Renewable Energy with Vernier

4th Edition

By
Alexandria Plank
Gretchen Stahmer
Michael Arquin
Joseph Rand
Frances J. Poodry

REV

Vernier

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Illustrated by Jeff A. Anderson

Vernier

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Vernier Software & Technology

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About the Authors

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Michael Arquin is the founder and director of the KidWind Project. Before starting KidWind in 2003, he was a middle and high school science teacher of biology, chemistry, and physical science. Michael was also a lead developer and teacher trainer at the Boston Museum of Science on a variety of energy and engineering projects; including the Engineering is Elementary (EiE) initiative. Unhappy with the high price and poor quality of products available for teaching wind energy science, Michael set out to develop his own methods and materials. With an initial investment of $1,000 and a fellowship at the Wright Center for Science Education at Tufts University, he developed a new approach to educating the world about wind energy.

Joseph Rand is the former director of Training and Outreach at the KidWind Project, where he trained more than three thousand K–12 teachers in the science of renewable energy. He worked for the DOE-funded Wind for Schools project while studying Sustainable Technology at Appalachian State University.

Fran Poodry earned a BA in Physics from Swarthmore College and an MSEd in Science Education from Temple University. She has more than 20 years of experience teaching physics in public and private schools, in the inner city and the suburbs, and in college instructional laboratories. She is a co-author of *Physics Explorations and Projects* and is interested in science pedagogy. Since 2013, Fran has worked in Tech Support and Research and Development at Vernier Software & Technology, where she is currently Director of Physics.

Proper safety precautions must be taken to protect teachers and students during experiments described herein. Neither the authors nor the publisher assumes responsibility or liability for the use of material described in this publication. It cannot be assumed that all safety warnings and precautions are included.

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Equipment Used in Experiments

		Sensors				Accessories				
		Light Sensor	Surface Temperature Sensor	Energy Sensor	Anemometer or Weather Sensor	Vernier Variable Load	KidWind Advanced Wind Experiment Kit	KidWind SimpleGEN Kit	KidWind 2V/400mA Solar Panel	KidWind Solar Thermal Exploration Kit
1	Renewable Energy: Why is it So Important?	1								
2	What is Energy?		1							
3	Project: Energy Audit		1							
4	Voltage and Circuits			1^		1*				
5	Current and Resistors			1						
6	Mechanical Power						1			
7	Generators			1				1		
8	Exploring Wind Turbines			1		1	1			
9	Effect of Load on Wind Turbine Output			1		1	1			
10	Blade Variables and Power Output			1		1	1			
11	Solidity			1		1	1			
12	Turbine Efficiency			1	1	1	1			
13	Power Curves			1	1	1	1			
14	Power and Energy			1		1	1			
15	Project: Maximum Energy Output			1		1	1			
16	Project: Build a Wind Farm			1		1	1			
17	Exploring Solar Panels	1		1		1			1	
18A	Effect of Load on Solar Panel Output			1		1			1	
18B	Fill Factor and IV Curve of a Solar Panel			1^^		2				
19	Variables Affecting Solar Panel Output	1**		1		1			1	
20	Effect of Temperature on Solar Panel Output		1	1		1			1	
21	Project: Build a Solar Charger			1		1			2–4	
22	Exploring Passive Solar Heating		1							
23	Variables Affecting Passive Solar Heating		2							
24	Exploring Solar Collectors	1	1							1
25	Variables Affecting Solar Collectors		1							1
26	Project: Solar Cooker		1							

^ If using Go Direct sensors, Go Direct Voltage is required; Go Direct Energy cannot be used.
^^ If using Go Direct sensors, Go Direct Voltage is required in addition to Go Direct Energy.
* Vernier Resistor Board can be used in place of Variable Load
** Optional sensor

Preface

This book contains 26 experiments using Vernier data-collection technology for collecting, displaying, printing, graphing, and analyzing renewable energy data. You will find a combination of explorations, traditional experiments, inquiry investigations, and projects in this book.

This book is aligned to the Next Generation Science Standards (NGSS). In the Instructor's pages for each experiment, you will find a table showing the Disciplinary Core Ideas, the Science and Engineering Practices, and the Crosscutting Concepts that are addressed in each experiment or project.

Electronic Resources

Rather than acting as stand-alone curriculum, the purpose of this book is to supplement the science-teaching materials adopted for use in your school or department. To that end, this book comes with Electronic Resources that include word-processing files and PDFs of the student experiments, in addition to other supporting files. Log into your account at **www.vernier.com/account** to download the Electronic Resources. If you don't have an account, you can create one on that same web page.

The site license that accompanies this book allows you to share the files in the Electronic Resources with others at your school or college department. You can upload the files to a password-protected intranet site, but please do not make the files available on the Internet or other sites that can be accessed by people outside of your school or college department.

Student Experiments

PDFs and word-processing files of the student experiments are provided in the Electronic Resources, so you can print and modify the experiments to best match your equipment and teaching preferences:

- **PDF files**: Print the PDF version of the student experiment and have students follow the procedures as they are written. This format is also ideal for viewing experiments on mobile devices or other platforms.
- **Word-processing files**: Edit the word-processing files to fit your teaching style. Some instructors update the materials list to match the specific equipment in their classroom. Instructors who prefer inquiry-style experiments often remove data tables and reduce the amount of detail in the procedures.

Instructor Information

The Instructor Information section for each experiment has sample results, answers to questions, directions for preparing solutions, and other helpful hints regarding the planning and implementation of the experiment.

Appendices

The appendices include valuable information:

Appendix A: Electronic Resources

There are multiple versions of each student experiment—one for each supported data-collection software (e.g., Graphical Analysis 4). Appendix A includes detail about which Vernier data-collection programs are supported in this book.

Appendix B: More Power: Designing Wind Turbine Blades

Appendix B provides tips for designing blades to increase power output.

Appendix C: Equipment and Supplies

A complete list of equipment and supplies needed for performing the experiments in this book can be found in Appendix C.

Acknowledgments

Since the initial publication of this book, multiple people have contributed valuable updates, including many teachers who have taken time to provide us with suggestions and tips. We are grateful to Dara Easley, John Gastineau, Jack Randall, and Steve Decker for their help with data collection, experiment testing, and ideas. We would also like to thank Jeff A. Anderson for his helpful illustrations.

Renewable Energy: Why is it So Important?

We all use energy—to travel to school, charge electronics, turn on lights, and even to fill a cup with water. Where does this energy come from? Energy sources fall into two categories: non-renewable and renewable.

Non-renewable energy comes from sources such as coal, natural gas, and petroleum, which are finite and cannot be replaced in a short time period. For example, all the petroleum we use today was formed hundreds of millions of years ago. Any petroleum we might try to make today would not be ready for millions of years. When used, non-renewable energy sources generate pollutants and contribute to climate change.

Renewable energy sources, in contrast, are replenished in a short period of time. Solar, wind, and hydroelectric energy are considered renewable. In some places, the sunshine provides usable solar energy on most days. In other regions, the wind blows regularly, making it possible to reliably generate energy from the wind. If people live close to a large river, they may be able to use a dam to produce hydroelectric energy throughout the year. When renewable energy sources are used, they produce little to no pollution.

In the United States in 2017, a majority of the energy consumed was generated using non-renewable resources.[1] The data in Figure 1 represent energy consumed for the transportation, residential, commercial, and industrial sectors, as well as energy used for the production of electricity. Petroleum and natural gas were used to produce more than 60% of the energy consumed.

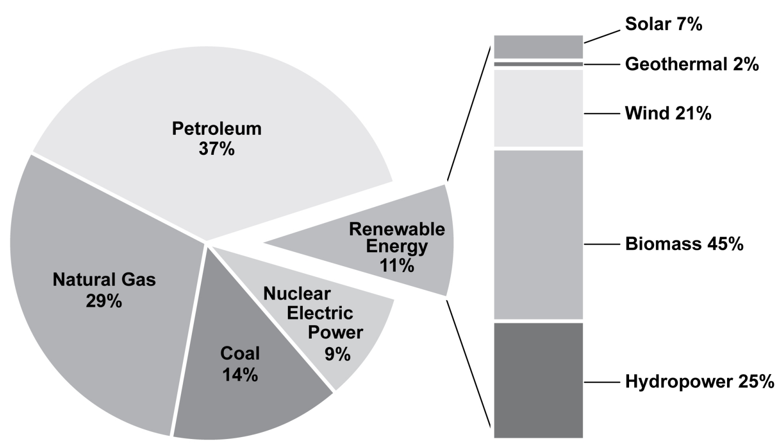


Figure 1 United States energy sources for all sectors, 2017

[1] US Energy Information Administration, November 2018, *Monthly Energy Review*, Table 1.3: www.eia.gov/totalenergy/data/browser/index.php?tbl=T01.03#/?f=A

If you examine only the energy used to produce electricity in the United States in 2017, the distribution of sources is quite different; petroleum and natural gas account for less than 40% of the energy consumed to produce electricity (see Figure 2).[2] The mixture of the sources of energy used to generate the electricity you use will vary depending on where you live.

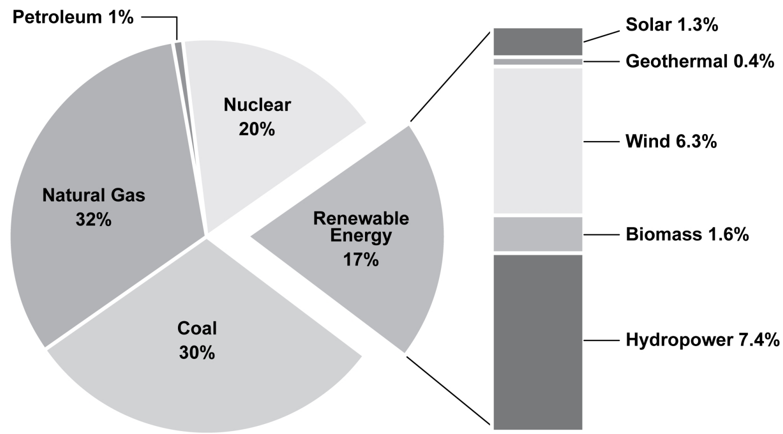


Figure 2 United States sources for electricity production, 2017

To produce electricity from a renewable or non-renewable source, energy must be converted from one form to another. For example, when you travel in a conventional car, the car is converting fossil fuel energy (gasoline) into the energies of motion and heat. If you heat up food on an electric stove, the stove converts electrical energy (which was converted from some other type of energy previously) into heat.

In this experiment, you will examine how a light bulb converts electrical energy to light energy. Light bulbs are usually sold according to the amount of electrical power they consume. You will investigate the relationship between the power rating of a light bulb and the amount of light it produces.

OBJECTIVES

- List examples of non-renewable and renewable energy sources and describe the differences between them.
- Learn about energy conversion.
- Gain familiarity with a Light Sensor and data-collection software.
- Calculate the reduction of carbon dioxide production when using renewable energy sources to generate electricity in place of non-renewable energy sources.

[2] US Energy Information Administration, FAQ: What is US electricity generation by source? www.eia.gov/tools/faqs/faq.cfm?id=427&t=3

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Light and Color
ring stand
utility clamp
60 W, 75 W, and 100 W (or equivalent) bulbs
large box
small box
light bulb socket or lamp

PRELIMINARY QUESTIONS

1. What job does a light bulb do? What are the unintended effects of turning on a light bulb?
2. What energy transformations take place when electrical energy is applied to an incandescent light bulb?
3. What factors should be considered when comparing different kinds of light bulbs?

PROCEDURE

1. Launch Graphical Analysis. Connect the Go Direct Light and Color Sensor to your Chromebook, computer, or mobile device.
2. Prepare for data collection.
   a. Clamp a lamp fitted with a 60 W (or equivalent) bulb to one ring stand using a utility clamp.
   b. Place the light sensor on a small box, pointing directly at the light bulb.

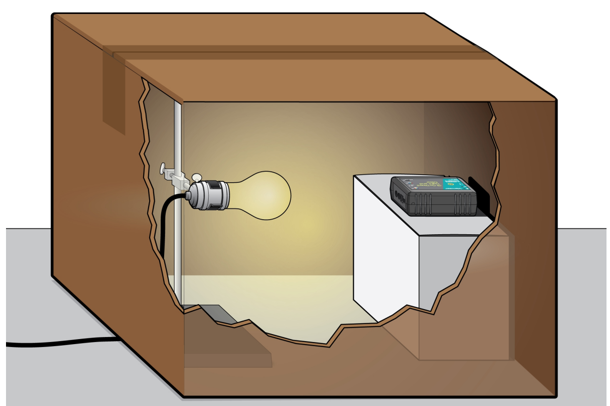


Figure 3

3. Turn on the lamp and place the large box over the lamp and light sensor.
4. Click or tap Collect to start data collection.

5. When data collection is complete, click or tap Graph Tools, , and choose View Statistics. Record the mean illuminance value. Dismiss the Statistics box.

6. Turn off the lamp and allow the bulb to cool. **Caution**: The bulb may be very hot.

7. Once the bulb is cool to the touch, replace it with the 75 W (or equivalent) bulb. Repeat Steps 3–6.

8. When the bulb is cool to the touch, replace it with the 100 W (or equivalent) bulb. Repeat Steps 3–6.

DATA TABLE

Table 1				
Light bulb (W)	Illuminance (lux)	How many bulbs needed for 9000 lux?	Total electricity usage for 8 hr/day for 20 days (kWh)	Cost ($)

PROCESSING THE DATA

1. Calculate the number of light bulbs needed to produce 9000 lux based on your experimental measurements. Perform this calculation for each wattage of bulb you tested, and record the results in the data table.

2. In a typical classroom, lights are on for 8 hours/day for 20 days in a month. Based on the number of light bulbs needed for each wattage, calculate the total electricity usage in kilowatt-hours (kWh) to run the bulbs for 8 hours/day for 20 days. **Note**: 1 kW=1000 W

3. Use the electricity cost from your region to calculate the cost to run the bulbs for 8 hours/day for 20 days.[3]

ANALYSIS QUESTIONS

1. Which wattage of light bulb would you choose to use to create a light level of 9000 lux? Why?

[3] The average cost of electricity in 2017 in the United States was $0.13 per kilowatt hour (kWh) (www.eia.gov). If you do not know the electricity cost for your region, you can use this value.

2. Determine the carbon dioxide production to generate electricity to light the light bulbs that you need to produce 9000 lux for 8 hours/day for 20 days. Perform calculations for the two types of fossil fuel in Table 2.

Table 2				
Type of fossil fuel	Light bulb (W)	Total electricity usage for 8 hr/day for 20 days (kWh)	CO_2 production[4] (lbs CO_2/kWh)	CO_2 production from energy production (lbs)
Natural gas	60		1.22	
Natural gas	75		1.22	
Natural gas	100		1.22	
Coal	60		2.08	
Coal	75		2.08	
Coal	100		2.08	

3. Electricity generation from non-renewable energy sources produces higher carbon dioxide levels than electricity generation from renewable energy sources.

   Determine how much carbon dioxide would be produced to light the bulbs for 8 hours/day for 20 days if you were to use wind or solar to produce electricity. How does this compare to the amount of carbon dioxide that would be produced if electricity was generated using natural gas as the energy source?

   When performing your calculations, imagine your classroom is set up using the light bulb configuration that produces the least amount of carbon dioxide based on your data from the previous question.

Table 3	
Energy source	CO_2 production[5] (lbs CO_2/kWh)
Wind	0.03
Solar	0.15

4. What are other ways you could reduce the amount of carbon dioxide produced when lighting your classroom?

---

[4] Source: http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11

[5] Source: http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/public-benefits-of-renewable.html

Note: CO_2 production from wind and solar energy comes from manufacturing, transportation, and installation. Wind turbines and solar panels do not generate CO_2 while they are operating and generating electricity.

EXTENSIONS

1. Some light bulbs have coatings to affect the quality of the light, making the light "soft," "bright," or "daylight." Using a selection of light bulbs with the same wattage rating, compare light levels.

2. Use a temperature probe and an equipment setup similar to the setup for this experiment to investigate the relationship between the energy a bulb consumes and the amount of energy that is converted to heat. Compare different wattage values for the same type of bulb as well as different types of light bulbs, such as LED and compact fluorescent light bulbs.

3. Research the mix of energy sources that are used to produce electricity in your region. Are renewable options available?

4. Research the environmental impact associated with producing and disposing of different types of light bulbs. You can also examine cost and expected lifetime of different types of bulbs. Write a letter to your school or family making recommendations for replacing the light bulbs in your classroom or house.

Renewable Energy: Why is it So Important?

In this experiment, students learn how to use Vernier technology for data collection and gain experience using a Light Sensor. They are also introduced to the importance of renewable energy and learn about energy production and consumption patterns in the United States.

The following website can be a useful resource for teaching students about how electricity is produced in the United States:
www.npr.org/templates/story/story.php?storyId=110997398&sc=emaf

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Set up equipment for data collection, including connecting and turning on equipment and starting the data-collection program.
- Use the Statistics tool in the data-collection app to calculate statistics.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Engaging in argument from evidence Obtaining, evaluating, and communicating information	PS3.A Definitions of Energy (HS-PS3) PS3.D Energy in Chemical Processes (HS-PS3) ESS3.A Natural Resources (HS-ESS3)	Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter

ESTIMATED TIME

We estimate that data collection and analysis can be completed in one 45-minute class period.

EQUIPMENT TIPS

1. Use a cardboard box with flaps that close when conducting the experiment, or place the box upside down over the equipment. This eliminates the effect from any room lighting. If you are using the Vernier Light Sensor (order code: LS-BTA), make a hole in each box just large enough for the shaft of the sensor to fit.

2. You may wish to use a fan to cool the light bulbs between runs.

3. It is important that the distance between the light sensor and the bulb remains constant.

4. Some light bulbs may result in fluctuating readings from the light sensor even though the light appears steady. This is fine, as the average value will still represent the illuminance of the bulb at the location of the light sensor.

5. This experiment was originally written for incandescent light bulbs. If standard incandescent bulbs are unavailable, you can use "eco-incandescent" (halogen) bulbs, LED bulbs, or compact fluorescent bulbs. Look for light bulbs that are "equivalent" to 60, 75, and 100 W.

6. If you are using a Vernier Light Sensor (order code: LS-BTA), the graphs in the data-collection app are labeled in illumination (lux) *vs.*time (s). We have used the word illuminance in the student instructions because that is the correct term for that which lux is the unit of measurement. Illuminance is essentially the amount of light that lands on a surface divided by the surface area (in meters), with an adjustment that corresponds to how human eyes perceive brightness. The Go Direct Light and Color Sensor (order code: GDX-LC) displays illuminance as the graph label rather than illumination.

DATA-COLLECTION AND ANALYSIS TIPS

1. The values for illuminance that students collect may not be similar to those collected by other groups or to the values in the Sample Results. The illuminance measurement depends on the type of light bulb, the distance between the light bulb and the light sensor, and whether any outside light enters the box. The value may also vary somewhat depending on how long the light bulb has been on. Regardless of the variations, students should discover the general trend that a higher watt rating on a light bulb corresponds to a greater illuminance measurement.

2. If your students are having trouble calculating total electricity usage for the light bulbs, you can give them the following equation:

$$\underline{\qquad}\ \mathrm{W} \times \text{number of bulbs} \times \frac{8\ \mathrm{hr}}{\mathrm{day}} \times 20\ \text{days} \times \frac{1\ \mathrm{kW}}{1000\ \mathrm{W}} = \text{total usage (kWh)}$$

   Note that this equation reflects the number of days and hours/day values that are given in the student version of the experiment. If students are using different values, adjust the equation with the appropriate numbers.

3. Using actual power bills can help students make real-world connections. It will also allow them to use actual numbers when calculating electricity costs. Sample energy bills can sometimes be found through many electricity providers' web pages (try doing a search for "understanding your bill").

4. In Step 1 of the Processing the Data section, students are instructed to assume a light level of 9000 lux. This number was chosen based on typical light level values that students will collect by following the procedure; it is not a typical light level for a classroom. You might have students measure the illuminance at the level of their desks, as a comparison. Generally, classroom light fixtures are located well above student desks.

5. In Analysis Question 3, students calculate the amount of carbon dioxide (CO_2) associated with renewable energy sources. Carbon dioxide production from wind and solar energy comes from manufacturing, transportation, and installation. Wind turbines and solar panels do not generate carbon dioxide while they are operating and generating electricity. These values will decrease if the power supplied to the manufacturing plants is generated from renewable resources.

ANSWERS TO PRELIMINARY QUESTIONS

1. Answers will vary. A light bulb produces light. We use them to light up a space. Heat production is an unintended effect of using light bulbs to illuminate a room.

2. When electrical energy is applied to a light bulb, energy is converted to light (radiant energy) and heat (thermal energy).

3. Answers will vary. Factors to consider include cost, light level, energy consumption, environmental impact of production and disposal, and lifetime of the bulb.

SAMPLE RESULTS

Table 1

Light bulb (W)	Illuminance (lux)	How many bulbs needed for 9000 lux?	Total electricity usage for 8 hr/day for 20 days (kWh)	Cost ($)
60	881	11	106	15.84
75	1588	6	72.0	10.80
100	1970	5	80.0	12.00

ANSWERS TO ANALYSIS QUESTIONS

1. Answers will vary. Students will likely choose either the configuration that requires the fewest number of bulbs or the one that has the lowest electricity cost.

2. Answers will vary. The following values were calculated based on the Sample Results.

Table 2				
Type of fossil fuel	Light bulb (W)	Total electricity usage for 8 hr/day for 20 days (kWh)	CO_2 production (lbs CO_2/kWh)	CO_2 production from energy production (lbs)
Natural gas	60	106	1.22	129
Natural gas	75	72.0	1.22	87.8
Natural gas	100	80.0	1.22	97.6
Coal	60	106	2.08	220
Coal	75	72.0	2.08	150
Coal	100	80.0	2.08	166

3. Answers will vary. The setup that produces the least amount of carbon dioxide based on the Sample Results is to use six 75 W bulbs. **Note**: Students may not present data in a table.

Table 3				
Energy source	Light bulb (W)	Total electricity usage for 8 hr/day for 20 days (kWh)	CO_2 production (lbs CO_2/kWh)	CO_2 production from energy production (lbs)
Natural gas	75	72.0	1.22	87.8
Wind	75	72.0	0.03	2.16
Solar	75	72.0	0.15	10.8

4. Answers will vary.

What is Energy?

Energy is involved in everything that happens, from the tiniest insect moving one antenna to a massive eruption of a volcano that spreads ash around the globe. Energy is constantly being transferred and transformed. If you use a microwave oven to heat your food, electromagnetic energy is transferred into the food and transformed into thermal energy. When you eat the food, your body turns the chemical energy in the food into a different form of chemical energy. If you kick a ball, you transfer some of the energy from your body into the ball.

There are two broad categories of energy: potential and kinetic. Potential energy is energy that is stored. Forms of potential energy include chemical, gravitational, elastic, and nuclear. Kinetic energy is the energy of motion. Electrical, radiant, thermal, and sound energy are all examples of kinetic energy.

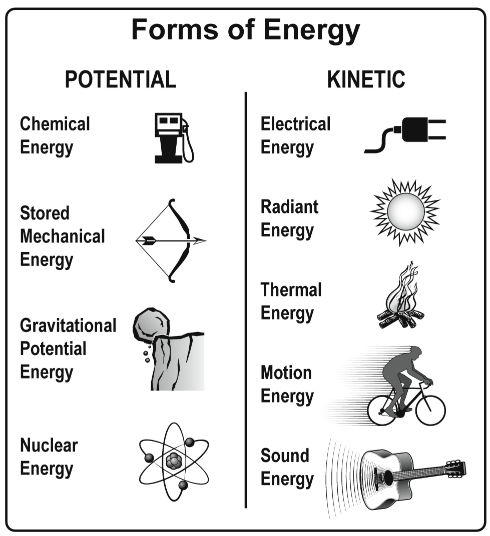


Figure 1 Adapted with permission from The NEED Project, www.need.org

Electrical energy is a convenient form of energy to transmit, sell, and use. Most electrical energy in the United States is generated from energy stored in fossil fuels, such as natural gas and coal. While these sources are forms of potential energy, they do not necessarily contain the same amount of energy per volume. To make it more complicated, different fuels are sold in different units of volume. We can use equations to calculate energy content and compare energy sources.

For example, if your house is heated with natural gas, your parents get a bill that tells them how much natural gas in cubic feet (ft^3) was used. If your friend's house is heated with a furnace that uses heating oil, your friend's parents get a bill that tells them how many gallons of oil were used. Imagine that your family used 14,300 ft^3 of natural gas last month, and that in the same month, your friend's family used 110 gallons of heating oil. Who used more energy to heat their home? You will answer this question in the Preliminary Questions.

