# Beyond Solar Cookers: Modeling and Designing Concentrated Solar Power as Engineering Projects in Physics Classrooms

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**Abstract**: Solar cookers are a favorite topic in physics education as they offer a solution to help people living in underresourced areas. The physics behind solar cookers can also be used to generate clean energy on a large scale to reduce our dependency on fossil fuel and decarbonize our economy. This article presents a free, cloud-based computer-aided design and simulation tool called *Aladdin* that can connect physics and engineering education using concentrated solar power as an example. As a generic modeling platform for renewable energy, *Aladdin* allows users to design and analyze all the four main configurations of concentrated solar power, 1) parabolic dishes, 2) parabolic troughs, 3) linear Fresnel reflectors, and 4) solar power towers, for any location in the world. As an integrated science, engineering, and computational tool that enhances scientific inquiry and engineering design with visual, interactive learning and teaching experiences, *Aladdin* supports teachers to meet the requirements of education standards such as the Next Generation Science Standards adopted by many US states.

## INTRODUCTION

The K-12 Next Generation Science Standards (NGSS) adopted by many states in the U.S. has elevated the importance of engineering design to the same level as scientific inquiry [1]. However, the educational technologies for engineering design still lag far behind those for scientific inquiry. For instance, there are many simulations designed to teach science concepts [2], but there are much fewer options for engineering design. This article presents our work to fill this gap, especially for physics teachers interested in incorporating engineering in their curricula to engage students and deepen learning through solving real-world problems. Our efforts have resulted in an open-source, Web-based computer-aided design (CAD) platform, named *Aladdin*, which is freely available to anyone. Situated in the field of renewable energy, *Aladdin* appeals to today's students who aspire to building a sustainable world to slow climate change. Aside from this motivation, the development of *Aladdin* is also based on the following pedagogical rationale.

### Connecting Science and Engineering

Engineering design tools intended for education must pave pathways to explicitly connect science and engineering education practices [3, 4]. Based on our own research on engineering design at the secondary level [5-7], a cognitive barrier for students to connect science and engineering arises from the fact that science concepts are often less evident than other design variables such as price and shape, especially when students are overwhelmed by the complexity of design. Furthermore, the ability to apply a science concept to improve a design rests not only on the understanding of the concept *per se*, but also on the understanding of its interplay with all the other variables that may affect the overall function of the whole system. The latter understanding, which is related to systems thinking, is a prerequisite to core engineering practices such as making tradeoffs that satisfy multiple criteria under multiple constraints. In a CAD environment, we can visualize the underlying science concepts on top of design artifacts to render their effects in an engineering context. Such scientific visualizations can create learning opportunities for students to see science concepts at work individually or concertedly in their own designs, thereby fostering the integration of different concepts and the linkage between science and engineering [6].

## Generating Formative Feedback

Apart from "creating the demand" for science [8] in an engineering project, another way to inspire students to learn and apply science in a design process is to continuously provide formative feedback [9] to illuminate how science concepts play out in their own designs. Specific feedback can help students learn the effect of a science concept and then make an actionable design choice. In typical engineering projects, students are challenged to design and construct an artifact that performs desirable functions under constraints. In a conventional design project, to determine whether a change of form can result in a specific function, students have to build and test a physical prototype or rely on the opinions of an instructor. This creates a delay in getting feedback at the most critical stage of the learning process, slowing down the iterative cycle of design and cutting short the exploration in the solution space. When students' time for a design project is limited, a long delay in the feedback loop can be detrimental to learning. Even if there is enough instructional time, not all teachers are expert at evaluating complex student designs and not all students have access to resources for meaningful prototyping and testing. All these problems can be addressed by supporting engineering design with an intelligent CAD system empowered by physics-based numerical simulations [5] and artificial intelligence [10] capable of analyzing students' design artifacts and then generate visual feedback to them on an ongoing basis.

