UNIT PLAN

Cost-Effective Solar Cells

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DESCRIPTION

Through a series of solar panel and solar cell construction activities, students will learn the basic principles of energy conversion from light energy to chemical & electrical energy. Students will assemble and test pre-constructed solar panels to gain a working knowledge of power generation in parallel and series circuits. Using pre-designed methods, they will then construct two solar cells; oxidized copper sheets and titanium dioxide coated glass plates. Using these known working systems, students will investigate how changes to the method will affect the power generating outcomes in an inquiry-based format.

After exploring known solar cell designs, students then shift to an engineering design project. Students will research and model their own unique solar cell designs. Finally, students will begin their own independent projects to build and test their own solar cells with the goal of creating cheaper, cleaner, or more efficient solutions.

GRADE LEVEL(S)

9-12

SUBJECT AREA(S)

Chemistry, Physics, Solar Panels, Solar Cells, Electrochemistry, N- and P-type doping, P-N junctions, Photoelectric Effect, Power, Current, Voltage, Electricity Generation

LEARNING GOAL(S)

1. Students will discuss social, cultural, and economic implications of sustainable solar energy.
2. Students will construct and test solar panel arrays to power LED lights, fan motors, and music players
3. Students will review circuitry basics and solar cell layers
4. Students will analyze and share out power generation results with classmates
5. Students will construct and test an oxidized copper sheet solar cell
6. Students will share and analyze oxidized copper sheet solar cell data
7. Students will construct and test titanium dioxide coated “raspberry juice” solar cells

8. Students will collect and analyze titanium dioxide coated “raspberry juice” solar cell data. Students will discuss results and draw conclusions about variables that may affect power generation.
9. Students will visit a solar cell or silicon manufacturing facility and/or engage with guest speakers. Students will learn more detailed solar cell principles and manufacturing techniques involved in solar cell construction
10. Students will research chemicals, materials and procedures for their own solar cell designs
11. Students will build and present models of their proposed solar cells
12. Students will construct and test unique solar cells
13. Students will present construction progress and project obstacles
14. Students will format solar cell data, draw conclusions, and construct an engineering report as a research poster

UNIT EXPERIENCES

Table 1. Suggested Teaching Times
Based on a modified block schedule with two 80 minutes periods per week, plus one 40 minute period.

The order of lessons below has been switched to show their alignment with the 5E framework. Lessons are intended to be conducted in the order indicated by their number, not the order below.

Lesson/Experience	*Time*
Engage/Explore	
L1: Solar Energy Equity and Sustainability L2: Engaging with Solar Panels L5: Copper(I) Oxide Solar Cell Construction and Testing L7: Titanium Dioxide (TiO_2) Solar Cell Construction and Testing L10: Researching Chemicals and Materials for Solar Cell Construction L12: Unique Solar Cell Construction & Testing	*L1: 40 m x 2 = 80 m (1 hrs 20 min)* *L2: 80 m x 2 = 160 m (2 hrs 40 min)* *L5: 80 m x 1 = 80 m (1 hrs 20 min) or 40 m x 2* *L7: 80 m x 2 = 160 m (2 hrs 40 min)* *L10: 80 m x 3 = 240 m (4 hrs 0 min)* *L12: 80 m x 4 = 320 m (5 hrs 20 min)*
Explain	
L3: Solar Cell Basics L9: Solar Cell Manufacturing Field Trip and/or Guest Speaker L14: Unique Solar Cell Engineering Report	*L3: 40 m x 1 = 40 m ((0 hrs 40 min)* *L9: 80 m x 2 = 160 m (2 hrs 40 min)* *L14: 80 m x 3 = 240 m (4 hrs 0 min)*
Elaborate/Evaluate	
L4: Solar Panel Data Sharing L6: Copper(I) Oxide Solar Cell Data Sharing L8: Titanium Dioxide Raspberry Solar Cell Data Sharing L11: Unique Solar Cell Model Sketch & Presentation L13: Construction Progress & Obstacles	*L4: 40 m x 1 = 40 m (0 hrs 40 min)* *L6: 40 m x 1 = 40 m (0 hrs 40 min)* *L8: 80 m x 1 = 80 m (1 hrs 20 min)* *L11: 80 m x 2 = 160 m (2 hrs 40 min)* *L13: 40 m x 1 = 40 m (0 hrs 40 min)*
Total	*1840 min (30 hr 40 min)*

NEXT GENERATION SCIENCE STANDARDS

Guiding Phenomenon	How can we create a cost-effective and efficient solar cell?
Supplementary Phenomena	• L3: Solar Panel Functionality/PV effect • L5: Battery science, Semi-conductive materials • L9: Materials Science – Local Solar PV Manufacturing or Installation • L10-12: Addiitonal technologies that convert light to energy

Table 2. Next Generation Science Standards Assessed in This Unit

Performance Expectation	How is this Assessed?
HS-PS3-3. ***Design, build, and refine a device that works within given constraints to convert one form of energy into another.***	*L2: Students will collect solar panel array data* *L4: Students will share solar panel array data with classmates* *L5, 6: Student will build Copper (I) Oxide Cells, gather data and share out copper plate data and results with classmates* *L7, 8: Students will build titanium dioxide raspberry juice solar cells, gather data and share results with classmates* *L10-L13: Students will design, build, and refine a unique solar cell*
HS-PS1-2. Construct and revise an explanation for the outcome of a simple chemical reaction based on the outermost electron states of atoms, trends in the periodic table, and knowledge of the patterns of chemical properties.	*L3-L9: Students will explain how atomic and crystalline structures of matter affect power generation outcomes through models, data collection, and written descriptions*
HS-PS2-6. Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials	*L3: Students will create a physical model of solar cell layers and/or designs* *L14: Students will analyze their unique solar cell designs and explain why those decisions are important to the power generation capacities of their cells in an engineering report introduction and discussion.*

THREE DIMENSIONAL LINKAGES

NGSS focuses not only on content, but also on process and building bridges between concepts within and across disciplines. The following tables outline the way in which this unit addresses this three-dimensionality as is essential to NGSS.

Table 3. Three-Dimensionality: Disciplinary Core Ideas (DCIs)

Disciplinary Core Ideas	Linkage in Unit
ETS1.A: Defining and Delimiting Engineering Problems *Criteria and constraints also include satisfying any requirements set by society, such as taking issues of risk mitigation into account, and they should be quantified to the extent possible and stated in such a way that one can tell if a given design meets them.*	*Students will consider the cultural, social and economic impacts of solar energy on their designs. Criteria and constraints will be based on socioeconomic needs in order to design a cost-effective solution.*
ETS1.B: Developing Possible Solutions *When evaluating solutions, it is important to take into account a range of constraints, including cost, safety, reliability, and aesthetics, and to consider social, cultural, and environmental impacts.*	*Students will consider the cultural, social and economic impacts of solar energy on their designs. Costs of production will be calculated as a part of their engineering reports.*
ETS1.C: Optimizing the Design Solution *Criteria may need to be broken down into simpler ones that can be approached systematically, and decisions about the priority of certain criteria over others (tradeoffs) may be needed.*	*Students will need to break down complex science concepts (layer thickness, light transmission/absorption/reflection, conductive metal size, etc.) within solar cells into derived constraints for their own unique solar cell designs.*
PS1.A: Structure and Properties of Matter *The periodic table orders elements horizontally by the number of protons in the atom's nucleus and places those with similar chemical properties in columns. The repeating patterns of this table reflect patterns of outer electron states.*	*Students will learn about silicon and other crystal structures related to atomic structure, valence electron numbers, available electrons in metals, and the repeating pattern of those elements.*
PS2.B: Types of Interactions *Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects.*	*Students will investigate N- and P-type doping along with the P-N junction atomic interactions. Decisions on their designs have impact on these interactions, along with insulation, light transmission, and conductive material connections.*
PS3.B: Conservation of Energy and Energy Transfer *Energy cannot be created or destroyed, but it can be transported from one place to another and transferred between systems.* *The availability of energy limits what can occur in any system.*	*Students calculate efficiencies of their solar cells based on available light energy, area of solar cells, concentration/purity of materials, and power generation. Energy limits will be discussed and researched during the project.*

