# Designing a Solar Cell to Optimize Efficiency

**Subject:** Modelling trade-offs between different sources of power loss and electron transport in a solar cell

**Grade Levels:** Middle school and higher

**Lesson length:** 40-60 minutes

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Solar cells have a limited amount of space on their surfaces. The silicon wafer itself must be exposed for electron/hole pair generation, and the metal overlays are present to transport the electrons to create current. Maximizing the number of electrons that can be used in a circuit requires tradeoffs in design between electron generation and electron transport and is expressed as optimization of the total surface area of the silicon wafer versus the total surface area of the metal configurations.

In this activity, participants will examine the effects of one factor, shading, on solar cell efficiency. Their goal is to optimize the front grid design of a solar cell to minimize power loss by drawing their own custom designs on a pre-drawn solar cell front panel grid. Students use a pre-determined formula to calculate the effects of shadowing on the cells' efficiency, estimating power loss associated with their design in order to compare and improve their designs.

## Learning Goals

- *Participants will learn how the metal contacts effect a solar cell's overall efficiency and how optimization must reach a happy medium between the materials' surface areas to maximize efficiency. Their goal is to optimize* *the front grid design of a solar cell to minimize power loss by designing the spacing of buss bars and fingers on a solar cell. They will draw their own custom designs, estimate power loss, then use a spreadsheet to develop a better design. Through these activities, they will come to understand some of the tradeoffs between the number of busbars and fingers and the area of exposed silicon.*

## Materials

Required for each participant:

- Copies of the front panel grid paper
- Straightedge
- Black marker
- Red pen

## Instructor Content Background Information

Richard Komp's Ted-Ed talk, "How do solar panels work?":

https://www.youtube.com/watch?v=xKxrkht7CpY

Richard Komp's Ted-Ed lesson:

https://ed.ted.com/lessons/how-do-solar-panels-work-richard-komp

Department of Energy's solar energy quiz:

https://www.energy.gov/articles/quiz-test-your-solar-iq

There are more resources on the QESST Education website, like PowerPoint slides on the mechanics of silicon solar cells developed Cody Anderson, or a competition spreadsheet.

## Instructions

Orient students toward the design activity by checking their prior knowledge. You could use some of these questions, depending on the age and background of the participants.

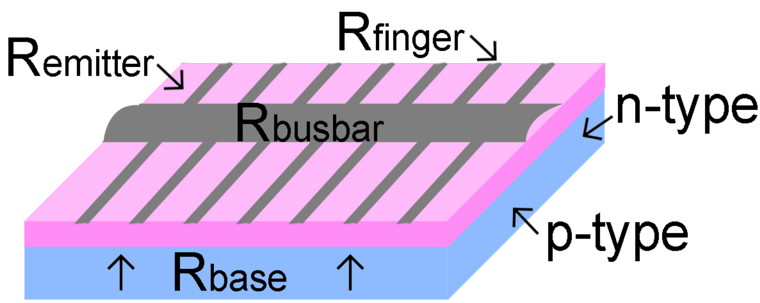
- What forms of energy do we use daily? List as many as you can think of.
- Where does this energy come from? List as many sources as you can.
- Do you think solar is a useful energy technology? Why or why not?
- What is light?
- What do solar panels do? How do they work?

Introduce participants to the mechanics of silicon solar cells. Participants should understand:

a. how solar cells convert sunlight to usable energy (electricity)
b. how silicon solar cells are manufactured

Several resources for exposing participants to this information are listed in the materials list above. You might, for instance, have them view and discuss Richard Komp's 5-minute Ted-Ed talk, "How Do Solar Panels Work", available on YouTube. You can also access his entire lesson that includes four steps: Watch (the video), Think (check your knowledge using 5 multiple choice and 3 open answer questions), Dig Deeper by exploring other online resources, and Discuss (questions in guided and open discussion forums). Another resource is Cody's PowerPoint on the mechanics of solar cells, which is available on QESST Education website. As a closing knowledge check, you might collectively take the solar energy quiz from the Department of Energy at energy.gov.