To the best of our knowledge, there are currently very few developmentally appropriate CAD software available to K-12 students that can achieve the above instructional goals—most CAD software used in industry not only appear to be science "black boxes" to students, but also require a complicated procedure of tool chaining involving pre-processors, solvers, and post-processors, making them more challenging to use in schools. To fill the gap, the Institute for Future Intelligence has developed the Web-based *Aladdin* CAD tool that opens the "black box" of science with rich interactive visualizations and integrates design and analysis seamlessly to eliminate tool chaining. As the numerical simulation capabilities of *Aladdin* are key to achieving the aforementioned instructiveness of the tool, it may be appropriate for us to begin the introduction of *Aladdin* with its accuracy. In the following section, we compare its predictions of solar irradiance in different locations with available sensor data.

# THE ACCURACY OF ALADDIN AS A SIMULATION TOOL

*Aladdin* is currently equipped with computational engines that support two types of physics simulation: solar energy simulation and building energy simulation. Since this paper focuses on concentrated solar power (CSP), we only describe solar energy simulations. Solar energy simulations in *Aladdin* are powered by a revised solar radiation model based on ray optics [11] that also considers the effects of sunlight attenuation in the atmosphere, diffuse sky radiation due to scattering by air molecules, reflection by the ground, and sky clearness from the weather data of the current location (as of August, 2022, *Aladdin* includes the weather data from a total of 762 locations worldwide). The credibility of the simulation engine is important to engineering education as the accuracy of CAD simulations is responsible for the authenticity of the engineering projects that it supports. To some extent, the authenticity helps justify replacing traditional prototype-based design activities with CAD-based design activities—while CAD-based activities remove some hands-on steps in prototype-based activities, accurate CAD simulations may boost the fidelity and quality of the design work as a compensation. For example, it is nearly impossible to calculate the annual outputs of solar panels without using a predictive simulation tool.

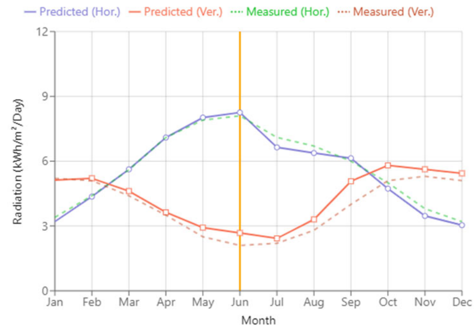
Fig. 1 provides some benchmark results of the average daily solar irradiance throughout a year for four geographically diverse U.S. locations. In each case, a virtual sensor is placed on a horizontal surface and a south-facing vertical surface, respectively, in *Aladdin*. The time series data of solar irradiance logged by the virtual sensors are generated based on simulating the movement of the sun across the sky from sunrise to sunset on the 22$^{nd}$ of each month. *Aladdin* calculates the intensity of solar radiation that strikes a sensor any time during a day, the daily average of which is then plotted against the month of a year with a built-in graph shown in Fig. 1. As the graphs illustrate, the calculated results agree reasonably well with the sensor data collected by the National Renewable Energy Laboratory (NREL) from 1961 to 1990 [12]. This validity was also confirmed independently by recent studies [13, 14] that used it to model both photovoltaic (PV) and CSP solar power plants in Muscat, Oman. According to the published studies, the difference between the annual output of electricity of a solar farm predicted by *Aladdin* and the *Global Solar Atlas* (GSA) program developed by the World Bank is less than 7% [14], whereas the difference between the annual outputs of a solar farm with a fixed tilt angle and a solar farm driven by azimuth–altitude dual axis trackers predicted by *Aladdin* and *PVWatts Calculator* developed by NREL are approximately 4% and 8%, respectively [13]. Similar agreements between *Aladdin* and yet another simulation program, *Photovoltaic Geographical Information System* (PVGIS) developed by the Joint Research Centre of the European Commission, on the value for the optimal tilt angle of solar panels were also found. This means that, when students design a solar energy solution with *Aladdin*, they can expect a degree of trustworthiness comparable with three widely-used professional tools developed by reputable research institutions.