Table 4. Three-Dimensionality: Science and Engineering Practices (SEPs)- Following the same procedure for identifying DCIs, distinguish what SEP's students engage in while carrying out your Unit, giving some supporting evidence. See examples below:

Science and Engineering Practices	Linkage in Unit
Asking questions and defining problems	*L1: Students will engage in Socratic dialog* *L9: Students will pose questions to guest speakers and/or tour guides* *L10: Students will define their solar cell design problem including defining criteria and constraints*
Developing and using models	*L2: Students will sketch models of working solar circuits* *L3: Students will actively model P-N junctions* *L11: Students will describe and sketch out solar cell models* *L11: Students will present models of proposed solar cells.*
Planning and carrying out investigations	*L2: Students will construct working solar panel arrays to power LEDs, fans, and music boxes* *L5: Students will construct copper oxide solar cells and gather data for analysis* *L7: Students will construct titanium dioxide and berry juice solar cells and gather data for analysis* *L12: Students will construct unique solar cells and test to evaluate against criteria for success*
Analyzing and Interpreting Data	*L4: Students will share out solar panel array data* *L6: Students will collect and analyze copper sheet solar cell data* *L8: Students will share and analyze titanium dioxide solar cell results, trends and variable effects* *L14: Students will gather unique solar cell data and create graphical presentations and analysis of the data.*
Using mathematics and computational thinking	*L14: Students will use basic statistical analysis on their unique solar data including averages and error calculation.*
Constructing explanations (for science) and designing solutions (for engineering)	*L10-L13: Students will design unique solar cells, making changes to designs after testing, and evaluate their final design against their proposed criteria and constraints.*
Engaging in argument from evidence	*L1: Students will discuss and connect evidence from 3 solar energy and sustainability articles in a Socratic Seminar dialog* *L8: Students will draw conclusions from Titanium Dioxide class results and data analysis* *L14: Students will discuss their design solution costs & efficiency in the results section of their engineering report*
Obtaining, evaluating, and communicating information	*L1: Students will read texts to obtain information, evaluate and communicate in dialog* *L10: Students will obtain and evaluate solar cell design ideas* *L14: Students will design and present research posters*

Table 5. Three-Dimensionality: Crosscutting Concepts (CCCs) - Following the same procedure for identifying DCIs and SEPs, use the NGSS list of Crosscutting Concepts to illuminate what this Unit focuses on.

Crosscutting Concepts	Linkage in Unit
Patterns	*Students will frequently share results with classmates on their solar cell power outputs. As they investigate multiple variables (size, temperature, concentration, etc.), the audience will be asked to listen for patterns in the results.*
Cause and Effect	*Students will be looking for qualitative and quantitative effects of solar cell design on the resulting power generation*
Systems and System Models	*Students will understand and analyze the modern energy system for its features, outputs, and impacts. They will also understand solar photovoltaic generation systems as systems, designing, sketching, and building solar cell models.*
Energy and Matter: Flows, Cycles and Conservation	*Students will be analyzing how the placement, concentration, and purity of bulk substances affects energy conversion within solar cell systems.*

COMMON CORE STATE STANDARDS

- CCSS.ELA-LITERACY.SL.11-12.1.A
  Come to discussions prepared, having read and researched material under study; explicitly draw on that preparation by referring to evidence from texts and other research on the topic or issue to stimulate a thoughtful, well-reasoned exchange of ideas.
- CCSS.ELA-LITERACY.SL.11-12.1.C
  Propel conversations by posing and responding to questions that probe reasoning and evidence; ensure a hearing for a full range of positions on a topic or issue; clarify, verify, or challenge ideas and conclusions; and promote divergent and creative perspectives.

CONTENT BACKGROUND

STUDENT BACKGROUND

At the start of this unit, students are expected to have some familiarity with the following scientific concepts and practices:

- Engineering design process
- Socratic dialogue
- Basic circuitry – voltage, current, and power
- Using multimeters
- Data sharing and discussion
- (Optional) Atomic structure and valence electrons
- (Optional) Crystal structure and crystal growing
- (Optional) Electrochemistry & batteries

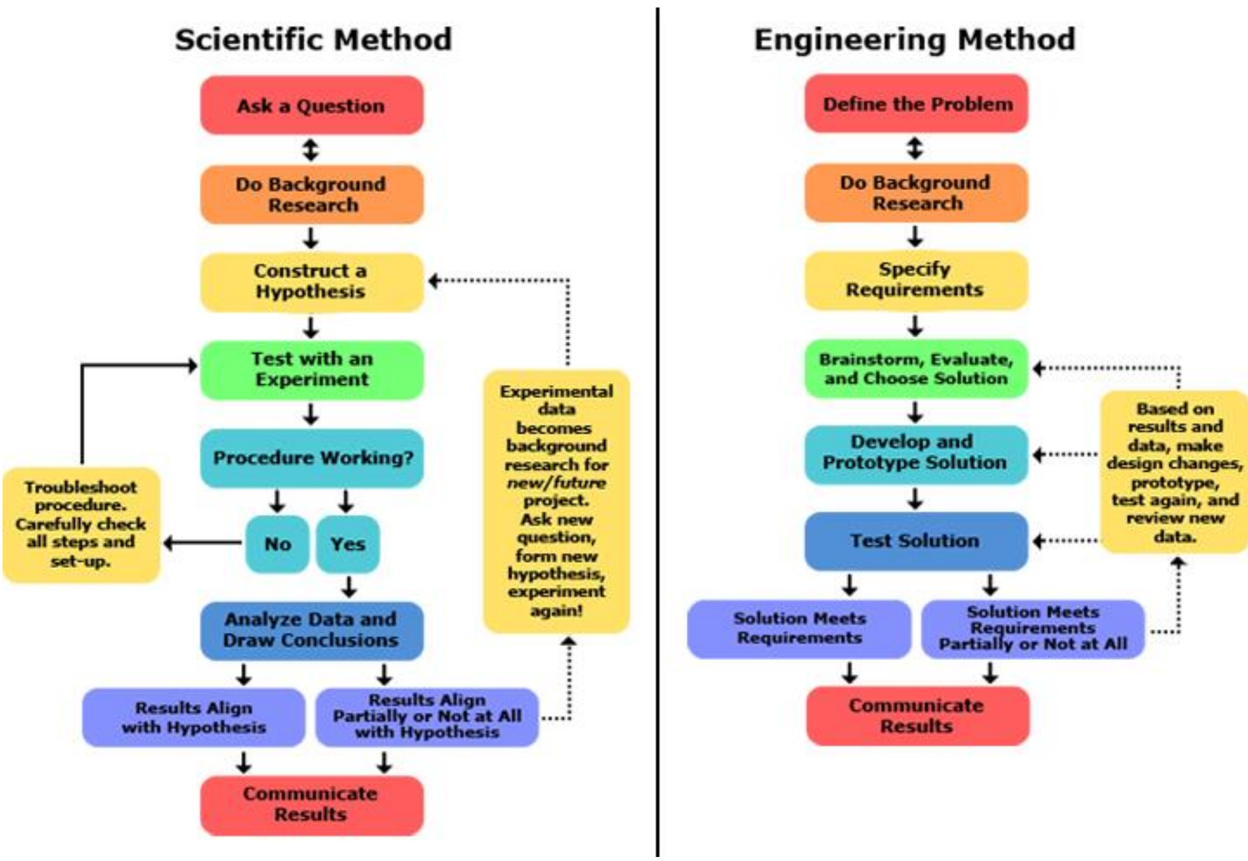
As a result of this unit, students will gain further insights into:

- Photoelectric effect
- Electron transfer
- P-N junctions
- N-type doping
- P-type doping
- Copper oxide solar cells
- Titanium dioxide solar cells
- Solar cell manufacturing

EDUCATOR BACKGROUND

ENGINEERING DESIGN PROCESS

Engineering is a field where societal concerns are raised that necessitate a designed solution. Solutions are tested and optimized to meet society's demand. At the core of the engineering method, the design process is problem solving through proposed solutions. It shares similarities with the scientific method, yet differs in several key ways. From a comparison website at https://www.sciencebuddies.org/blog/understanding-the-engineering-design-process, the following graph illustrates the similarities and differences therein:



Both processes are iterative and demonstrate that science and engineering are ongoing, dynamic processes. Both processes are used at points in this unit, with Lessons 10-15 engaging fully in the engineering method as students work with unique projects.

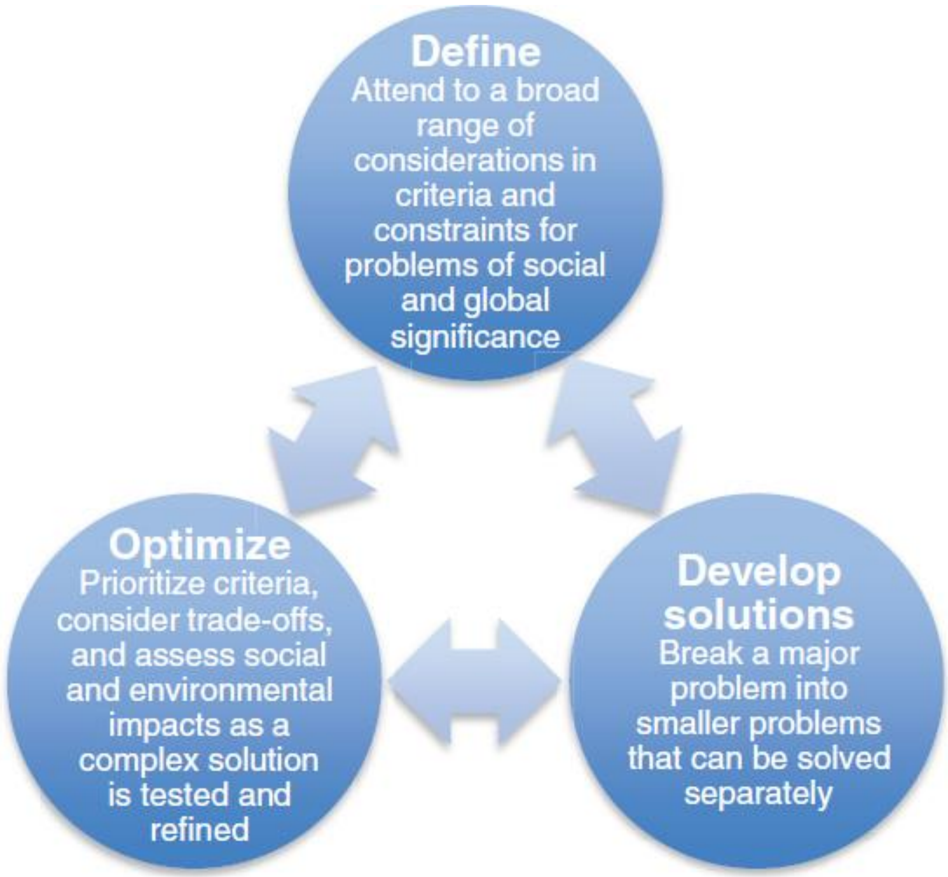
The key steps in the engineering design process used in this unit are as follows:

- Defining the Problem
- Performing Background Research
- Specifying Criteria and Constraints
- Designing and Modeling a Solution
- Building the Solution (Prototype)
- Testing the Solution
- Analyzing Results Within Criteria and Constraints
- Communicating Results

The Next Generation Science Standards parallel these steps with their Science and Engineering Practices, which will be used to assess students:

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

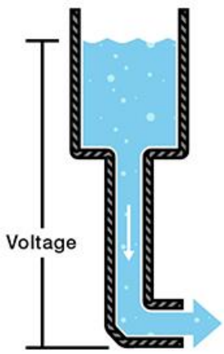
In addition, the Next Generation Science Standards utilizes four Engineering Design performance expectations that align with three components of the following 9-12 grade model found within Appendix 1: https://www.nap.edu/read/18290/chapter/15#440



BASIC CIRCUITRY

Voltage

Voltage is the amount of potential energy between two points on a circuit. It is represented by the letter "V," with a unit known as the volt. It represents work that can be performed on electrons in a circuit and is also known as an electromotive force. A simple analogy is often that of a water tank, where voltage is represented by the pressure of gravity's downward pull on water in the tank. From https://learn.sparkfun.com/tutorials/voltage-current-resistance-and-ohms-law/all, the voltage is shown as follows:

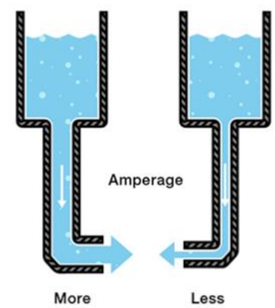


If water is in the top of the tank, then pressure is into the system and can push water through the pipes below. If too much water is released below, then the voltage will drop. In this same way, a battery will drain and at a certain point, it will lose voltage—causing the music to slow down or the light to dim. Electrical outlets in the households maintain a voltage between 110 – 120 V or between 220 – 240 V.

In a solar cell, the size and chemical makeup of the cell will determine the maximum amount of voltage that the cell can generate. ***A typical individual solar cell will generate a maximum of 0.5 - 0.6 V.*** More voltage can be generated by attaching multiple solar cells into a solar panel array.

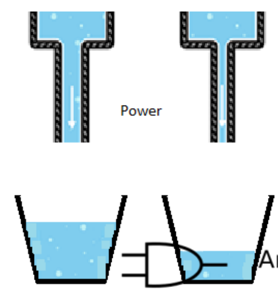
Current

We can think of the current as the size of the pipes. In the drawing below, the right tank has the smaller outlet pipe, giving a lower rate of flow. In general, the size of a conductive wire in a circuit can determine the maximum current—a smaller wire can carry less current that a larger wire.



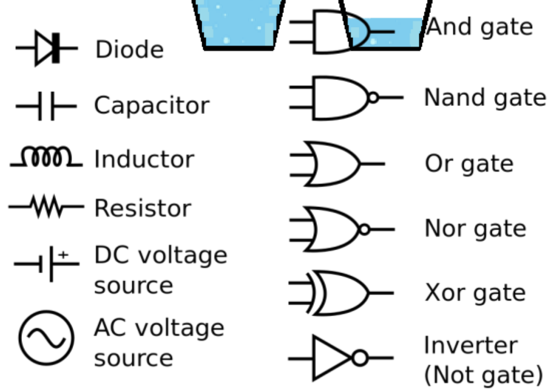
Power

Power (P) can be represented by multiplying the current (I) by the voltage (V), such that $P = I \times V$. In our water tank example below, power would be represented by the speed at which a bucket would be filled with water. With the upper tanks being equal volume, the larger outlet pipe will fill the bucket faster than a smaller pipe. Similarly, if the outlet pipes were equal diameter, a larger volume tank would fill the bucket faster than a smaller tank due to gravity.