Once students have this background knowledge, lead them in discussing design considerations of a solar cell. Introduce them to the sources of power loss including optical losses (shading and surface reflection), shunt resistance (defects leading to tiny short circuits), and series resistance (base, emitter, contact, fingers and busbars).




The power loss associated with the front panel design of a solar cell can be mathematically modeled using this equation:

$$P_{loss} = P_{loss,emitter} + P_{loss,fingers} + P_{loss,shading}$$

Each source of power loss can also be mathematically modeled. Help participants interpret these equations by explaining how power loss associated with each of the sources is calculated. Point out that all three types of loss depend on finger spacing. Furthermore, power loss from shading ($P_{loss,shadin}$g) also depends on the area of the busbars:

$$P_{loss,emitter} = (S_f^2\ J_{mp}\ \ p) / (12\ V_{mp})$$

$$P_{loss,finger} = (L_f^2\ S_f\ J_{mp}\ \rho)\ / (3\ w_f\ d_f\ V_{mp})$$

$$P_{loss,shading} = A_{shaded}/A_{cell}$$

The main equation excludes power loss due to busbar resistance (which is negligible) and contact resistance (which cannot be modeled well since it is highly dependent on material variability). These equations assume equal finger spacing throughout cell. Finger Width ($w_f$) can be variable, but must be at least 50 μm due to manufacturing constraints.

Definitions of parameters and typical values for a solar cell

$S_f$ = finger spacing [mm]
L = finger length [mm] (i.e., busbar spacing)
$J_{mp}$ = current density at max power ~0.35 mA/mm$^2$
$V_{mp}$ = voltage at max power ~ 0.5 V
$\rho$ = metal resistivity ~ 3x10$^{-5}$ Ω·mm
p = emitter sheet resistivity ~ 60 Ω
$d_f$ = depth of finger ~ 0.02 mm
$w_f$ = width of finger ~ 0.01 mm
$A_{cell}$ = total surface area of cell (150mm x 150mm for the given cell, minus the area of the corner cutouts)
$A_{shaded}$ = shaded surface area, estimated as
$A_{shaded} = A_{busbar} + w_f / S_f \ (A_{cell} - A_{busbar})$
Busbar width = 2 mm

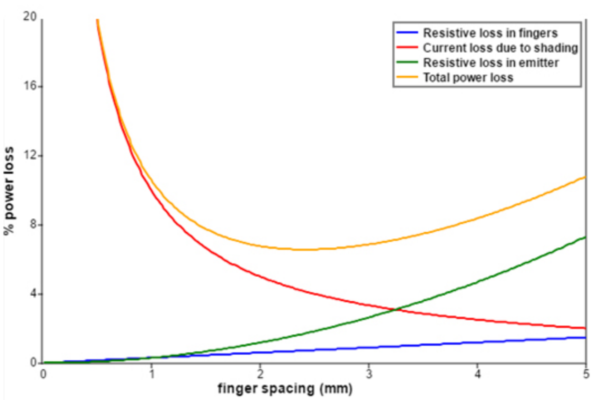
Help participants interpret these equations by explaining how power loss associated with each of the sources is calculated. Point out that all three sources of loss depend on finger spacing. Furthermore, $P_{loss,shading}$ and $P_{loss,shading}$ also depend on the area of the busbars.

Participants need to recognize that there are tradeoffs among the variables. Some examples include:

- Finger spacing ($S_f$): A short distance between fingers decreases losses in emitter and fingers but increases shading losses.
- Minimum finger width ($w_f$): The thinner the fingers, the higher the finger resistance but with less shading losses.
- Finger height-to-width aspect ratio ($d_f/w_f$): The higher the ratio, the lower the resistance without shading losses.
- Resistivity of metal ($\rho$): The lower the resistivity, the lower the finger resistance typically silver is used, which is conductive ($\rho$ = 3x10$^{-8}$ Ω·m) but expensive (cost = 1.0 $/g).