In the following sections, we show how Aladdin can be used to model and design all the four main types of CSP [15], even for real-world projects. We start with parabolic dishes since they are the closest ones to solar cookers.

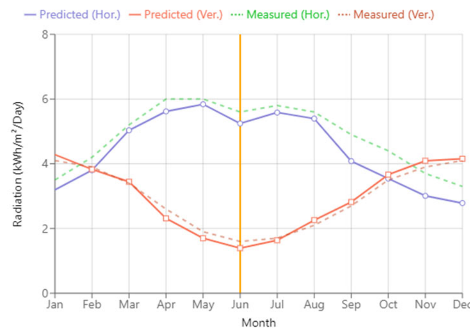
## PARABOLIC DISHES

Like a solar cooker, a parabolic dish for CSP focuses sunlight that strikes it onto a focal point above it, where a receiver absorbs the light energy and turns it into thermal energy. Unlike a solar cooker, a parabolic dish for CSP is motorized and programmed to follow the sun throughout the day to maximize the input. Parabolic dishes are often coupled with Stirling engines operated by the cyclic compression and expansion of a working fluid like air or helium to convert up to 32% of incoming solar energy into electricity.

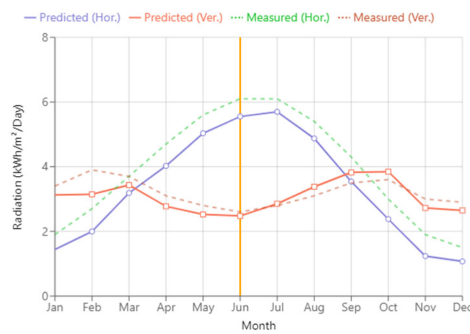
Fig. 2a shows a single parabolic dish designed using *Aladdin*. To illuminate the physics concept, we show the optical paths of a number of rays from the sun to the cylinder of the Stirling engine placed at the focal point to receive the concentrated solar radiation. These optical paths change as the dish rotates to follow the sun, allowing students to see how it works to collect solar energy in a daily cycle. Designers can adjust the diameter of the dish rim, the latus rectum, and so on to create dishes of different sizes and shapes [16]. They can also add many dishes to form an array (Fig. 2b). Note that, in the current version of *Aladdin*,



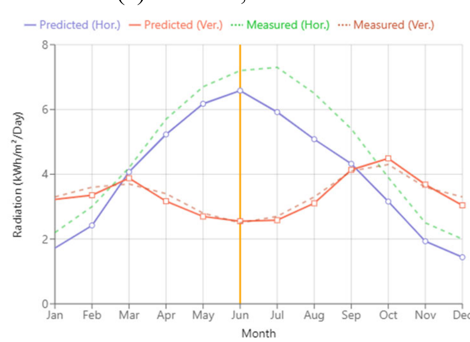

(a) Tucson, Arizona




(b) Miami, Florida




(c) Boston, Massachusetts




(d) San Francisco, California

*Fig. 1: Comparing the results of daily average solar irradiance received on the horizontal and vertical (south-facing) surfaces throughout a year predicted by Aladdin and measured by sensors in four U.S. locations. The sensor data are from the National Solar Radiation Database (1961-1990).*

we model the movement of a parabolic dish by changing its azimuth and tilt angles, but we do not explicitly model the mechanism that drives it and the Stirling engine that uses thermal energy to do the mechanical work to generate electricity.

Fig. 2b also shows a heatmap that visualizes the distribution of solar irradiance, which includes direct and indirect solar radiation (though the latter does not contribute to the CSP output). Due to the projection effect (the solar irradiance on a surface is inversely proportional to the cosine of the angle of incidence) and the curvature of the paraboloid, an area closer to the center receives stronger irradiance than an area closer to the rim, as indicated by the color gradient in the radial direction on the surface of a dish. Heatmap analysis provides a visual tool for students to quickly make sense of their designs. For instance, a larger contrast of color on a deeper dish suggests less efficient use of materials as a larger area near the rim may contribute less to the total output, prompting students to consider adjusting the shape to improve cost effectiveness.

