CO-OPTIMIZATION OF SOLAR TRACKING FOR SHADING AND PHOTOVOLTAIC ENERGY CONVERSION

Forrest Meggers[1,2], Dorit Aviv[1], Victor Charpentier[3], Eric Teitelbaum[3], Adam Ainslie[1], Sigrid Adriaenssens[1,3]
[1]Princeton University, School of Architecture, Princeton, NJ, USA
[2]Princeton University, Andlinger Center for Energy and the Environment, Princeton, NJ, USA
[3]Princeton University, Civil and Environmental Engineering, Princeton, NJ, USA

Abstract

We investigate the geometric co-optimization of shading and solar photovoltaic tracking with a single surface. The simulation combines ideal solar tracking with a unique method for continuous shading of a fixed surface area through all sun angles. For photovoltaics, a panel achieves maximum power production by maintaining a normal orientation to the sun vector. This is achieved by tracking the 2-axis solar motion. Shading is also increased with standard tracking, but the area shaded is not effectively controlled by normal tracking alone. By rotating the panel along a path in space that maps the arc the sun makes across the sky, it is possible to also provide constant shading to a fixed position at the centroid of the arc while simultaneously maintaining a normal orientation to solar rays. The simulations were made as part of the development of a solar photovoltaic powered outdoor work table with a continuously shaded work surface. The results show the ability to maintain continuous shading, and to double the potential PV generation as compared to a fixed panel. We built a prototype that achieved this operation, and in that process used a curved panel, which has led to further simulation of curved PV surfaces. This analysis demonstrates the potential leveling of the power curve. Although it decreases total energy produced per area of panel, we show curved surfaces can significantly increase the power per unit area of panel footprint.

Introduction, motivation and background

Introduction

Solar tracking negotiates compound sun angles, complex field geometries, and mechanical systems in pursuit of optimal energy generation. Solar tracking also results in an optimally oriented shading surface, but in order to co-optimize the shading of target areas (e.g. work surfaces, windows, playgrounds) it is necessary to consider both the geometry toward the sun and also the geometry underneath the shade. The novel implementation of shades that also implement energy harvesting though photovoltaic panels raises the question of how to negotiate both shading and generation most effectively. When a fixed surface is the desired shading target, the geometry of rotation must extend the shading panel out into an arc whereby the panel remains both normal to the sun and also stays on the vector from the target surface to the sun. This cannot be achieved with conventional 2-axis gearboxes or gimbal system operation. We have approached this issue from a geometric perspective considering curved PV surfaces, which are underrepresented in the literature. The ever changing sun angles, orbit eccentricities, and shading constraints parameterize our novel solar tracking and shading methodology. The goal of this research is to investigate optimal positioning/tracking through simulation of a roof or awning geometry and curvature for both PV energy generation and shading. The simulation maximizes the normal orientation of solar panels to the incoming solar rays to maximize the power factor, while also fixing a defined shadow form to maintain shading on a specific target area.

Motivation

Such a toolset has applications in building integrated photovoltaics (BIPV) power generation, curved façades/roofs, shading, occupant comfort, and radiative heat transfer. Most work focuses on tracking systems for photovoltaic power factor or basic actuation of shading, but has not considered the opportunity to optimize both simultaneously. It can also be used to help manipulate the variability of and generate smoother power production to reduce the impact of variable sunlight on grids and battery backup requirements. The motivation is to achieve optimal power generation, and then by continuously shading a target surface, co-optimize occupants' outdoor lighting and glare conditions, or strategically control sunlight entering a building to manage HVAC loads.

A first embodiment of this concept resulted in a tracking solar table, constructed by an undergraduate class, "ARC 311 - Building Science and Technology: Building Systems", where an outdoor solar-powered work table was designed for use by students where laptops and electronics could be powered and charged by a local photovoltaic panel. The prototype is shown in Figure 1. A track that matches the solar path is mounted to the table and a panel moves around the track to follow the daily sun path. The table is designed to face south and the track can rotate up and down to match the solar-noon azimuth, and also to have the axis of rotation shifted to match the varying horizon intercept of the sun at sunrise and sunset. The table was also designed to be manually operated to communicate and educate users on how sun motion relates to building operation. The concept could be scaled up to larger pavilions or integrated into building façade or roof design.