Circuit diagrams:

Circuit diagrams show a visual representation of the components of a circuit. Components have common symbols as illustrated by the below diagram (from https://en.wikipedia.org/wiki/Circuit_diagram)



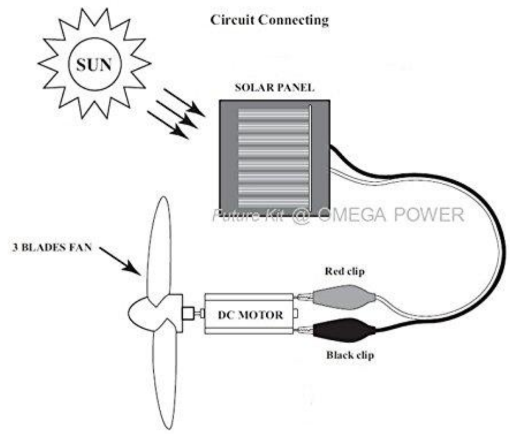
Multimeters

Multimeters are tools used to measure voltage, amperage, or resistance in electrical circuits. A multimeter cheat sheet for measure voltage and current can be found on the Clean Energy Bright Futures website: https://cebrightfutures.org/sites/default/files/multimeter-cheatsheet.pdf

Solar Cell Wiring Diagram:

Examples of solar cell wiring diagrams that students might generate during this lesson can be found below:

Image from: https://www.amazon.in/Solar-Electronic-Circuit-Student-Learning/dp/B00KUL9VX6



Solar Cell Circuit

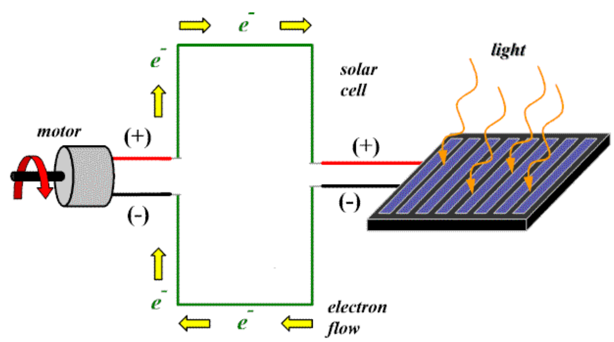


Image from: http://www.makeitsolar.com/science-fair-ideas/07-solar-parallel-circuit.htm

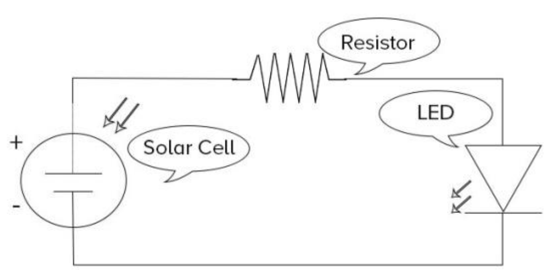


Image from: https://www.sciencefriday.com/educational-resources/hack-a-solar-circuit/

SCIENCE FRIDAY EDUCATE

Photoelectric Effect:

Concept history & introduction only: https://www.youtube.com/watch?v=0b0axfyJ4oo

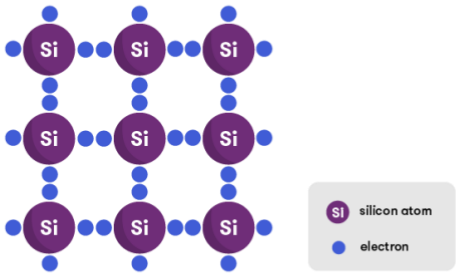
Photoelectric effect with Physics equations: https://www.youtube.com/watch?v=vuGpUFjLaYE

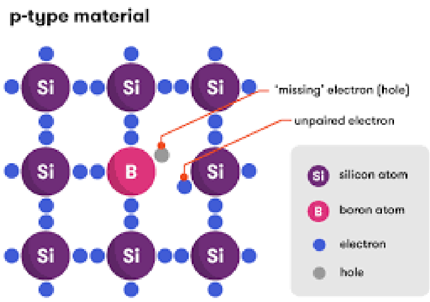
P-N JUNCTIONS

Solar cells are constructed by creating an imbalance of charge between layered materials. When electrons are freed by the photoelectric effect, the imbalance is essentially a voltage which induces electrons to travel in a predetermined current. The basic materials and principles are below.

P-type material

Normally, silicon (and carbon) have four valence electrons available to form bonds with other atoms or to form regular crystal structures.

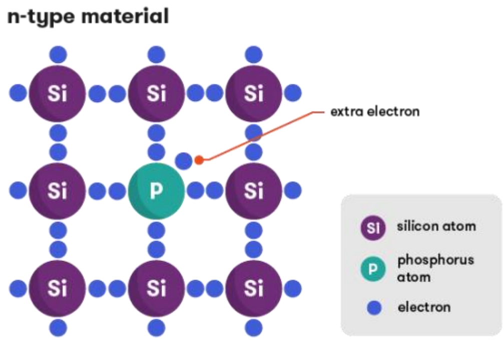




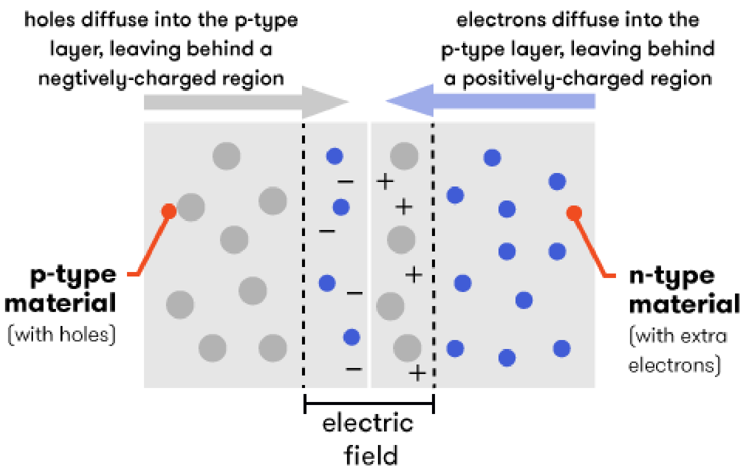
When pure silicon is P-doped with a 3-valence electron atom like boron, the boron atoms displace the silicon atoms from their location. The "missing" electron when the 4-valence silicon was replaced by the 3-valence boron results in an "electron hole" that acts like a positive charge.

N-type material

When pure silicon is N-doped with a 5-valence atom like phosphorus, you are replacing the 4-valence silicon atom and leaving an extra electron. This extra electron adds a negative charge to the N-type material.