Through the integration with *Google Maps*, *Aladdin* allows students to model or design renewable energy projects in the real world. All students need to do is to type the address or coordinates of a site in *Google Maps* and *Aladdin* will load a map image into the scene for them to draw a CSP power plant on top of the image. Fig. 2c shows a model of the 1.5MW parabolic dish array at Tooele Army Depot in Utah, created in *Aladdin* and rendered on top of the satellite image of the site.

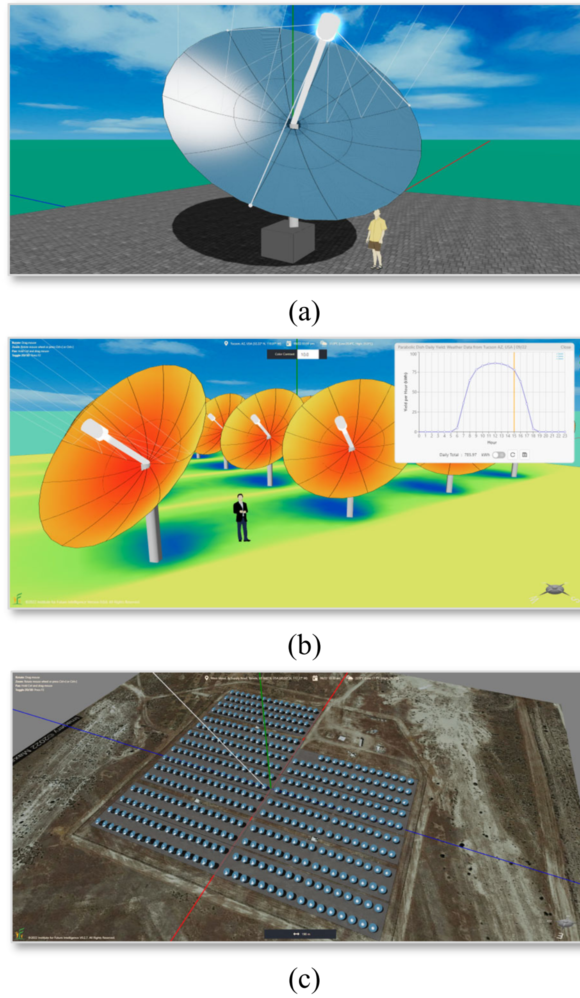
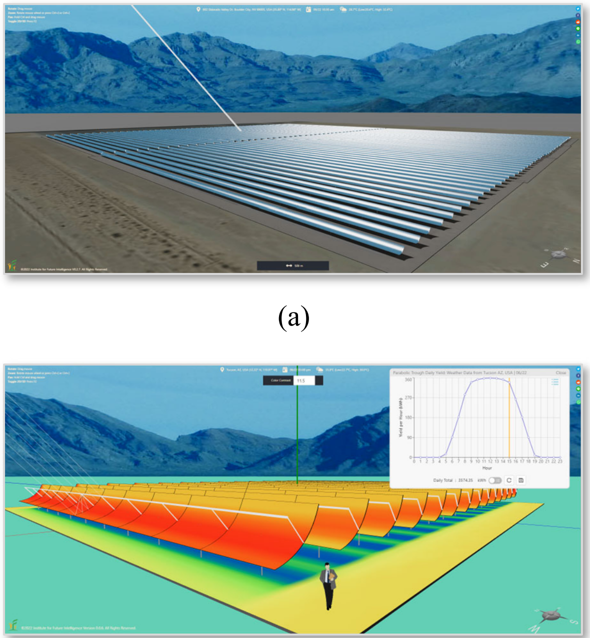