Figure 1: The Solar Table - a physical prototype built at Princeton University

Background

Previous literature examining the optimization of shading devices tested the efficiency of a system in shading glass facades. Binder et al. (2008) examined the efficiency of a rotating shading device of venetian blinds. Sherif et al. (2012) simulated the effect of rotating a shading panel around a single axis. The axis is dependent of the glazed facade orientation to optimize the resultant shading for the specific vertical facade surface. The efficiency analysis of the system is measured by calculating the reduced heat gain and the consequent reduced cooling load. Since fixed shading cannot adapt to variation of the environment, Loonen et al. (2013) argue that it can lead to an oversized system to fulfill function, while adaptive systems can perform with significantly fewer resources. In addition, adaptive shading has been shown to provide a substantial reduction of energy consumption in moderate climates. Kasinalis et al. (2014) shows that in the Dutch climate adaptive shading provides up to a 15% energy consumption reduction. The efficiency can be even higher in warmer climates (Lee et al., 2004).

As expressed previously, the adaptive geometry of solar panels increases their capacity to block solar radiation. A full solar tracking entails a two degree of freedom mechanism to track both the sun azimuth and elevation. Recent studies have shown, however, that due to smaller yearly variations, the effect of the elevation tracking was less than the azimuth tracking (Calabrò, 2013). Additionally, the amount of solar panel area lost when introducing a 2-axis system to prevent self-shading can actually result in less annual energy generation with flat panels. The ability of a solar panel to adapt to the solar position greatly influences the power output. Increases of between 30 and 50 % of the output have been reported (Patil et al., 1997; Huld et al., 2010; Lubitz, 2011). The adaptability of those solar panels typically consists of horizontal planes rotating around a north-south axis (Lorenzo et al., 2002). The increase of energy due to tracking is due the increase of projected panel area in the plane normal to the sun ray. This is shown in Figure 2. Depending on the state of the atmosphere, the percentage of direct radiation varies in the solar energy distribution. However, ensuring that the panel surface is as perpendicular as possible to the sun's rays increases the projected surface for solar energy collection. In addition, the cost of the complex mechanical tracking system often outweighs the benefits that can be reaped from the second axis (Clifford et al., 2004). As such, the best compromise of cost and efficiency in adaptive solar panel seems to be one axis tracking solar panels, and azimuth tracking in particular (Lorenzo et al., 2002). The efficiency of solar panels decreases with an increase of latitude (Martín-Chivelet 2016) for fixed and panels oriented at the optimal tilt angle. The addition of an axis of rotation can increase the efficiency in those cases and allows for an increase in the duration of collection in the morning and in the later afternoon (Vieira et al. 2016).

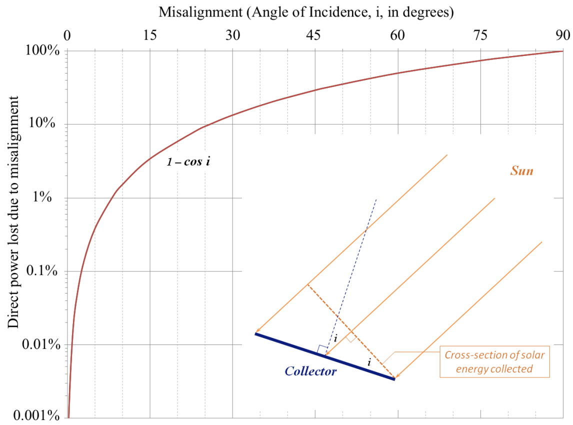

Figure 2: Reduction in potential from a solar panel due to misalignment (Clarke, 2011)

The integration of solar power generation through PV panels with a shading system has been previously explored by Yoo et al. (1998), in an architectural case study of a Samsung building in Korea. In this case study, PV panels were placed on the south facade and the roof of the building to both generate power and shade the interior of the building during the summer months simultaneously and thus reduce its cooling load. In this case, the PV panels were fixed and their location was determined to optimize summer shading and allow for winter passive heating on the south facade. In order to improve the radiation gain of the PV panels, reflectors were additionally placed on the facade to concentrate sun radiation on the PV panels.

Our method of integrating energy production and shading is unique in its co-optimization of both systems simultaneously by using a rotation method that allows to continuously track the sun vectors. This results in benefiting both energy saving from shading when considering HVAC loads on buildings and energy generation from photovoltaics.

Methods

Overview

Using architectural 3D-modeling tools and geographic parameters, sun paths for a given location are created.

We chose our location in Princeton, New Jersey at 40° N latitude. The sun paths are used as inputs for ray tracing studies of shading of surfaces as shown in Figure 3. For a base case comparison to a fixed panel we assume a standard flat panel of the same dimension as used in our prototype oriented south and tilted by its latitude of 40° off of azimuth as is common practice for fixed installations thereby averaging summer and winter gains.