In order to be able to compare energy sources more easily, conversion into measurements of a common unit is necessary. The SI unit for energy is the joule (J). In this experiment, you will determine the energy content in J/g of different fuels. You will do this by burning a known mass of the fuel and calculating the heat transferred to a known mass of water in a can. If you measure the initial and final temperatures, the energy transferred can be calculated using the equation

$$Q = mc\Delta T$$

where Q = heat energy absorbed (in J), ΔT = change in temperature (in °C), m = mass (in g), and c = specific heat capacity (4.18 J/g°C for water). Dividing the resulting energy value by grams of fuel burned gives the energy content per unit of mass.

OBJECTIVES

- Identify the units that are used to measure energy.
- Determine the energy content of fuels by mass.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Surface Temperature Sensor
safety goggles
50 mL graduated cylinder
ring stand and 10 cm (4") ring
utility clamp
fuel samples (candle and gel chafing fuel)
balance
matches
small can
cold water
pencil
stirring rod

PRELIMINARY QUESTIONS

1. List activities in your life that rely on fossil fuel.
2. What energy sources are used to generate electricity and heat in your region?
3. Are renewable fuel sources available in your region? If yes, what options are available?
4. You were presented with a problem in the introduction to this experiment. There are two households that use different types of fuel for heating. Last month, Household A (your house) used 14,300 ft^3 of natural gas and Household B (your friend's house) used 110 gallons of heating oil. Use the information below to determine which household used the most energy.

   1 ft^3 of natural gas contains 1.08×10^6 J
   1 gallon of heating oil contains 1.46×10^8 J

PROCEDURE

1. Obtain and wear goggles.
2. Launch Graphical Analysis. Connect the Surface Temperature Sensor to your computer, Chromebook, or mobile device.
3. Set up the data-collection mode.
   a. Click or tap Mode to open Data Collection Settings.
   b. Change End Collection to 300 s. Click or tap Done.
4. Measure and record the initial mass of the candle or gel chafing fuel assigned to you.
5. Set up the equipment (see Figure 1).
   a. Measure and record the mass of the empty can.
   b. If you are using a candle as your fuel source, place 50 mL of cold water into the can. If you are using gel chafing fuel, place 100 mL of cold water in the can.
   c. Measure and record the mass of the can plus water.
   d. Use a 10 cm ring and a pencil through the can to suspend the can about 5 cm above the candle or chafing fuel.
   e. Use the utility clamp to suspend the temperature sensor in the water. The temperature sensor should not touch the bottom or sides of the can.

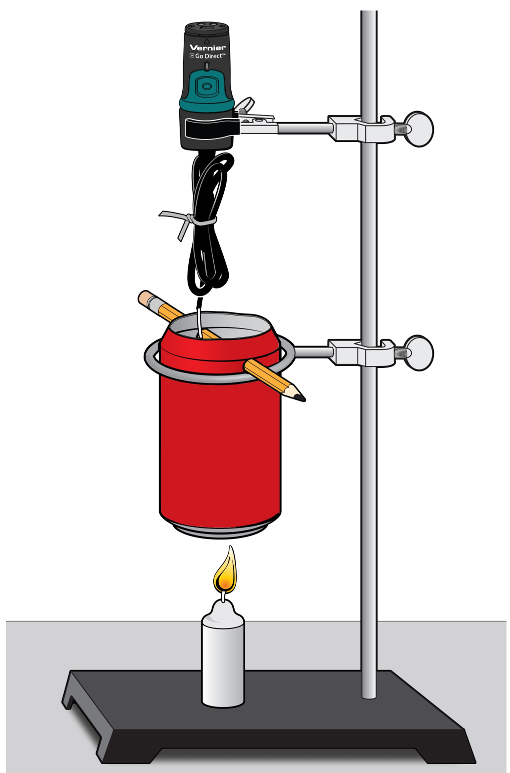


Figure 1

6. Click or tap Collect to start data collection. Monitor temperature for about 10 seconds and record the initial temperature of the water in the data table. Light the gel chafing fuel or candle. Heat the water until the temperature reaches about 35°C and then extinguish the flame. **Caution**: *Keep hair and clothing away from an open flame.*

7. Stir the water with a stirring rod until the temperature stops rising. Record the final temperature (round to the nearest 0.1°C). Data collection will stop after 5 minutes.

8. Click or tap Graph Tools, , and choose Statistics. Confirm the initial and maximum values you recorded earlier.

9. Measure the final mass of the candle or gel chafing fuel and record in the data table.

10. Repeat data collection using a different fuel. Start with a new volume of cold water.

DATA

	Candle	Gel chafing fuel
Initial mass of fuel (g)		
Final mass of fuel (g)		
Mass of fuel burned (g)		
Mass of empty can (g)		
Mass of can plus water (g)		
Mass of water heated (g)		
Initial water temperature (°C)		
Final water temperature (°C)		
Change in water temperature (°C)		
Energy content (J/g)		

PROCESSING THE DATA

1. Calculate the change in water temperature, ΔT, for each sample by subtracting the initial temperature from the final temperature. Record your answers in the data table.

2. Calculate the mass of the water heated for each sample. Subtract the mass of the empty can from the mass of the can plus water. Record your answers in the data table.

3. Use the results to determine the heat energy gained by the water (in J). Record your answers in the data table. Use the equation

$$Q = mc\Delta T$$

   where Q = heat energy absorbed (in J), ΔT = change in temperature (in °C), m = mass (in g), and c = specific heat capacity (4.18 J/g°C for water).

4. Calculate the mass of fuel burned. Subtract the final mass from the initial mass. Record your answers in the data table.

5. Use the results to calculate the energy content (in J/g) of the fuel samples. Record your answers in the data table.

6. If instructed to do so, obtain the results of other groups and create a table with the compiled data.

ANALYSIS QUESTIONS

1. Which of the fuels you tested has the greatest energy content?

2. Natural gas has an energy content of 53,600 J/g. Heating oil has an energy content of 46,200 J/g. How do the energy content values for these two types of fossil fuels compare to the energy content values that you determined?

3. In addition to energy content, what are at least two other factors that might be important in choosing a fuel?

EXTENSIONS

1. Research accepted values for the energy content of the fuels you tested in this experiment. Account for the differences that you find between the accepted values and the values you determined.

2. Conduct this experiment for other fuels and compare the results. Which fuel would you use to heat your home? **Note**: Before you conduct the experiment, submit a plan to your instructor. Include safety precautions that you will take.

3. Research accepted values for the energy content of other common energy sources. How do they compare to the fuels you studied in this experiment and to natural gas and heating oil? If you were designing a heating system for a house, what energy source would you use? Take into consideration cost and availability.

What is Energy?

In this experiment, students determine the energy content of different fuels by burning a known mass of the fuel and capturing the released heat in a known mass of water in a can. Students then compare these values to known values of common energy sources and think about reasons for choosing one fuel source over another.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Change data-collection parameters.
- Examine data and determine maximum and minimum.

ESTIMATED TIME

We estimate that data collection for this experiment can be completed in one 45-minute class period. You may need to allow extra time for the Analysis and Extensions.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Engaging in argument from evidence	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3) PS3.D Energy in Chemical Processes (HS-PS3) ESS3.A Natural Resources (HS-ESS3)	Patterns Cause and effect Systems and system models Energy and matter

EQUIPMENT TIPS

1. Comply with all pertinent regulations concerning burning and open flames in the laboratory.
2. Beeswax candles and paraffin wax candles work well for this experiment. Mount the candles on small pieces of cardboard or index cards. The bases will catch candle drippings.

3. Gel chafing fuel, mostly commonly known as Sterno®, made by SternoCandleLamp, LLC, is a good fuel source for this experiment. Gel chafing fuel can be found in home improvement stores and restaurant supply stores.

4. While gel chafing fuel is easy to use, safe to handle and easy to extinguish, the flame is diffuse, there is heat loss, and the flame is initially difficult to see.

5. If burning gel chafing fuel, which supplies heat at a greater rate than candles, students are directed to use 100 mL of chilled water instead of 50 mL.

6. Make ice water available, and remove the ice from the water before it is used. Water initially at 4–5°C gives best results, because starting 17–19°C below and finishing 17–19°C above room temperature tends to equalize heat exchange with the room.

7. Aluminum beverage cans or steel soup cans are both good options for the can. Both are readily available. Aluminum cans are easily cut with a scissors.

8. A balance that measures to the nearest 0.01 g should be used for this experiment since the amount of candle burned is small.

9. If students will be comparing their data, it is important that all groups use the same type of container for the water sample. The calculations made by students do not take into account the change in temperature of the container or its specific heat capacity. If the containers are made of different materials, the data are not comparable.

10. You may decide to have students take into account the change in temperature of the container. In order to do so, assume the change in temperature of the container is the same as the change in temperature of the water. Use the equation

$$Q = m_{\text{water}}c_{\text{water}}\Delta T + m_{\text{can}}c_{\text{can}}\Delta T$$

    The specific heat capacity for aluminum is 0.900 J/g°C and the specific heat capacity for steel is 0.502 J/g°C.

11. This experiment is written using the Surface Temperature Sensor, but other Vernier temperature probes, such as the Stainless Steel Temperature Probe or Go Direct Temperature, will also work, just not as well. The Surface Temperature Sensor was chosen because of its low thermal mass and fast reaction to changes in temperature.

HAZARD ALERTS

The chemical safety signal word DANGER, as used in the Globally Harmonized System of Classification and Labeling of Chemicals (GHS), is included in this experiment to help identify hazardous chemicals. We urge you to refer to the *Science Catalog Reference Manual*, published yearly by Flinn Scientific (phone: 800-452-1261 or web site: **www.flinnsci.com**), if you have questions about ordering, storing, and disposing of chemicals.

Gel chafing fuel (ethanol, 95%, denatured), CH_3CH_2OH: **DANGER**: Highly flammable liquid and vapor. Keep away from heat, sparks, open flames, and hot surfaces. Do not eat or drink when using this product—harmful if swallowed. Causes skin and serious eye irritation. May cause respiratory irritation. Avoid breathing mist, vapors, or spray. Causes damage to organs. Addition of denaturant makes the product poisonous. Cannot be made nonpoisonous.

Paraffin wax: See safety documentation that came with the product for handling, storage, and disposal information.

ANSWERS TO PRELIMINARY QUESTIONS

1. Answers will vary. Automobiles use gasoline; houses require heat from gas or oil, electricity generated from burning of coal.
2. Answers will vary. See the chart in student handout for Experiment 1.
3. Answers will vary. In many areas, renewable energy sources include wind energy and/or hydroelectric power, and some areas have solar power available.
4. Household A (my house) used 1.54×10^{10} J of energy and my friend's house (household B) used 1.61×10^{10} J.

Household	Amount of fuel used	Energy used (J)
A (natural gas)	14,300 ft^3	1.54×10^{10}
B (heating oil)	110 gallons	1.61×10^{10}

SAMPLE RESULTS

Student results will vary.

	Candle	Gel chafing fuel
Initial mass of fuel (g)	105.94	93.44
Final mass of fuel (g)	105.68	90.97
Mass of fuel burned	0.26	2.47
Mass of empty can (g)	15.15	15.15
Mass of can plus water (g)	66.04	114.83
Mass of water heated (g)	50.89	99.68
Initial water temperature (°C)	9.22	10.43
Final water temperature (°C)	36.49	37.98
Change in water temperature (°C)	27.27	27.55

PROCESSING THE DATA RESULTS

1. ΔT = 36.49°C – 9.22°C = 27.27°C
2. 66.04 g – 15.15 g = 50.89 g water heated
3. Q = 2 (50.89 g)(4.18 J/g°C)(27.27°C) = 5,801 J
4. 105.94 g – 105.68 g = 0.26 g candle burned
5. 5,801 J / 0.26 g = 22,300 J/g
6. Typical class averages:

   candle (paraffin wax): 22,000–25,000 J/g

   gel chafing fuel: 3,000–6,000 J/g

   The actual value for paraffin wax is about 42.0 kJ/g. Gel chafing fuel often contains methanol, ethanol, and diethylene glycol. The actual value for methanol is 22.7 kJ/g. For ethanol, the actual value is 28.3 kJ/g. Since gel chafing fuel is a mixture and the ratio of ingredients is not identified, the actual value for the gel chafing fuel you use will not be known. However, the actual will be higher than the value your students obtain. You may want to discuss factors causing the values obtained in this experiment to be lower than the actual values.

ANSWERS TO ANALYSIS QUESTIONS

1. Answers will vary. Based on the sample data, candle wax has the greatest energy content, measured in J/g.
2. Answers will vary. Based on the sample data, natural gas has the greatest energy content.
3. Other possible factors to consider in the selection of a fuel are convenience, cost, availability, burning efficiency, carbon emissions, and renewability.

ANSWERS TO EXTENSIONS

1. Answers will vary. A major factor contributing to the inefficiency of this experimental procedure is loss of heat to the air.
2. Answers will vary. Other potential fuels include: butane, 2-propanol, and 1-butanol. Portable butane burners can be used as a butane source.

Project: Energy Audit

We all use energy to turn on lights, heat and cool our homes, get to school, and power our electronics. In the United States, energy consumption is broken down into four sectors: residential, commercial, industrial, and transportation.

- Residential includes energy used in places like houses and apartment buildings.
- Commercial accounts for energy used in public spaces such as office buildings, schools, and hospitals.
- Industrial includes energy to grow and make goods such as food, cars, and buildings.
- Transportation includes the gasoline and fuel used to drive cars and fly planes.

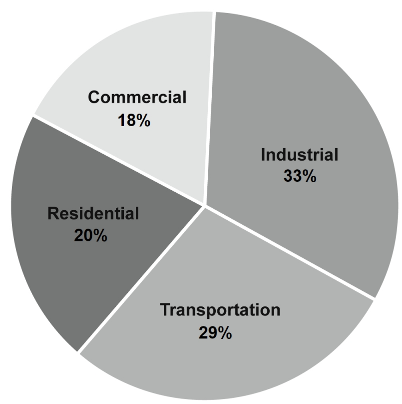


Figure 1 Share of total energy consumed by major sectors in the United States, 2017

Conducting an energy audit will allow you to better understand how much energy is used by the devices in your home and classroom. Based on this information, brainstorm ways to reduce the amount of energy you use.

OBJECTIVES

- Measure electricity usage by several devices in your classroom and at home.
- Make a plan for how you will conduct a home energy audit.
- Calculate energy usage per person in your home.
- Consider ways to conserve energy at home and school.
- Determine ways your classroom, school, or home could become more efficient.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Surface Temperature Sensor
multiple devices that use electricity

PRELIMINARY QUESTIONS

1. List as many devices in your classroom that are using electricity as you can. Do the same for your home.
2. What is "phantom" energy? What types of phantom energy use are occurring in your classroom or home right now?
3. What is the difference between energy efficiency and energy conservation?

PROCEDURE

Part I Classroom energy audit

1. Perform a general assessment of your classroom by answering the following questions.
   - How many devices are plugged in?
   - How many lights are on? What types of light bulbs are in use?
   - Is temperature controlled directly in the classroom or centrally for the building? What temperature is the thermostat set to?
   - How high are the ceilings?
   - What is the source for energy at your school?
2. Examine the devices your teacher has provided to find the energy information. Record the voltage and current, and the power if available. Use this information to determine how much energy is consumed by these devices in a given amount of time.
3. Use a Surface Temperature Sensor to measure the temperature in various parts of your classroom.
   - Near the door
   - Close to the thermostat
   - Near the windows
   - Close to the ceiling

Part II Home energy audit

1. Create a plan for conducting a home energy audit. Consider the following questions as you develop your plan.
   - How many rooms are in your home? What is the square footage? How many people live in your home?
   - How many lights are in the house? What types of light bulbs are in use?
   - What direction do the windows face? Are they single- or double-pane windows?
   - Is temperature controlled in each room or centrally? What temperature is the thermostat set to?
   - How high are the ceilings?
   - What is the source for energy for your home?
   - What is the energy cost for your home on average each month (include electric bill, natural gas bill, etc.)?

2. Determine how much energy is used by the devices in your home. Create a table modeled after the following example.

Device	Energy usage (W)	Estimated usage/month (kWh)	Operating cost (usage/month × cost/kWh) (use $0.13 if you don't know) ($)
Refrigerator			
Computer			
TV			

3. Use a Surface Temperature Sensor to measure the temperature in various parts of your home. Record the values in a separate table.

DATA ANALYSIS

Part I Classroom energy audit

1. What device used the most energy? The least?
2. For three of the devices, calculate how much energy is consumed during the year. How could you conserve energy use for the devices?
3. How does the temperature compare in different places in your classroom? What are ways to reduce energy use for heating or cooling in your classroom?
4. What are ways your class could help conserve energy at school?

Part II Home energy audit

1. Which devices in your home use the most energy? The least?
2. Calculate energy usage/person in your home.
3. Research to find the carbon emission values for the source of energy that is used to produce the electricity that is used in your home (e.g., natural gas or coal). Calculate the carbon footprint for the devices you measured.
4. What are ways can you make your home more energy efficient?

EXTENSIONS

1. Use a smart outlet to measure energy use over a 24-hour period for a single device. How does energy use change during the day? Estimate how energy use would change over the entire year due to varying factors such as temperature and amount of daylight.
2. Conduct research to compare your energy usage to people in other parts of the country. What role does climate play in affecting energy use in different regions?

3. Learn about ways that buildings can be designed to reduce energy consumption. Some factors to consider include: green roofs, insulation, vegetation, and paint color.
4. Research to find an energy audit tool that will allow you to measure all the energy you use, including transportation.
5. Write a letter to an administrator at your school to share ideas for how your school can reduce energy consumption and save money
6. Share your results from this experiment with people living in your home. Work together to come up with a plan for how you can reduce energy use in your home. In a month or two, repeat your measurements and determine if there have been changes in energy consumption patterns.
7. Imagine you are responsible for replacing a device in your home that uses electricity, such as a TV, water heater, or light bulb. Do research to find the most energy efficient product you could buy. Is it more expensive than less efficient options? How will you balance cost with energy savings?
8. Learn about how energy use in your country compares to energy use in other parts of the world.
9. You have now spent a lot of time thinking about the importance of energy conservation. Imagine that you are having a conversation with someone who does not think it is important to conserve energy. Explain different reasons that might make them change their mind.
10. Does it take more energy to charge something every day (such as a laptop) or to leave it plugged in overnight? Support your answer.

Project: Energy Audit

When this experiment was originally written, a tool called Watts Up Pro was available. Watts Up Pro allowed the logging of energy use data directly into Vernier data-collection software. This tool is no longer available, but if you have one, feel free to use it for taking direct measurements of energy use. In the meantime, "smart outlets" have become available, and these are addressed in the Equipment Tips, below.

In addition to collecting data for devices that are obviously using energy (e.g., a television that is on), it can be interesting to teach students about a phenomenon that is sometimes called phantom energy. Phantom energy is one of the names given to the "invisible" use of energy caused by devices that are in standby mode or that continue to draw electricity when they are plugged in but not in use. Devices that consume phantom energy are sometimes called "energy vampires." Televisions that can be turned on by a remote control and mobile device chargers are two examples of devices that may use electricity when they are plugged into an outlet but are not being used. If you have access to a Watts Up Pro or a smart outlet, this phantom energy can be measured.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Set up equipment for data collection, including connecting and turning on equipment and starting the data-collection program.
- Collect data at home, without direct supervision of an instructor.

ESTIMATED TIME

We estimate that data collection and analysis for Part I can be completed in one 45-minute class period. In Part II, students will create a plan for a home energy audit and collect and analyze data. This will take multiple days.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking questions and defining problems Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Engaging in argument from evidence Obtaining, evaluating, and communicating information	PS3.A Definitions of Energy (HS-PS3) PS3.D Energy in Chemical Processes (HS-PS3) ESS3.A Natural Resources (HS-ESS3) ETS1.B Developing Possible Solutions (HS-ESS3)	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter Stability and change

EQUIPMENT TIPS

1. Devices that work well for the classroom energy audit include:
   - Computer and monitor
   - Projector
   - Anything with a power brick or transformer-type AC power cord
   - Devices that need to be charged. (How much does the charger alone use? When the device is connected and charging? When it is charged and still connected?)

2. Smart outlets are devices that connect to your home Wi-Fi network and can be controlled via an app on a compatible smartphone or tablet. Many smart outlets also incorporate the ability to monitor energy use. For example, we tested a Wemo® Insight Switch manufactured by Belkin. It took less than 10 minutes to set up the switch, and using the free smartphone app, we were able to download energy usage data in the form of a .csv file (which can be opened in a spreadsheet program). The .csv file included the total energy consumed while the outlet was turned on, in half-hour increments. Taking the sum of the energy data gave the total energy use for the amount of time the outlet was on.

   We also tested the Kasa™ Smart Wi-Fi Plug with Energy Monitoring, using the free Kasa app. Like the Wemo device, this outlet took less then 10 minutes to set up with the required Wi-Fi network and smartphone app. The Kasa app gives a real-time measurement of the power consumed and calculates the amount of energy consumed since being activated, in addition to a daily average, but does not provide detailed data that can be downloaded to a spreadsheet for analysis.

   While both smart outlets were relatively easy and quick to set up, it is important to note that they can only be used by students at home if the student has a home Wi-Fi network and access to a smartphone or tablet. Once in place and set up, the smart outlet should not be moved to a different location (even in the in the same room), or you may need to re-setup the device from scratch.

3. The discontinued Watts Up Pro measures the power used by an appliance or device. In order to determine the amount of energy that is used, the time that the appliance or device is consuming power must be known. Therefore, students need to either keep track of the amount of time the appliance or device is plugged in or they will need to use the integral function of the software to determine the energy usage.

   Watts Up Pro can be used as a standalone device or, if you want to log data, connected to a LabQuest interface (running LabQuest App 1.3 or newer) or a computer running Logger *Pro* (version 3.8 or newer). For standalone use, plug devices directly into Watts Up and read values from its on-board display. (**Note**: If data are not logged, the integral function of the software cannot be used to determine energy usage.) For tech tips, videos, innovative uses, and sensor specs, visit **www.vernier.com/wu-pro**

4. This experiment is written using the Surface Temperature Sensor, but other Vernier temperature probes will also work. Students should allow enough time for the temperature sensor to come into equilibrium with its surroundings.

5. As an extension to this project, consider having students use the surface temperature sensor or a thermal camera to measure the temperature of power bricks and transformers of plugged-in devices. Discuss with students how this thermal energy is being "consumed" by the home or school but not being used to power the device that is plugged in.

DATA-COLLECTION AND ANALYSIS TIPS

1. Examples of energy audits are available on the Internet if you would like to give your students a more-structured starting point.

2. If you want students to compare their home energy audit data, they should collect similar data.

3. Many power bricks and transformer-type AC power cords list the input and/or output current and voltage. The power (in watts) is calculated by multiplying the output voltage (in volts) by the output current (in amperes). Multiplying the power by the estimated hours a device is on gives the energy use in watt-hours. To convert watt-hours to kilowatt-hours, divide by 1000.

ANSWERS TO PRELIMINARY QUESTIONS

1. Answers will vary.

2. See the introduction of this Instructor Information for a description of phantom energy.

3. Answers will vary. Put most simply, energy efficiency is performing the same work but using less energy (e.g., replacing an older-style CRT television with a newer LED television). Energy conservation is changing behavior so less energy is necessary (turning off a computer when not in use is an example).

ANSWERS TO ANALYSIS QUESTIONS

Part I Classroom energy audit

Answers will vary for all questions.

Part II Home energy audit

Answers will vary for all questions.

Voltage and Circuits

You have used electricity throughout your life, but do you know what it is? Electricity can be the sparks and crackling when clothing is pulled apart, and it can be lightning during a storm. It can also be channeled through wires and put to work turning fans, toasting bread, lighting lamps, and connecting you to the world over television, the internet, and phones.

The particles that make up atoms have a property known as charge. It is the presence and motion of these charged particles that gives rise to the phenomenon known as electricity. While we cannot see the charged particles themselves, we are able to investigate how they behave in various devices and materials.

The moving particles in an atom are in the outermost part of the atom's structure and are called electrons. Electrons are about 2000 times smaller than the other particles that make up atoms. Their small size, as well as other factors, makes electrons the easiest part of an atom to push and move. Electrons typically do not move very far or very fast, but very large numbers of them moving at once can deliver a painful shock or heat your home.