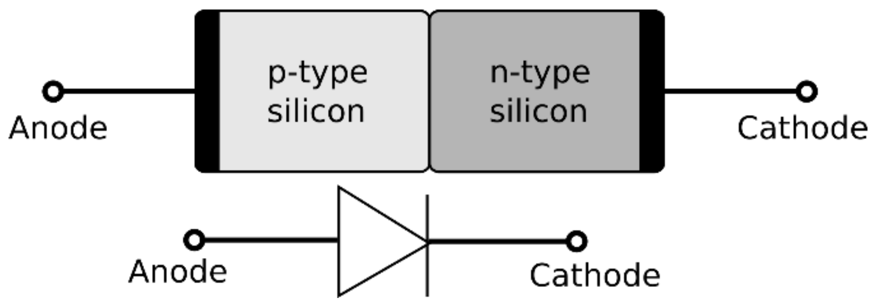
Images from https://www.science.org.au/curious/technology-future/solar-pv



P-N junctions

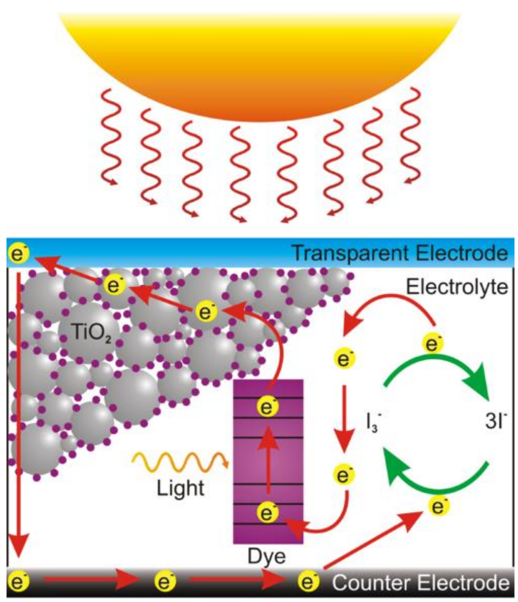
At the junction of an n-type material and a p-type material, the positive "holes" from the n-type material will diffuse towards the negatively charged p-type material. Likewise, the extra electrons from the p-type material will diffuse towards the positively charged n-type material. As the positive charges move towards the junction, they will leave behind a negatively charged region, and vice-versa.

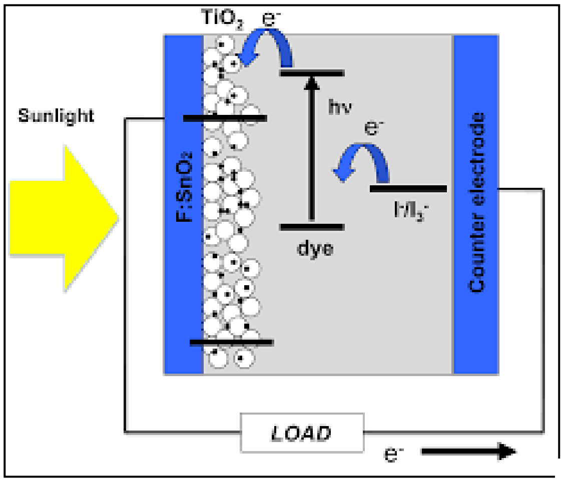
By attaching conductive material to the N-type and P-type materials, we can set up an anode and cathode for the system—allowing the electron flow to do work in a circuit. Image from https://en.wikipedia.org/wiki/P%E2%80%93n_junction



Organic Dye-Sensitized Solar Cells:

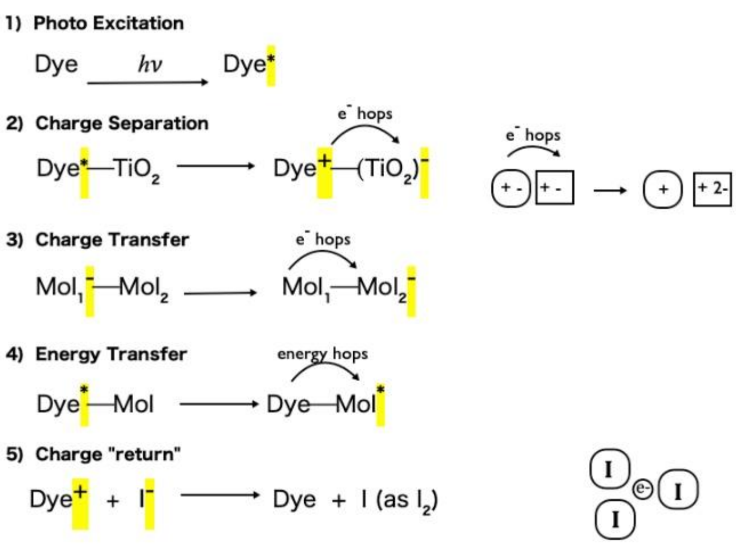
Students will be constructing and testing a solar cell made out of titanium dioxide and raspberry juice. The solar cells will be layered on FTO-coated glass, while potassium tri-iodide and a carbon soot layer will complete the solar cell circuit. This solar cell functions well under sunlight, but has a limited lifespan based on the organic anthocyanins found in the raspberries.





The transportation of electrons is a bit more complex in this cell. The FTO layer of the glass slide provides a means of electrical conductivity along a transparent surface. The students will layer the conductive side with Titanium dioxide, which helps capture light in the cell and serves as a binder for the anthocyanins. The anthocyanin will transport electrons when hit with light photons, allowing electrons to flow into the FTO conductive layer. A second FTO-coated cell is layered with carbon soot from a candle, acting as the counter electrode in the solar cell. Finally, the electrons are cycled back to the anthocyanins via a potassium tri-iodide electrolyte solution.

The anthocyanins are found in raspberries and many other fruits, vegetables, and leaves with purple-red coloring such as blackberries, blueberries, blood oranges, pomegranates, cherries, grapes, eggplants, and plums. With light, the anthocyanin pigment reaches an excited state where electrons can then be transferred or "hopped" along the anthocyanin layer to the titanium dioxide layer and to the FTO layer of the solar cell. Electrical work can be performed and the electron returns to the positively charged dye interacting with the iodide anion. As the dye receives the electron, the iodide cycles into iodine.



Images and concepts provided by Basil Paulson (https://drive.google.com/file/d/1b9NhoLYH2KP9uqVnHeCyM1USoigTlTA_/view?usp=sharing)

VOCABULARY

Alligator Clips	*A sprung metal clip used to connect electric cables to another electric component.*
Anode	*The portion of a device where electrons leave.*
Anthocyanin	*A reddish-blue pigment found in some parts of plants. Can convert light energy to electrical energy in Organic Dye-Sensitized Solar Cells.*
Band gap	*The energy range between the valence band and the conductive band in solids. Conductors have little to no band gap. Insulators have very large band gaps while semi-conductors have smaller band gaps.*
Battery	*A container of one or more cells that convert chemical energy to electrical energy. A battery generates power as opposed to a load, which consumes power.*
Cathode	*The portion of a device where electrons can enter the device.*
Circuit	*A closed and complete path in which an electric current can flow.*
Circuit Diagram	*A pictorial representation of a circuit (see Educator Background above).*
Conductive Band	*A band of energy filled with electrons in a crystalline solid. These electrons can move within the band easily and are responsible for conducting electricity.*
Conductor	*A material that allows the flow of charge in one or more directions.*
Current	*The rate of flow of electric charge, measured in amperes (see Educator Background above).*
Crystal	*A solid substance having a natural geometric form.*
Doping	*The introduction of chemical impurities into a material with semi-conductor properties.*
Electricity	*The physical phenomena associated with matter that has a negative or positive electric charge, including electromagnetism, lightning, static electricity, hydroelectricity, etc.*
Electron	*A subatomic particle carrying a negative charge found surrounding atoms.*
Electron hole	*The lack of an electron where one could exist in a crystal lattice. Electron holes can move through the valence band like electrons.*
Electron Orbitals	*The specific regions around an atom's nucleus where electrons have a high probability of being found.*
Engineering Design Process	*A series of steps that engineers follow to come up with a solution to a problem (see Educator Background above).*
Incident Angle of Sunlight	*Description found at* https://cebrightfutures.org/learn/incident-angle-sunlight .
Insulator	*A substance or device that does not conduct electricity. These materials have a large band gap between the valence and conductive bands, meaning that it takes a very large amount of energy to create a current.*
Irradiance	*Description found at* https://cebrightfutures.org/learn/solar-energy#Irradiance%20&%20Insolation .