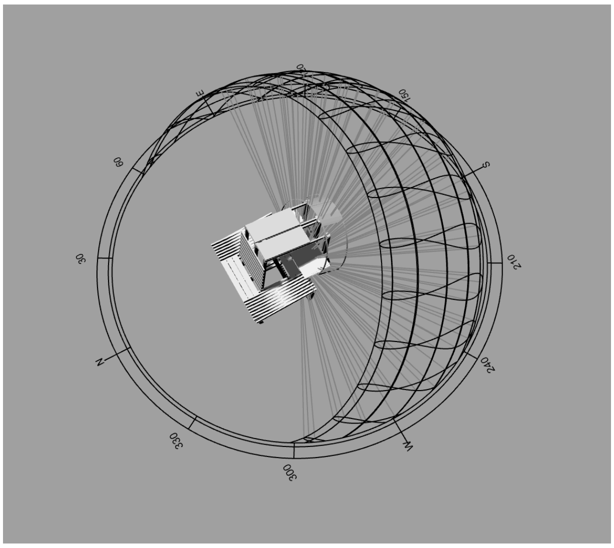

Figure 3: Methodological diagram, sun direction in relation to study object

For a given sun orientation and a given target surface we assess the corresponding planar shading surface that maintains its normal vector collinear to the sun rays. Reverse mapping is used to determine the outline of the planar shading surface and its position in space. Using scientific computing packages, simulations are setup to analyze the solar irradiation and energy conversion under the ideal shading surface geometries and actuations. A flat surface is the ideal energy harvesting surface for a given moment in time. It does however necessitate a constant readjustment of the position of the surface (azimuth, elevation) to remain optimal. In this paper we also evaluate the benefits of having slightly curved surfaces to reduce variability of solar generation without needing continuous actuation.

An energy and geometry model that maintains normal solar tracking and fixed point shading was built using solar position data and geometric solar ray tracing. The tracking system simulation was modeled after the prototype constructed in Figure 1, but the results could be scaled for various size systems. Larger panels could create more power and more shade, but would generate structural and mechanical challenges in construction. The tracking results are followed with consideration for the performance of simple fixed curved structures that also match the sun path and provide regular shading. By being curved to the sun, they create a more even power production, but have lower generation per unit photovoltaic area.

The simulation and prototype incorporate the unique tracking element that can be positioned for both daily and seasonal tracking. The solar panel is modeled to slide diurnally on an arc that pivots seasonally to match the sun path. This panel provides continuous shade to the work surface as it optimally tracks the sun. Through the optimization of shading the work table, the geometry of the structure creates an implicit understanding of solar tracking and maximizes the electricity generation of the solar panel. We show that variations in shape and position of the shading area provide better occulting than fixed shading. While this panel does not require curvature, this is also researched whereby we consider unequal power generation in the solar cells and this overall effect on panel efficiency. The co-optimization of solar tracking and shading can double the generation as compared to a fixed panel, and also and decreases the radiant heating load on the optimally shaded surface by up to 1000 W/m^2 in direct sun.

We simulate the motion of the panel and determine the effectiveness of its solar generation, and of the shading it provides to the workspace on the table. We then determine the impact of using curved surfaces for photovoltaic deployment where constant shade can be achieved from a fixed formal logic rather than with tracking.

Our goal was to simulate the annual radiation and hours of sunlit surface of the solar panel and work area surfaces. For this purpose we used Ladybug, an open source environmental simulation tool, developed by Mostapha Sadeghipour Roudasri, which allows for the import and analysis of weather data from .epw weather files into Grasshopper, a graphical algorithm editor built for parametric modeling in Rhino 3D software (Sadeghipour, 2016). We used two of the simulation components in Ladybug - Radiation Analysis, and Sunlight Hours Analysis - to simulate the performance of the solar table for simultaneous optimization of radiation on the rotating surface and minimal sunlight exposure for the work surface of the table.

Radiation analysis of tracking panel:

The Radiation Analysis component in Ladybug calculates yearly irradiation for a given surface in a specific geographic location, accounting not only for direct sun radiation, but also for diffused radiation, during all weather conditions throughout the year. To calculate radiation, Ladybug uses the code GENDAYMTX (Ashdown et al., 2016), which generates an annual Perez sky matrix from a weather data file. This method allows us to describe the mean instantaneous sky luminance angular distribution for all types of weather (Perez et al., 1993).