*Fig. 2. (a) A parabolic dish designed and rendered in Aladdin with the optical paths of sun rays. (b) An array of parabolic dishes, a graph showing the total hourly output of electricity on September 22 (autumnal equinox), and the heatmap that visualizes the distribution of the total daily solar irradiance on the dishes and the ground. (c) An Aladdin model of an array of 429 parabolic dishes deployed in Tooele, Utah, rendered on top of the satellite image of the site.*

## Parabolic Troughs

Unlike parabolic dishes, parabolic troughs are linear solar collectors with a parabolic cross section. They are typically aligned along the north-south axis and rotate from east to west to track the sun. A receiver tube filled with a thermal fluid such as molten salt is installed along the focal line to absorb the concentrated solar energy. The thermal energy is then passed through a heat exchanger to a turbine engine for generating electricity. Although parabolic troughs are less efficient in focusing sunlight than parabolic dishes, they are the most deployed CSP technology—with about two thirds of the operational capacity as of 2020 [17], largely because of their cost effectiveness.

Fig. 3a shows an array of parabolic troughs modeled after Nevada Solar One in Nevada with *Aladdin* (users can create an array by copy-and-paste). Similar to the case of parabolic dishes, there exists a gradient of solar irradiance in the cross section due to the projection effect, as shown in the heatmap of Fig. 3b. Different from the case of parabolic dishes, though, the effect of shadowing between adjacent rows of troughs



(a)

(b)

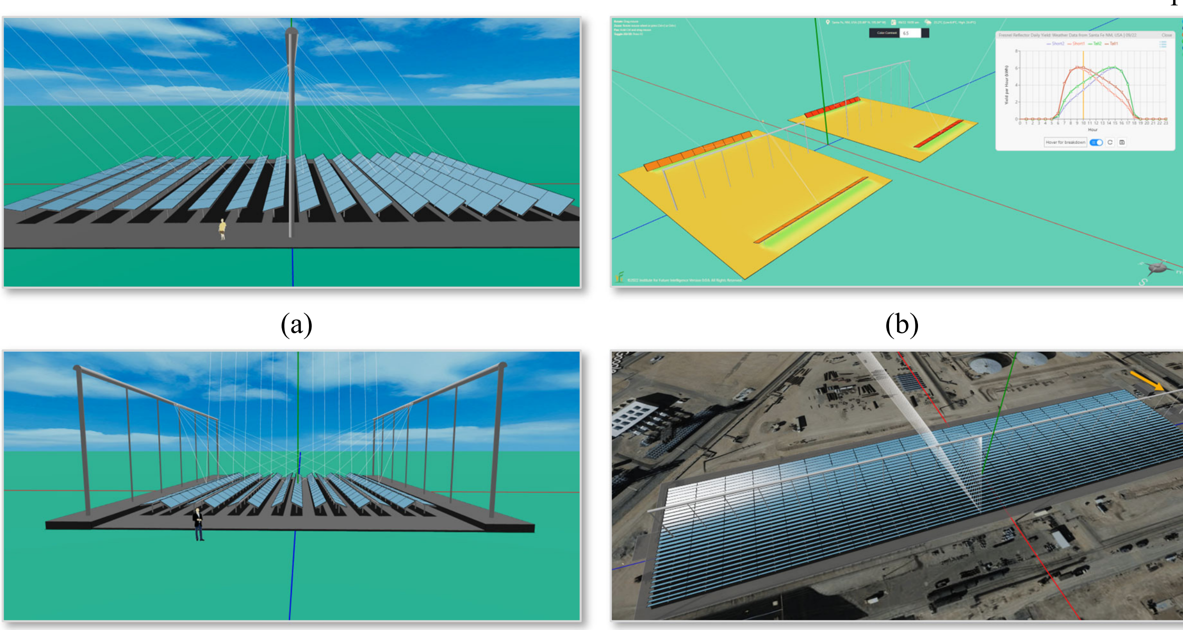
*Fig. 3. (a) An Aladdin model of an array of parabolic troughs in Nevada Solar One. (b) A graph showing the total hourly output of electricity from a parabolic trough array on June 22 (summer solstice) and the heatmap that visualizes the spatial distribution of solar irradiance.*

also increases this gradient as the lower side of a trough in the middle of the array is blocked from direct sunlight when the sun is low in the sky.