Two terms that are used when discussing electricity are *voltage* and *current*. Voltage is a colloquial term for potential difference, which is a way of describing the available energy for electrons to use for moving. The unit used to measure potential difference is the volt (V). Current is the term for the flow of charged particles. In general, the higher the voltage, the more energy is available for electrons to use, and the greater the current. Current is measured in a unit called the ampere (A).

In this experiment, you will have an opportunity to use electricity in small, safe amounts. By investigating how electricity interacts with different objects, you will gradually learn to use electricity effectively to create your own circuits, systems, and devices.

OBJECTIVES

- Detect the presence of current in a wire.
- Explore different types of light bulbs.
- Measure voltage.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Voltage
resistors **or** Vernier Resistor Board **or** Vernier Variable Load
3 wires with clips
red LED
7.5 V light bulb and socket
2 D-cell batteries and holder
3-V, coin-cell battery
magnetic compass

PRELIMINARY QUESTIONS

1. What is electricity?
2. How do we know electricity is flowing?
3. What conditions are required for electricity to flow?

PROCEDURE

Part I Is current present?

1. Clip several wires together. Place the magnetic compass over the wires as shown in Figure 1. Connect the battery to the ends of the wire and observe the compass. Try this several times, moving the orientation of the wire relative to the room each time. Record your observations.

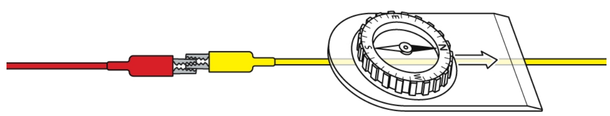


Figure 1

2. Discuss what you have learned with your classmates.

Part II Lighting a bulb

3. Obtain a small light bulb. Using a single wire and a single D-cell battery, try different ways of touching them together in order to light the light bulb. You may not cut the wire. Once you determine one way to do it, see if you can find a different way.
4. Discuss with your classmates the variety of ways the light bulb may be made to glow. Draw or otherwise show what to do to light the bulb, and also discuss and draw unsuccessful methods. Label your diagrams.
5. Obtain a red LED bulb and a 3-V, coin-cell battery. Light the LED. Determine a way to always be sure the LED will light.

Part III Measuring voltage in a circuit

6. Launch Graphical Analysis. Connect Go Direct Voltage to your Chromebook, computer, or mobile device.
7. Set up the equipment.
   a. Insert the two D-cell batteries into the battery holder (see Figure 2).
   b. Insert the light bulb into the light bulb socket.
   c. Use the wires to connect the battery holder to the socket so that the bulb glows.

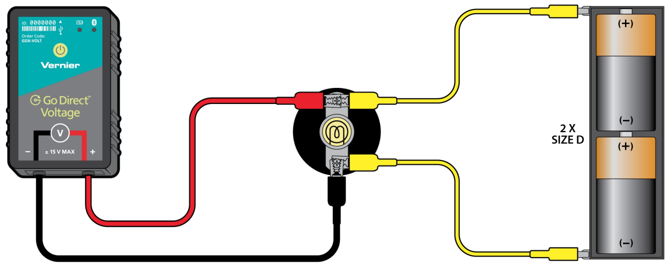


Figure 2

8. Use the voltage probe to measure the voltage across each battery individually, the two batteries together, the light bulb, and each wire by touching the terminals of each component with the voltage probe wires. If your readings are negative, switch the wires to opposite terminals. Record the voltage values in your data table.

9. Add resistance to the setup. There should be a complete circuit from the batteries to the light bulb to the resistor and back to the batteries. The light bulb should still light, but it may be dimmer than before (see Figure 3).

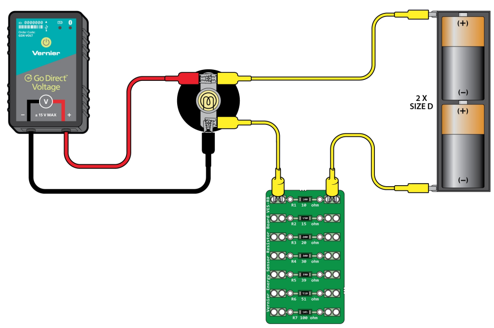


Figure 3

10. Measure the voltage across each battery individually, the two batteries together, the light bulb, the resistor, and each wire. Record the voltage values in your data table.

DATA

Part I Is current present?

Record your observations of how the magnetic compass behaved around the wire.

Part II Lighting a bulb

Draw a diagram of the wire, light bulb, and battery.

Part III Measuring voltage in a circuit

Component	Potential difference (V) (bulb only)	Potential difference (V) (bulb and resistor)
Battery 1		
Battery 2		
Both batteries together		
Light bulb		
Wire 1		
Wire 2		
Resistor		
Wire 3		

ANALYSIS QUESTIONS

1. How can you determine whether current is present in a wire?
2. How would you light a light bulb with only one wire and one battery? Can you do the same with an LED?
3. What are some differences between incandescent light bulbs and LEDs?
4. When you investigated the voltage across various components in a complete circuit, what patterns did you see?

EXTENSIONS

1. Add more light bulbs or more resistors to a circuit and investigate if or how the voltage changes.
2. Use the PhET simulation "Circuit Construction Kit" to further explore circuits. To use the PhET simulation, see **http://phet.colorado.edu/en/simulation/circuit-construction-kit-dc**

Voltage and Circuits

This exploratory activity is designed to introduce students to the basic concepts of electric potential (voltage), current, and circuits. Students do not need to have had any prior experience with electric circuits. While the term current is used in this experiment, it is not measured quantitatively and not formally defined here.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

Important: If you are using Go Direct sensors, this experiment is written for Go Direct Voltage rather than Go Direct Energy; due to a fundamentally different design, which relies on adding a load to the circuit, Go Direct Energy is not appropriate for this experiment. If using Graphical Analysis 4 and LabQuest sensors, use the Vernier Energy Sensor (order ode: VES-BTA).

RELATED SKILLS

- Zero a sensor.
- Connect a circuit.

ESTIMATED TIME

We estimate that this exploration can be completed in one to two 45-minute class periods, depending on the amount of class discussion.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Planning and carrying out investigations Analyzing and interpreting data	PS2.B Types of Interactions (HS-PS2)	Cause and effect Energy and matter

EQUIPMENT TIPS

1. Students are instructed to clip several wires together to create a long wire. Caution students to avoid leaving the wire connected to the batteries for longer than a few minutes at a time to avoid discharging the battery. If the wire gets too warm, you can insert a small resistor (less than or equal to 10 Ω) into the circuit.

2. A 7.5 V or 6.3 V miniature light bulb works well in this activity. Appropriate 7.5 V bulbs are included with the Vernier Circuit Board 2 (order code: VCB2) and are available separately as Replacement Lamps for Vernier Circuit Board (order code: VCB-BULB).

3. Test all the batteries, bulbs, and wires before giving them to students.

4. Most LED bulbs have two leads, one that is longer than the other. This is the type of LED that students should use for this experiment. Of the two leads, the shorter one should be connected to the negative terminal of the coin cell battery. (If you look at the plastic housing of the LED, there is often a flattened edge at the base close to the shorter lead, which is another indication of the negative side.) If you can find large (10 mm) LEDs, we recommend using them, as they are easier to handle and less likely to get lost.

5. The CR2032 is a fairly common 3-V, coin-cell type battery that works well for this experiment. If you can find them in bulk on the Internet, they are often less expensive than when purchased individually at a local store.

6. If you do not have Vernier Energy Sensors, you can use Voltage Probes or Differential Voltage Probes for this experiment. In that case, you may wish to modify the instructions slightly.

7. A 10 Ω resistor is appropriate for this experiment and one is included on the Resistor Board. The Vernier Variable Load can be used in place of the resistor. Adjust the Variable Load to a low resistance level so that the bulb still glows.

DATA-COLLECTION AND ANALYSIS TIPS

1. Students should notice that when the wire is oriented roughly in the east-west direction, the compass needle either stays still or flips direction. In all other orientations, there is probably some movement of the needle toward an orientation perpendicular to the wire when the battery is connected to the wire.

2. Remind students to keep trying different ways of putting the materials together to get the light bulb to light. Suggest there is more than one way to do it, and encourage students to find more ways after they have done it once.

3. To measure the voltage across any component in a circuit, touch the wires from the sensor to both terminals of the component. If the value is negative, reverse the positions of the wires. It is not necessary to clip the wires to the components.

4. The sum of the two voltages across the two batteries measured individually should equal the voltage measured across both batteries at once. The sum of the voltages across each of the circuit components should also equal the voltage measured across both batteries at once. The wires should have very low (zero or a tiny fraction more) voltage from end to end.

5. The voltages across the circuit elements may not sum to exactly the voltage across both batteries together. This is likely due to measurement variations inherent in the sensor, and such differences will be very small.

ANSWERS TO PRELIMINARY QUESTIONS

Answers will vary. Allow students to state multiple ideas. Most students will not have clear answers to these questions.

SAMPLE RESULTS

Student results will vary.

Component	Potential difference (V) (bulb only)	Potential difference (V) (bulb and resistor)
Battery 1	1.42	1.43
Battery 2	1.55	1.55
Both batteries together	2.98	2.98
Light bulb	2.85	1.84
Wire 1	0.00	0.00
Wire 2	0.00	0.00
Resistor		1.02
Wire 3		0.00

ANSWERS TO ANALYSIS QUESTIONS

1. Any of the following observations indicate that current is flowing in the wire:
   - If the wire is oriented north-south, a magnetic compass brought near will not read correctly.
   - If there is a light bulb connected to the wire, the bulb may glow.
   - If there is a motor connected to the wire, the motor may turn on its own.

2. To light a light bulb with a single wire and battery, touch the wire to one end (terminal) of the battery and touch the other end of the wire to the side of the light bulb, on the metal part that screws into a socket. Touch the metal tip of the light bulb to the other terminal of the battery where the wire is not touching.

   You can do something similar with an LED, but instead of touching the wire to the metal of the light bulb, touch it to one of the two leads coming off the LED. Touch the other lead of the LED to the battery. This will only work if the LED is in the correct orientation (the long lead touches the positive battery terminal and the short lead touches the negative terminal).

3. Some differences between incandescent light bulbs and LEDs are that the light bulb gets warmer than the LED and that the light bulb glows white or yellow instead of red. Also, it matters which direction electricity flows through the LED, but it does not matter for the light bulb.

4. Some patterns include: The voltage measured across two batteries together is about the same as the sum of the voltage across the two batteries measured individually. The wires had a very small or zero voltage. When there was just a light bulb in the circuit, the voltage of the two batteries together was about the same as the voltage across the light bulb. When the resistor and the light bulb were in the circuit, the voltage across the two batteries together was about the same as the voltage across the light bulb and the voltage across the resistor added together.

Current and Resistors

When electricity flows through an object or material, charged particles get a push from the potential difference, or voltage, applied to the material. In many cases, the more voltage there is, the more flow, or current, there is.

The flow of charged particles is different from the flow of water in a river or pipe. Typically, all the material in a river or pipe moves together and only rubs against the riverbed or the walls of the pipe. But charged particles often move through solid materials, such as copper, carbon, and tungsten. While moving things through solids may seem impossible, electrons are extremely tiny and can move among the atoms that make up a solid. In fact, at the scale of an electron, an atom is mostly empty space.

However, electrons moving through a solid material cannot move as swiftly as they would through a truly empty space, especially since the nuclei of the atoms stay still instead of going with the flow. The movement of electrons is so hampered by the structure of a solid material that they move at speeds on the order of mere centimeters per second.

Sometimes it is useful to allow only small currents, and objects called resistors are used in circuits to decrease electron flow by specific amounts. In this experiment, you will investigate how different resistors in a circuit affect voltage and current. Resistance is measured in ohms (Ω).

OBJECTIVES

- Measure current.
- Measure voltage.
- Explore the relationship between voltage, resistance, and current.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Energy
Vernier Resistor Board **or** various resistors < 100 Ω
3 wires with clips
2 D-cell batteries and holder
magnetic compass

PRELIMINARY ACTIVITY

Observation 1

Connect three wires together to make one long wire. Connect the ends of the long wire to the two batteries in the holder to make a complete circuit. Break the circuit by disconnecting the wires at the clips. Place the magnetic compass under one of the wires in the circuit. Align that wire with the compass needle. Close the circuit by reconnecting the wires at the clips and observe the compass needle. Break the circuit again by disconnecting the wires and leave the circuit open.

Observation 2

Connect three wires together to make one long wire. Connect the ends of the long wire to the two batteries in the holder and one of the resistors to make a complete circuit. Break the circuit by disconnecting the wires at the clips. Place the magnetic compass under one of the wires in the circuit. Align that wire with the compass needle. Close the circuit by reconnecting the wires at the clips and observe the compass needle. Break the circuit again by disconnecting the wires and leave the circuit open.

Putting a compass needle by a wire can indicate whether there is current present in the wire or not. Make a conjecture about the effect of resistance on the current in the wire.

PROCEDURE

1. Set the switch on the Energy Sensor to External Load. Connect the Energy Sensor to your Chromebook, computer, or mobile device.

2. Set up the sensor.
   a. Expand the Sensor Channels list.
   b. Use the check boxes to deactivate all the channels except potential and current.
   c. Click or tap Done to enter data collection mode.

3. Set up the equipment.
   a. Connect the wires on the Energy Sensor to the battery terminals. Connect the red Energy Sensor wire to the + side of the batteries.
   b. Connect two wires to the External Load terminals.

4. Set up the data collection mode.
   a. Click or tap Mode to open Data Collection Settings. Change Mode to Event Based.
   b. Enter **Resistance** as the Event Name and **ohm** as the Units. Click or tap Done.

5. You are now ready to collect current and voltage data.
   a. Click or tap Collect to start data collection.
   b. Connect the two External Load wires to the resistor with the lowest value.
   c. Click or tap Keep and enter the value of the resistor on the screen. Click or tap Keep Point to store the resistor value, current, and voltage data.
   d. Disconnect the External Load wires and re-connect them to the resistor with the next-lowest value.
   e. Continue this procedure until you have used all your resistors once.
   f. Click or tap Stop to stop data collection.

6. Record the potential, current, and resistance values in the data table (or, if directed by your instructor, print a copy of the table).

DATA

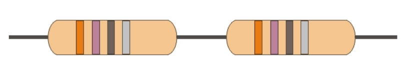
Resistor value (ohm)	Potential (V)	Current (mA)

ANALYSIS QUESTIONS

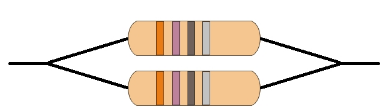
1. Display a graph of potential (V) *vs*. resistance (ohm). Sketch the graph.
2. Predict what the graph would look like for higher resistor values such as 200, 500, or 1000 Ω.
3. How does the resistor value affect the measured voltage of the circuit?
4. Display a graph of current (mA) *vs*. resistance (ohm). Sketch the graph.
5. Predict what the graph would look like for higher resistor values such as 200, 500, or 1000 Ω.
6. How does the resistor value affect the measured current of the circuit?

EXTENSIONS

1. Investigate why the measured potential does not remain constant for this experiment, despite the fact that the batteries you used were the same for the entire experiment. Report on your findings.
2. Look up Ohm's law and apply it to your data to calculate experimental values for the resistors you used. Compare your calculated values to the given values for each resistor. Account for any differences you discover.
3. Investigate the voltage and current for a circuit in which you combine two or more resistors in series. Do the same for a circuit in which you combine two or more resistors in parallel. Are the results what you expected? Research how resistances combine in different types of circuits.



Series Resistors



Parallel Resistors

Current and Resistors

This experiment is designed for students who have some familiarity with circuits and how they function. Having performed Experiment 4, "Voltage and Circuits," will greatly increase the ease with which students can conduct this experiment, because in this experiment, complex concepts such as potential (voltage) are referenced with very little description.

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RELATED SKILLS

- Zero sensors, if using a Vernier Energy Sensor.
- Set up and use the Events with Entry data-collection mode.

ESTIMATED TIME

We estimate that data collection for this experiment can be completed in one 45-minute class period.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Planning and carrying out investigations Analyzing and interpreting data	PS2.B Types of Interactions (HS-PS2)	Cause and effect Energy and matter

EQUIPMENT TIPS

1. The Materials list in the student experiment includes a Vernier Resistor Board (order code: VES-RB). If you are using individual resistors instead of the Resistor Board, we recommend using power resistors capable of carrying the current. Various online suppliers sell 1-W resistors with values of 15, 20, 33, 47, 51, 68, and 82 Ω. A suggested list of suppliers of resistors is available at **www.vernier.com/til/3719**

2. The Vernier Variable Load is not recommended for this activity because it does not provide values for resistance other than those calculated by the software. Voltage and current values are

affected by the internal resistance of the D-cell batteries, and the calculated resistance will not be the same as the resistance provided by the Vernier Variable Load.

3. Students using the Vernier Energy Sensor (order code: VES-BTA) need to zero the sensor before collecting data. Instructions for zeroing are included in the student experiment. Students using Go Direct Energy (order code: GDX-NRG) do not have to zero the sensor.

ANSWER TO PRELIMINARY ACTIVITY

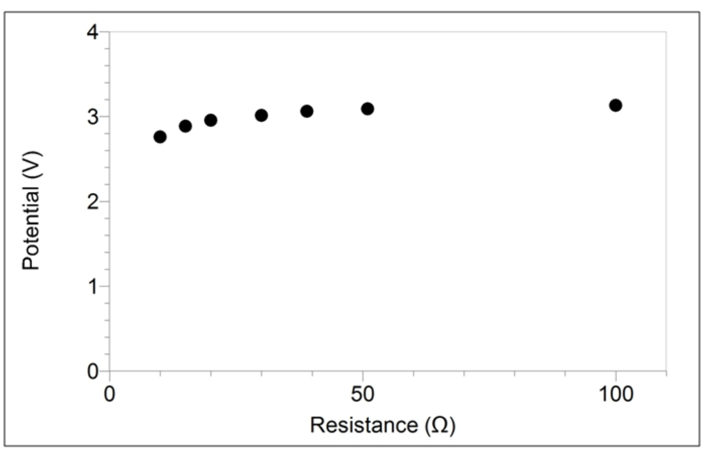
The compass needle deflects less when the resistor is included in the circuit, indicating less current in the circuit.

SAMPLE RESULTS

Resistance (Ω)	Potential (V)	Current (mA)
10	2.76	237.8
15	2.89	166.4
20	2.95	128.9
30	3.01	88.5
39	3.06	69.2
51	3.09	53.4

ANSWERS TO ANALYSIS QUESTIONS

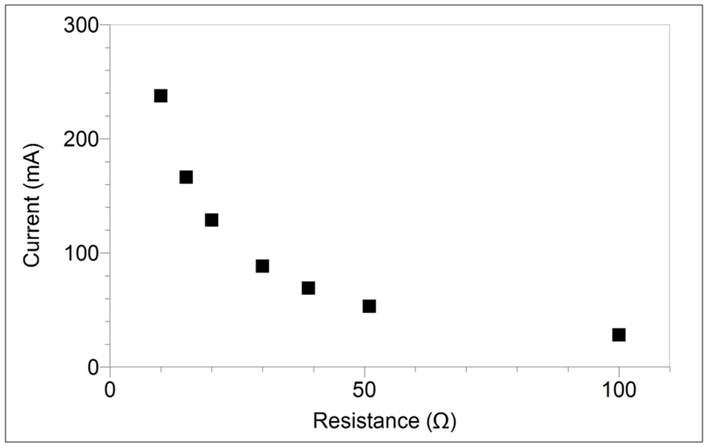
1.



2. For higher resistor values, the potential graph should be pretty nearly flat at a little more than 3 V.

3. The higher the resistor value, the closer the voltage reading comes to its value with no load applied.

4.



5. For higher resistor values, the current graph will approach zero asymptotically.

6. Resistors reduce current, with higher resistor values leading to lower currents.

Mechanical Power

You have been introduced to energy as something that is involved in making things happen. Energy can be transferred or transformed between objects, materials, and ways of accounting for energy. For example, the act of stretching a rubber band transfers energy into the rubber band, which we call *elastic potential energy*. *Elastic* because it is related to the stretchiness of the rubber band and *potential energy* because as long as the rubber band remains stretched, the energy is stored but available for use. Releasing the rubber band in a certain way so as to project the rubber band through the air allows the elastic potential energy to transform into kinetic energy (the energy associated with motion).

To stretch the rubber band, a force is applied to part of the rubber band, which causes part of the rubber band to move a certain distance. Whenever a force moves an object some distance, we say that mechanical work is done. Mechanical work, like energy, is measured in joules (J). Work is one way to transfer or transform energy.[1]

Just as you can do work to stretch a rubber band, you can also do work to lift a weight. In order to lift an object from a lower position to a higher position, a vertical force must be applied. In this case, the work done gives the object moved upward *gravitational potential energy*,[2] because instead of being pulled against a stretchy material, the object is moved against the direction of the force of gravity. In this experiment, you will use a wind turbine to lift an object (a bucket of washers) from a lower position to a higher position.

Power is defined as the rate at which energy is used, applied, or transformed. It is also the rate at which work is done. If an amount of energy is analogous to a specific distance, power is analogous to speed, which is the rate at which an object travels a distance. The faster an object is lifted, the more power is being used. The unit of power is the watt (W), which is equivalent to one joule per second (J/s).

In this experiment, you will calculate power using the equation

$$\text{power} = \frac{\text{amount of work done}}{\text{how long it took}}$$

You will use a wind turbine to do the work of lifting a mass. You will vary the pitch (angle) of the blades of the wind turbine and measure the time it takes to lift a mass a given distance. Based on these measurements, you will calculate the mechanical power generated by the turbine as it lifts the weights.

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[1]Typically, we think of there being two ways to transfer energy into and out of a system: work is one way and heat is the other.

[2]Technically, the gravitational potential energy is stored in the earth-object system. Without the earth in the system, there would be no force of gravity to work against.

OBJECTIVES

- Identify the units that are used to measure power.
- Measure the power generated by a wind turbine.
- Determine the relationship between wind turbine blade pitch and power generated.

MATERIALS

items needed from Advanced Wind Turbine Kit:
- Wind Turbine Tower
- Base
- Nacelle, assembled
- Hex Shaft
- Wind Turbine Hub
- Weightlifter spool and bucket
- 2 Hex Locks
- Blade Pitch Protractor
- 10–15 washers
- 1 m of string

blade materials
scissors and hot glue
fan
stopwatch or timer
tape
balance
meter stick
safety goggles

PRELIMINARY QUESTIONS

1. Account for the transformation of energy from the kinetic energy of air molecules in wind to the gravitational potential energy of the washers at their highest position. Note that there is work involved. Where are the forces involved that move things?

2. How do you think changing the pitch of the wind turbine blades will affect the forces involved in transferring energy from the wind to the washers?

3. Use your hands to rotate the spool, winding up the string and lifting the mass. In what way are you doing work? Remember that work is a process of transferring or transforming energy.

PROCEDURE

1. Set up the fan and turbine.
   a. Assemble the wind turbine with the nacelle set up for weight lifting, including connecting the weightlifter spool (see Figures 1 and 2). Do not attach the gears or generator.
   b. Connect three blades to the Hub. Space them evenly apart and set each one with a pitch of 25°.
   c. Position the fan so the center of the fan is in line with the center of the hub of the turbine. The fan should be about 25 cm from the turbine. Keep this distance the same for each run.

d. Clear off your area and make sure that when the fan and the turbine are moving, nothing will be in the way.

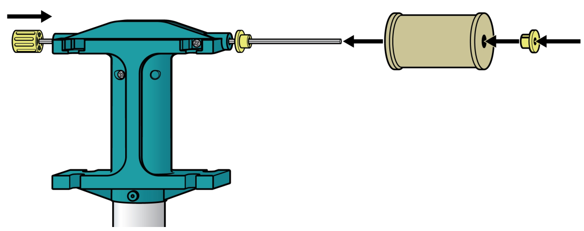

Figure 1

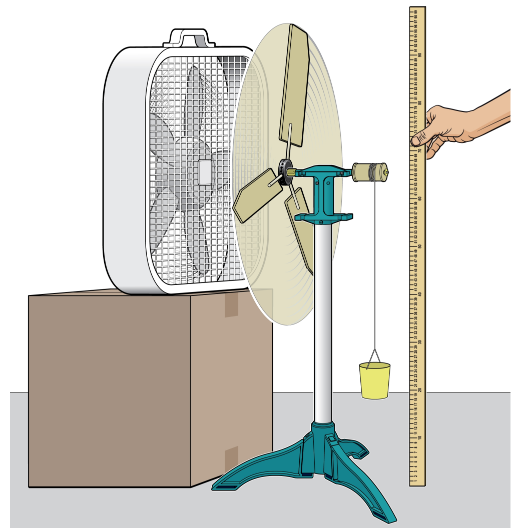

Figure 2

2. Finish setting up the equipment.
   a. Start with 6 or 7 washers. Place them in the bucket, and then determine the mass of the washers and the bucket. Record the mass in the data table.
   b. Tie the string to the bucket. Use tape to connect the free end of the string to the weightlifter spool.
   c. Position the bucket so it is located directly below the spool.
   d. Hold the meter stick next to the string.