We simulated a panel rotating along an axis to face the sun vectors at a given hour of the day. In this manner the panel will receive maximum direct radiation at any given hour. The surface area of the rotating panel is 0.57 m^2, but because it is slightly curved to allow for its placement on a curved track (see Figure 1) its projected area is slightly less at 0.55 m^2 which reduces its total irradiation slightly. For the simulation we chose to use the weather data of Princeton, New Jersey, USA, where our physical prototype exists, so that the simulation results could eventually be compared to empirical results. The total yearly radiation received by a panel which rotates on a track to change its position for the diurnal solar arc and also adjusted arc elevation and horizon intercepts for the seasonal shifts in the solar-noon azimuth and sun path was then compared to the radiation received by the same panel when it was placed statically in one location, where yearly radiation is maximized based on sun vector and the radiation sky matrix. The simulation tool defines a number of test-points on the surface of the panel and outputs a total number of the sum of incident irradiation on the whole surface throughout the year.

Sun vector surface shading analysis

Simultaneously, we calculated the percentage of surface area shaded by the panel under the same conditions of a rotating versus static position. In this manner, the panel is both receiving radiation and shading the work surface underneath at the same time. We first tested the shading ability of the rotating panel over a surface of 25cm by 35cm (0.0875) which is the surface area required to support a standard laptop. Our design assumption is that the panel size we chose for our prototype – of 0.57 m^2– would be able to keep this area in constant shade based on its motion. We compare this complete shading performance to that achieved by a fixed panel over the smaller workspace.

We then tested the shading ability of the panel over a larger work surface area of 1.65 m^2 based on the full table size of the prototype in Figure 1. The panel is small, 0.57 m^2, as it is designed to shade only the central work area of the table, thus only partial shading is to be expected.

For both cases, we kept the rotation arc radius constant at 1.2 m, based on the prototype design to allow room for a person to sit and work under the panel.

For the shading simulation we used the Sunlight Hours Analysis component of Ladybug. The work surface's shaded percentage is simulated for the period during which the sun is high enough to consistently illuminate it throughout the year. For the geographic location we simulated of Princeton, NJ, this means from 8h00 (8am) until 16h00 (4pm). The shading panel moves at one hour intervals, to optimally shade the work surface. This simulation tool tests different grid-points on the surface, but the result is given as a percentage of the work surface shaded by the rotating panel. For this part of the simulation, we only observed direct radiation based on the sun position and did not consider cloudiness.

Fixed shading curved panel analysis

Creating the tracking panel system on the curved arc required adding a slight curvature to the panel itself. In the case of the tracking panel this reduced the projected area by 1% during tracking, but we noticed a potential to increase normal hours of incident light by using the curvature, so we setup another simulation to look at how a fixed panel performs when curvature is added. The same shading of a fixed position can be achieved by creating a solid surface that is in the shape of the sun path. This strategy was employed in a previous evaporative radiant cooling pavilion, the Thermoheliodome (Read et al., 2015). In order to maintain shading diurnally and seasonally a double curved surface is needed such as the dome used previously.

We compare the performance of a flat solar panel with curved panels in one or two directions (Figure 4). Two different curvature directions are implemented on the solar panel depending on which solar movements (diurnal or seasonal) are targeted. The objective of the added curvature is to maintain at anytime of the day a normal incidence of the sun's rays on part of the solar panel. By doing so the area exposed to the sun throughout the day is more consistent than with a flat panel, which in turn increases the production of energy. The diurnal movement of the sun creates a wide variation of sun orientation from the east to the west. A single curvature ensures the constant perpendicularity of part of the panel to the sun vector throughout the day if the direction of this curvature is contained in the diurnal sun path plane (Figure 4b). Seasonal variation of sun orientation at a specific hour of the day (in this case 12h00) can be realized by a panel curved once in the plane of the angle variation (Figure 4 c).

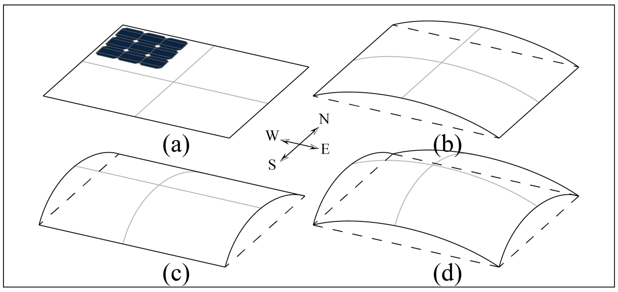

Figure 4: Solar panels considered are (a) flat, (b) 1D curved to follow diurnal sun movements (c) 1D curved to follow seasonal sun movements and (d) 2D curved to follow both seasonal and diurnal movements

The potential of each curvature is investigated separately. Our hypothesis is that although overall production may be diminished slightly per unit panel area deployed, the curvature will decrease the variability of production compared to a flat panel, and will have more potential per unit footprint area while again creating a more consistent shading pattern as explored with the tracking panel following the sun path. In addition, all the cases tested have the same footprint. The curved panels however have a larger surface area due to their curved geometry. If PV panel area is cheap, there is a benefit to implementing curved panels since the overall production will be increased (and the variability of output potentially decreased).

