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Materials:

- Vernier 2V/400mA Solar Panel
    - Need at least two per group
    - $19 per panel plus shipping
    - These panels are high quality and you can easily fix/replace leads for use in many classes. Cheaper panels exist, but may have to use solder to fix.
    - KW-SP2V Link: https://www.vernier.com/products/kidwind/solar-energy/kw-sp2v/

- 3V to 5V 1A Adjustable Step-up Boost Power Supply Module USB DC-DC Converter
    - Need one per group, but they break easily so you may want to get extra
    - Ebay. $1.06 per step up plus shipping
    - https://ebay.us/qvGROL

- USB Charging Cables ~Optional~ many students have their own.
    - Need two per group - one striped, one regular
    - Amazon Prime. $10.99 per pack of 10 cables
    - Stripping a cable allows you to easily find voltage from the USB output with a classroom multimeter. I personally like to use a USB multimeter instead

- USB multimeter
    - This will allow you to easily test the voltage and current of a completed solar charger. Also allows you to avoid the issue of newer iPhones rejecting the charger
    - https://www.amazon.com/dp/B00J3JSEG6/ref=cm_sw_em_r_mt_dp_U_UlzPCbK2Q1YXF

- Infrared thermometers
    - Need one per group
    - Amazon Prime. $14.39
    - https://www.amazon.com/dp/B00837ZGRY/

- AA Batteries
    - Amazon Prime. 16 pack $23.99
    - https://www.amazon.com/AmazonBasics-AA-Rechargeable-Batteries-16-Pack/dp/B007B9NV8Q/

- Battery holder
    - One per group. I've also tried 3D printing them using designs on thingaverse edited by students. Fun way to incorporate 3D printers.
    - 10 pack. $12.41
    - https://www.amazon.com/uxcell-Battery-Storage-Batteries-Switch/dp/B076V2X43Y

- Diodes
    - Use 2 Schottky diode (1N581) to direct current to and from battery. We lose and break a lot of these. Electrical tape is nice to insulate once connected
    - Amazon Prime $5.99 for 100
    - https://www.amazon.com/100-Pieces-1N5817-Schottky-Rectifier/dp/B079KDQQPD

- Sterilite Large Flip Top Storage Box, Set of 12
    - Need one per group
    - The flip tops will come in handy for changing angle of elevation. Velcro solar panels to lid. I like to reinforce with epoxy
    - Amazon Prime. $42.99 per pack of 12 boxes
    - https://www.amazon.com/dp/B015M3M4HG/ref=ord_cart_shr?_encoding=UTF8&th=1

- VELCRO Brand - Sticky Back - 5' x 3/4" Tape - Black
    - Velcro solar panels to lid.
    - Amazon Prime
    - $7.47 per roll
    - https://www.amazon.com/VELCRO-Brand-Sticky-Back-Black/dp/B00006IC2L

- Multimeters - any type that measures Voltage & Current

Prior Knowledge:

- Electricity Basics:
    - What is voltage
    - What is current
    - How to complete a circuit
    - Basic use of multimeter
    - Series and parallel

- Circuit diagrams

Day-by-Day:

*Each "Day" corresponds to approximately a 90 minute block or 2 50 min class periods

DAY 1: INTRO TO ENERGY SOURCES * Optional*

Objectives:

- Identify renewable and nonrenewable energy sources.
- Compare the advantages and disadvantages of different energy sources.
- NGSS ESS3-1,2,4

Lesson Plan:

- Presentation: how the U.S. gets its energy
    - Renewable and nonrenewable resources
    - Current world distribution of energy
    - Projections for increases in energy
- Jigsaw - pros and cons of each energy source
    - Assign each group a source to research
        - Push for credible resources (some listed on worksheet to get students started)
    - Jigsaw students so they can fill in the pros and cons of the other resources
    - See more scaffolded Jigsaw questions here
- If time: CO2 emissions youtube emphasizing evidence for changing climate
- Homework: redraw pie chart and defend decisions

Notes:

I often follow this project by a much more in-depth unit on energy and will often use this project as a way to get students excited about learning more about electricity. Use this introduction purely as a suggestion for one way to get started and ground this project in real-world challenges.