3. Collect data. **Note**: This process works best if one person is responsible for the fan, one person is responsible for the stopwatch and data collection, and one person is in charge of holding the meter stick and stopping the bucket as it reaches the top.
   a. Put on safety goggles.
   b. Hold the turbine blade with your hand to keep it from turning. Turn on the fan. After the fan has reached a constant speed, release the blade. Give the blade a gentle push as you release it.
   c. The spool will start to wind the string, and then the bucket will start to lift as the string winds onto the spool.
   d. You will need to measure the time it takes for the bucket to lift a 15 cm distance near the top of the trip. Looking at the meter stick, decide where you will start and end timing. Start the timer when the top of the bucket passes the starting point.
   e. Stop the timer just as the top of the bucket passes the ending point.
   f. Turn off the fan. Unwind the string and reposition the bucket and string.
   g. Record the time it took to lift the bucket the 15 cm in the data table.
   h. Repeat this process two more times for a total of three runs at this blade pitch.

4. Increase the pitch of the blades by 10° and repeat Step 3. Continue to collect data until you have collected data for 25°, 35°, 45°, and 55°.

5. If time allows, add more washers into your bucket and repeat Steps 2–4. Collect a second set of data for this new mass.

DATA

Mass (kg):

Distance to lift (m):

Force (N):

Work (J):

Blade pitch (°)	Trial	Time to lift (s)	Average time to lift (s)	Power (W)
	1			
	2			
	3			
	1			
	2			
	3			
	1			
	2			
	3			
	1			
	2			
	3			

PROCESSING THE DATA

1. Calculate the average time to lift for each pitch.
2. Calculate the force required to lift the bucket and washers. This is the same as the weight, or force of gravity acting on the bucket and washers. Use the equation

$$\text{force (N)} = \text{mass (kg)} \times \text{gravitational field strength (9.8 N/kg)}$$

3. Calculate the work done (in joules) to lift the bucket and washers the 15 cm. Use the equation

$$\text{work (J)} = \text{force (N)} \times \text{distance (m)}$$

4. Calculate the power for each blade pitch using the equation

$$\text{power (W)} = \frac{\Delta\text{work (J)}}{\Delta\text{time (s)}}$$

ANALYSIS QUESTIONS

1. Describe the relationship between power and time to lift.
2. Describe the relationship between blade pitch and mechanical power.
3. When energy is transferred or transformed, some of the energy contributes to the random motion of molecules and atoms (thermal energy). This energy is considered to be "lost" since it cannot then be used to do meaningful work. These energy losses are typically caused by friction, collisions, and deformations. Determine where and how energy is lost in the conversion from the kinetic energy of the air to the final gravitational potential energy of the washers and bucket.
4. If a typical electric generator is 80% efficient, how much electrical power (in watts) could your turbine generate? Base your answer on the average power of your most powerful blade pitch.

EXTENSIONS

1. Compare your result to the data collected by other groups.
2. Test an additional blade variable or varying wind speeds to examine how a different variable affects the power generated.

Mechanical Power

In this experiment, students are introduced to the concept of mechanical power. They use a wind turbine to do the work of lifting a mass a given distance. They then vary the pitch of the blades in a series of trials and calculate the mechanical power (in watts) generated by the turbine as it lifts the weights.

This experiment is intended to be performed prior to Experiment 7 "Generators," in which students learn about the role of an electric generator in converting mechanical power to electric power.

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ESTIMATED TIME

We estimate that data collection can be completed in one 45-minute class period.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3) PS3.C Relationship Between Energy and Forces (HS-PS3)	Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter

EQUIPMENT TIPS

1. Set up a safe testing area.
   - Clear the area of debris and materials.
   - Instruct your students to not stand in the plane of rotation of the turbine blades. Also tell them that they should not touch the blades while they are spinning. Blades can be moving very fast and can hurt if they hit someone.
   - Provide safety goggles for your students. Students should wear safety goggles when they are working with a turbine that is spinning.

2. You may find it helpful to set up the wind turbines with the spools and buckets ahead of time. In that case, omit the assembly portion of the student instructions. If you are setting up the wind

turbines for the first time, the video at **www.vernier.com/kw-bwx** can be helpful. Adding the spool and bucket for lifting weights starts at 2:03 in this video. The user manual at **www.vernier.com/files/manuals/kw-bwx.pdf** also includes instructions on how to assemble the nacelle and wind turbine. The motor mount is not required, but it does not hurt to install it on the nacelle.

3. This experiment might take a bit of work to organize in a way that allows your students to collect good data. The strength of the fan as well as the blade setup affect how quickly the bucket lifts. We suggest encouraging your students to experiment with several runs before starting formal data collection in order to figure out a system that works well for the group.

4. The length of the piece of string included in the student Materials list is necessary to allow the turbine to reach a constant speed. You may need a different length if your setup differs from that described in the student experiment.

DATA-COLLECTION AND ANALYSIS TIPS

1. A team of three people works well—one to start/stop data collection, one to manage the bucket/string, and one to manage the fan and blades.

2. Increasing the distance over which the students measure the time to lift the bucket of washers to 20 cm may produce better results. However, the turbine blades must be up to approximately a constant speed before timing is started, so the distance cannot be increased to much more than 20 cm.

3. If students are struggling to measure the lifting distance, you may want to have them use masking tape to mark the place on the turbine tower or on the meter stick where they will start and stop timing.

ANSWERS TO PRELIMINARY QUESTIONS

1. Wind is simply air molecules in motion, which therefore have kinetic energy. The air molecules transfer some of their energy to the turbine blades by hitting the blades (a pushing force), and the turbine spins with kinetic energy. The spinning motion is used to pull the string upward, which pulls the bucket of washers upward (a pulling force), transforming some of the kinetic energy into gravitational potential energy.

2. Answers will vary. In general, The pitch of the blade affects how much force the air molecules can exert on the blade. If the blades are flat to the wind, the turbine blades will not rotate. If they are angled too much, the wind will blow right past the blades without exerting any force. In between these extremes, smaller angles get less force from the wind for rotation, but the blades slice through the air with less drag. At larger angles, the wind may exert more force, but the blades moving through the air as they rotate will experience more drag.

3. Turning the spool requires a force which rotates the spool, doing work. This gives the spool energy and wraps the string around the spool. When the bucket starts to lift, it becomes harder to turn the spool, since energy also gets transferred to the bucket and washers. The work done turning the spool turns into gravitational potential energy of the bucket of washers, and kinetic energy for the spool and the bucket of washers.

SAMPLE RESULTS

Mass (kg): 0.12

Distance to lift (m): 0.15

Force (N): 1.176

Work (J): 0.176

Blade pitch (°)	Run	Time to lift (s)	Average time to lift (s)	Power (W)
25	1	1.54	1.47	0.119
	2	1.52		
	3	1.36		
35	1	0.71	0.76	0.233
	2	0.81		
	3	0.75		
45	1	0.84	0.84	0.210
	2	0.83		
	3	0.85		
55	1	1.18	1.14	0.155
	2	1.16		
	3	1.08		

ANSWERS TO ANALYSIS QUESTIONS

1. In order to lift the same amount of mass faster, you must apply more power. The relationship between time and power is an inverse relationship.

2. Very low pitch angles will not generate much mechanical power because they do not generate enough torque. Very high pitch angles experience too much drag (resistance) as they rotate and do not spin quickly. When the blade pitch is 45°, the deflected air molecules will move parallel (in the exact opposite direction) to the rotation, which will therefore exert the most force on the rotating blades.

3. Friction between the spinning shaft and the nacelle will cause energy to be lost. Also, when the turbine blades spin, they run into air molecules that slow them down (drag), causing energy loss. (You may want to discuss the Betz Limit with students. The Betz Limit tells us a turbine will be most efficient when 41% of the air passes through the rotor).

4. 0.18 W = 0.23 W × 80%

Generators

How is electrical energy made? Electricity is seen in nature on a large scale as lightning, but lightning is not "harvested" to light buildings, run air conditioning, or power computers and mobile devices. Instead, electricity has to be generated by converting it from another form of energy.

A device called a generator is often used in the process of converting energy from one form to another. Generators can vary in size and shape, but all generators are composed of a few essential parts: a coil of wire, one or more magnets, and a frame to hold everything in place. To produce electricity, the generator is designed so the magnet and/or coil moves (either the coil is stationary and the magnet moves, or the magnet is stationary and the coil spins).

In this activity, you will build a your own generator and then explore how different variables affect how much electricity you can produce.

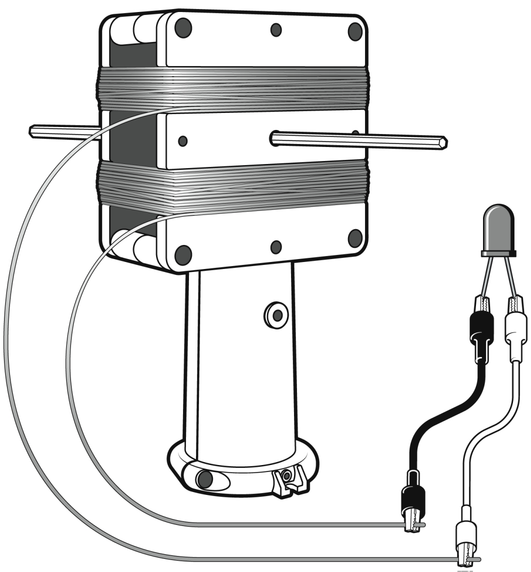

Figure 1

OBJECTIVES

- Generate electricity using magnets and coils of wire.
- Compare the voltages produced by spinning magnets within different numbers of turns of wire.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Energy
SimpleGEN Kit **or**
  strong magnets
  magnet wire (enameled copper wire)
  axle rod
  open box (cardboard or PVC) with holes for axle
  sandpaper
100 Ω resistor
2 wires with clips
drill
small incandescent light bulb (holiday-light style)
red LED
tape

PRELIMINARY QUESTIONS

1. What are the primary sources of energy that are converted to electricity in the United States? Can you think of some sources that are not thermally driven and do not require the burning of fuels?
2. What components make up a typical electrical generator?
3. What are some variables that may affect generator performance?
4. What are some of the ways we can move magnets and coils relative to one another?

PROCEDURE

Part I Preliminary activity

1. Set up the equipment.
   a. Tape one end of the wire to the housing.
   b. Wrap the wire so it creates a clean coil, winding the wire in the same direction each time (see Figure 1). **Note**: Your instructor will tell your group how many "wraps" or "windings" of wire to use on your generator. Different groups will use a different number of windings.
   c. Sand the ends of the wire until they are a bright copper color.
   d. Insert the magnets into the magnet holder.
   e. Position the magnet holder inside the housing and slide the rod through the housing and magnet holder so the magnet holder can spin freely.
   f. Connect the red LED to the free ends of the coil.
2. Spin the axle by hand so that the magnet assembly turns inside the coils of wire. Does the LED bulb light when you spin the magnet? Replace the LED bulb with the small incandescent holiday-light style bulb. Can you light the incandescent bulb? Record your answer in the data table.
3. If you have access to a drill, connect the drill chuck to the axle rod. Spin the drill, starting slowly. Can you light either bulb using the drill? Record your answer in the data table.

Part II Quantitative analysis

4. Set the switch on the Energy Sensor to External Load. Launch Graphical Analysis. Connect the Energy Sensor to your Chromebook, computer, or mobile device.
5. Set up the data-collection mode.
   a. Click or tap Mode to open Data Collection Settings.
   b. Change Rate to 60 samples/s. Click or tap Done.
6. Connect the red and black Energy Sensor Source wires to your copper coil. Make sure the metal clips are attached to the area of the copper wire that you sanded in Step 1c.
7. Connect the Energy Sensor External Load terminals to a 100 Ω resistor.

8. Click or tap Collect to start data collection. Data will be collected for 30 seconds. Spin your generator by hand several times over the course of data collection.

9. When data collection is complete a graph of voltage *vs*. time is displayed. Click or tap graph Tools, , and choose View Statistics. Record the maximum and minimum voltage in the data table.

10. If you have access to a drill, repeat Steps 8–9, spinning the generator with the drill instead of by hand.

DATA

Number of coil windings: ________________

	Hand-spin trial	Drill-spin trial
Light LED bulb?		
Light incandescent bulb?		
Minimum voltage recorded (V)		
Maximum voltage recorded (V)		

PROCESSING THE DATA

Share your results with the class to compare the generators used by each group.

ANALYSIS QUESTIONS

1. Does the number of coil windings affect the voltage output of the generator? Support your answer with your data.

2. Does the speed at which the magnets rotate affect the voltage output of the generator? Support your answer with your data.

3. What other factors may affect the power output of an electric generator?

4. If you were able to light the LED bulb, why did it flicker on and off?

EXTENSIONS

1. Using your own materials, make a homemade generator that will light more than one bulb wired in series. Document your project and compare it to the generators made in this exploration.

2. Turn your generator into a motor.

3. Turn your generator into a wind turbine. Can you get your device to spin and generate electricity when the wind blows on it?

4. Test generators with smaller or larger gauge wire. Does it affect voltage output of the generator?

5. Test different magnets in the generator. How does that affect voltage output?

Generators

In this experiment, students build and test electrical generators using magnets, copper wire, and a few other basic materials. To get a wide range of data, assign each group a different number of windings (wraps of copper wire) for their generator design.

In the first part of the experiment, each group will build a generator and then test whether their generator can light a small LED when spun by hand or with a battery-powered drill. Next, students connect their generators to an energy sensor to collect quantitative data about the electrical output of the generators. Students then record observations and share results regarding the number of windings and the method of rotation.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Zero sensors, if using the Vernier Energy Sensor.
- Use the Statistics tool to calculate statistics.

ESTIMATED TIME

We estimate that data collection for this experiment can be completed in one 45-minute class period. Winding the copper wire around the generator frames will add time proportional to the number of windings.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Planning and carrying out investigations Analyzing and interpreting data	PS2.B Types of Interactions (HS-PS2) PS3.C Relationship Between Energy and Forces (HS-PS3)	Patterns Cause and effect Systems and system models Energy and matter

EQUIPMENT TIPS

1. Set up a safe testing area by clearing the area of debris and materials.
2. This experiment was designed using a KidWind SimpleGEN kit (order code: KW-SGEN). You can also use other materials to build the generators. Power output will vary.
3. The user manual for the KidWind SimpleGEN kit has detailed assembly instructions. It is recommended to assemble the housing before beginning this experiment (see **https://www.vernier.com/files/manuals/kw-sgen.pdf** for additional information).
4. The SimpleGEN classroom pack (order code: KW-SGENC) includes enough materials for 10 setups. You may decide not to disassemble the wire-wrapped SimpleGEN frames, and to keep them, labeled with the number of turns, for future years.
5. The number of wire windings can vary quite a lot. The spool of wire included with the KidWind SimpleGEN has enough wire for about 500 turns of wire around the frame.
6. This experiment was designed using an energy sensor. It may also be done with a voltage probe. For more information, see **www.vernier.com/til/3184**
7. Ensure that students sand the two ends of copper wire after they build their generator. Copper wire is often coated in a clear enamel insulation, which needs to be removed in order to conduct electricity.
8. Battery-powered drills work well for this experiment.

DATA-COLLECTION AND ANALYSIS TIP

The generators produced with the KidWind SimpleGEN kit will output alternating current (AC), which will appear as a sine wave on the graphs in the data-collection software. It is important for students to collect both the maximum and minimum recorded voltage during the trial because the "maximum" voltage may actually be a negative number.

ANSWERS TO PRELIMINARY QUESTIONS

1. Coal, natural gas, and nuclear are the primary sources of energy in the United States. Energy from batteries, wind turbines, hydro turbines and solar (photovoltaic) panels are examples of energy sources that do not require the burning of fuel or are not thermally driven.
2. Magnets and copper wire are the two key components of an electric generator.
3. Variables that may affect the amount of electricity generated include the number of windings of wire, the strength or number of magnets, and the speed of spinning the magnets (or wire).
4. In order to generate electricity, the amount of the magnetic field (flux) within the copper coil must change. Spinning the magnets is the easiest way to maintain a changing magnetic flux. Other ways to move the magnets are moving the magnet up and down through a coil of wire, and dropping a magnet through a coil over and over.

SAMPLE RESULTS

Number of coil windings: 150

	Hand-spin trial	Drill-spin trial
Light LED bulb?	yes	yes
Light incandescent bulb?	yes	yes
Minimum voltage recorded (V)	–3.201	–3.02
Maximum voltage recorded (V)	3.322	2.98

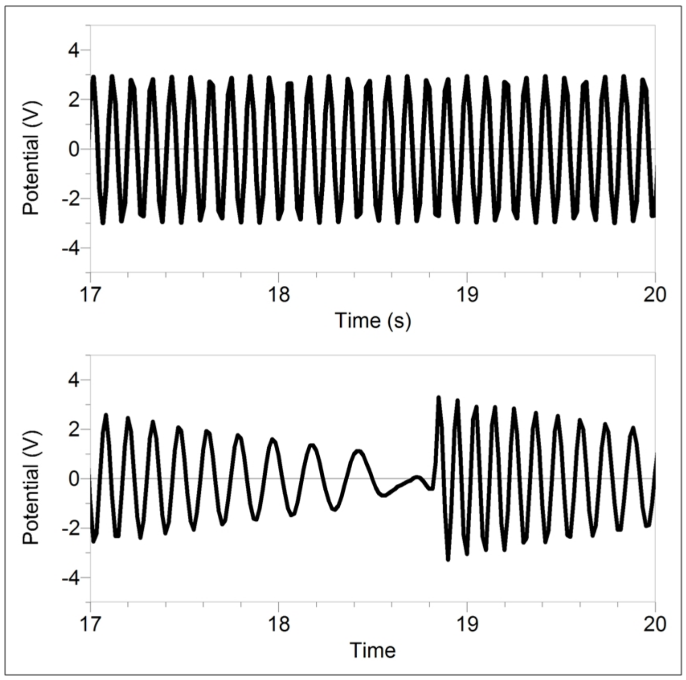

Figure 1 Potential data for a generator spun with a drill (top) and by hand (bottom)

ANSWERS TO ANALYSIS QUESTIONS

1. Yes, more windings of copper wire yields a higher voltage. If each group uses a different number of windings, the class results should show this trend.

2. In general, faster rotation of the magnets will yield higher voltage. In the Sample Results, notice that the graph of potential *vs*. time for a generator spun by hand shows a smaller range of potential when the spin slows down and a greater range of potential when the spinning is fastest.

3. The strength of the magnets, the proximity of magnets to copper wire, and "neatness" of copper coils are examples of other factors that may affect the power output of an electric generator.

4. The LED flickers because you are creating an alternating voltage and the polarity of the wires is flipping many times each second (the wave form on the graph shows you this). LEDs only allow electrons to pass in one direction, so they only light up when the polarity of the wires is correct.

Exploring Wind Turbines

For thousands of years, people have been harnessing wind energy to do work—from traveling around the world on sailing ships to milling grain using windmills. Today, wind is becoming more common as a renewable energy source through the use of wind turbines.

Wind turbines have four basic parts–a tower, turbine blades, a gear box, and a generator–that function together to convert kinetic energy from the wind into electrical energy. As the blades turn, they cause the gear box to turn, via a shaft. The turning gear box causes the generator to turn via a second shaft. The turning of the generator generates electricity.

The amount of electrical power that can be generated by a wind turbine is affected by many variables. In this experiment, you will explore variables that affect how a turbine turns. You will then use data-collection equipment to quantitatively investigate the effect of fan speed on the power output of a wind turbine.

OBJECTIVES

- Explore how wind turbines turn.
- Predict variables that affect how fast a wind turbine turns.
- Investigate the effect of fan speed on the power output of a wind turbine.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Energy
items needed from Advanced Wind Turbine Kit:
    Wind Turbine Tower
    Base
    Nacelle, assembled
    Hex Shaft
    2 Hex Locks
    8-tooth Pinion gear
    32-tooth gear
    Hub
    Blade Pitch Protractor
    2 wires with clips
fan
blade materials
scissors and hot glue
safety goggles

PROCEDURE

Part I Exploring wind turbines qualitatively

In Part I, you will use a fan and a wind turbine to learn more about how wind turbines work. You will make changes to the setup to explore how variables affect the wind turbine and how it turns.

1. Set up the fan and wind turbine.
   a. Assemble the turbine with three blades spaced evenly apart.
   b. Position the fan so the center of the fan is in line with the center of the hub of the turbine. The fan should be about 15 cm from the turbine.
   c. Clear off your area and make sure that when the fan and the turbine are moving, nothing is in the way.
2. Explore: What affects the direction in which a turbine spins?
   a. Put on safety goggles and turn on the fan to its lowest setting. In what direction is the turbine turning? If it is not turning, adjust the blades so that the turbine turns. **Caution**: Do not stand in the plane of rotation of the wind turbine rotor.
   b. Create a plan to make the turbine turn in the opposite direction.
   c. Carry out your plan after it is approved by your instructor.
   d. Were you successful in making the turbine turn in the opposite direction? Explain what you did to make the turbine change direction.
3. Explore: How does fan speed affect turbine speed?
   a. Make a prediction about how fan speed affects how fast the turbine turns. Explain why you think it will have this effect.
   b. Create a plan to investigate how fan speed affects how fast the turbine turns. What are you purposefully changing in this investigation? What will you keep constant?
   c. Carry out your plan after it is approved by your instructor.
   d. What is your conclusion about the relationship between fan speed and turbine speed based on your observations?
4. Explore: How does the distance between the fan and the turbine affect the turbine speed?
   a. Make a prediction about how the distance between the fan and the turbine affects how fast the turbine turns.
   b. Create a plan to investigate how the distance between the fan and the turbine affects how fast the turbine turns. What are you purposefully changing? What will you keep constant?
   c. Carry out your plan after it is approved.
   d. What is your conclusion based on your observations?
5. Explore: What are some additional variables that affect turbine speed?
   a. List at least three other variables that could affect how fast the turbine turns.
   b. Choose one variable and create a plan to investigate the effect of the variable on turbine speed.
   c. Carry out your plan after it is approved.
   d. What are you conclusions based on your observations?

Part II Exploring wind turbines quantitatively

In this part of the experiment, you will add data-collection equipment to the setup. You will explore how wind speed affects the wind turbine, but this time you will measure the electrical power generated.

6. Set the switch on the Energy Sensor to Internal Load. Launch Graphical Analysis. Connect the Energy Sensor to your Chromebook, computer, or mobile device.

7. Set up the equipment (see Figure 1).
   a. Connect the wind turbine to the Energy Sensor Source terminal wires.
   b. Adjust the blades so the turbine is set up with three blades spaced evenly apart and pitched at 30°.
   c. Position the fan so the center of the fan is in line with the center of the hub of the turbine. The fan should be about 15 cm from the turbine.
   d. Clear off your area and make sure that when the fan and the turbine are moving, nothing will be in the way.

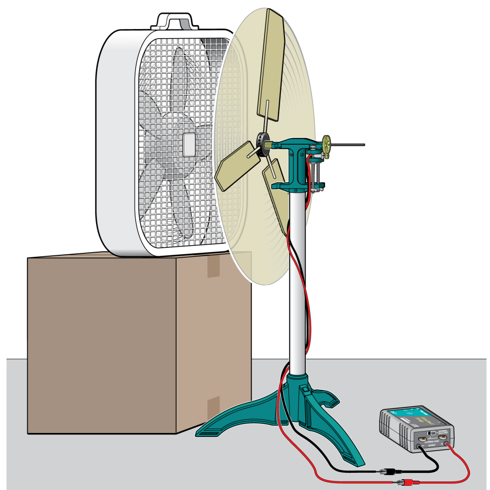

Figure 1

8. Check the current and voltage values.
   a. Put on safety goggles, and then turn on the fan. The wind turbine should be spinning. **Caution**: Do not stand in the plane of rotation of the rotor.
   b. Note whether the current and voltage values are positive, negative, or zero.
   c. Turn the fan off.
   d. The setup is correct if the values are positive. If the values are negative or zero, switch the wires connected to the Source terminal wires so they are connected to the opposite terminal wires.