## LINEAR FRESNEL REFLECTORS

The linear Fresnel reflectors (LFRs) are a type of CSP that uses long, flat mirrors to focus sunlight onto a fixed absorber pipe mounted at a common focal line of the reflectors, similar to a Fresnel lens (Fig. 4a). There are several design options for an LFR array. The key factors include the dimension and spacing of the reflectors, the height of the absorber pipe (Fig. 4b), and the azimuth of the reflectors. There can also be multiple absorbers (Fig. 4c). In that case, the reflectors are laid in the same way but they reflect the sunlight alternately to the two absorbers (e.g., #1, #3, #5, ... reflect to the absorber on the east side and #2, #4, #6, ... to that on the west side).

Fig. 4d shows the LFR array of the 5MW Sundt Generating Station in Tucson, Arizona. One of the "strange" things that students may notice from the satellite image is that the absorber pipe stretches out a bit at the northern end of the reflector array (as indicated by the arrow in Fig. 4d), whereas it does not at the southern end. The reason that the absorber pipe



(a) (b)

(c) (d)

*Fig. 4. (a) An LFR array aligned along the north-south axis designed in Aladdin. (b) The effect of the height of the absorber pipe on the output (the taller it is mounted, the higher the output of the reflectors is, as shown in both the heatmap and the graph). (c) An array of LFRs aiming alternately at two absorber pipes mounted to the east and west of the array. (d) An Aladdin model of an LFR array deployed at the 5MW Sundt Generating Station in Tucson, Arizona (the arrow at the upper-right corner points to the extension of the absorber pipe to the north).*

was designed in such a “strange” way becomes apparent when we show the optical paths. As the sun rays come from the south in the northern hemisphere, the focal point on the absorber pipe shifts towards the north. During most days of the year, the shift decreases when the sun rises from the east to the zenith position at noon and increases as the sun sets to the west. This shift would have resulted in energy losses if the absorber pipe had not extended to the north to allow for the capture of sunlight bounced off the LFR modules near the northern end.

## SOLAR POWER TOWERS

A solar power tower (SPT) is surrounded by numerous mirrors controlled by computers, called heliostats, to follow the sun and reflect the light to a central receiver installed at the top of the tower (Fig. 5a). To some extent, a SPT plant is a gigantic Fresnel lens formed by many discrete reflectors (instead of rings or stripes). Its design involves deciding the layout of the heliostat field, the height of the tower, among other factors. Unlike the design of PV solar panel arrays in which we only need to consider the shadowing among the panels, in the design of the heliostat field, we also need to ensure that the mirrors of the heliostats do not block the light reflected by others from reaching the central receiver. Fig. 5b shows the heatmaps of the heliostats that account for both shadowing and blocking losses.