DAY 2: PROBLEM DEFINITION

Objectives:

- Complete Engineering Design Phase 1: Problem Definition.
- NGSS ESS3-1,2; ETS1-1,2; SEP1

Lesson Plan:

- Transition from previous class looking at pros and cons of all energy sources to focusing on solar energy

- How do solar panels work video
- http://switchenergyproject.com/education/energy-lab - how-solar-works

- Phase 1: Problem Definition- student worksheet
    - Brainstorm inspiration: solar camel, backpack, vaccine refrigerator, water purifier, camping shower, unreliable energy,
    - Example stakeholder: long distance swimmer (who wants to listen to music on her while swimming, so she needs to keep it charged)
    - Example criteria: floatability
    - Example measurement of criteria: for floatability, # of cm bag sits below the water

DAY 3 (or 4): Design Exploration

Objectives:

- Complete Engineering Design Phase 2: Design Exploration in order to successfully build a solar cell phone charger and explore the science of batteries
- NGSS PS3-3; ESS3-1,2; ETS1-1,2; SEP 3,4

Lesson Plan:

- Phase 2: Design Exploration- student worksheet
    - This phase can be split for simplicity. You can choose to just do the solar cell exploration or combine the exploration of solar cells and batteries. Making the charger with batteries is more complex, but provides a better end product. Solar cells need full sun to produce enough current to charge a phone. Any drop in sun intensity/shading will often cause charger to stop working and frustrate students. However, you can cut the battery part and make what is called a “stand-alone” charger.
    - Each solar panel is ~2V, Batteries are 1.2V, USB is 5V.
    - Panels/batteries should be connected in series to add voltage in order to meet the 3-5V input requirement for the USB step-up. Minimum: 2 panels and 3 AA batteries. Use diodes to direct current flow into battery and out of battery, otherwise, battery will feed panels and/or steal power from phone battery.
    - Tutorial for students/teachers on multimeters: https://learn.sparkfun.com/tutorials/how-to-use-a-multimeter
    - Batteries: https://learn.sparkfun.com/tutorials/what-is-a-battery
    - Teacher background on diodes: https://learn.sparkfun.com/tutorials/diodes/all

Notes: students should check in with teacher before connecting panels to the USB step-up. If polarity is reversed, the USB will get very hot and melt. For a great resource for explaining basic electrical engineering and teaching different skills check out: http://learn.sparkfun.com
Diodes are essential when using batteries because current can easily drain from the batteries into your solar panels. This isn't especially dangerous (and is used in some places to de-ice solar cells) but it will produce heat. Likewise, without a diode, current from a student's phone battery may flow into the solar cells and likewise drain the battery, negating the whole "build a charger" idea.

DAY 4: OPTIMIZE AZIMUTH

Objectives:

- Complete Engineering Design Phase 3 Round I: Optimization for Azimuth
- Get used to using the multimeter to measure voltage and current to calculate power
- NGSS PS3-3;ESS1-4; ESS3-1,2; ETS1-1,2; SEP 3,4,5

Lesson Plan:

- Warm Up: brainstorm – How do you think might change how much power a solar panel can produce?
    - Focus in on azimuth, i.e. which direction the solar panel is facing. We use azimuth to make this more quantitative and require students to plot data on a scatter plot
- Phase 3 Round I: Optimization for Azimuth – Student Worksheet
    - IV: azimuth angle (use compass app on phone)
      DV: power (current and voltage)
      C: solar elevation angle (45 degrees), temperature (as best you can)
    - Should see current change, voltage remains somewhat constant (note; voltage is dependent to some degree on temperature and current so this may fluctuate)
    - Teacher should be aware of declination (difference between magnetic and true north) - see declination map
    - Graph should roughly be parabolic with the optimal azimuth matching the direction of the sun during that time of day. In the N. Hemisphere, solar arrays are often optimized for "peak production" during the middle of the day in the summer. For this reason they face 180 degrees South. However, some users will optimize for production at different times of the say/year to match electrical demand. More and more users are optimizing for afternoon peak production to meet high energy demand from air conditioning. Most users use whatever their roof angle will allow. Using E or W azimuths rarely decreases performance more than 20% over the entire year.

Notes: Can use this as an opportunity to teach about earth science principles: rotation of earth, seasons, sun intensity at different latitudes, etc. I will use this as a stand-alone NGSS-aligned task in earth science lessons about sun direction at different seasons, latitudes and times of the day.

DAY 5: OPTIMIZE SOLAR ELEVATION

Objectives:

- Complete Engineering Design Phase 3 Round 2: Optimization for Solar Elevation
- NGSS PS3-3;ESS1-4; ESS3-1,2; ETS1-1,2; SEP 3,4,5

Lesson Plan:

- Phase 3 Round 2: Optimization for Solar Elevation Angle (i.e. tilt) – student worksheet
    - IV: solar elevation angle (use “Angle Meter” app on phone)
      DV: power (current and voltage)
      C: azimuth (face the sun!), temperature (as best you can)
    - Should see current change, voltage remains somewhat constant
    - You are measuring what is called short circuit current (Isc) and it is actually much higher than the actual current produced when the panel is under a load. Be careful measuring current with large solar panels.
    - Graphs should be parabolic with the optimal solar elevation angle matching the latitude if taking data in spring or fall (38 degrees here in Colorado.)
        - Note: if taking data in the summer, optimal angle will be much shallower (latitude - 15 degrees lower)
        - Note: if taking data in winter, optimal angle will be much steeper (latitude + 15 degrees higher)
        - Show video of solar panels tracking both azimuth and solar elevation angle to reinforce optimal levels from Optimization Round 1 & Round 2
    - Brainstorm how their design could make for adjustable solar elevation angles. Also think about the stakeholder. If the stakehoilder is a farmer in a developing country near the equator, the angle will be nearly flat (0 degrees.) For a skier in the mountains of Colorado in the winter, it may be close to 60 degrees.