9. Collect data.
   a. Click or tap Collect to start data collection. Data will be collected for 30 seconds. When data collection is complete, graphs of potential *vs*. time and current *vs*. time are displayed.
   b. Turn off the fan.
   c. Click or tap View, ⊞, and choose 1 Graph.

   d. Tap the y-axis label and select Power only. A graph of power *vs*. time is displayed.
   e. Click or tap Graph Tools, , and choose View Statistics to determine the mean power value. Record the value in the data table.

10. Collect additional data and determine the mean power.
    a. Turn the fan to the next setting. Wait 30 seconds, or until the fan and the turbine blades reach a constant speed.
    b. Click or tap Collect to start data collection.
    c. When data collection is complete, turn off the fan. Click or tap Graph Tools, , and choose View Statistics to determine the mean power value. Record the value in the data table.

11. If your fan has more than two settings, repeat data collection and analysis once more, for a total of three trials.

DATA TABLE

Fan setting	Power (mW)

DATA ANALYSIS

1. Create a graph of power *vs*. fan setting.
2. Write a statement that describes the relationship between fan setting and power output of the wind turbine.

EXTENSION

Using the list of variables that you created in Part I, choose one and design an experiment to measure the effect of the variable on the power output of the turbine. Have your experimental design approved by your instructor before testing your prediction.

Exploring Wind Turbines

In this experiment, students are introduced to wind turbines. They begin with a qualitative examination, exploring how different variables affect how the wind turbine spins. In the second part of the experiment, students quantitatively measure how fan speed affects the power output of the wind turbine using data-collection equipment.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Zero sensors, if using the Vernier Energy Sensor.
- Use the Statistics tool in the data-collection app to calculate statistics.
- Create a graph from data collected during data collection.
- Change what is plotted on the graphs.

ESTIMATED TIME

We estimate that data collection and analysis can be completed in one 45-minute class period. You may want to limit the number of variables that are investigated in Part I or assign groups to a variable.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking questions and defining problems Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Engaging in argument from evidence	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3)	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter

EQUIPMENT TIPS

1. Set up a safe testing area.
   - Clear the area of debris and materials.
   - Instruct your students to not stand in the plane of rotation of the turbine blades. Also tell them that they should not touch the blades while they are spinning. Blades can be moving very fast and can hurt if they hit someone.
   - Provide safety goggles for your students. Students should wear safety goggles when they are working with a turbine that is spinning.
2. Assemble the wind turbine towers in advance, if they are not already assembled. The video found at **https://vimeo.com/114691934** shows how to assemble the tower, nacelle, and generator mounting.
3. This experiment was designed using a KidWind Advanced Wind Turbine and three blades. Any of the classroom KidWind wind turbines will work for this experiment, as they all use a DC motor for a generator. Different generators will produce different power levels and may have a different internal resistance.
4. This experiment was designed using an energy sensor. It may also be done with a current probe and a voltage probe; students will need to create a calculated column in the data-collection app to calculate power. For more information, see **www.vernier.com/til/3184**
5. If you do not have a Vernier Variable Load, you can perform this experiment using the Vernier Resistor Board (order code: VES-RB). Otherwise, students can build a circuit to create the appropriate resistance value.
6. A classroom set of blades that are known to give good results will be helpful for this experiment. Blades that start near the hub of the wind turbine work well. For best results, the radius of the wind turbine should not exceed the radius of the fan. See Appendix B for additional tips about designing blades.

DATA-COLLECTION AND ANALYSIS TIP

For Part I, give students time to explore their wind turbine before giving them the answer.

SAMPLE RESULTS

Fan setting	Power (mW)
High	50.87
Medium	27.65
Low	10.30

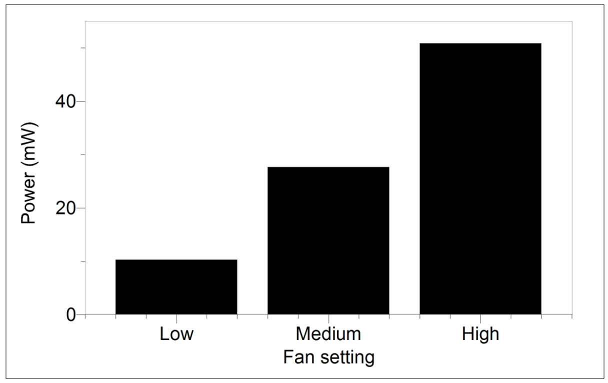

Figure 1 Power output levels for different fan settings

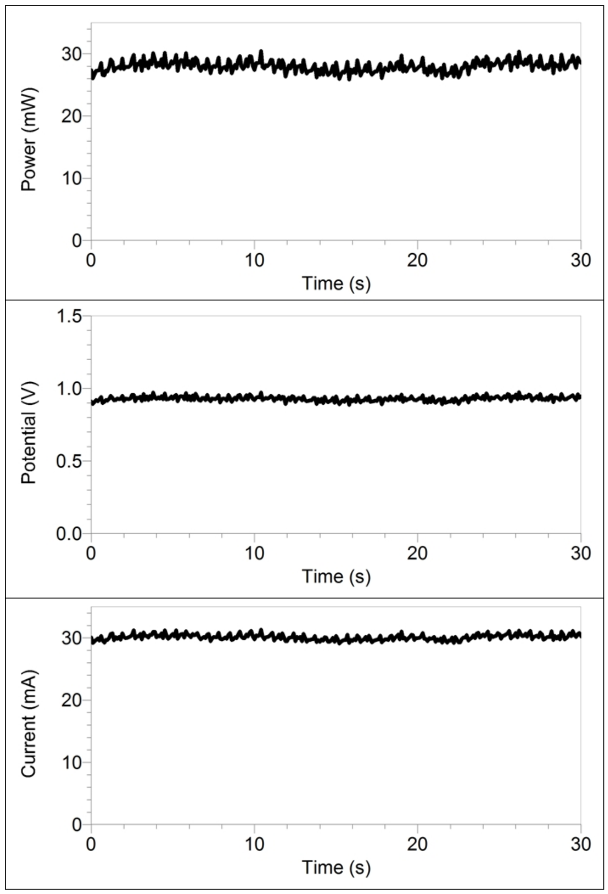

Figure 2 Raw data for a fan set to the medium setting

ANSWERS TO ANALYSIS QUESTIONS

1. See Sample Results.
2. The higher the fan setting, the greater the power production.

Effect of Load on Wind Turbine Output

Electricity is used to run many things in our daily lives, and each device that uses electricity can be considered a *load*. A load uses electrical energy to accomplish its task. The simplest form of a load is a resistor, which converts electrical energy into thermal energy. In most cases, resistors are used to adjust the amount of energy getting to part of a device by changing a voltage or diverting a current, but in a few cases thermal energy is the desired result, as with space heaters and toasters.

If you have done Experiment 5 "Current and Resistors," you found that as the amount of load (resistance) in a circuit increases, the current decreases. You also found that as you change the amount of load in the circuit, the voltage changes only a small amount. If you have done Experiment 8 “Exploring Wind Turbines,” you found that when voltage and/or current increases in a circuit, the amount of power also increases.

In this experiment, you will measure the power output of a wind turbine and determine the optimal load. That is, you will determine the resistance for which the power output is greatest. You will then compare the optimal load to the internal resistance of the generator.

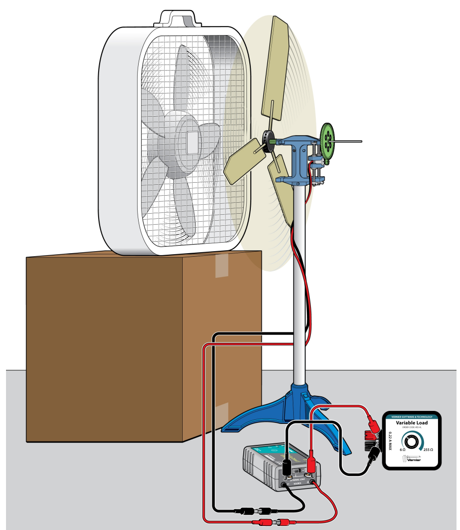

Figure 1

OBJECTIVES

- Determine how power output of turbine varies depending on the resistance (load) in the circuit.
- Compare internal resistance and optimal load.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Energy
Vernier Variable Load
items needed from the Advanced Wind Turbine Kit:
  Wind Turbine with Nacelle, Gears, and Generator, assembled
  Wind Turbine Hub
  Blade Pitch Protractor
  2 wires with clips
fan
blade materials
scissors and hot glue
safety goggles

PRELIMINARY QUESTIONS

1. What is an electrical load?
2. Do you think the generator (and therefore the turbine) will spin faster with a large load or with a small load? Why do you make that guess?
3. Sketch a graph showing your prediction of the relationship between power output and resistance (load).

PROCEDURE

1. Set the switch on the Energy Sensor to External Load. Launch Graphical Analysis. Connect the Energy Sensor to your Chromebook, computer, or mobile device.
2. Set up the equipment.
   a. Connect the wind turbine to the Energy Sensor Source terminal wires.
   b. Connect the Variable Load to the Energy Sensor External Load terminals.
   c. Assemble the turbine with three blades spaced evenly apart.
   d. Position the fan so the center of the fan is in line with the center of the hub of the turbine. The fan should be about 15 cm from the turbine.
   e. Clear off your area and make sure that when the fan and the turbine are moving, nothing will be in the way.
3. Check the current and voltage values.
   a. Put on safety goggles and turn on the fan. The wind turbine should be spinning. **Caution**: Do not stand in the plane of rotation of the rotor.
   b. Note whether the current or voltage values are positive, negative, or zero. Turn off the fan.
   c. The setup is correct if the values are positive. If the values are negative or zero, switch the wires connected to the Source terminal wires so the connections are opposite.

4. Turn on the fan to the highest setting. Wait 30 seconds, or until the fan and the turbine blades reach a constant speed.

5. Adjust the load.
   a. Note the Resistance value in the Resistance meter. Adjust the load by turning the knob on the Variable Load until the resistance is approximately 10 Ω.
   b. Record the calculated resistance from the Resistance meter in the data table.

6. Click or tap Collect to start data collection. Data will be collected for 30 seconds.

7. Determine the mean power.
   a. Click or tap View, , and choose 1 Graph. A single graph is shown.
   b. Tap the y-axis label and select Power only. A graph of power *vs*. time is displayed.
   c. Click or tap Graph Tools, , and choose View Statistics. Record the value.

8. Repeat Steps 6 and 7 to collect data for a second trial with the same resistance. **Note**: When you repeat data collection, you can skip Steps 7 a–b.

9. Repeat Steps 5–8 with a resistance of 20 Ω. The location of the turbine and fan should remain the same for each trial.

10. Repeat Steps 5–8 for the following resistance values: 30, 40, 50, 60, 70, 80, 90, 100, 150, and 200 Ω. When you are done, turn off the fan.

DATA TABLE

Resistance (Ω)	Trial	Power (mW)	Average power (mW)	Resistance (Ω)	Trial	Power (mW)	Average power (mW)
About 10	1			About 70	1		
Calculated: _______	2			Calculated: _______	2		
About 20	1			About 80	1		
Calculated: _______	2			Calculated: _______	2		
About 30	1			About 90	1		
Calculated: _______	2			Calculated: _______	2		
About 40	1			About 100	1		
Calculated: _______	2			Calculated: _______	2		
About 50	1			About 150	1		
Calculated: _______	2			Calculated: _______	2		
About 60	1			About 200	1		
Calculated: _______	2			Calculated: _______	2		

PROCESSING THE DATA

1. Calculate the average power for each resistance.

2. Create a graph of average power *vs*. resistance.

ANALYSIS QUESTIONS

1. Does power output remain the same or vary depending on resistance?

2. What is the optimal load, the resistance at which there was a maximum power output, for your wind turbine?

3. What is the internal resistance of your generator? You can determine this by using a digital multimeter that can measure resistance. Your teacher may provide you with this number.

4. How does the internal resistance of your generator compare to the optimal load for power output?

EXTENSIONS

1. In this experiment you held the wind speed constant as you collected power output data. Design and perform an experiment to vary the wind speed and determine what effect it would have on the power output.

2. Do research to learn about maximum power point trackers. What is a maximum power point tracker (MPPT) and what does it do? Why are they important to renewable energy devices such as wind turbines and solar panels?

Effect of Load on Wind Turbine Output

In this experiment, students measure the power output of a KidWind wind turbine under a variety of loads. They will use their data to determine the relationship between optimal resistance and internal resistance.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Zero sensors, if using the Vernier Energy Sensor.
- Use the Statistics tool in the data-collection app to calculate statistics.
- Create a graph using data collected during the experiment.

ESTIMATED TIME

We estimate that data collection for this experiment can be completed in one 45-minute class period. You may need to allow extra time for the Analysis and Extension.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Obtaining, evaluating, and communicating information	PS2.A Forces and Motion (HS-PS2) PS2.B Types of Interactions (HS-PS2) PS3.A Definitions of Energy (HS-PS3)	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter

EQUIPMENT TIPS

1. Set up a safe testing area.
   - Clear the area of debris and materials.
   - Instruct your students to not stand in the plane of rotation of the turbine blades. Also tell them that they should not touch the blades while they are spinning. Blades can be moving very fast and can hurt if they hit someone.
   - Provide safety goggles for your students. Students should wear safety goggles when they are working with a turbine that is spinning.
2. Assemble the wind turbine towers in advance, if they are not already assembled. The video found at **https://vimeo.com/114691934** shows how to assemble the tower, nacelle, and generator mounting.
3. This experiment was designed using a KidWind Advanced Wind Turbine and three blades. Any of the KidWind wind turbines will work, as they all use a DC motor for a generator. Different generators will produce different power levels and may have a different internal resistance.
4. This experiment was designed using an energy sensor. It may also be done with a current probe and a voltage probe; students will need to create a calculated column in the data-collection app to calculate power. For more information, see **www.vernier.com/til/3184**
5. A quick way to measure the internal resistance of the wind turbine generator is to use a digital multimeter that can measure resistance. The turbine should not be turning when the resistance reading is made.
6. If you do not have a Vernier Variable Load, the resistors on the Vernier Resistor Board (order code: VES-RB) allow you to collect some of the data for this experiment. Students will be able to answer the Analysis Questions based on their data, but they will not see a complete set of data. If you do not have a Vernier Resistor Board, students can wire combinations of resistors in series and parallel to create similar resistance values to those in the data table.
7. The fan should be set on a speed setting so that it will spin the turbine at all available load levels. This may require turning the fan to the highest setting or moving it closer to the turbine, depending on the model of fan you are using.
8. A classroom set of blades that are known to give good results will be helpful for this experiment. Blades that start near the hub of the wind turbine work well. For best results, the radius of the wind turbine should not exceed the radius of the fan. See Appendix B for additional tips about designing blades.

DATA-COLLECTION AND ANALYSIS TIPS

1. The internal resistance of the generator used to collect sample data, which was the same type as the generator in the KidWind Advanced Wind Experiment Kit, was about 50 Ω.
2. In this experiment, students record the resistance value from the Resistance meter in the data-collection software. This value is calculated from the voltage and current measurements, which is why the student instructions refer to the calculated resistance from the Resistance meter.

3. You may wish to discuss with students why it is more difficult for the wind to turn the turbine under certain loads. Consider the following points in your discussion.
    - Imagine that there is no load on the turbine and the circuit is open (unconnected). This means that the turbine will not be transforming any of the wind's kinetic energy into electrical energy, since current cannot flow. When no energy transformation is taking place, the blades of the turbine spin easily, taking very little effort to spin by hand and very little wind to make them move.
    - Now imagine a different case, when there is a load. In this situation, the turbine is transforming the kinetic energy of the wind into kinetic energy of the spinning blades and electrical energy. Since some of the wind's energy is transforming into electrical energy, less of the wind's energy will transform into kinetic energy of the blades. Thus the turbine will spin slower.
    - If you were to vary the load from infinite resistance (open circuit) to zero resistance (short circuit, such as connecting a plain thick copper wire instead of a resistor), the amount of energy transformed from kinetic to electric will also vary. Depending on the details of the generator, there may be an optimum load where the turbine transforms the most energy from the wind into electrical energy. Maximizing the energy transformed from kinetic to electrical by the turbine and load system is one of your design goals. This optimum load will also be the load where it takes the most work from the wind to spin the turbine.

4. A Genecon hand-cranked generator, available from a variety of online retailers, can be a good way for students to get a feel for the difference between operating a generator under a load versus operating a generator without a load. Let students turn the crank under situations where the Genecon wires are not connected to anything, when the wires are clipped together, and when a small light bulb or another Genecon is connected to the wires (doing this will turn the handle of the other Genecon). They will be able to feel the difference.

ANSWERS TO PRELIMINARY QUESTIONS

1. An electrical load is something in a circuit that draws current to do work.
2. Answers will vary.
3. Answers will vary.

SAMPLE RESULTS

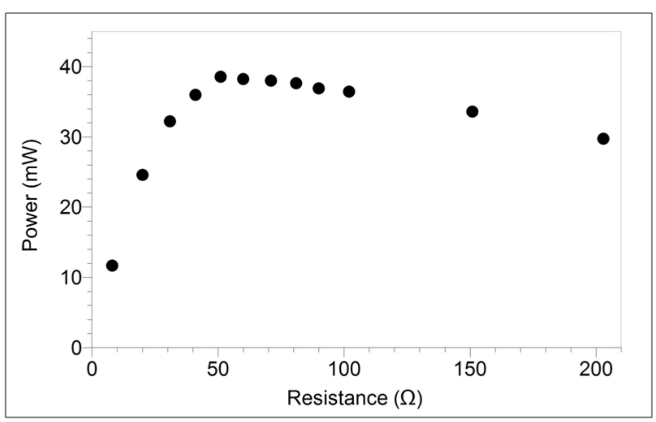

Figure 1 Effect of load on power output

Resistance (Ω)	Trial	Power (mW)	Average power (mW)	Resistance (Ω)	Trial	Power (mW)	Average power (mW)
About 10	1	11.29	11.65	About 70	1	38.25	37.99
Calculated: 8	2	12.01		Calculated: 71	2	37.72	
About 20	1	22.86	32.19	About 80	1	36.23	36.88
Calculated: 20	2	26.27		Calculated: 81	2	28.2	
About 30	1	31.56	38.53	About 90	1	37.01	33.58
Calculated: 31	2	32.81		Calculated: 90	2	36.29	
About 40	1	36.20	11.65	About 100	1	36.48	37.99
Calculated: 41	2	35.75		Calculated: 102	2	36.18	
About 50	1	38.52	32.19	About 150	1	33.44	36.88
Calculated: 51	2	38.54		Calculated: 151	2	33.71	
About 60	1	37.93	38.53	About 200	1	29.46	33.58
Calculated: 60	2	38.84		Calculated: 202	2	29.91	

ANSWERS TO ANALYSIS QUESTIONS

1. Power output varies depending on resistance.
2. Answers will vary. The optimal load for this generator was found to be at 50 Ω.
3. Answers will vary. The internal resistance of the wind turbine used to collect sample data was 50 Ω.
4. The internal resistance of the generator is very close to the optimal load for power output.

Blade Variables and Power Output

The blades of a wind turbine are what capture the kinetic energy of the wind so it can be converted into electrical energy, and therefore, blade design and engineering is one of the most complicated and important aspects of wind turbine technology. When designing blades, engineers try to develop blades that extract as much energy from the wind as possible throughout a range of wind speeds. Engineers must also consider durability and affordability when selecting materials for the blades.

Over time, engineers have experimented with many different shapes, designs, materials, and number of blades to find what works best. In this experiment, you will experiment with different blade designs to maximize power output.

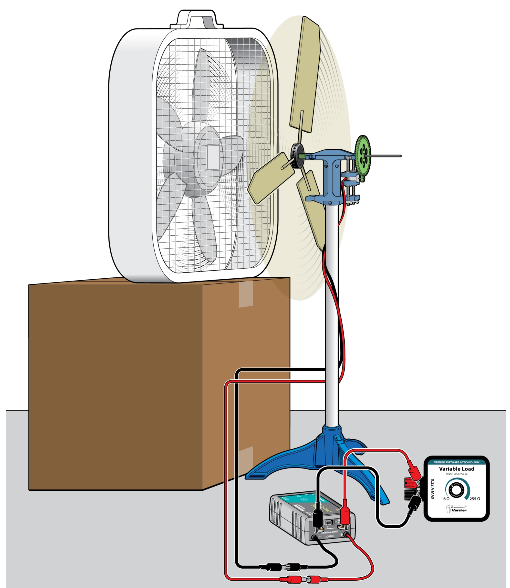

Figure 1

OBJECTIVES

- Test blade design variables.
- Understand how blade design variables affect power output.
- Evaluate data to determine which blade design is best at generating power.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Energy
Vernier Variable Load
items needed from the Advanced Wind Turbine Kit:
  Wind Turbine with Nacelle, Gears, and Generator, assembled
  Wind Turbine Hub
  Blade Pitch Protractor
  2 wires with clips
fan
ruler
blade materials
scissors and hot glue
safety goggles

PRELIMINARY QUESTIONS

1. What are some blade variables that may affect turbine performance?

2. What are some variables other than blades that may affect turbine performance and power output?

3. Choose a blade variable to adjust for improved turbine power output. Why did you choose that variable?

PROCEDURE

1. Create a plan to collect data for the blade variable you are testing. You will modify the blades 3–5 times for your blade variable. For example, if you are testing blade pitch, you will collect data for 3–5 different angles.

2. Set the switch on the Energy Sensor to External Load. Launch Graphical Analysis. Connect the Energy Sensor to your Chromebook, computer, or mobile device.

3. Set up the equipment.
   a. Connect the wind turbine to the Energy Sensor Source terminal wires.
   b. Connect the Variable Load to the Energy Sensor External Load terminals.
   c. Connect blades to the wind turbine based on your plan. For example, if you are testing blade length, your blades should be at the longest length that you will test.
   d. Position the equipment as shown in Figure 1. Align the center of the fan with the center of the wind turbine hub. Measure the distance between the fan and the turbine hub and ensure that the distance remains constant throughout the experiment.
   e. Clear off your area and make sure that when the fan and the turbine are moving, nothing will be in the way.

4. Check the current and voltage values.
   a. Put on safety goggles and turn on the fan. The wind turbine should be spinning. **Caution**: Do not stand in the plane of rotation of the rotor.
   b. Note whether the current or voltage values are positive, negative, or zero.
   c. Turn the fan off.
   d. The setup is correct if the values are positive. If the values are negative or zero, switch the wires connected to the Source terminal wires so they are connected to the opposite terminal wires.

5. Adjust the load.
   a. Turn on the fan to the highest setting. Wait 30 seconds, or until the fan and the turbine blades reach a constant speed.
   b. Note the Resistance value in the meter. Adjust the load by turning the knob on the Variable Load until the resistance is approximately 35 Ω or equal to the internal resistance of the generator you are using.

6. Collect data and determine the mean power.
   a. Click or tap Collect to start data collection. Data will be collected for 30 seconds. When data collection is complete, graphs of potential *vs*. time and current *vs*. time are displayed.
   b. Click or tap View, ⊞, and choose 1 Graph.
   c. Tap the y-axis label and select Power only. A graph of power *vs*. time is displayed.
   d. Click or tap Graph Tools, 📈, and choose View Statistics to determine the mean power value. Record the value in the data table.

7. Collect data for the second trial.
   a. Click or tap Collect to start data collection. Data will be collected for 30 seconds. When data collection is complete, turn off the fan.
   b. Click or tap Graph Tools, 📈, and choose View Statistics to determine the mean power value. Record the value in the data table.

8. Collect additional data.
   a. Modify the blades according to your plan.
   b. Return the fan and wind turbine to the correct positions. Check the distance between the fan and turbine. This distance should be the same each time you collect data.
   c. Turn on the fan to the same setting. Wait 30 seconds, or until the fan and the blades reach a constant speed.
   d. Repeat Steps 7 two times to collect a total of two runs of data for this modification.

9. Repeat Step 8 until you have collected all the data that you need to test your variable.

DATA TABLE

Variable: ______________	Trial	Power (mW)	Average power (mW)
	1		
	2		
	1		
	2		
	1		
	2		
	1		
	2		
	1		
	2		
	1		
	2		

PROCESSING THE DATA

1. Calculate an average power value for each modification.
2. Create a graph of average power *vs*. the variable you tested.

ANALYSIS QUESTIONS

1. Which blade modification produced the greatest power output? The least?
2. If you had the opportunity to collect data again, how would you modify your blades while still testing the same variable?
3. Share your results with the rest of the class. When you do this, describe your testing plan, how you designed the blades, and your results. After you have heard all the results, use the information to write a paragraph explaining which variable has the greatest affect on power output.