Load	*An electrical component that consumes electric power as opposed to battery which generates power.*
Multimeter	*An instrument designed to measure voltage, amperage, and resistance (see Educator Background above).*
N-doping	*The doping of an N-type material (see Educator Background above).*
N-type material	*A material doped with impurities so that it has an excess of conductive electrons (see Educator Background above).*
Organic Dye-Sensitized Solar Cells	*A dye-sensitized solar cell (DSSC) is a solar cell based on a photo-sensitized anode from organic materials, like anthocyanin or other pigments. An electrolyte provides the mechanism for the cathode to return electrons to the organic material.*
P-doping	*The doping of a P-type material (see Educator Background above).*
P-type material	*A material doped with impurities so that it has an excess of electron holes (see Educator Background above).*
P-N junction	*The boundary between a p-type and n-type material in a semiconductor.*
Parallel circuit	*Description found at* https://cebrightfutures.org/learn/parallel-circuit-wiring
Photoelectric Effect	*The ejection of electrons from the surface of a material in response to the incident light. This energy moves electrons from the valence band to the conductive band in a semi-conductor. If the electron stays within the material it can cause the photovoltaic effect.*
Photovoltaic Effect	*The creation of voltage and current in a material upon exposure to light. The closely-related photoelectric effect ejects the electron, and the photovoltaic effect contains the ejected electron in an electrical circuit.*
Photovoltaic Materials	*Materials that are capable of converting electromagnetic energy (light) into electrical energy.*
Photovoltaic Systems	*A power system designed to supply usable solar power via the photovoltaic effect. Usually consists of solar panels and a solar inverter to change the current from DC to AC.*
Power	*The rate at which electrical energy is transferred by a circuit. It is a function of the voltage and amperage of the system. It is produced by generators or batteries and consumed by electrical loads.*
Semi-conductor	*A solid substance that has conductivity between that of an insulator and a conductor. It can conduct electricity when the valence band electrons move into the conductive band due to temperature, light, or other energy inputs.*
Series circuit	*Description found at* https://cebrightfutures.org/learn/series-circuit-wiring
Silicon	*A nonmetal with semi-conducting properties. Atomic number is 14 and it contains 4 valence electrons. Silicon forms crystals due to covalent bonding in the valence band, and its crystalline structure provides a base for constructing solar cells.*
Socratic Seminar	*A formal discussion based on text, in which the leader asks open-ended questions. Students listen to one another, ask clarifying questions, and use critical thinking to respond to the thoughts of others.*

Solar Cell	*A device converting solar radiation into electricity through the photovoltaic effect. Multiple solar cells can make up a solar panel, which in turn can make up a photovoltaic system.*
Solar Cell Wiring Diagram	*A pictorial depiction of the wiring of a solar cell (see Educator Background above).*
Solar Energy	*Radiant energy emitted by the sun.*
Solar Panel	*A panel designed to absorb solar energy to generate electrical power via the photovoltaic effect. Consists of an array of solar cells wired together.*
Sustainability	*Avoidance of the loss of natural resources to maintain an ecological balance.*
Valence band	*The band of electron orbitals in a solid corresponding to the valence electrons. Electrons can jump out of the valence band when excited to enter the conductive band.*
Voltage	*The potential difference or electromotive force. Measured in volts (see Educator Background above).*
Work	*The energy between two points that performs a function by a charged particle in an electrical system. The voltage between two points.*

REQUIRED MATERIALS

HANDOUTS/PAPER MATERIALS

- Lesson 1:
  - Socratic Seminar articles (links to articles in Lesson 1 / Newslea)
  - Current Events Article Summary Sheets
- Lesson 2: Solar Panel Challenge! worksheet (to collect solar panel data and sketch circuits)
- Lesson 5: Copper(I) Oxide Solar Cell Procedures and Data Sheet
- Lesson 7:
  - Anthocyanins Presentation (powerpoint)
  - Titanium Dioxide Raspberry Solar Cell Procedure and Data Sheet (designed to show variables during construction)
- Lesson 8:
  - Titanium Dioxide Raspberry Results Form (Google Forms-sample)
  - Titanium Dioxide Raspberry Results Response Page (Google Sheets)
- Lesson 10-12:
  - Materials Request Form

CLASSROOM SUPPLIES

- Chalkboard or Dry Erase board
- Electric hot plates
- Tin snips
- Dish soap
- Stir rods or spoons
- Access to water
- Weigh boats or paper squares for dry chemicals
- Plastic cups
- Masking or clear tape
- Highlighters
- Fume hood
- Matches or lighter
- Chemical waste disposal – wet and dry
- Incandescent or halogen light bulbs of various wattages

ACTIVITY SUPPLIES (PER GROUP OF 3-4 STUDENTS)

- Lesson 2: Solar Classroom Set
  - 32 0.5-Volt solar panels (3-4 per group)
  - 8 3-Volt solar panels (1 per group)
  - 18 small DC motors with fan attachments (1 per group)
  - 18 small-load music players (1 per group)
  - 18 LEDs (1 per group)
  - 36 alligator clips (3-4 per group)
  - Multimeter (1 per group)
- Lesson 3: Solar Cell Basics
  - > 10 ping pong balls

    - Sidewalk chalk
    - Optional: flashlight, bucket with water or other demonstration of “work”
- Lesson 5: Copper sheet solar cells
    - 32-gauge (or higher) Copper sheet or foil, cut into 1” x 2” strips (2 per group)
    - 8-ounce clear plastic cups (1 per group)
    - Salt (about ¼ cup per group)
    - Multimeter (1 per group)
    - Alligator clips (2 per group)
- Lesson 7: Titanium dioxide & berry solar cells
    - FTO (TEC15) 1” x 1” coated glass slides (2 per group)
        - These slides can be ordered here: https://www.msesupplies.com/products/fluorine-doped-tin-oxide-fto-coated-tec-15-glass-tec15-fto-can-customize-pattern-as-required?variant=19973837956
    - Titanium dioxide (about 0.2 grams per group)
    - Dilute acetic acid (a few drops per group)
    - Anthocyanin-containing berries (raspberry, blackberry, blueberry, pomegranate) (a few berries per group)
    - Tea candle (1 per group)
    - Potassium tri-iodide solution (a few drops per group)
    - Small binder clips (2 per group)
    - Multimeter (1 per group)
    - Alligator clips (2 per group)
- Lesson 12: Inquiry Materials Kit for unique solar cells
    - Titanium dioxide
    - Tin oxide
    - Dilute acetic acid
    - Potassium tri-iodide solution
    - Copper sheets or foil
    - Tin sheets or foil
    - Aluminum sheets or foil
    - Zinc sheets or foil
    - FTO (TEC15) 1” x 1” coated glass slides
        - These slides can be ordered here: https://www.msesupplies.com/products/fluorine-doped-tin-oxide-fto-coated-tec-15-glass-tec15-fto-can-customize-pattern-as-required?variant=19973837956
    - Uncoated glass slides
    - Graphite
    - Stannous chloride for coating glass
    - Fluoride toothpaste for coating glass
    - Inkjet printer / refillable ink cartridges for thin-layer printed cells
    - Transparency sheets
    - Spray bottles / misters
    - Methylammonium Iodide (for perovskite crystals)
    - Triphenylamine (electron hole transport)
    - Binder clips

- Multimeter
- Alligator clips
- Centrifuge
- Spin coater / attachment for centrifuge

UNIT PROGRESSION

LESSON SUMMARIES

LESSON 1: SOLAR ENERGY EQUITY AND SUSTAINABILITY

This lesson is designed to span 2 days with 40-minute sections. On the introduction day, three solar power articles will be read to set up a Socratic Seminar dialogue on Day 2. A teacher will need to read the articles. The articles investigate the pros and cons of solar energy, the sustainability of solar energy technology, and newer solar energy technology advances. As this is an introductory lesson, teachers do not yet need to feel confident about solar cell basics.