For the diurnal curvature analysis, a simulation was setup with a flat panel mounted at the ideal seasonal angle for its latitude, 40° from azimuth for Princeton, NJ. The hourly production difference is analyzed based on the geometric projected area toward the sun at each hour of the day. The same analysis is done for a curved panel with the same azimuthal angle and a curvature with initial and final tangents around ±60° from solar noon creating a more constant projected area toward the sun during peak hours, and also providing a more consistent shade beneath. The potential of the fixed panel and the curved panel are compared for the peak day of the spring and fall solstice when the sun is directly normal at solar noon for the latitude-based azimuthal angle. The output is compared per unit area of panel, and also per unit area of footprint as for a roof-scale curved surface, the deployment area is not panel-dependent, but rather footprint-dependent.

For the analysis of the panel with curvature in the direction of seasonal angle variation we use the same setup as above, but we compare a panel that is curved to tangents ±23.5° from 40° azimuthal angle. We then simulate the potential output based on projected area for the peak hour of solar noon at each day of the year, and compare the total potential to the variability across the year.

Finally, we consider the potential of the doubly curved surface with the same angles as above where we simulate the normalized output across the whole year to see if the influence on the potential is changed significantly by having both directions of curvature.

Results and Discussion

Incident Irradiation Results

The Total Radiation result from the Ladybug simulation gives a sum of incident irradiation on all test-points for the photovoltaic surface on the surface throughout the year. The tracking panel was simulated through the full rotation, and so increases dramatically in the morning and evening potentially resulting in 2270 kWh of incident solar energy for tracking as compared to 920 kWh for the fixed panel. As expected, the slight curvature of the panel used in the prototype reduces its potential slightly to 2220 kWh for tracking and 910 kWh for the fixed panel.

The simulation includes the full analysis of solar irradiation potential for each daytime hour in the year shown in Figure 5. For Princeton the longest day of the year is 4:30am to 7:30pm, and the shortest day is 7:20am to 4:40pm, so the shoulders are generated by the lack of sun for times of the year when it has not yet risen. For the time between, the variation is due to the effect of the atmosphere on brightness of diffuse and beam radiation in the Perez sky model used by Ladybug. Figure 6 shows how each hour was simulated in the geometry tool for the tracking panel.

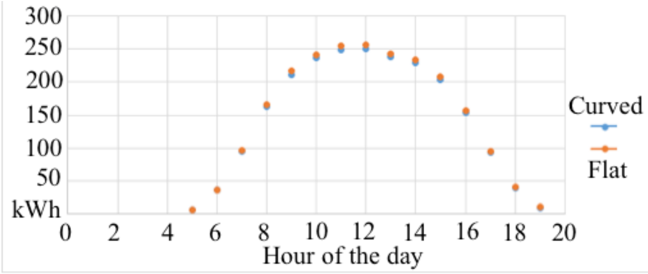

Figure 5: Diurnal analysis of radiation on flat and curved panels

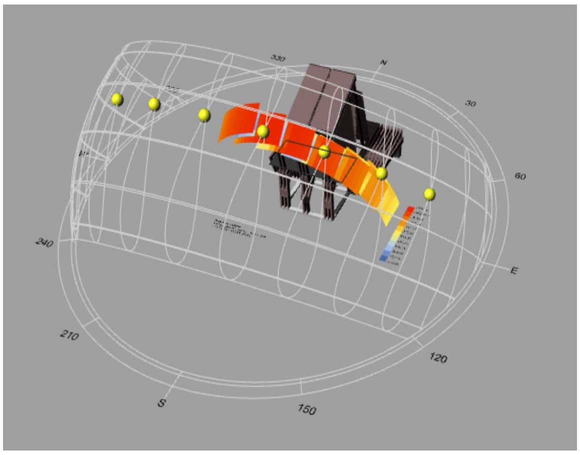

Figure 6: visual representation of simulation process for the radiation analysis. The panel rotates according to the sun position and receives different values throughout the day.

Tracking Sunlight/Shade Hours:

The results for the smaller test surface of 25cm by 35cm in the center of our work surface area, where a standard laptop could be positioned, confirmed our assumption that we are able to fully shade it with our existing panel during the 8 hours of high altitude sunlight based on the optimized rotation of the panel along the sun vector direction. If the shading panel is a fixed panel at the latitude angle, the working surface area is shaded only 28 percent of the 8 brightest hours of the day. This is important to the reduction of glare on the computer screen while working on the work surface (see figure 2).