EXTENSIONS

1. Summarize the group findings in a report. Answer at least some of the following questions in your summary.
   - What variable has the greatest impact on power output?
   - What type of blades were the most powerful at low speeds? High speeds?
   - What number of blades resulted in the most power output?
   - What shapes worked best?
   - What length worked best? Did longer blades bend in the wind? Was this a problem?
   - What problems did you encounter?
   - What happened when the diameter of the turbine rotor was bigger than the diameter of the fan?

2. Use the collected data to design wind turbine blades that result in the greatest power output and test what you predict will be the best combination.

3. Test blades at a different wind speed. Does this affect the power output?

Blade Variables and Power Output

In this experiment, students test blade design variables and calculate the power output for each modification using current and voltage measurements.

We suggest starting the experiment with a brainstorming session. Record students' ideas and have the groups pick different variables. This way, as a class, you will cover a wide variety of variables. If you would rather, simply assign variables to the groups. Options for variables include (among others)

- Length
- Number of blades
- Pitch
- Shape (outline, tip shape, or airfoil shape)
- Width
- Blade material

See Appendix B for additional tips about blade variables.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Zero sensors, if using Vernier Energy Sensor.
- Use the Statistics tool to calculate statistics.
- Create a graph using data collected during the experiment.

ESTIMATED TIME

We estimate that data collection for this experiment can be completed in one 45-minute class period. Allow for time in following class period(s) to complete analysis and for students to share their data.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking questions and defining problems Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Obtaining, evaluating, and communicating information	PS3.A Definitions of Energy (HS-PS3)	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter

EQUIPMENT TIPS

1. Set up a safe testing area.
   - Clear the area of debris and materials.
   - Instruct your students to not stand in the plane of rotation of the turbine blades. Also tell them that they should not touch the blades while they are spinning. Blades can be moving very fast and can hurt if they hit someone.
   - Provide safety goggles for your students. Students should wear safety goggles when they are working with a turbine that is spinning.

2. Depending on the variable being tested, some groups will have to build multiple sets of blades, while other groups will only build one set. For example, the group testing blade material will have to build one set of identical blades for each material being tested. The group testing pitch/angle, however, will only build one set of blades and then test the angle of these blades on the turbine. As it can take quite a bit of time to build sets of blade, groups that test multiple sets may require more time.

3. All students should understand the concept of blade pitch (angle), how they will measure it (e.g., a Blade Pitch Protractor), and how they will vary it or keep it constant. Small changes in blade pitch can greatly affect efficiency and power output.

4. This experiment was designed using an energy sensor. It may also be done with a current probe and a voltage probe; students will need to create a calculated column in the data-collection app to calculate power. For more information, see **www.vernier.com/til/3184**

5. This experiment was written using a KidWind Advanced Wind Turbine. Any of the KidWind wind turbines will work, as they all use a DC motor for a generator. Different generators will produce different power levels and may have a different internal resistance.

6. The student version of the experiment is written assuming the use of the Vernier Variable Load. Remind your students to use a resistance value that most closely matches the internal resistance of the turbine. Generally, for KidWind generators, this is a resistance value of 35–50 Ω. If your students will be using the Vernier Resistor Board or a single resistor, you may need to help them set up the circuit.

7. Wind from a fan is very turbulent and does not accurately represent the wind a turbine would experience in the real world. To clean up the turbulent wind from the fan, students can build a "honeycomb" in front of the fan using milk cartons, PVC pipe, or paper towel rolls. Note that this will also slow the wind coming off the fan.

DATA-COLLECTION AND ANALYSIS TIPS

1. In most cases, the center of the fan hub should be aligned with the center of the wind turbine. If this does work, you can move the fan as necessary.
2. Unless students are testing pitch, they must keep pitch constant.
3. In the Analysis Questions, students are instructed to share their results with the class. You may choose to alter this question and have students simply write a report of their findings.

ANSWERS TO PRELIMINARY QUESTIONS

1. Answers will vary. Some answers may include blade pitch, blade length, number of blades, blade weight, blade shape, blade material, and blade twist (variable pitch).
2. Answers will vary. Some answers may include type of generator, wind speed, tower vibration, and turbine orientation relative to wind direction.
3. Answers will vary.

SAMPLE RESULTS

To collect sample data, we investigated the effect of blade pitch. Student results will vary.

Variable: blade pitch (°)	Trial	Power (mW)	Average power (mW)
10	1	36.41	35.80
	2	35.18	
20	1	47.70	47.55
	2	47.39	
30	1	38.67	37.95
	2	37.22	
40	1	25.79	24.93
	2	24.06	
50	1	16.95	16.99
	2	17.03	

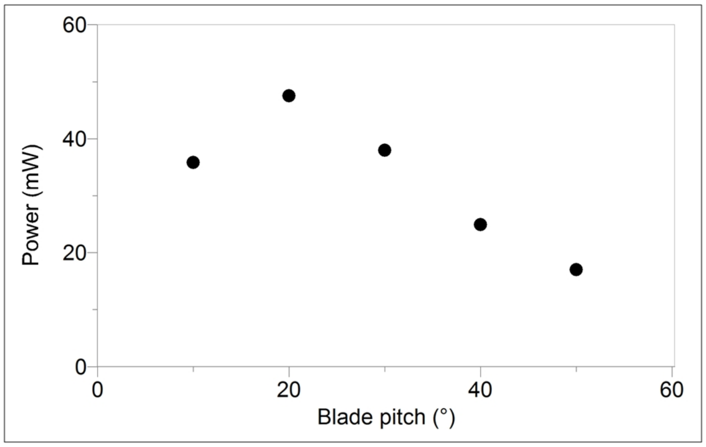

Figure 1 Relationship between power and blade pitch

ANSWERS TO ANALYSIS QUESTIONS

1–3. Answers will vary depending on the blade variables examined.

Solidity

Consider the wind turbines in Figures 1 and 2. What differences do you observe? These two examples are designed for two different purposes. The windmill in Figure 1 is designed to pump water; the turbine in Figure 2 is designed to generate electricity. In addition to variations in the tower design and number of blades, notice that the total surface area of the blades in each turbine is very different.

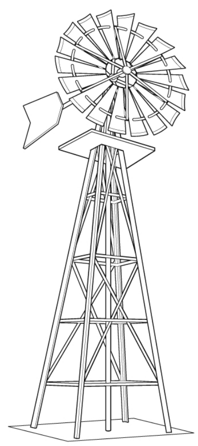

Figure 1

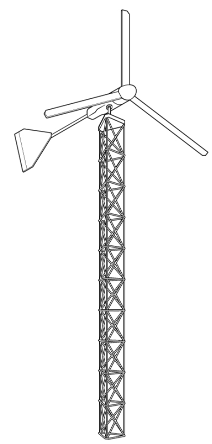

Figure 2

Solidity, the ratio of the total surface area for all blades to the total swept area, is calculated using the equation

$$\text{solidity} = na/A$$

where n is the number of blades, a is the area of a single blade, and A is the swept area of the turbine.

Turbines with a high solidity (e.g., greater than 0.80), rotate at a low speed, while turbines with a low solidity (e.g., 0.10), rotate at a higher speed.

Blade pitch dramatically affects the torque, speed, and the amount of drag experienced by the blades of the rotor. It also affects the solidity of the turbine. Blades with a shallow pitch (10–30°) have less drag, and provide greater solidity by presenting more of their surface to the wind. However, they can't provide as much torque (turning force) to the generator. A greater pitch (30–60°) has less solidity and more drag, but can provide more torque to the generator.

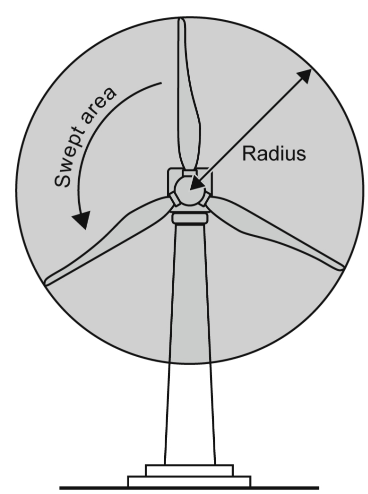

Figure 3

In this experiment, you will calculate the *planform* area, the area the blade projects onto the plane of rotation, using the area of the blade and its pitch. You will use the total planform area (for all blades) to calculate the solidity of the wind turbine. You will then investigate how the turbine solidity affects electrical power output.

OBJECTIVES

- Measure the total blade planform area.
- Calculate the total area swept by a wind turbine blade.
- Calculate solidity of a wind turbine.
- Investigate the relationship between power output and solidity.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Energy
Vernier Variable Load
items needed from the Advanced Wind Turbine Kit:
  Wind Turbine with Nacelle, Gears, and Generator, assembled
  Wind Turbine Hub
  Blade Pitch Protractor
  2 wires with clips
fan
blade materials
scissors and hot glue
ruler
safety goggles

PRELIMINARY QUESTIONS

1. What is solidity? Can you describe what solidity is without using the formula?
2. What type of application would be good for a high-solidity wind turbine?
3. What type of application would be good for a low-solidity wind turbine?

PROCEDURE

1. Create a plan to collect data to investigate how turbine solidity affects power output. The only variable you will change when collecting data is the number of blades—the blade design and blade pitch will be kept constant.
2. Set the switch on the Energy Sensor to External Load. Launch Graphical Analysis. Connect the Energy Sensor to your Chromebook, computer, or mobile device.

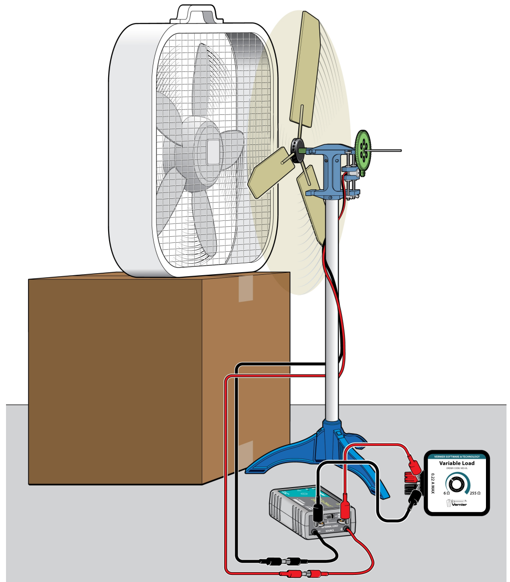

Figure 4

3. Set up the equipment.
   a. Attach the blades to the hub based on your plan.
   b. Connect the Variable Load to the Energy Sensor External Load terminals.
   c. Measure the radius of the turbine (see Figure 3) and record the value in Table 1.
   d. Position the fan and wind turbine as shown in Figure 4. Align the center of the fan with the center of the turbine hub. Measure the distance between the fan and the turbine hub and ensure that the distance remains constant throughout the experiment.
   e. Clear off your area and make sure that when the fan and the turbine are moving, nothing will be in the way.

4. Check the current and voltage values.
   a. Put on safety goggles and turn on the fan. The wind turbine should be spinning. **Caution**: Do not stand in the plane of rotation of the rotor.
   b. Note whether the current or voltage values are positive, negative, or zero.
   c. Turn off the fan.
   d. The setup is correct if the values are positive. If the values are negative or zero, switch the wires connected to the Source terminal wires so they are connected to the opposite terminal wires.

5. Adjust the load.
   a. Turn on the fan to the high setting. Wait 30 seconds, or until the fan and the turbine blades reach a constant speed.
   b. Note the Resistance value in the meter. Adjust the load by turning the knob on the Variable Load until the resistance is approximately 35 Ω or equal to the internal resistance of the generator you are using.

6. Collect data and determine the mean power value.
   a. Click or tap Collect to start data collection. Data will be collected for 30 seconds. When data collection is complete, graphs of voltage *vs*. time and current *vs*. time are displayed.
   b. Click or tap View, , and choose 1 Graph.
   c. Tap the y-axis label and select Power only. A graph of power *vs*. time is displayed.
   d. Click or tap Graph Tools, , and choose View Statistics to determine the mean power value. Record the value in the data table.

7. Collect additional data.
   a. Click or tap Collect to start data collection. Data will be collected for 30 seconds. When data collection is complete, turn off the fan.
   b. Click or tap Graph Tools, , and choose View Statistics to determine the mean power value. Record the value in the data table.

8. Add blades and collect additional data.
   a. When the blades have stopped turning, increase the number of blades based on your plan, ensuring that the blade pitch remains the same.
   b. Return the fan and wind turbine to the correct positions. Check the distance between the fan and turbine. The wind speed (fan setting) should be the same each time you collect data.
   c. Turn on the fan to the high setting. Wait for 30 seconds or until the fan and the blades reach a constant speed. **Caution**: Do not stand in the plane of rotation of the rotor.
   d. Repeat Step 7 to collect a total of two runs of data for this number of blades.

9. Repeat Step 8 until you have collected data for 3–5 different numbers of blades.

DATA TABLE

Table 1

Number of blades	Radius (m)	Trial	Power (mW)	Average power (mW)
		1		
		2		
		1		
		2		
		1		
		2		
		1		
		2		
		1		
		2		

Table 2				
Number of blades	Planform area per blade (m^2)	Total planform area (m^2)	Swept area (m^2)	Solidity

DATA ANALYSIS

1. Calculate an average power value for each number of blades.
2. Determine the planform area of the blade.
   a. Measure the length and width of the blade and calculate its area.
   b. Determine the planform area by multiplying the blade area by the cosine of the blade pitch. Record this value in Table 2.
3. For each set of blades, calculate the total planform area of the blades and record this value in your table.
4. Calculate the swept area, A, using the measured radius r, where $A=\pi r^2$.
5. Calculate the solidity for the number of blades. Solidity can be calculated as the ratio of the total planform area to the swept area:

$$\text{solidity} = \frac{\text{total planform area}}{\text{swept area}}$$

6. Examine your power and solidity data. How does solidity affect power? Make a graph of average power *vs*. solidity.

ANALYSIS QUESTIONS

1. Based on your data, do you want to maximize or minimize solidity for a turbine that is generating electricity? Why?
2. If you had the opportunity to collect data again, how would you modify your blades while still testing solidity?

EXTENSIONS

1. Collect and graph solidity and power data from classmates. How does power vary with solidity?

2. Repeat this experiment with modified turbine blades according to your answer in the second analysis question. Do the results hold up?

3. Attach the spool to the Advanced Wind Turbine as in Experiment 6 "Mechanical Power." Investigate the relationship between solidity and mechanical power generation.

Solidity

In this experiment, students use wind turbines to investigate how blade pitch affects power generation. An interesting way to investigate this phenomenon is through the turbine solidity, which is the ratio of the total planform area of all blades to the swept area of the blades.

We suggest setting up groups to collect a wide range of solidities. Some groups can have a large number of blades while others can use shorter or longer blades. If you do this, students can share their data and have a broader data set with which to do analysis.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Zero sensors, if using the Vernier Energy Sensor.
- Use the Statistics tool in the data-collection app to calculate statistics.
- Use the Photo Analysis tool, if using Logger *Pro*.

ESTIMATED TIME

We estimate that data collection for this experiment can be completed in one 45-minute class period. Allow for time in following class period(s) to complete analysis and for students to share their data.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking questions and defining problems	PS3.A Definitions of Energy (HS-PS3)	Patterns
Developing and using models	PS3.B Conservation of Energy and Energy Transfer (HS-PS3)	Cause and effect
Planning and carrying out investigations		Scale, proportion, and quantity
Analyzing and interpreting data		Systems and system models
Using mathematics and computational thinking		Energy and matter
Obtaining, evaluating, and communicating information		

EQUIPMENT TIPS

1. Set up a safe testing area.
   - Clear the area of debris and materials.
   - Instruct your students to not stand in the plane of rotation of the turbine blades. Also tell them that they should not touch the blades while they are spinning. Blades can be moving very fast and can hurt if they hit someone.
   - Provide safety goggles for your students. Students should wear safety goggles when they are working with a turbine that is spinning.
2. Students using Logger *Pro* can determine the planform area of one blade by using photo analysis. When taking a photo to import into Logger *Pro*, capture at least one complete blade and the center of the Hub. This will make it possible to use the radius to scale your photo in Logger *Pro*. Students need to be able to transfer the photos between their camera and their computer. Photos taken with a cell phone camera work well.
3. Students not using Logger *Pro* will need to determine the planform area of one blade using the area of the blade multiplied by the cosine of the blade pitch angle. Students using this method should use rectangular blades.
4. All students should understand the concept of blade pitch and how they will measure it (e.g., using a Blade Pitch Protractor). Small changes in blade pitch can greatly affect efficiency and power output.
5. Students will be changing only the number of blades between runs. It is important that all other factors remain constant, including blade design, blade pitch, and distance to fan.
6. This experiment was designed using an energy sensor. It may also be done with a current probe and a voltage probe; students will need to create a calculated column in the data-collection app to calculate power. For more information, see **www.vernier.com/til/3184**
7. This experiment was designed using a KidWind Advanced Wind turbine. Any of the KidWind wind turbines will work, as they all use a DC motor for a generator. Different generators will produce different power levels and may have a different internal resistance.
8. Remind your students to set the Variable Load to the resistance that most closely matches the internal resistance of the turbine. If your students will be using the Vernier Resistor Board or an individual resistor, you may want to make changes to the student version of the experiment.
9. Wind from a fan is very turbulent and does not accurately represent the wind a turbine would experience in the real world. To clean up the turbulent wind from the fan, students can build a "honeycomb" in front of the fan using milk cartons, PVC pipe, or paper towel rolls. Note that this will also slow the wind coming off the fan.

DATA-COLLECTION AND ANALYSIS TIPS

1. In most cases, the center of the fan hub should be aligned with the center of the wind turbine. If this does not work for your equipment, move the fan as necessary.
2. If taking photos for use in Logger *Pro*, emphasize to your students the importance of aligning the camera plane parallel with the plane of motion of the turbine. If not in alignment, the planform areas calculated in Logger *Pro* will be incorrect.

ANSWERS TO PRELIMINARY QUESTIONS

1. Solidity is a measure of how much of the circle swept by the turbine blades is covered up by the turbine blades. More wind can pass through a wind turbine rotor with a low solidity than can pass through a wind turbine with high solidity.
2. A wind turbine with high solidity can be used for pumping water.
3. A wind turbine with low solidity can be used for generating electricity.

SAMPLE RESULTS

Student results will vary.

Number of blades	Radius (m)	Trial	Power (mW)	Average power (mW)
2	0.195	1	7.30	7.72
		2	8.14	
3	0.195	1	21.73	21.47
		2	21.21	
4	0.195	1	46.17	44.61
		2	43.05	
6	0.195	1	108.9	106.3
		2	103.6	
12	0.195	1	88.53	92.03
		2	95.53	

Number of blades	Planform area per blade (m^2)	Total planform area (m^2)	Swept area (m^2)	Solidity
2	4.89×10^{-3}	9.78×10^{-3}	0.119	0.082
3	4.89×10^{-3}	1.47×10^{-2}	0.119	0.123
4	4.89×10^{-3}	1.96×10^{-2}	0.119	0.164
6	4.89×10^{-3}	2.93×10^{-2}	0.119	0.246
12	4.89×10^{-3}	5.87×10^{-2}	0.119	0.493

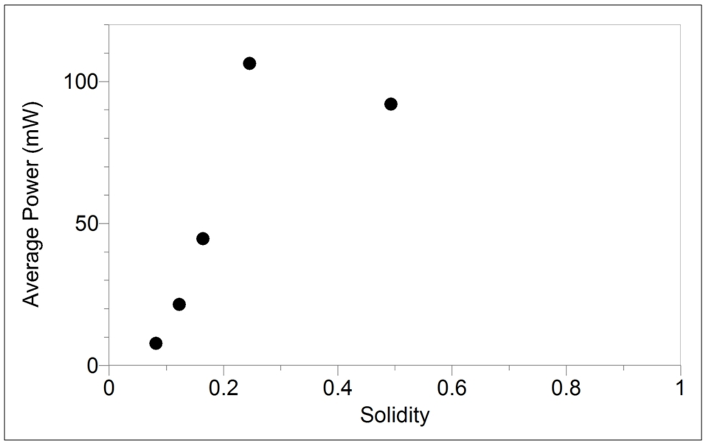

Figure 1 Relationship between power output and solidity

ANSWERS TO ANALYSIS QUESTIONS

1. In the sample data, the turbine with a solidity of about 0.25 performed the best. This was not the lowest or the highest solidity tested.

2. Answers will vary.

Turbine Efficiency

The efficiency of a wind turbine can be defined by the following equation:

$$\text{efficiency} = \frac{\text{electrical power transformed by the wind turbine}}{\text{power available in the wind}}$$

For a wind turbine to be 100% efficient, all of the energy available in the wind would be converted into electricity. In other words, all of the energy in the wind would be transformed and the air would stop moving. This is not possible in practice because a rotor only spins if the wind passes over the blades. If a rotor were to stop all the moving air, the turbine would not be able to convert the wind's kinetic energy to electrical energy.

A German physicist, Albert Betz, calculated that it is impossible to design a wind turbine that is able to convert more than 59.3% of the kinetic energy of the wind into mechanical energy turning a rotor. Known as the Betz Limit, 59.3% is the theoretical maximum efficiency for any wind turbine operating in real-world conditions (open air flow). In typical operating wind speeds, most modern wind turbines are 25–45% efficient.

The Betz Limit applies only to the transformation of the kinetic energy in the wind into mechanical energy in the rotating blades. The generator in the wind turbine, which transforms the mechanical energy into electrical energy, further reduces the total efficiency. To understand this process, imagine that the blades of a wind turbine convert 50% of the available power in the wind into mechanical energy (rotation). Then, the generator converts 80% of this mechanical energy into electrical energy. The overall efficiency of this wind turbine would therefore be 0.5 × 0.8 = 0.4, or 40% efficient.

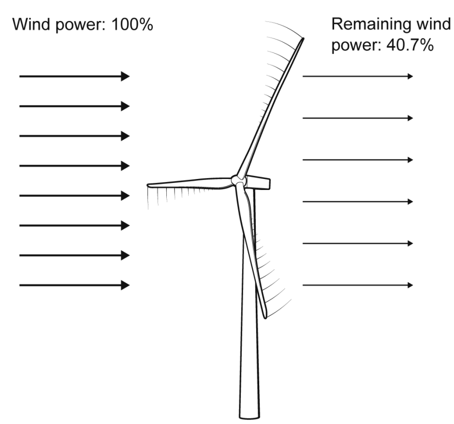

Figure 1 A wind turbine operating at the Betz Limit

When designing blades for a wind turbine, engineers try to maximize the efficiency of the rotor across a range of wind speeds—a wind turbine needs to be highly efficient at low wind speeds (4 to 8 m/s), which are most common, but it also needs to perform and survive in extreme wind speeds (>25 m/s)! Over time, engineers have experimented with many different shapes, designs, materials, and number of blades to find which work best. In this experiment, you will experiment with different blade designs to maximize efficiency.

OBJECTIVES

- Measure the power produced by a wind turbine.
- Calculate the efficiency of a wind turbine.
- Test blade design variables.
- Evaluate data to determine which blade design is most efficient.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Energy
Go Direct Weather
Vernier Variable Load
items needed from the Advanced Wind Turbine Kit:
    Wind Turbine with Nacelle, Gears, and Generator, assembled
    Wind Turbine Hub
    Blade Pitch Protractor
    2 wires with clips
fan
blade materials
scissors and hot glue
ruler
safety goggles

PRELIMINARY QUESTIONS

1. How many blades do most electrical generating wind turbines have? Do you think adding more blades would improve or decrease the efficiency? Why?
2. Why can't wind turbines convert 100% of the moving wind into rotational energy to be used by the generator?
3. Choose a blade variable to adjust for improved turbine efficiency. Why did you choose that variable?

PROCEDURE

1. Create a plan to collect data for the blade variable you are testing. You will modify the blades 3–5 times for your blade variable. For example, if you are testing blade pitch, you will collect data for 3–5 different blade pitches.
2. Set the switch on the Energy Sensor to External Load. Launch Graphical Analysis. Connect the Energy Sensor as well as the Weather Sensor to your Chromebook, computer, or mobile device.

3. Set up the equipment.
   a. Set up the blades based on your plan. For example, if you are testing blade length, your blades should be at the longest length that you will test.
   b. Measure the radius of the turbine (see Figure 2) and record the value in Table 2.
   c. Connect the wind turbine to the Energy Sensor Source terminal wires.
   d. Connect the Variable Load to the Energy Sensor External Load terminals.
   e. Position the equipment as shown in Figure 3. Align the center of the fan with the center of the wind turbine hub. Measure the distance between the fan and the turbine hub and ensure that the distance remains constant throughout the experiment.