- *Day 1: Solar Power article readings*
- *Day 2: Socratic seminar dialogue on solar power equity and sustainability*

LESSON 2: ENGAGING WITH SOLAR PANELS

This lesson is designed to span 2 days with 80-minute sections. On the first day, the teachers will challenge the students to assemble circuits with solar panels that can power up 1) a motor with fan, 2) a music-playing circuit, and 3) an LED. Students will discover through trial and error circuits and solar panels that generate and utilize electricity. Teachers should encourage students to play and discover interesting new combinations and arrays. On Day 2, Teachers will demonstrate use of a multimeter, demonstrate series and parallel circuit diagrams and have students take measurements of voltage and current indoors and outdoors. Teachers should be familiar with the operation of a multimeter. Teachers should be familiar with the concepts of voltage, current, power, serial circuits, and parallel circuits for curious students. However, they will teach the concepts expressly in Lesson 3.

- *Day 1: Solar panel array construction, discovery and play*
- *Day 2: Solar panel array testing and data gathering*

LESSON 3: SOLAR CELL BASICS

This lesson is designed to be completed in one 40-minute section. Students will have already learned the concepts of basic circuits, including voltage, current, power, parallel and serial circuits. Teachers will then explain the basic concept of solar cells, introducing the concepts of N-type doping, P-type doping, and P-N junctions through a short video. Teachers will lead students in a physical model of the P-N junctions and electron flow through an outdoor activity. Teachers will need to be familiar with these physical science concepts on an introductory level only—more detailed lessons will follow as the unit progresses.

LESSON 4: SOLAR PANEL DATA SHARING

This lesson is designed to be completed in one 40-minute section. The teacher will facilitate the sharing of student solar panel data from indoor and outdoor testing with fans, music circuits, LEDs and any other combinations that were constructed. Teachers will guide students in making connections to basic circuitry and solar cell power generation limits. Teachers should facilitate discussion leading toward the most efficient solar panel arrays based on power generation needs, loads, and environmental conditions.

LESSON 5: COPPER OXIDE SOLAR CELL CONSTRUCTION AND TESTING

This lesson is designed to be completed in one 80-minute section. The teacher will facilitate student construction of copper oxide plates with electric burners or hot plates. Teachers will guide students in making a basic solar-activated chemical battery with copper plates and salt water. Testing should take place both indoors and outdoors (weather-dependent). The solar cells are short-lasting and construction and testing preferably take place on the same day, although the cells can still show some slight reactivity after a 3-day (weekend) pause.

- *One 80-minute day: students construct and test copper oxide sheets indoors and outdoors*
- *Two 40-minute days:*
    - *Day 1: Students begin oxidation of copper sheets on electric hot plates, turn off hot plates, and leave oxidized copper sheets on the hot plates to cool slowly and un-disturber until the next day*
    - *Day 2: Students remove oxidation layers and begin testing*

LESSON 6: COPPER(I) OXIDE SOLAR CELL DATA SHARING

This lesson is designed to be completed in one 40-minute section. The teacher will facilitate the sharing of student solar cell data from indoor and outdoor testing through a gallery walk session. Variables such as lighting, photovoltaic effect, copper properties, salt water, and circuits should be discussed. Teachers will guide students in making connections to solar cell power generation limits, basic circuitry, and batteries. Teachers should understand the differences between a renewable solar cell and the copper sheet experiment, which is photo-reactive but more similar to a battery than a solar panel. Teachers should facilitate discussion leading toward the most efficient copper solar cells based on environmental conditions. Understanding of the optimal conditions and the roles of each component of the solar cell are emphasized.

LESSON 7: TITANIUM DIOXIDE SOLAR CELL CONSTRUCTION AND TESTING

This lesson is designed to be completed in two 80-minute sections. The teacher will show a basic procedure and video. The teacher will facilitate the construction of Organic dye-sensitized solar cells on coated glass plates with Titanium Dioxide. A fume hood with outlets for electric hot plates must be used for the first part of the construction. On Day 2, Teachers will facilitate final solar cell treatment and solar cell testing indoors and outdoors. Teachers should be knowledgeable of the Titanium Dioxide / Berry (anthocyanin) solar cell electron transfer mechanisms.

- *Day 1: Introduce procedure and bake titanium dioxide onto coated class slides*
- *Day 2: Further treatment of slides, assembly of solar cell, and testing*

LESSON 8: TITANIUM DIOXIDE RASPBERRY SOLAR CELL DATA SHARING

This lesson is designed to be completed in one 80-minute section. The teacher will facilitate the sharing of student titanium dioxide solar cell results with emphasis on variables during data collection. Teachers will demonstrate spreadsheet sorting for students and allow time for students to draw conclusions from the class data using an optional framed paragraph for conclusions. Teachers will guide students in making connections to the titanium dioxide, anthocyanin, and potassium tri-iodide electron system.

LESSON 9: SOLAR CELL MANUFACTURING FIELD TRIP AND/OR GUEST SPEAKER

This lesson is designed to be completed in two 80-minute sections. The teacher will facilitate a field trip to a nearby silicon manufacturing facility, solar panel manufacturing facility, or other semiconductor facility. These facilities often require long advance notice and time is needed to work through school district field trip logistics. The teacher will also facilitate a solar panel, semiconductor, chemist, metallurgist, or semiconductor guest speaker in the classroom. The intent of the trip and guest speaker is to expose Chemistry students to manufacturing techniques and career opportunities in the local area. The trip or guest speaker can occur anywhere within the unit, but ideally takes place after students have experimented with solar cells themselves and before constructing their own unique solar cells.

- *Day 1: Local field trip: Silicon producers, Semiconductor companies, Photovoltaic companies, State-by-state interactive map*
- *Day 2: Guest speaker (see resources above)*

LESSON 10: RESEARCHING CHEMICALS AND MATERIALS FOR SOLAR CELL CONSTRUCTION

This lesson is designed to be completed in three 80-minute sections. The teacher will facilitate student research on solar cell designs centering around the engineering problem: How can we make a cheaper, cleaner or more efficient solar cell? Teachers should encourage students easy-to-obtain materials either found already in the Chemistry classroom, in the recommended Inquiry Materials Kit, in a local supermarket or thrift store, or to be ordered on short notice. Ideas can range from changing conditions on the copper or titanium dioxide cell process, graphite solar cells, using perovskite mineral, printable inkjet layers, organic green solar cells, to wildly creative cell designs. The teacher is encouraged to facilitate student ideas, valuing the design process more than the success or failure of the design itself. Large blocks of time are dedicated for student research, thinking, and leading towards the sketching a design model.