We then conducted a shading simulation for a larger surface based on the table built for the prototype in Figure 1 of 1.65 m^2. Figure 7 shows the percentage of the horizontal work surface that is shaded by a panel of 0.57 m^2 and rotating to face the sun vector at the specific hour and day of the year. We simulated this for the 8 brightest hours – 8 am to 4pm, and show the results for the winter solstice, summer solstice, and spring/fall equinox, to provide an understanding of the variations in the panel's shading capacities throughout the year. The results are also visualized in Figure 8, demonstrating the shaded regions on the work surface during various hours of the day.

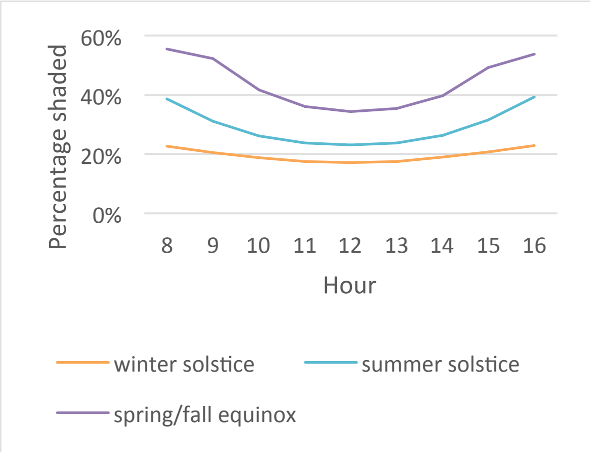

Figure 7: Diurnal analysis of percentage of surface shaded

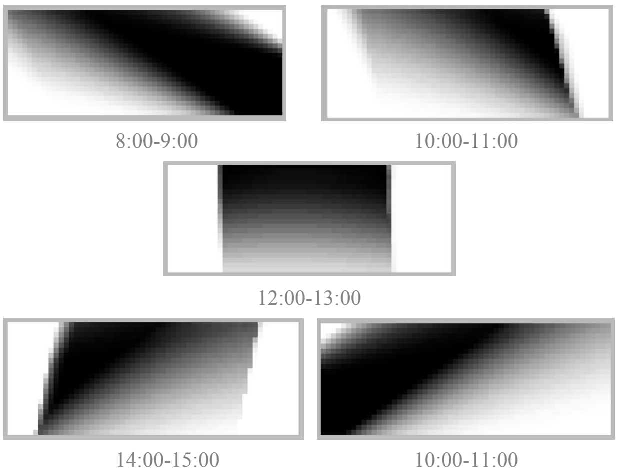

Figure 8: The horizontal surface shading profile at various hours throughout the day on the work surface

The average annual shading percentage for the horizontal work surface under a rotating panel during the 8 brightest hours based on this sample result is 31%. We compare this result to the one obtained by a fixed panel of the same size and distance from the work surface, positioned at the summer solstice, which gives us a much lower average shading percentage of 14% for the same surface size of 1.65 m^2.

Fixed shading curved panel results

As expected, the single curved surface output per unit area was 3.8% less than the fixed panel, but for the same footprint its area was 11.1 % larger resulting in a potential increase in production of 3.6% in production. Figure 9 shows the variation of exposed panel surface over the course of the day normalized by panel area and normalized by footprint area. This geometric result can then be linked to energy output with knowledge of the solar panel conversion rate. The production of a curved and flat panel are similar from 9AM and 3PM, however outside of these limits the curved panel produces significantly more than the flat panel (Figure 9). In the case of the flat panel the minimum production is 2.78% of the maximum output, it is 22.18% in the case of the 1D curved panel. This ratio is 22.43% for the 2D curved panel. Although minimal, these shifts bring added power to the system at critical moments for residential demand in the mornings and evenings.

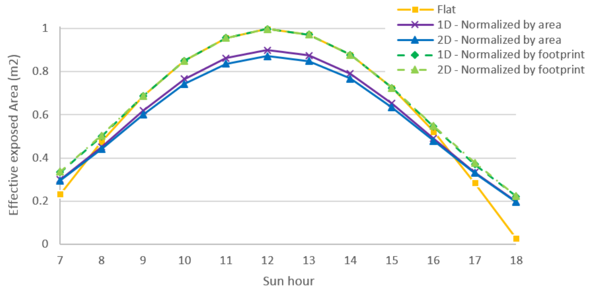

Figure 9: Diurnal analysis of single and double curved solar panels on June 21st – Exposed panel area results normalized by surface area and by footprint of the solar panel

For the seasonal analysis of fixed curved surfaces, the reduced change in angle eliminates any advantage to having the curved panel as seen in Figure 10. The effect of the 23° shift in angle for the fixed panel from summer to winter only causes an 8% reduction in potential as seen in Figure 2. This small change is not compensated for by having a curved surface in the direction of the azimuthal change of the sun position.