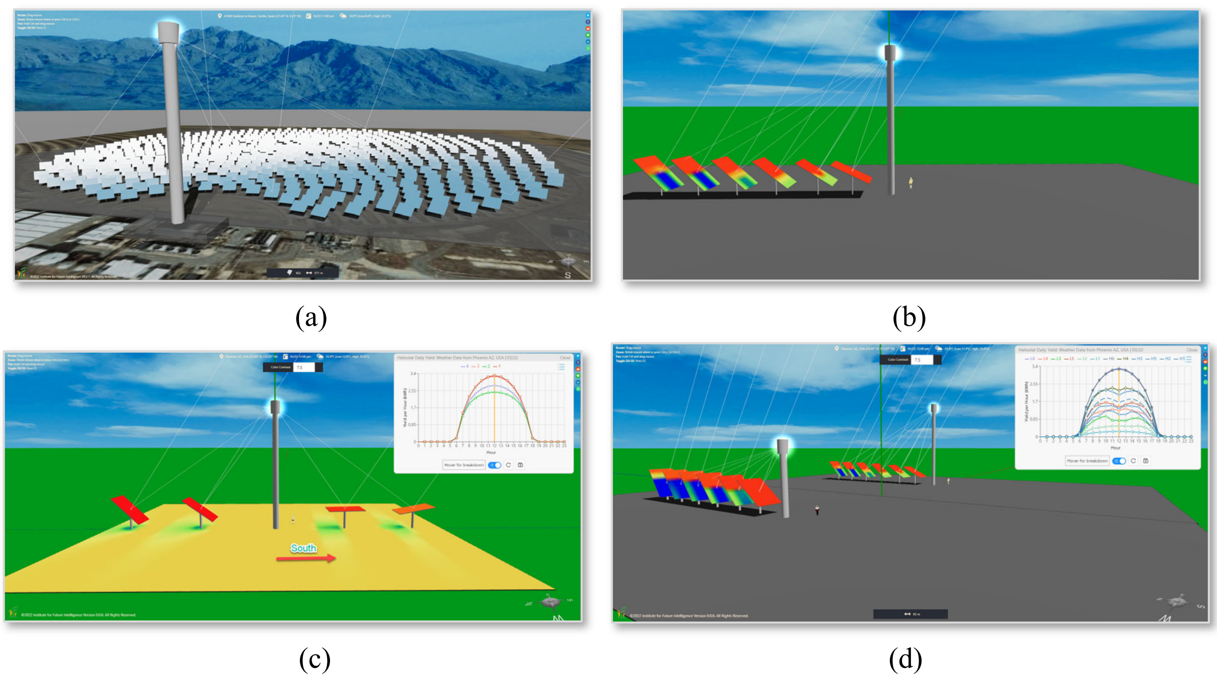



*Fig. 5. (a) An Aladdin model of the PS10 SPT plant in Seville, Spain that is surrounded by 624 heliostats. (b) Visualizing shadowing and blocking losses of the heliostats. (c) Visualizing the cosine efficiency of heliostats to the south and north of the tower. (d) Visualizing the effect of the tower height on the outputs of heliostats.*

A key factor that affects the design of the heliostat field is the so-called cosine efficiency [18]. The heliostats to the south of the tower have lower cosine efficiency because they reflect less sunlight than those to the north of the tower (assuming that the SPT plant is in the northern hemisphere). This is the reason why many SPT plants do not use a simple concentric heliostat field layout that has a north-south symmetry. The cosine efficiency can be clearly visualized in *Aladdin* (Fig. 5c). Another design factor is the height of the tower. The taller the tower is, the more sunlight the heliostats reflect (Fig. 5d). This is the reason why engineers build very tall towers for large SPT plants. For example, the Ashalim Power Station in the Negev Desert of Israel, which powers 120,000 homes, has a tower 260 meters tall, almost two thirds of the height of the Empire State Building.

## CONCLUSION

We have demonstrated *Aladdin* as a versatile CAD platform for modeling and designing four types of CSP plants, which can be adopted by teachers as a design tool to connect physics and engineering. In terms of NGSS learning, the tool has the potential to support all the performance expectations set in HS-ETS1 of NGSS. In particular, it represents an appropriate, even needed, response to HS-ETS1-4 that 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." The modeling, simulation, and designing capabilities of *Aladdin* demonstrated in this paper can be used to entice students to learn and apply physics to engineer renewable energy solutions, which are critical to the sustainability of our society. In a sense, *Aladdin* can be used as a tool to enhance, or even replace, solar cooker activities widely used in science education to engage and motivate students.

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