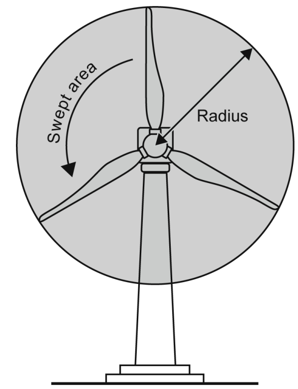

Figure 2

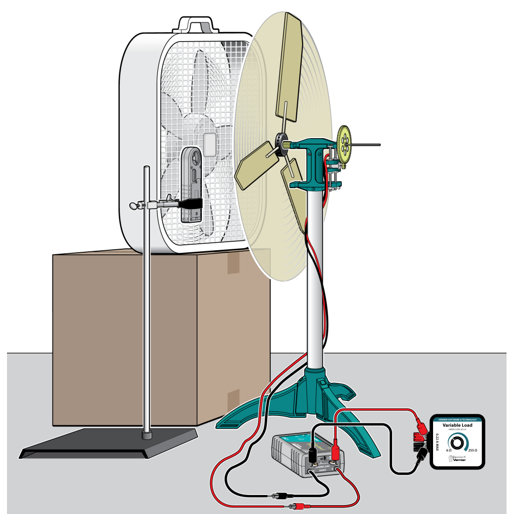

Figure 3

   f. Position the Weather Sensor between the fan and the turbine. It should be in the same position each time you collect data.
   g. Clear off your area and make sure that when the fan and the turbine are moving, nothing will be in the way.

4. Check the current and voltage values.
   a. Put on safety goggles and turn on the fan. The wind turbine should be spinning. **Caution**: Do not stand in the plane of rotation of the rotor.
   b. Note whether the current or voltage values are positive, negative, or zero.
   c. Turn the fan off.
   d. The setup is correct if the values are positive. If the values are negative or zero, switch the wires connected to the Source terminal wires so they are connected to the opposite terminal wires.

5. Adjust the load.
   a. Turn on the fan to the high setting. Wait 60 seconds, or until the fan and the turbine blades reach a constant speed.
   b. Note the Resistance value in the meter. Adjust the load by turning the knob on the Variable Load until the resistance is approximately 35 Ω or equal to the internal resistance of the generator you are using.

6. Adjust the view and the graphs.
   a. Click or tap View, , and choose 2 Graphs.
   b. Click or tap the y-axis label of the top graph and adjust the columns so that only Power is selected. A graph of power *vs*. time is displayed.
   c. Click or tap the y-axis label of the bottom graph and adjust the column so that only Wind Speed is selected. A graph of wind speed *vs*. time is displayed.

7. Collect data and determine the mean power and the mean wind speed values.
   a. Click or tap Collect to start data collection.
   b. When data collection is complete, click or tap Graph Tools, , for the top graph and choose View Statistics to determine the mean power value. Record the value in the data table.
   c. Click or tap Graph Tools, , for the bottom graph and choose View Statistics to determine the mean wind speed value. Record the value in the table.

8. Collect additional data.
   a. Click or tap Collect to start data collection.
   b. When data collection is complete, determine and record the average power and wind speed values in the data table.

9. Adjust the blades and collect additional data.
   a. Turn off the fan.
   b. Modify the blades according to your plan.
   c. If necessary, measure the radius of the turbine and record the value in Table 2.
   d. Return the fan, wind turbine, and Weather Sensor to the correct positions. Check the distance between the fan and turbine and the position of the Weather Sensor. The wind speed should be the same each time you collect data.
   e. Turn on the fan to the high setting. Wait for 60 seconds, or until the fan and the blades reach a constant speed.
   f. Repeat the necessary steps to collect a total of two runs of data.

10. Repeat Step 9 until you have collected all the data that you need to test your blade variable.

DATA TABLE

Table 1					
Variable: ________	Trial	Wind speed (m/s)	Average wind speed (m/s)	Power (mW)	Average power (mW)
	1				
	2				
	1				
	2				
	1				
	2				
	1				
	2				
	1				
	2				

Table 2					
Variable: ________	Average wind speed (m/s)	Radius (m)	Swept area (m^2)	Wind power available (W)	Efficiency (%)

Table 3	
Air density, ρ (kg/m^3)	

DATA ANALYSIS

Part I Turbine power

Wind turbines contain generators to transform rotational kinetic energy into electrical energy. Using the data-collection equipment, you can determine the power generated by the wind turbine for each blade variable tested.

1. Using the wind speed values you recorded, calculate an average wind speed for each modification you made.
2. Using the power values you recorded, calculate an average power value for each modification.

Part II Wind power

Only a fraction of the wind energy available is converted to electricity. In order to determine the efficiency of the turbine, you will first need to determine the wind energy theoretically available in a column of wind of a certain area.

3. Copy the variable information and the average wind speed values from Table 1 into Table 2.
4. Record the air density, ρ, in Table 3. At sea level and at 15°C, air has a density of approximately 1.225 kg/m^3. If you are located at a high altitude or extreme temperature, consult your instructor for the appropriate value for your area.
5. Calculate the swept area, A, for each blade modification. If you did not change the length of the blade, you may only have to do this calculation one time.
   a. The blade sweeps out an area in the shape of a circle of radius, r (see Figure 2). Calculate the swept area, $A = \pi r^2$, for each modification that you made and record the results in Table 2.
   b. Using your values for air density (ρ), swept area (A), and average wind speed (v), calculate how much power is theoretically available in the wind.

$$P = \frac{1}{2}\rho A v^3$$

   Record your result in Table 2 for each blade modification.

Part III Efficiency

The efficiency of a wind turbine can be defined by the following equation

$$\text{efficiency} = \frac{\text{electrical power transformed by the wind turbine}}{\text{power available in the wind}}$$

6. Calculate the ratio of turbine power to wind power to determine the efficiency for each blade modification. To convert mW to W, divide the power in milliwatts by 1000 mW/W.
7. Create a graph of turbine efficiency *vs*. the variable you tested.
8. Which blade modification produced the most efficient wind turbine? The least?
9. Compare the wind turbine efficiency values to the Betz Limit.
10. Most modern wind turbines are 25–45% efficient. How do your values compare? Explain any discrepancies.

EXTENSIONS

1. Summarize the group findings in a report. Answer at least some of the following questions in your summary.
   - What variable has the greatest impact on power output?
   - What type of blades were the most powerful at low speeds? High speeds?
   - What number of blades had the greatest efficiency?
   - What shapes worked best?
   - What length worked best? Did longer blades bend in the wind? Was this a problem?
   - What problems did you encounter?
   - What happened when the diameter of the turbine rotor was bigger than the diameter of the fan?

2. Use the collected data to design more efficient wind turbine blades and test what you predict will be the best combination.

3. Test blades at a different wind speed. Does this affect the efficiency?

Turbine Efficiency

Students will use wind turbines to test different blade design variables and calculate the power output for each modification. Students will also calculate the wind energy available and determine the efficiency of the turbine as they change variables.

We suggest starting the experiment with a brainstorming session. Record students' ideas and then assign or have the groups pick different variables. This way, as a class, you will cover a wide variety of variables. If you would rather, simply assign variables to the groups. Options for variables include (among others)

- Length
- Number of blades
- Pitch
- Shape (outline, tip shape, or airfoil shape)
- Width
- Blade material

See Appendix B for additional tips about blade variables.

As an extension, have students share their data with the class. Students should describe their testing plan, how they designed the blades, and their results. After all groups have presented, encourage a group discussion or have students write a report, so students can practice summarizing and drawing conclusions from class results. Topics that students should consider when discussing results or writing a report can be found in the student version of this experiment.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Zero sensors, if using Vernier Energy Sensor and Vernier Anemometer.
- Use the Statistics tool to calculate statistics.
- Create a graph using data collected during the experiment.

ESTIMATED TIME

We estimate that data collection for this experiment can be completed in one 45-minute class period. Allow for time in the following class period to complete analysis and for students to share their data, if you so choose.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking questions and defining problems Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Obtaining, evaluating, and communicating information	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3)	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter

EQUIPMENT TIPS

1. Set up a safe testing area.
   - Clear the area of debris and materials.
   - Instruct your students to not stand in the plane of rotation of the turbine blades. Also tell them that they should not touch the blades while they are spinning. Blades can be moving very fast and can hurt if they hit someone.
   - Provide safety goggles for your students. Students should wear safety goggles when they are working with a turbine that is spinning.
2. Depending on the variable being tested, some groups will have to build multiple sets of blades, while other groups will only build one set. For example, the group testing blade material will have to build one set of identical blades for each material being tested. The group testing pitch/angle, however, will only build one set of blades and then test the angle of these blades on the turbine. As it can take quite a bit of time to build sets of blade, groups that test multiple sets may require more time.
3. All students should understand the concept of blade pitch (angle), how they will measure it (e.g., a Blade Pitch Protractor), and how they will vary it or keep it constant. Small changes in blade pitch can greatly affect efficiency and power output.
4. This experiment was designed using an Energy Sensor. It may also be done with a current probe and a voltage probe; students will need to create a calculated column in the data-collection app to calculate power. For more information, see **www.vernier.com/til/3184**
5. The student version of the experiment is written assuming the use of the Vernier Variable Load. Remind your students to use a resistance value that most closely matches the internal resistance of the turbine. Generally, for KidWind turbines, this is a resistance value of 35–50 Ω. If your students will be using the Vernier Resistor Board or a single resistor, you will need to help them set up the circuit.
6. This experiment was written using a KidWind Advanced Wind Turbine. Any of the KidWind wind turbines will work, as they all use a DC motor for a generator. Different generators will produce different power levels and may have a different internal resistance.

7. Wind from a fan is very turbulent and does not accurately represent the wind a turbine would experience outside. To clean up this turbulent wind, students can build a "honeycomb" in front of the fan using milk cartons, PVC pipe, or paper towel rolls. Note that this will also slow the wind coming off the fan.

8. When positioning the Anemometer or Go Direct Weather, you may need to experiment to find the best position. The students are instructed to position it between the fan and the turbine. It should be in the same position each time because of the turbulence described above.

DATA-COLLECTION AND ANALYSIS TIPS

1. In most cases, the center of the fan hub should be aligned with the center of the wind turbine. If this does work, you can move the fan as necessary.

2. Unless students are testing pitch, pitch must kept constant.

3. To determine the wind power, students need to know the air density at their location. At sea level and at 15°C, air has a density of approximately 1.225 kg/m^3. If you are located at a different altitude or temperature, you will want to provide the appropriate value to your students.

4. If you want students to have a more complete understanding of the wind power calculation, you can share the derivation that follows.

   The volume of air pressing against the turbine each second, V, is the volume of a cylinder given by

   $$V = LA$$

   where L is length of the cylinder and A is the area of the base of the cylinder.

   The length of the cylinder, L, is determined by the velocity of the wind multiplied by the time of interest, in this case, 1 second

   $$L = v \times 1 \text{ second}$$

   The area of the base of the cylinder, A, is equal to pi times the radius, r, squared

   $$A = \pi r^2$$

   Note: This value is the same as the swept area calculated during the data analysis section in the student experiment.

   The mass, m, of the air pressing against the turbine is the density of the air times the volume of the cylinder is calculated as

   $$m = \pi r^2 \times v \times 1 \text{ second} \times \rho$$

   The kinetic energy of the moving air is

   $$\text{KE} = \frac{1}{2}mv^2$$

Substituting for m, we get

$$\mathrm{KE} = \frac{1}{2}\pi r^2 \times v^3 \times 1 \text{ second} \times \rho$$

The power available from the wind is the kinetic energy passing the blades each second

$$\mathrm{P} = \mathrm{KE/second} = \frac{1}{2}\pi r^2 \times v^3 \times \rho$$

$$P = \frac{1}{2}\rho A v^3$$

ANSWERS TO PRELIMINARY QUESTIONS

1. Most electrical generating turbines have three blades. Adding more blades will typically add additional costs due to materials, structural load, and other factors. Student investigations may determine if adding more blades will reduce the efficiency or power generated.
2. Some of the air must move through the turbine to allow it to spin. If all of the kinetic energy of the wind were captured, the wind speed on the back side of the turbine would be zero.
3. Answers will vary. Some answers may include blade pitch, blade length, number of blades, blade weight, blade shape, blade material, and blade twist (variable pitch).

SAMPLE RESULTS

To collect sample data, we investigated the effect of blade pitch. Student results will vary.

Table 1

Variable: Blade pitch (°)	Trial	Wind speed (m/s)	Average wind speed (m/s)	Power (mW)	Average power (mW)
10	1	4.332	4.326	36.41	35.80
	2	4.320		35.18	
20	1	4.335	4.314	47.70	47.55
	2	4.293		47.39	
30	1	4.373	4.347	38.67	37.95
	2	4.320		37.22	
40	1	4.365	4.345	25.79	24.93
	2	4.304		24.06	
50	1	4.298	4.293	16.95	16.99
	2	4.288		17.03	

Table 2					
Variable: Blade pitch (°)	Average wind speed (m/s)	Radius (m)	Swept area (m^2)	Wind power available (W)	Efficiency (%)
10	4.326	0.322	0.326	16.17	0.22
20	4.314	0.322	0.326	16.03	0.30
30	4.347	0.322	0.326	16.40	0.23
40	4.345	0.322	0.326	16.38	0.15
50	4.293	0.322	0.326	15.80	0.11

Table 3	
Air density, ρ	1.225 kg/m^3

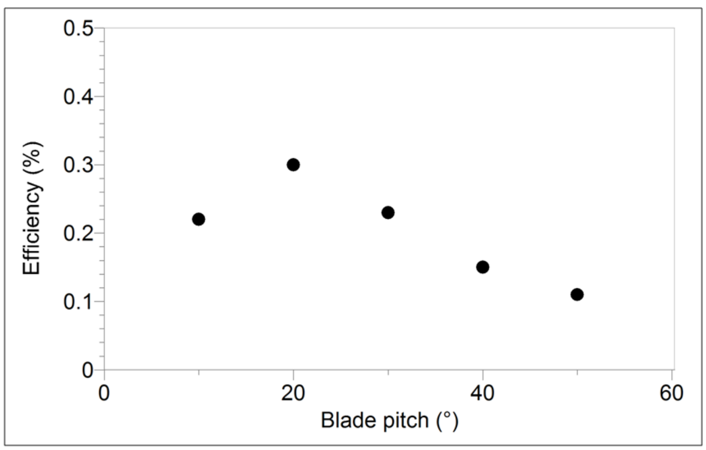

Figure 1 Relationship between efficiency and blade pitch

ANSWERS TO ANALYSIS QUESTIONS

8. Student answers will vary depending on the blade variables examined.

9. Yes, efficiency values are below the Betz Limit of 59.3%.

10. It is likely that the small tabletop turbines examined in your classroom are much less efficient than full-size wind turbines. Do not be surprised by efficiencies on the order of 1% or less. Small-scale wind turbines (1–100 kW) always have lower efficiencies than large-scale wind turbines. This can be due to many factors, including the type of blades and generators used.

Power Curves

Wind turbine power curves describe how much power a wind turbine can extract from the wind at a variety of different wind speeds. Most power curves have a fairly similar shape, but each model of wind turbine has a unique power curve based on its design characteristics. By examining the power curve, you can tell the wind speed at which a wind turbine will start generating power, the wind speed at which it produces its maximum power output, and in what range of wind speeds it can safely operate.

The following concepts are important to understand when discussing power curves for wind turbines:

Cut-in Speed: The cut-in speed is the wind speed at which the turbine blades begin to rotate the generator shaft. This value is dependent on the number of blades, blade design, turbine inertia, and how smoothly the generator operates (gears or other friction elements in the drive train can affect this).

Maximum Power Output: This value is the maximum amount of power the turbine can produce. In Figure 1, the maximum amount of power the turbine can produce is approximately 105 kW at a wind speed of about 15 m/s.

Overspeed Protection: A wind turbine must be able to protect itself by slowing down in extreme wind speeds (in the example, above 15 m/s). At these speeds, the rotor or generator may spin too fast and cause electrical or mechanical problems. To mitigate the potential for damage, engineers have developed several different strategies: 1) *feathering* or adjusting blade pitch to make the blades less aerodynamic 2) applying a mechanical brake to slow the rotor 3) *furling* or turning the rotor so the plane of the rotor is parallel to the wind direction rather than perpendicular.

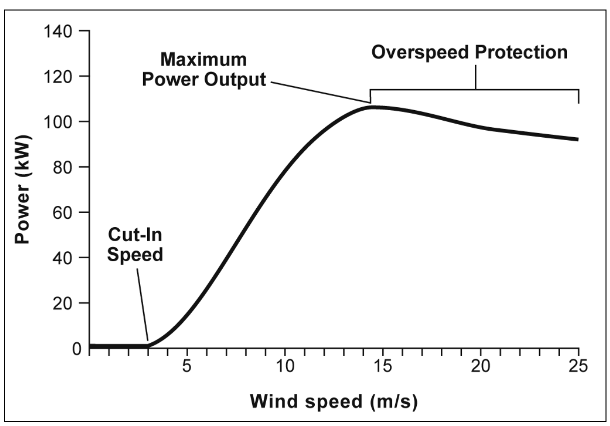

Figure 1 Idealized power curve for 100 kW wind turbine

Power curves help us understand certain characteristics of a wind turbine, such as how much instantaneous power a turbine may generate at a specific wind speed. However, power curves do not necessarily give us a good idea of how much *energy* a wind turbine will produce at a given location because average wind speeds are generally well below the wind speed required for maximum power output.

OBJECTIVES

- Describe a power curve and its importance in understanding blade efficiency.
- Generate a power curve for a classroom wind turbine.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Energy
Go Direct Weather
Vernier Variable Load
items needed from the Advanced Wind Turbine Kit:
  Wind Turbine with Nacelle and Generator, assembled
  Wind Turbine Hub
  Blade Pitch Protractor
  2 wires with clips
fan
blade materials
scissors and hot glue
piece of cardboard
ruler
safety goggles

PRELIMINARY QUESTIONS

1. How would wind power curves help you select the right turbine for your house, school, or business?
2. Do wind power curves tell us how much energy a wind turbine will produce for a specific time period?
3. While wind power curves are a similar shape for different turbines what physical characteristics of a wind turbine could affect maximum power output?

PROCEDURE

In this experiment, you will generate a power curve for a wind turbine. The basic procedure is below. Collecting a complete set of data will require creativity and experimentation on the part of you and the rest of your group.

1. Set the switch on the Energy Sensor to External Load. Launch Graphical Analysis. Connect the Energy Sensor as well as the Weather Sensor to your Chromebook, computer, or mobile device.
2. Set up the equipment.
   a. Connect the Variable Load to the Energy Sensor External Load terminals.
   b. Position the equipment as shown in Figure 2. Set the blades at 15°. Align the center of the fan with the center of the wind turbine hub. Measure the distance between the fan and the turbine hub and ensure that the distance remains constant throughout the experiment.

c. Position the Weather Sensor between the fan and the turbine. It should be in the same position each time you collect data.

d. Clear off your area and make sure that when the fan and the turbine are moving, nothing will be in the way.

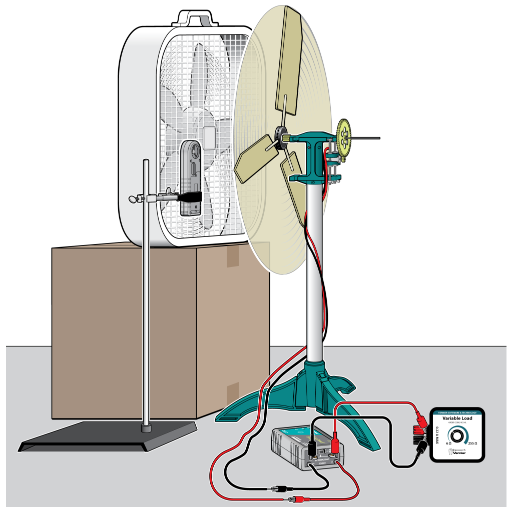

Figure 2

3. Check the current and voltage values.
   a. Put on safety goggles and turn on the fan. The wind turbine should be spinning. **Caution**: Do not stand in the plane of rotation of the rotor.
   b. Note whether the current or voltage values are positive, negative, or zero.
   c. Turn the fan off.
   d. The setup is correct if the values are positive. If the values are negative or zero, switch the wires connected to the Source terminal wires so they are connected to the opposite terminal wires.

4. Adjust the load.
   a. Turn on the fan to the high setting. Wait 60 seconds, or until the fan and the turbine blades reach a constant speed.
   b. Note the Resistance value in the meter. Adjust the load by turning the knob on the Variable Load until the resistance is approximately 35 Ω or equal to the internal resistance of the generator you are using.

5. Set up the graphs and the data-collection mode.
   a. Click or tap Mode to open Data Collection Settings.
   b. Change End Collection to 120 s. Click or tap Done.
   c. Click or tap View, ⊞, and choose 2 Graphs.
   d. Click or tap the y-axis label of the top graph and adjust the columns so that only Power is selected. A graph of power *vs*. time is displayed.
   e. Click or tap the y-axis label of the bottom graph and adjust the column so that only Wind Speed is selected. A graph of wind speed *vs*. time is displayed.

6. Create a plan to collect data for a wide range of wind speeds, including 0 m/s. Consider how you will measure wind speeds other than those produced by the settings of the fan.
7. When you are ready to collect data, click or tap Collect to start data collection and follow your plan to collect data.
8. Examine the data and decide if you need to collect data again. If so, repeat data collection until you have a complete power curve.

DATA ANALYSIS

1. What is the cut-in speed for your turbine?
2. Did you reach maximum power output for your turbine? Why do you think this happened? If you did not reach maximum output, what stopped your turbine from achieving maximum power output?
3. Describe the relationship between wind speed and power. Is the relationship linear over the entire data set?
4. Were you able to collect data for a complete power curve for your wind turbine? Explain.

EXTENSIONS

1. Create power curves for different types of blades and compare to see how power output varies based on blade variables.
2. Generate power curves for multiple generators using the same blade configuration and keeping all other variables constant. Compare the power curves for the different generators.
3. Research the Weibull distribution, which is the theoretical statistical distribution of wind speeds. Compare a Weibull distribution to a wind speed histogram and to a wind turbine power curve. Report on your findings.

Power Curves

This experiment is designed for students who have some familiarity with wind turbines and how they function. Having performed the preceding experiments in this book that explore wind turbines will greatly increase the ease with which students conduct this experiment.

If you would like to examine wind speed maps for your region, starting points for finding an appropriate graph include

United States

Visit the WINDExchange section of the US Department of Energy, Energy Efficiency and Renewable Energy web site:

https://windexchange.energy.gov/

Global

Try the following site or search the internet for "global wind map":

https://earth.nullschool.net/

For information about wind speed distribution graphs, try the following site for an accessible explanation of the Weibull distribution:

http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/weibull.htm

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Change data-collection settings.
- Zero sensors, if using Vernier Energy Sensor and Vernier Anemometer.
- Change graph view.
- Change what is graphed on the graph axes.

ESTIMATED TIME

We estimate that data collection and analysis can be completed in one 45-minute class period.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Analyzing and interpreting data Using mathematics and computational thinking	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3)	Scale, proportion, and quantity Systems and system models Energy and matter

EQUIPMENT TIPS

1. Set up a safe testing area.
    - Clear the area of debris and materials.
    - Instruct your students to not stand in the plane of rotation of the turbine blades. Also tell them that they should not touch the blades while they are spinning. Blades can be moving very fast and can hurt if they hit someone.
    - Provide safety goggles for your students. Students should wear safety goggles when they are working with a turbine that is spinning.

2. This experiment was designed using an Energy Sensor. It may also be done with a current probe and a voltage probe; students will need to create a calculated column in the data-collection app to calculate power. For more information, see **www.vernier.com/til/3184**

3. The student version of the experiment is written assuming the use of the Vernier Variable Load. Remind your students to use a resistance value that most closely matches the internal resistance of the turbine. For KidWind turbines, this is generally a resistance value of 35–50 Ω. If your students will be using the Vernier Resistor Board or a single resistor, you may need to help them set up the circuit.

4. The piece of cardboard listed in the student Materials list should be about the same size as the fan. Students can change the wind speed by placing the cardboard on the opposite side of the fan from the wind turbine. By covering different amounts of the fan's area, they can vary the wind speed. This may take practice.

5. Wind from a fan is very turbulent and does not accurately represent the wind a turbine would experience outside. To clean up this turbulent wind, students can build a "honeycomb" in front of the fan using milk cartons, PVC pipe, or paper towel rolls. Note that this will also slow the wind coming off the fan.

