their findings.

In addition to rooftop PV and solar canopies, students can also identify other existing structures that are amenable to solar development and experiment with more creative PV designs, such as solar bleachers and solar bus stops. While these infrastructure-integrated PV projects may be small in scale, such designs increase visibility of solar development within the campus (Fig. 4).

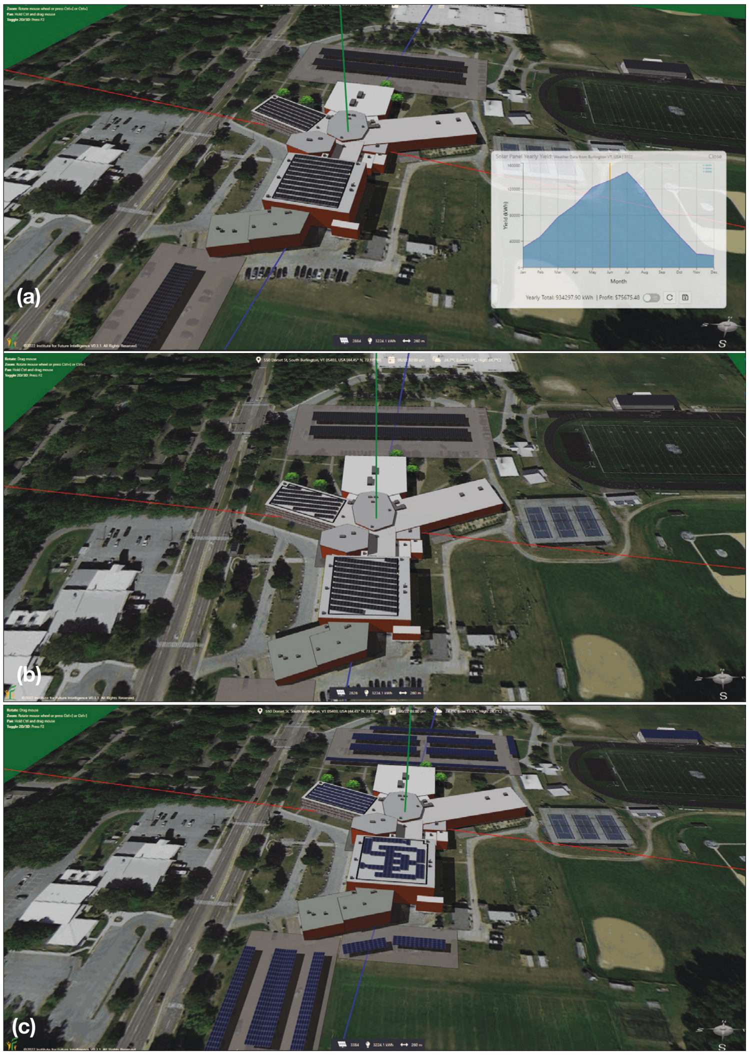

Fig. 4. Three examples of different PV designs for South Burlington High School, VT. All three designs use both rooftop PV and solar canopies. (a) In the first design, the rooftop solar panels are aligned with the roof edges. All solar canopies are Y-shaped, regardless of their location. The simulated yearly energy output and profit are also displayed in the pop-up window, along with a graph showing the monthly energy output. (b) In the second design, the rooftop solar panels are oriented toward due south to optimize the energy output per panel. However, fewer panels are able to fit onto the roofs due to the geometry of the new layout. (c) In the third design, the layout of the rooftop solar panels resembles the school logo. The solar canopies use a combination of L-shaped, T-shaped, and Y-shaped configurations, depending on the layout and orientation of the parking lots.

Agrivoltaics: Solarize your farm

Agrivoltaics (AV) is the integration of a PV system and agriculture on the same land, also known as *solar and agriculture co-location*.[26] A common example is planting crops underneath a solar panel array or between the solar panel rows. Agrivoltaics has attracted extensive interest around the world as it promises to generate clean electricity while growing food. A main challenge in agrivoltaics is to balance the sometimes competing objectives of energy production and crop yield, since crop yield is affected by the shading from the solar panels. In the *Solarize Your Farm* project, students will explore how solar radiation affects both objectives, design an agrivoltaic project themselves, and attempt to optimize its perfor-

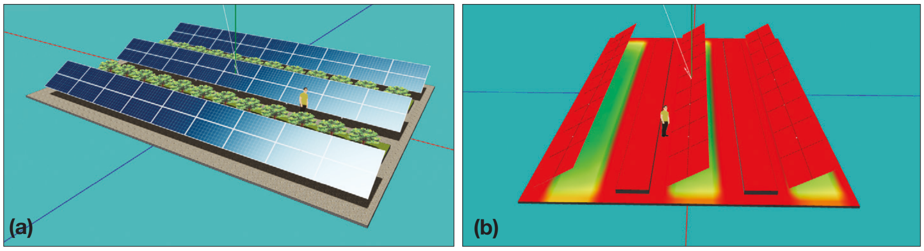

Fig. 5. (a) One possible configuration of an agrivoltaic project: Rows of solar panels are spaced far enough apart from one another to avoid shading on the panels. Sun-loving crops are planted between the solar panel rows to capture the solar energy striking outside the solar panels. The white line represents the incident sunbeam. (b) Heat map visualization indicates that the spaces underneath the solar panels receive a reduced amount of solar radiation, while the spaces between the solar panels receive largely unobstructed solar radiation.