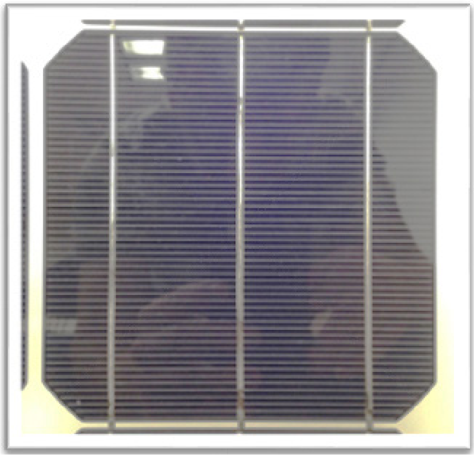
To highlight some of the tradeoffs, show this graph that represents power losses under typical conditions. Help students interpret the graph and lead a discussion on how the relative contribution of each source to total power loss depends on finger spacing. The graph is available at:

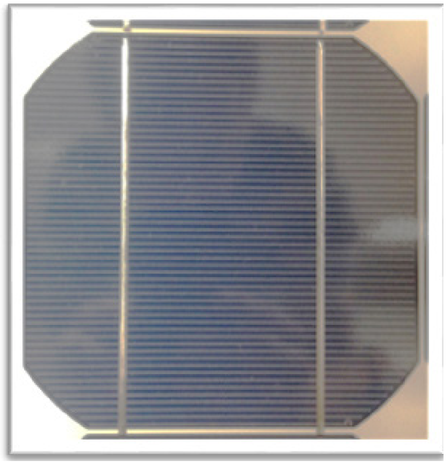
http://bit.ly/2ozGTBz



Next, focus in on the two key adjustable parameters for this activity: Finger spacing ($S_f$) and busbar spacing/finger length (L). Show two different front grid designs. Ask two questions:

- What is similar/different between these two cells?
- What impacts might the differences have on cell efficiency?





Discuss the impacts of each of the adjustable parameters in order to help participants check their understanding and apply their knowledge (e.g. What happens if we space the fingers further apart? How does it impact each of the three power loss terms? How does it impact the total power loss?).

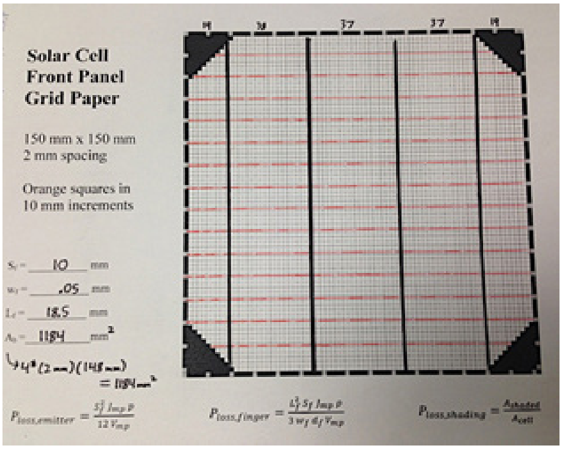
Once participants understand the parameters that affect power loss in a solar cell, they are ready for you to introduce the design challenge. In this outreach activity, participants are challenged to optimize the front grid design of a solar cell to minimize power loss. Explain that they will do this by drawing their own custom designs and estimating power loss, then comparing different designs and making adjustments to improve optimization. Participants are able to adjust two of the parameters in order to optimize efficiency of their solar cells.

- Finger spacing ($S_f$). Point out that this parameter plays into all three of the power loss terms.
- Busbar spacing/finger length (L). Busbars should be spaced evenly and the finger length sized accordingly.

For the optimization challenge, participants draw their own front grid designs, partner up, compute power losses from their drawings, and compare results with each other.

Working alone, participants take the following steps:

1) Take a copy of the front panel grid paper, ruler, red pen, and black pen.
2) Decide how many busbars you'd like to use (between 1 and 8). Draw your busbars in black marker. The width of each busbar is set at 2 mm, which is one cell's width on the grid paper. All the busbars you will draw should run vertically and be evenly spaced. The example on the next page was done using four busbars (black lines).