Notes: This is a very simple NGSS-aligned task and I use it often as a stand-alone task for collecting data, creating a scatter plot and then creating an argument from evidence.

DAY 5: TEMPERATURE (optional)

Objectives:

- Complete Engineering Design Phase 3 Round 3: Optimization for Temperature
- NGSS PS1-5; PS3-3,4;ESS1-4; ESS3-1,2; ETS1-1,2; SEP 3,4,5

Lesson Plan:

- This is the most complex optimization task and can be skipped for simplicity
- Background info for teacher:
    - http://sinovoltaics.com/solar-basics/measuring-the-temperature-coefficients-of-a-pv-module/
    - http://www.itacanet.org/a-guide-to-photovoltaic-panels/photovoltaic-pv-cells/

- Phase 3 Round 3: Optimization for Temperature- student worksheet

    - To change temperature of solar panel, dump ice water on top until cold. Remove ice and then start testing in sun. Use an infrared thermometer to measure temperature. This is much easier to do with larger solar panels if you have access to them
    - IV: temperature
      DV: voltage (difficult to measure current and will not change much.)
    - C: azimuth (180 south), solar elevation angle (45 degree)
    - Voltage for a solar panel is inversely proportional to temperature. High temperatures produce a drop in voltage due to resistance in the circuits of the solar cells. Optimal temperature should be lowest possible.
    - How do you keep solar panels sunny but cool? Recommendations?
        - Solar PV designers will often elevate panels a few inches off a roof to minimize conductive transfer of heat from roof to PV and increase airflow to the underside of panels. Also some new panels are coated with special coatings to reduce heat gain. White back sheets can do this, but many homeowners prefer the look of black panels.
    - Map of best solar locations: https://energy.gov/maps/solar-energy-potential

Notes: This often surprises students, because they think “hot sunny” = best for solar. This is true, however high temperatures decrease voltage and can impact power. This data is great for producing a line of best fit of Voltage and Temperature and then modeling that with an equation. Great math connection! Because of this relationship, solar engineers will always calculate the maximum system voltage using the lowest expected temperatures. Here in the mountains of Colorado there is a noticeable voltage spike when cells are first exposed to light in cold, clear mornings. We also see a very significant voltage drop (and reduced power) during hot afternoons when the cell temperature can reach close to 55 degrees C!

DAY 6-?: WORK DAYS AS NEEDED

Objectives:
- Build the completed solar charger. Evaluate the charger for the student-defined criteria
- Complete Engineering Design Phase 4 Communication
- NGSS ETS1-1,2; SEP 4-8

Lesson Plan:
- Give ample time for students to build, test and iterate their designs.

Notes: I try to encourage students to create another criteria (besides power) to optimize and collect data. Since we scaffolded this process with Azimuth and Angle they often will follow similar procedures. Their design criteria does not necessarily need to be less quantitative and could incorporate consumer preference (survey data about appearance.) Many of my groups choose something like “weight” and they iterate their final designs to decrease total weight.

- Phase 4: Communication
    - Optional: writing instructions for making a PBJ Sandwich activity
        - Great video
        - Link to lesson write up
    - Have several instructions manual (from games, Ikea, etc.) out for students to look at
- Pass out rubric
    - So that students to know how their grade will be determined

Notes:
- I encourage students to be building and refining their charger throughout the whole project. I introduce the communication phase early because some groups have very simple designs, but the communication phase for a specific stakeholder group (hunters in November wanting a solar charged game camera) makes the communication very interesting and complex. I also do this because of time and material constraints, some groups cannot build a prototype. I encourage them to use cardboard and other stand-ins and then use their instruction manual to show what the finished design “could” be if they had the materials.

Reflections:

Ben Graves (ben.graves@kstf.org) teaches at a rural public school in Colorado. He co-wrote and has implemented many of these lessons independently and as a whole design challenge with 9th graders and with vocational students in a solar electricity class (11th-12th.) He often incorporates earth science principles relating the sun and earth's orbit into the discussion on azimuth and elevation angle. He has attempted to have students construct I-V curves using solar panels wired to different sized resistors to simulate different loads.

Kate Miller co-wrote and implemented this unit with IB and General Physics students in suburban Maryland. Feel free to email her at kate.miller@kstf.org.