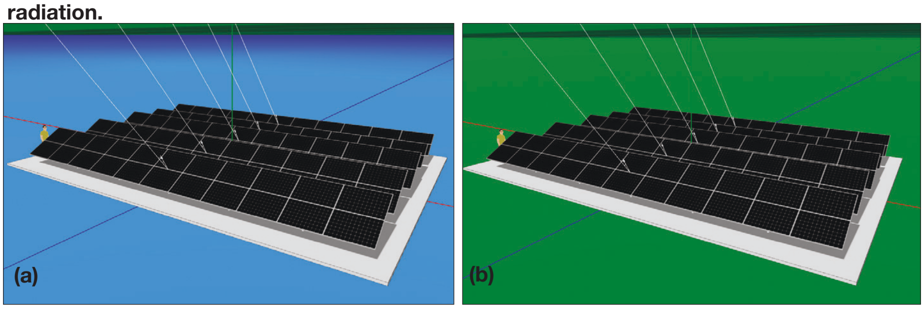

Fig. 6. (a) An FV system consisting of a solar panel array on water. White lines represent incident sunbeams. (b) The same solar panel array as a ground-mount PV system. The temperature of the solar panels in an FV system will be lower than if they were installed on land, and an FV system will generate more electricity than an equivalent PV system. Given the limited area available, students also need to optimize the yearly profit of the FV system by trying different combinations of tilt angle, row width, interrow spacing, and solar panel model.

mance between the two objectives.

To engage students, the teacher can ask the driving question: How can we harvest solar energy and crops on the same land? The teacher can make connections to previously learned physics concepts such as energy conversion and energy transfer in ecosystems. For example, a solar panel converts light energy into electricity through photovoltaics, while a crop converts light energy into chemical energy through photosynthesis.

Students can then explore various AV system designs. In addition to changing PV-related design variables such as tilt angle, row width, and interrow spacing, students can also decide which crops to plant and where to plant them. The shade tolerance of a crop is determined by its light saturation point[27,28]: Crops with a lower light saturation point are more shade loving and will see less decrease in yield when planted underneath solar panels. Crops with a higher light saturation point are more sun loving and are best planted between solar panel rows. Using the solar radiation heat map and the virtual light sensors in Aladdin, students can construct a solar array prototype, analyze the solar radiation received at different parts of the plot, and select the best crops to plant (Fig. 5).

Floatovoltaics: Solarize your pond

Floatovoltaics (FV) refers to PV systems floating on bodies of water. Among the many advantages of floatovoltaics, one of particular relevance to physics teachers is the increased solar cell efficiency due to the cooling effect of the water.[29] In the *Solarize Your Pond* project, students will explore the effect of temperature on solar cell efficiency and optimize the performance of an FV system.

To start, the teacher can engage students with the driving question: Why do people put solar panels on water? The teacher can make connections to previously learned physics concepts through additional questions like "Is heat good for solar panels?" and "How does water affect the solar panels above it?" The first question addresses the fact that solar panels convert light—not heat—into electricity. The second question leads into a discussion of heat transfer, phase changes, heat of evaporation, and the specific heat capacity of water.

To explore the benefits of floatovoltaics, the students can design two PV systems with the same total area and same design variables (tilt angle, row width, interrow spacing, etc.) and put one on land and the other on water in Aladdin (Fig. 6). A comparison of the simulated energy output of both PV systems will show that FV generates more electricity than traditional ground-mount PV under the same conditions.

Once students can explain this observation, the teacher can encourage students to optimize the yearly profit of the FV system. Since floatovoltaics typically involves rectangular solar panel arrays, this design challenge is similar to the optimization of a solar farm. Given the commercial nature of such projects, the main design criterion is often profitability (measured by yearly profit), a balance between energy production (measured by yearly energy output) and cost-effectiveness (measured by yearly energy output per solar panel).

The teacher can introduce two new concepts related to the temperature effects of solar panels: 1) nominal operating cell temperature (NOCT), which describes the temperature of a solar panel under a prescribed test condition. Solar panels with a higher NOCT will generate more heat than those with a lower NOCT under the same solar radiation conditions; 2) temperature coefficient, a negative value that describes how much the panel efficiency will decrease per unit temperature increase. Solar panels with a better temperature coefficient will maintain their efficiency better under high temperature conditions. Higher-end solar panel models may have a lower NOCT or a better temperature coefficient that makes them more efficient, but they are often more expensive too. Now that FV provides an alternative, would brand name panels still maintain enough edge on energy production to justify the higher price, or would budget panels offer the same performance at a more competitive price? Students need to create and test different designs in Aladdin to find out. This activity provides another example where students can apply physics knowledge in engineering design to solve real-world problems.

Conclusion

As solar energy continues to gain momentum in the U.S., it becomes imperative that students become more familiar with this common type of renewable energy, so that enough students develop interest and competence in this field as they join the workforce. While there are already a wealth of resources that explain the physics principles governing the human exploitation of solar energy, students may still wonder how they can use their knowledge to create solutions that will benefit their own families and communities. With Aladdin as an engineering design platform easy for everyone to use, the *Solarize Your World* curriculum can guide students to model the built environments around them, design various types of PV systems, and gain actionable knowledge to meet the challenges of climate change.

Web link

Aladdin and additional curriculum materials are freely available at http://intofuture.org/aladdin.html.

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