3) Choose a finger spacing ($S_f$) between 1 mm and 10 mm. Draw your fingers in red pen.
4) Compute power loss using the given equations. Verify that your units work out. Check a partner's work. (Note: 1 V = 1 A·Ω).
5) Compute the spacing of the busbars. Use the following table to help you (if you choose a different # of busbars, follow the pattern shown). The busbar spacing is based on a 150mm-wide solar cell and rounded to the nearest mm.

| # busbars | 1 | 2 | 3 | 8 |
|---|---|---|---|---|
| Fraction of solar cell reached by each side of the busbar | 1/2 | 1/4 | 1/6 | 1/16 |
| Busbar spacing from left edge of cell | 75 mm | 38 mm | 25 mm | 9 mm |
| Busbar spacing from each other | -- | 76 mm | 50 mm | 18 mm |

6) Next to your design, write down the values for $S_f$, $w_f$, $L_f$, and $A_{busbar}$.
   - You have already chosen Sf and wf
   - Lf is essentially the same as the busbar spacing from the left edge of cell (minus half the width of the busbar)
   - $A_{busbar}$ can be computed by realizing that all the busbars are rectangles; add all the areas of the individual busbars together.

Help the participants compare their results and discuss which designs were optimized. Discuss the following questions, taking special note of the tradeoffs that exist.

1) What are the impacts of increasing finger spacing?
2) What are the impacts of increasing finger width?
3) What are the impacts of having more busbars?
4) To which parameter(s) are your power losses most sensitive? Least sensitive?
5) What were the power losses for each of your designs? Why do you believe one performed better than the other?

## Deepen Your knowledge

To reinforce and extend learning, connect this activity to the Electron Chairs or Construction Paper Solar Cells activity.

As an extension activity, you could use the Excel "Competition_Spreadsheet" found on the QESST Education Website to inform participants' front grid designs and help them develop

**Solar Cell Front Panel Grid Paper**

150 mm x 150 mm
2 mm spacing

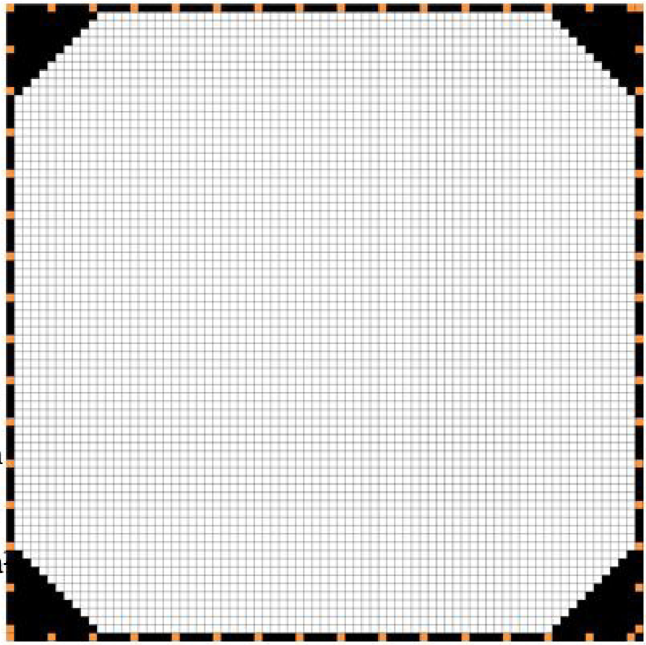
Orange squares in 10 mm increments

$S_f$ = ___________ mm

$w_f$ = ___________ mm

$L_f$ = ___________ mm

$A_b$ = ___________ mm



$$P_{loss,emitter} = \frac{S_f^2\, J_{mp}\, \rho}{12\, V_{mp}} \qquad P_{loss,finger} = \frac{L_f^2\, S_f\, J_{mp}\, \rho}{3\, w_f\, d_f\, V_{mp}} \qquad P_{loss,shading} = \frac{A_{shaded}}{A_{cell}}$$

their most efficient design. Participants share the parameters for their optimal design and see who demonstrates the smallest power loss. Depending on the sophistication of participants, the outreach leader can input the data. See the community college solar engineering unit in the Classroom Lessons section for more information.

This outreach activity is adapted from a solar energy unit designed for community college students by QESST RETs Cody Anderson (SCC) and Liz Adams (CGCC), which you can find in the Classroom Lessons section of this book.