- *Day 1: Introduce driving question, introduce constraints, develop student success criteria, and assist in the research process*
- *Day 2: Solar cell procedures and background writing*
- *Day 3: Background writing, design and model research*

LESSON 11: UNIQUE SOLAR CELL MODEL SKETCH AND PRESENTATION

This lesson is designed to be completed in two 80-minute sections. The teacher will facilitate brief class presentations on the unique solar cell models. Teachers will model and encourage students to provide warm and cool feedback to the presenters, propelling projects forward.

- *Day 1: Model sketching, Audience expectations and student presentations*
- *Day 2: Student presentations*

LESSON 12: UNIQUE SOLAR CELL CONSTRUCTION & TESTING

This lesson is designed to be completed in four 80-minute sections. The teacher will facilitate the construction of unique solar cells for student projects. General chemistry equipment and fabrication equipment will be needed for student construction and testing. The teacher will facilitate student note-taking and celebrating failures. The teacher will encourage students to take photos frequently to document progress and the upcoming Engineering Report in Lesson #14. Lesson #13 can break up the 4 construction days and allow students to share out obstacles and receive audience feedback. Teachers will facilitate solar cell testing indoors and outdoors. This lesson can be expanded or contracted in day number based on student progress.

- *Day 1: Construction #1*
- *Day 2: Construction #2*
- *(Optional) Lesson #13*
- *Day 3: Construction & Testing*
- *Day 4: Construction & Testing*

LESSON 13: CONSTRUCTION PROGRESS & OBSTACLES

This lesson is designed to be completed in one 80-minute section. The teacher will facilitate 3-4 groups as they share their construction progress and obstacles. Students will share individual results in a fishbowl setting and will participate in providing warm and cool feedback. Teachers should assign students to heterogenous groups, so that students of all abilities can receive feedback from their peers. Teachers will encourage students to celebrate their failures alongside the successes. This lesson can be used to break up the 4 days of Lesson #12 if students are "stuck" and need peer review and feedback.

LESSON 14: UNIQUE SOLAR CELL ENGINEERING REPORT

This lesson is designed to be completed in three 80-minute sections. The teacher will have students write their engineering reports with the following sections: Introduction (taken from Lesson #10), Design (incorporating the model from Lesson #10), Methods, Results, and Discussion. The teacher has students design research posters for a hallway display or a poster session, using the engineering report and photos taken throughout the unique solar cell construction and testing.

- *Day 1: Engineering Report #1 (Introduction, Design, and Methods)*
- *Day 2: Engineering Report #2 (Results and Discussion)*
- *Day 3: Engineering Report #3 (Citations, Acknowledgments, and Poster Formatting)*

ASSESSMENT AND EXTENSIONS

FORMATIVE ASSESSMENTS

Teacher should be making observations and notes throughout the investigations and encouraging students to take notes and observations in their own science notebooks or journals. Students can be assessed on their lab progress & behavior, written responses, group responses and teacher observations to check for and correct understandings of content and students should receive feedback throughout the project. Consider adding in the atomic structure extension or crystal unit extensions if students are struggling with conceptual learning. As these experiments may be tricky for some students, determine whether another day of construction or testing will be necessary (if possible) or ensure that student discussion corrects or at least questions any major misconception.

SUMMATIVE ASSESSMENT

As the final part of the unit, the engineering report and/or design poster serve as the key summative assessment for the entire unit, especially lessons 10-14. IN their reports and presentations, students should be able to demonstrate understanding of the following concepts:

- Electricity basics: current, voltage, conductance, circuits
- The photovoltaic effect, as understood at a molecular level
- Engineering design, including proper documentation of problem definition, materials, procedures, and results representation and analysis
- Proper laboratory procedures
- Real-life implications of solar PV technologies

Within that report, the following standards (in parentheses) should receive a summative score:

- Introduction:
    - Providing background information (HS PS1-2, HS PS2-6)
    - Defining the problem (SEP1)
        - Addressing societal need
        - Criteria and Constraints defined
    - Sketching a model of the solution (SEP2)
- Methods:
    - Materials and Procedures (SEP3)
- Design:
    - Design Solution (SEP6)
        - Broken into smaller steps
        - Photographs taken of design building
        - Testing and re-testing process described
- Results:
    - Numerical table of results & graph (SEP4)
    - Data analysis with basic statistics (SEP5)
        - Efficiency calculations
        - Averages
        - Error
- Discussion:

- Did the solution meet criteria & constraints? (SEP7)
    - Real-world applications (SEP7)
        - Cost
        - Efficiency
        - Natural resource usage
        - Equity
    - Errors & Validity (SEP8)
- Citations (SEP8)
- Report Layout and Communication (SEP8)

UNIT EXTENSIONS

- *After Lesson 1: Additional Socratic Seminar*
    - *An additional seminar on new solar technologies can be performed after Lesson 9 (see below)*
- *After Lesson 2: Additional Solar Panel Challenges*
    - *Solar Car Challenge: https://cebrightfutures.org/teach/teacher-activity-center/build-solar-cars-lesson-3*
    - *Solar Boat Challenge: https://cebrightfutures.org/teach/teacher-activity-center/building-solar-boats-lesson-7*
    - *Solar Cell Phone Recharger: https://cebrightfutures.org/teach/teacher-activity-center/designing-solar-phone-charger-lesson-7*
- *After Lesson 3: Alternate models of the photovoltaic effect and P-N junctions*
    - *Conductors, Semiconductors, and Insulators*
    - *Tupperware models*
- *After Lesson 4: New circuit diagrams*
    - *Teachers and students can practice drawing circuit diagrams for new electrical device loads including ones from the Lesson 2 extensions (see above)*
- *After Lessons 5: Investigate variables that affect Copper(I) oxide solar cells*
    - *Surface area, lighting, salt, temperature, and other variables can be investigated and discussed.*
- *After Lesson 6: Investigate variables that affect Copper(I) oxide solar cells*
    - *Surface area, lighting, salt, temperature, and other variables can be investigated and discussed.*
- *After Lesson 6: Crystal Structures*
    - *Students can model crystal structures with BBs and Styrofoam spheres*
    - *Students can grow a variety of crystals in the lab*
- *After Lesson 7: Investigate variables that affect Titanium Dioxide & Raspberry Solar Cells*
    - *Types of berries, lighting conditions, thickness of TiO_2 layer, vinegar/soap additions to TiO_2, bake times, Tri-iodide amounts/concentrations*
- *After Lesson 8: Investigate variables that affect Titanium Dioxide & Raspberry Solar Cells*

- *Types of berries, lighting conditions, thickness of TiO_2 layer, vinegar/soap additions to TiO_2, bake times, Tri-iodide amounts/concentrations*

- *After Lesson 8: Crystal Structures*
    - *Students can model crystal structures with BBs and Styrofoam spheres*
    - *Students can grow a variety of crystals in the lab*
- *After Lesson 9: Solar Cell Technology Socratic Seminar*
    - *A second seminar works well when the students are beginning their research into their own solar cell designs. The driving question for the seminar can be:*
        - *What new solar cell technologies are being implemented?*
    - *Because the solar cell technology is rapidly changing, current event articles are highly suggested. Some possible topics in 2019 included:*
        - *Perovskite nanocrystals*
        - *Organic Photovoltaic systems (OPVs)*
        - *Cadmium-Telluride solar cells*
        - *Thin film solar cells*
        - *Wearable solar cells*
        - *Graphene nanotubes*
        - *CZTS solar cells*
- *After Lesson 10: Thin-Layer Chromatography*
    - *Students extracting natural pigments (chlorophyll, carotenes, anthocyanins, etc.) may benefit from a lesson on Thin-layer chromatography.*
- *After Lesson 14: Public Demonstration of Learning*
    - *Students can display, present and defend their work during an in-school or evening poster session.*

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