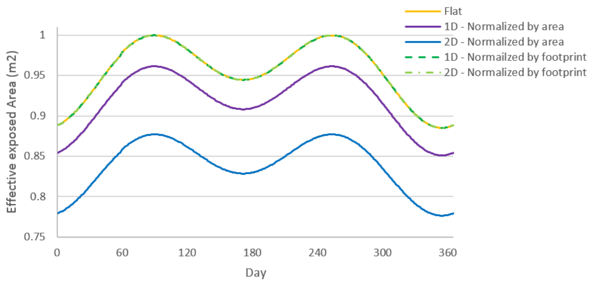

Figure 10: Seasonal analysis of single curved and double curved solar panels at 12 pm. Exposed panel area results normalized by footprint overlap perfectly the flat control panel.

The single curved surface for seasonal operation produces no impact on the exposed surface area as shown in Figure 10. With a constant footprint, there is no difference in exposed area for this panel compared to the flat panel. Following those results, the surface area of the single curved surface is 4% greater than the flat panel. Consequently the output per unit area is 4% smaller than the flat panel.

The double curved (2D) panel presents similar behaviors to the single curved panel in both diurnal and seasonal operations of Figures 9 and 10. However, the surface area of this panel is 14.4% superior to a flat panel of equivalent footprint. This reduces by an equivalent amount the output per unit area of the panel, but also adds additional area possible over a single footprint, so it remains a potentially interesting area of investigation for formal design integration with architectural roofs and pavilions. The double curved panels may present technological challenges to their implementation. In addition to the fabrication challenges, the second curvature (in the plane of the seasonal angle variation) does not add any significant advantage due to the small variation of seasonal angles with the equinox baseline (+/-23°).

Although the production generated by a fixed amount of photovoltaic is lower, in many building cases there is limited space for a panel, and taking advantage of a curved surface may be interesting to the architect, as exemplified at the Gemini House in Austria.

In practice, conflicting design interests could limit the overall interpretation of our methodology. For instance, curved solar panels may be an optimal intervention for a given location as determined through geometric and irradiance arguments, yet a juxtaposition between aesthetic and functional motifs may limit the full potential of our approach.

Even so, with the low cost of the PV panels themselves currently, the cost of panel area is less important, and the installation and interface have become the larger portion of the system cost. The increased production in the morning may be important as well. Even for the reduced peak power generation, the curved panel has 5-17% greater production for the first hours of morning and last two hours of evening, and based on footprint area production is nearly 20% better at the tail of the day. This helps mitigate the so-called Duck-back effect (CAISO, 2016). The total production is reduced, but considering the added cost of batteries for small off-grid installations and the strain on ramping capacity of grid scale generators having to compensate for weak afternoon solar production of fixed panels concurrent with peak loads, there is potentially enough added value to justify the loss in total production. In California, the west-facing systems installed with azimuth between 259 and 281 degrees will receive monetary incentive, as expressed by the California Energy Commission in the New Solar Homes Partnership Guidebook as soon as 2014.

Conclusions

The analysis of the integrated tracking and shading system based on the prototype built at Princeton University demonstrated the significant capacity to increase solar generation. Although it assumed access to sun from horizon to horizon, it demonstrated the ability for both shading and electrical production to be maximized with the same mechanism. In addition, the manual operation of the tracking system eliminates complicated mechanisms in the prototype and helps to educate users about solar power - by simply keeping the shadow of the panel on the workspace, the user makes the panel track the sun. The simulation shows that basic geometry is also scalable and could be considered for larger systems shading larger areas and generating more power.

It appears from the results that a single curvature is sufficient for leveling the solar production on fixed panels. These results from the diurnal analysis confirm the research on solar PV that report only 5% production increases for the two axis tracking system, taking into account the seasonal variation of sun angle over the single axis tracking system (Lubitz 2011). By adding more surface area through geometric curvature, a satisfactory condition for leveling is seen in the increase in power outputs for early and late hours of the solar day. This is purely geometric and amounts to increasing the projected surface of the panel visible to the sun in those extremes of the day. For constant footprint, the power output should be similar for curved panels or flat panels for the designed orientation (e.g. midday). In terms of unit area efficiency, curved panels perform worse than flat panels around the design orientation. However, they have the advantage of increasing the radiation outside of the design orientation and produce a flatter, more regular power output. The analysis of the curved fixed panels demonstrates a potential to do some load leveling with the solar production by changing the shape, a similar effect to what is achieved with tracking panels, but without the complicated actuation.

Both shading and solar energy capture can be optimized by actuated surfaces. This simulation provided critical data in the growing fields of building integrated photovoltaics (BIPV) and adaptive facade shading systems. Variation of geometries in shading systems are now more popular. Our simulation not only quantifies the performance gains from co-optimizing the shading and PV systems, but it also characterizes geometric design opportunities for novel architecture enabled by new technology.

References:

Ashdown, Ian, Delaunay's, Jean-Jacques and Ward, Greg, GENDAYMTX, http://www.radiance-online.org/learning/documentation/manual-pages/pdfs/gendaymtx.pdf ,extracted December 10, 2016

CAISO, *California ISO Fast Facts*. 250 Outcropping Way, Folsom, CA 95630 CommPR. 2016 https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

Calabrò, E. (2013). An algorithm to determine the optimum tilt angle of a solar panel from global horizontal solar radiation. *Journal of Renewable Energy*, *2013*.

Clarke, N. (2011). *The effective collection area of a flat-panel solar collector*. Retrieved from https://commons.wikimedia.org/wiki/File:SolarPanel_alignment.png

Clifford, M. J., & Eastwood, D. (2004). Design of a novel passive solar tracker. *Solar Energy*, *77*(3), 269-280.

Huld, T., Cebecauer, T., Šúri, M., & Dunlop, E. D. (2010). Analysis of one□axis tracking strategies for PV systems in Europe. *Progress in Photovoltaics: Research and Applications*, *18*(3), 183-194.

Kasinalis, C., Loonen, R. C. G. M., Cóstola, D., & Hensen, J. L. M. (2014). Framework for assessing the performance potential of seasonally adaptable facades using multi-objective optimization. Energy and Buildings, 79, 106-113.

Lee, E., Yazdanian, M., & Selkowitz, S. (2004). The energy-savings potential of electrochromic windows in the US commercial buildings sector. Lawrence Berkeley National Laboratory.

Loonen, R. C., Trčka, M., Cóstola, D., & Hensen, J. L. M. (2013). Climate adaptive building shells: State-of-the-art and future challenges. Renewable and Sustainable Energy Reviews, 25, 483-493.

Lorenzo, E., Perez, M., Ezpeleta, A., & Acedo, J. (2002). Design of tracking photovoltaic systems with a single vertical axis. *Progress in Photovoltaics: Research and Applications*, *10*(8), 533-543.

Lubitz, W. D. (2011). Effect of manual tilt adjustments on incident irradiance on fixed and tracking solar panels. *Applied energy*, *88*(5), 1710-1719.

Martín-Chivelet, N. (2016). Photovoltaic potential and land-use estimation methodology. Energy, 94, 233-242.

Patil, J. V., Nayak, J. K., & Sundersingh, V. P. (1997). Design, fabrication and preliminary testing of a two-axes solar tracking system. *International Energy Journal*, *19*(1).

Perez, R., R. Seals, and J. Michalsky. “All-Weather Model for Sky Luminance distribution—Preliminary Configuration and Validation.” *Solar Energy* 50, no. 3 (March 1, 1993): 235–45. doi:10.1016/0038-092X(93)90017-I

Read, J. R., Meggers, F., Houchois, N., Aschwanden, G., Teitelbaum, E., Adriaenssens, S., … Pantelic, J. (2015). Thermoheliodome design, optimization and fabrication. In *6th International Building Physics Conference, IBPC 2015*. Torino, Italy: Elsevier.

Sadeghipour Roudasri, Mostapha, LADYBUG + HONEYBEE, http://www.food4rhino.com/app/ladybug-honeybee, extracted December 10, 2016

Sherif, Ahmed H., Hanan M. Sabry, and Mahmoud I. Gadelhak. “The Impact of Changing Solar Screen Rotation Angle and Its Opening Aspect Ratios on Daylight Availability in Residential Desert Buildings.” Solar Energy 86, no. 11 (November 2012): 3353–63. doi:10.1016/j.solener.2012.09.006.

Simmler, Hans, and Bruno Binder. “Experimental and Numerical Determination of the Total Solar Energy Transmittance of Glazing with Venetian Blind Shading.” *Outdoor Testing, Analysis and Modelling of Building Components* 43, no. 2 (February 2008): 197–204. doi:10.1016/j.buildenv.2006.10.011.

Yoo, Seung-Ho, Eun-Tack Lee, and Jong-Keuk Lee. “Building Integrated-Photovoltaics: A Korean Case Study.” *Solar Energy* 64, no. 4–6 (December 1, 1998): 151–61. doi:10.1016/S0038-092X(98)00115-7