6. When positioning the Anemometer or Go Direct Weather, you may need to experiment to find the best position. The students are instructed to position it between the fan and the turbine. It should be in the same position each time because of the turbulence described above.

7. A classroom set of blades that are known to give good results will be helpful for this experiment. Blades that start near the hub of the wind turbine work well. For best results, the radius of the wind turbine should not exceed the radius of the fan. See Appendix B for additional tips about designing blades.

8. This experiment was written using a KidWind Advanced Wind Turbine. The KidWind Basic turbine will also work, as it also uses a DC motor for a generator. Different generators will produce different power levels and may have a different internal resistance.

DATA-COLLECTION AND ANALYSIS TIPS

1. In most cases, the center of the fan hub should be aligned with the center of the wind turbine. If this does work, you can move the fan as necessary.
2. We found during testing that blocking the fan with a piece of cardboard from behind the fan, rather than between the fan and the turbine, resulted in the cleanest data.

ANSWERS TO PRELIMINARY QUESTIONS

1. Wind power curves can tell us the maximum power output for a turbine. Knowing that information, as well as how much power we consume, can help us select the right size turbine to power our home or business.

   You may wish to discuss with students that turbines rarely produce in the maximum area of the power curve, so experienced installers will pick turbines based on the estimated annual energy output of the turbine, rather than the power curve alone.
2. No. Wind power curves tell us how much instantaneous power a wind turbine can produce, not total energy produced. Using a wind power curve and additional wind speed data (average wind speed or wind speed distributions) we can predict energy output. This is an important distinction as people are often sold turbines on maximum power output not energy output.
3. Possible answers include blade length, generator efficiency, blade configuration, and orientation (either vertical or horizontal axis).

SAMPLE RESULTS

Student results will vary.

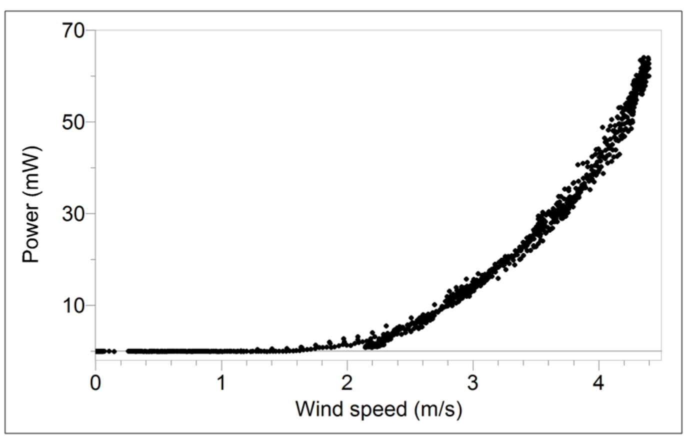

Figure 1 Sample data collected with a KidWind Advanced Wind Turbine

ANSWERS TO ANALYSIS QUESTIONS

1. Cut-in speed for the sample data is 1.5 m/s.
2. Answers will vary. For the sample data, maximum power output was not achieved because the fan did not produce enough wind.
3. As wind speed increases, power output increases. The relationship is not linear.
4. Most groups will not be able to reach the maximum power output of their turbine using a household box fan as their wind source. Therefore most groups will not be able to collect data for a complete power curve. However, answers will vary.

Power and Energy

People often use the words *power* and *energy* interchangeably, when in fact these two words mean very different things.

Imagine if people used the words "kilometers per hour" and "kilometers" interchangeably. That would be very confusing! It would sound like this: "How fast can you ride your bike?" "About 5 kilometers." This is basically what we are doing if we use power and energy to mean the same thing.

Power is a *rate*–just like meters per second, miles per hour, and gallons per minute are rates. Power is the rate at which energy is transferred or work is done. It can be calculated using the equation

$$\text{power} = \frac{\text{amount of work done}}{\text{how much time it takes}}$$

The base unit of power is the watt (W), which is equal to one joule per second (1 W = 1 J/s).

We can think of energy, on the other hand, as a *quantity*–just like gallons and meters are quantities. Energy refers to the amount of energy transferred or work performed. The base unit of energy is the joule (J). You can calculate energy by rearranging the power expression in the following way:

amount of work done = power × how much time it takes

As an example, let's say you leave a 12 W light bulb on for 10 seconds. Using the expression above, you can calculate the amount of work:

$$12\ \text{W} \times 10\ \text{s} = \text{amount of work done}$$

$$12\,\frac{\text{J}}{\text{s}} \times 10\ \text{s} = 120\ \text{J}$$

In the United States, a common unit of energy is the watt-hour (Wh) or kilowatt-hour (kWh). With small classroom wind turbines and solar panels, we sometimes use the unit "milliwatt-second" (mWs), which is equal to one thousandth (1/1000) of a joule and could also be called a millijoule.

In this experiment, you will explore power and energy. You will learn how power and energy are related to each other. You will use this knowledge and the data-collection software to measure the power and calculate the amount of electrical energy generated by a small wind turbine.

OBJECTIVES

- Understand the difference between power and energy.
- Calculate the amount of electrical energy generated by a wind turbine during a time period.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Energy
Vernier Variable Load
items needed from the Advanced Wind Turbine Kit:
- Wind Turbine with Nacelle and Generator, assembled
- Wind Turbine Hub
- Blade Pitch Protractor
- 2 wires with clips

fan
ruler
blade materials
scissors and hot glue
safety goggles

PRELIMINARY QUESTIONS

1. When people pay their electric bill every month, are they paying for power or energy?
2. Which do you think would be more useful to someone thinking about buying a wind turbine for their home: The rated *power* output of the turbine or the estimated annual *energy* production for their site?
3. What are some ways you could reduce the amount of energy used in your home?

PROCEDURE

1. Set the switch on the Energy Sensor to External Load. Launch Graphical Analysis. Connect the Energy Sensor to your Chromebook, computer, or mobile device.
2. Set up the equipment.
   a. Connect the wind turbine to the Energy Sensor Source terminal wires.
   b. Connect the Variable Load to the Energy Sensor Load terminals.
   c. Adjust the blades so the turbine is set up with three blades spaced evenly apart and pitched at 30°.
   d. Position the fan so the center of the fan is in line with the center of the hub of the turbine. The fan should be about 15 cm from the turbine.
   e. Clear off your area and make sure that when the fan and the turbine are moving, nothing will be in the way.

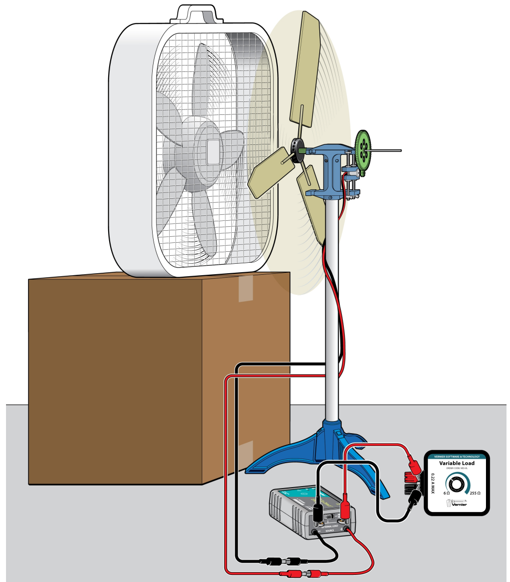

Figure 1

3. Check the current and voltage values.
   a. Put on safety goggles, and then turn on the fan. The wind turbine should be spinning. **Caution**: Do not stand in the plane of rotation of the rotor.
   b. Note whether the current or voltage values are positive, negative, or zero.
   c. Turn the fan off.
   d. The setup is correct if the values are positive. If the values are negative or zero, switch the wires connected to the Source terminal wires so they are connected to the opposite terminal wires.

4. Adjust the load.
   a. Turn on the fan to the highest setting. Wait 30 seconds, or until the fan and the turbine blades reach a constant speed.
   b. Note the Resistance value in the meter. Adjust the load by turning the knob on the Variable Load until the resistance is approximately 35 Ω or equal to the internal resistance of the generator you are using.

5. Collect data.
   a. Click or tap Collect to start data collection. Data will be collected for 30 seconds. When data collection is complete, graphs of potential *vs*. time and current *vs*. time are displayed.
   b. Turn off the fan.

6. Determine energy.
   a. When data collection is complete, tap the y-axis label of the top graph and select Power only. A graph of power *vs*. time is displayed.
   b. Click or tap Graph Tools, , for the top graph and choose View Integral.
   c. Record the value for the integral in your data table.

7. Repeat data collection to collect data for a total of three trials.

DATA TABLE

Trial	Energy (J)
1	
2	
3	
Average energy	

PROCESSING THE DATA

1. Calculate the average energy.
2. Print, export, or sketch a graph of power *vs*. time.
3. Show how energy is calculated using your graph.

ANALYSIS QUESTIONS

1. What is an "integral" of a graph? How did you use an integral to relate power and energy?
2. What information would you need in order to estimate how much energy a wind turbine could generate in a year? How could you get this information?

EXTENSIONS

1. Choose a blade variable to change, such as blade pitch, blade length, or another variable. Compare the energy generated in a 30-second trial for several different values of your variable. As with this experiment, perform three trials and average them for each variable change. Which blade set generates the most energy?
2. Compare the energy generated by your wind turbine with the energy generated by a small solar panel during the same time interval. Which generated more energy?

Power and Energy

This experiment is designed for students to be able to explore the difference between power and energy. They will use the Integral tool in the data-collection program.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Zero sensors, if using the Vernier Energy Sensor.
- Use the Integral tool.

ESTIMATED TIME

We estimate that data collection and analysis can be completed in one 45-minute class period.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking questions and defining problems Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Engaging in argument from evidence Obtaining, evaluating, and communicating information	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3)	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter

EQUIPMENT TIPS

1. Set up a safe testing area.
   - Clear the area of debris and materials.
   - Instruct your students to not stand in the plane of rotation of the turbine blades. Also tell them that they should not touch the blades while they are spinning. Blades can be moving very fast and can hurt if they hit someone.
   - Provide safety goggles for your students. Students should wear safety goggles when they are working with a turbine that is spinning.

2. A classroom set of blades that are known to give good results will be helpful for this experiment. Blades that start near the hub of the wind turbine work well. For best results, the radius of the wind turbine should not exceed the radius of the fan. See Appendix B for additional tips about designing blades.

3. This experiment was designed using an energy sensor. It may also be done with a current probe and a voltage probe; students will need to create a calculated column in the data-collection app to calculate power. For more information, see **www.vernier.com/til/3184**

4. The student version of the experiment is written assuming the use of the Vernier Variable Load. Remind your students to use a resistance value that most closely matches the internal resistance of the turbine. For KidWind turbines, this is generally a resistance value of 35–50 Ω. If your students will be using the Vernier Resistor Board or a single resistor, you will need to help them set up the circuit.

5. This experiment was written using a KidWind Advanced Wind turbine. The KidWind Basic Wind turbine will also work, as it also uses a DC motor for a generator. Different generators will produce different power levels and may have a different internal resistance.

DATA-COLLECTION AND ANALYSIS TIPS

1. In most cases, the center of the fan hub should be aligned with the center of the wind turbine. If this does not work, you can move the fan as necessary.

2. Wind from a fan is very turbulent and does not accurately represent the wind a turbine would experience outside. To clean up this turbulent wind, students can build a "honeycomb" in front of the fan using milk cartons, PVC pipe, or paper towel rolls. Note that this will also slow the wind coming off the fan.

ANSWERS TO PRELIMINARY QUESTIONS

1. People pay for the amount of energy their household has used.

   Typically, customers in the United States pay per kWh (kilowatt-hour). Cost per kWh varies from $0.08–$0.25 depending on where you live.

2. Since most people are more concerned with offsetting their energy use, the usual approach is simply to find a turbine that has the maximum energy production and fits their budget. Those concerned about meeting maximum power load requirements would want a wind turbine with a high output rating.

3. Answers will vary but will come in two forms—use less by not using electricity (conserving) or use less by having more energy efficient appliances. The more energy you save by doing this, the less turbine you have to purchase!

SAMPLE RESULTS

Student results will vary.

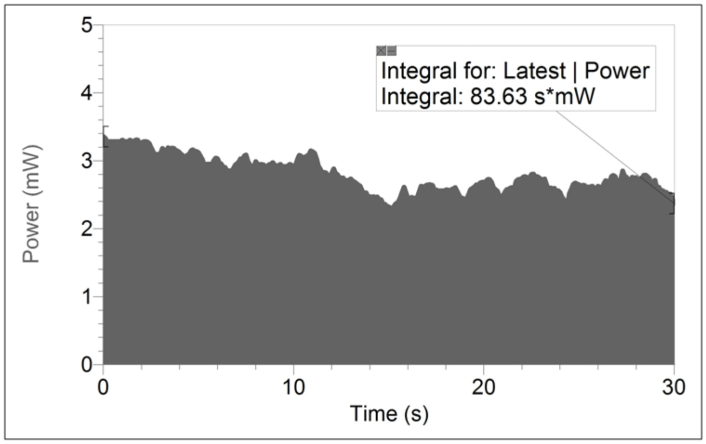

Figure 1 Determining energy from a power vs. *time graph*

ANSWERS TO ANALYSIS QUESTIONS

1. An integral is the area between the curve on a graph (or the connected data points on a graph) and the horizontal axis of the graph. Energy is found by taking the integral of the power *vs*. time graph. Energy is the amount of work done or energy transformed, which is equal to the power multiplied by the time duration.

2. Answers will vary. To estimate how much energy a wind turbine could generate in a year, you would need to know how much energy is generated in a given time period and then multiply by the number of given time periods in a year. You would need to know the average wind speed, the turbine's height above the ground, and the turbine specifications.

Project: Maximum Energy Output

Generating electricity from fossil fuels (primarily coal and natural gas) produces carbon dioxide (CO_2) and an array of other pollutants that are injected into the atmosphere each year. The Intergovernmental Panel on Climate Change (IPCC) estimates that 20–25% of the CO_2 produced by humans comes from the generation of electricity around the world. Increasing CO_2 concentrations in the atmosphere is one of the key drivers of climate change.

While electricity generation produces a significant amount of the CO_2 released by humans, there are millions of people around the world who do not currently have access to electricity. When individuals or communities seek out reliable electricity, they have a variety of options, including generators that run on gasoline or diesel. Developing ways to efficiently produce electricity from renewable sources, such as wind or solar power, can greatly improve people's quality of life and ability to sustainably support themselves and their communities.

Wind turbines are a rapidly maturing technology that can help reduce the carbon footprint of electricity generation and bring electricity to even the most remote communities. In this project, you will construct a small wind turbine that maximizes energy output at low and high wind speeds. This turbine could be used to provide energy that would charge small electronics or provide lighting. During the project, you will work with your group to design, test, and then optimize your wind turbine design. At the end of the project, you will submit a set of deliverables.

DESIGN REQUIREMENTS AND CONSTRAINTS

- Turbine diameter: No larger than 50 cm
- Wind speed range: 2–6 m/s
- Output: Unregulated Direct Current
- Generator: Any available DC generator or you can build your own generator
- Turbine must be robust enough to withstand outdoor conditions over time
- Turbine should track the wind direction (yaw)
- Do not exceed the project budget

DELIVERABLES

- Prototype
- Detailed design specifications (so the unit can be replicated)
- Expected energy output over a 24 hour period at wind speeds of 2 m/s, 4 m/s, and 6 m/s
- Social and environmental impact statement on the benefit of your design

Project: Maximum Energy Output

The goal of this project is for students to design and build their own wind turbines. You may or may not decide to let them use KidWind kit parts. We have capped velocity at 6 m/s as this is the wind speed of a standard household box fan. We also set the maximum rotor diameter at 50 cm, which is appropriate because it is the size of most household box fans. You may wish to edit the parameters to fit your situation.

Students will need to consider the following as they construct their wind turbines:

Towers: Students can make a tower out of practically anything. They must make sure the turbine has a firm base or that it can be attached securely to a base. The tower must be tall enough that the blades do not hit the base/ground/table top and sturdy enough that it can withstand stress from the wind.

Generators: A generator is the device that converts mechanical energy into electrical energy. Student turbines will generate electricity using a generator of their choice. Students can choose any commercially available DC generator or even build their own.

Drivetrain: Students must decide to build a direct drive or a geared drivetrain. Gears can significantly increase the rotational speed of the generator and therefore power output, but gear boxes can be challenging to build. Students can use gears or pulleys for the systems.

Blades: Blade design has a huge impact on turbine power output. As students build their turbines, they will want to perform experiments to see which blades work best.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

ESTIMATED TIME

We estimate that this project can be completed in 7 to 10 class periods. Students may need 4 to 5 class periods to construct a good turbine. They will need one class period to collect data and then one to two periods to refine their design. Finally, students will need one class period to complete their report and calculations.

You can vary the complexity and time to complete the project through the materials you provide. For example, if you have KidWind Advanced Wind Experiment Kits, you could use the generators, gearboxes, and towers that come with the kits. This would allow you to focus on maximum energy output related to the design of the blades and spend less time on tower and generator design.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking questions and defining problems Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Engaging in argument from evidence Obtaining, evaluating, and communicating information	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3) ETS1.A Defining Engineering Problems ETS1.B Developing Possible Solutions ETS1.C: Optimizing the Design Solution	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter Structure and function Stability and change

SUGGESTED PROJECT PLAN

1. Assign students a research project in which they are expected to research the purpose of a wind turbine. Students should be able to define the problems addressed by a wind turbine, including global, social, and environmental issues that would be affected by using wind energy as an energy source. A great way to start this activity is by reading the book, *The Boy Who Harnessed the Wind*, by William Kamkwamba. It is a true story of a young boy in Malawi who builds his own turbine to charge small electronics in his house.

2. It can be very useful to perform some basic turbine experiments on blades, generators, and gearboxes to understand how they affect turbine performance. This can be in done in a more structured or a more inquiry-based fashion before students try to build a final turbine to test for this project. Other experiments in this book that use wind turbines can be good tools.

3. Give students time to design and build the wind turbine based on the design requirements (The student experiment includes a list of requirements and constraints, but you may have additions or changes based on how you do the project.). You will want to consider providing materials and/or setting a budget to limit how much students can spend on materials.

4. Once students have constructed a wind turbine, they will need to do performance testing. As wind turbines can rotate at a high rate of speed and things can come off if not well attached, the testing area should be set up with strict safety rules. Based on testing, students will need time to make refinements to their turbine.

5. After refinements, students will need to collect data for their best turbine setup. Based on this data they will need to extrapolate and determine how much energy their turbine could generate based on the wind speed they are testing.

6. Give students an opportunity to develop and present a social and environmental impact statement on the benefits of their design. In the report, ask students to share ideas on what they would improve if they had more time. This can give you insights into how they are interpreting their data.

PROJECT TIPS

1. The KidWind organization has developed a national competition, called the KidWind Challenge, that offers students hands-on opportunities to apply their knowledge of renewable energy through friendly and challenging competitions. To learn more about the KidWind Challenge, visit **www.kidwind.org/challenge**

2. Consider developing a rubric with which to grade students' projects. Possible criteria include:
   - Energy production at low speeds and high speeds
   - Quality of construction
   - Cost of construction
   - Durability
   - Aesthetics
   - Evaluate quality of each component: blades, drive train, and/or tower
   - Integration of wind turbine design theory

3. Perfecting blade performance can take quite a while because of the number of variables. Students will need a significant amount of time to "discover" an optimal design if they have not experimented with blade variables in earlier activities. See Appendix B for additional tips about designing blades.

4. By far the most complicated part of building a wind turbine from scratch is creating the gearbox. If this is the first year you are doing this project or your students are relatively new to the design process, we recommend either using KidWind Advanced Wind Experiment Kits or allowing only direct drive systems with different generators. As you and your students become more experienced, you can add in more complexity.

5. Power output from the generator is dependent on the load that is applied to the turbine. Maximum power will depend on the load. For this project, instruct students to use the ideal load for their generator.

6. The generators that come with the KidWind Advanced Wind Experiment Kits have maximum outputs of approximately 2 W (10–15 V at 100–150 mA, when spinning at very high RPM (8,000–12,000 RPM)). There are many other DC motors available that you can use as generators. They will all perform differently under load and have varying torque requirements. Experimenting with generators can be very interesting.

7. As it can be challenging to measure energy output for 24 hours, students will need to collect data for a specific amount of time and extrapolate. This type of experimentation also assumes that the wind will blow at the same speed all day, which would rarely happen in real life.

8. To produce a more realistic testing environment you could have students set up their turbines outside for a number of hours and see how much energy they produce. This can be challenging and show students the weaknesses in their design as the device needs to react to different wind speeds, wind gusts, and rapid changes in wind direction.

9. If you want to improve your knowledge, considering reading the books, *Wind Power for Dummies*, by Ian Woofenden and *Homebrew Wind Power*, by Dan Bartmann, Dan Fink, and Mick Sagrillo.

EQUIPMENT TIPS

1. Set up a safe testing area.
   - Clear the area of debris and materials.
   - Instruct your students to not stand in the plane of rotation of the turbine blades. Also tell them that they should not touch the blades while they are spinning. Blades can be moving very fast and can hurt if they hit someone.
   - Provide safety goggles for your students. Students should wear safety goggles when they are working with a turbine that is spinning.

2. An energy sensor makes it very simple for students to determine power and energy output. Keep in mind that Vernier energy sensors have an input limit of ±30 V and ±1 A. KidWind generators almost always stay below these limits, but if you are using other generators, test them with a multimeter so you do not damage the sensor. The Go Direct Energy Sensor has a 1 W internal 30 Ω resistor. We recommend using a power resistor connected to the External Load terminals if students are regularly exceeding 1 W of power production.

3. We recommend the Vernier Variable Load (order code: VES-VL) as a way to determine the optimal resistance for the generators, especially if you are allowing students to experiment with different generators. See Experiment 9, "Effect of Load on Output." The Vernier Resistor Board can also be used to relatively easily determine the optimal resistance for each generator.

4. If you are requiring students to present energy output projections at different wind speeds, we recommend using an anemometer to collect wind speed measurements and tailoring the requirements to wind speeds you are able to produce.

5. If you have a mix of KidWind Advanced Wind Experiment Kits and Basic Wind Experiment Kits, you can combine materials if building turbines from scratch. Hubs, gears, and drive shafts from all KidWind wind experiment kits will work together.

Project: Build a Wind Farm

The need to pump water for human consumption and irrigation is critical in rural communities all over the globe.

> The most common technology for off-grid communities, diesel engine pump sets, is also the least sustainable. Diesel engines are attractive to infrastructure developers and donors because they are inexpensive to purchase and they are widely available; but they are also heavy polluters, can be expensive to operate, and their reliability is sensitive to proper operations and regular maintenance. Fuel availability is seldom a problem but the support infrastructure for diesel pumps commonly breaks down, leaving users without safe water for long periods. It is amazing how often diesel pumps are automatically employed in development projects in spite of the overwhelming evidence that they have poor sustainability.[1]

In this project, you will design a *wind farm*, a collection of wind turbines grouped together to create a single wind power plant. The wind farm you design will provide electricity to one or more KidWind Small Water Pumps with the goal of moving as much water as you can in a set period of time. The more power you provide to the pump, the more water you can move and the higher the pressure you can create. During the project, you will work with your group to design, test, and then optimize the orientation and design of your wind farm. At the end of the project, you will submit the set of deliverables.

DESIGN REQUIREMENTS AND CONSTRAINTS

- Construct a system that pumps water between two reservoirs
- Must be able to vary the height between the two reservoirs
- Must power the system using a KidWind turbine
- Must use the KidWind Small Water Pump
- Can use multiple turbines (minimum 2, maximum determined by your instructor)
- Can use multiple pumps (between 1 and 3 pumps)
- Construction materials must be readily available (recycled materials are encouraged)
- Do not exceed the project budget

DELIVERABLES

- Detailed system specifications (so the unit can be replicated exactly)
- Volume of water pumped between two containers in 5 minutes
- Height distance between the two containers where water was pumped
- Wind speed used to drive turbines
- How much water your system could move in 24 hours based on your best setup
- Social and environmental impact statement on the benefit of your design

[1] Source: Excerpt from *Wind-Electric Pumping Systems for Communities*: http://bergey.com/wind-school/articles/wind-electric-pumping-systems-for-communities-2

Project: Build a Wind Farm

OVERVIEW

In this challenge, each group will use one to three KidWind Small Water Pumps to move water. This pump requires only 1.5 V at 75 mA to start moving water; compared to 12 V pumps generally used in aquariums, the KidWind pump requires much lower voltage and less power.

While it is possible to move water with a single KidWind Advanced Turbine, if you start to combine multiple turbines in series or parallel arrangements, you can generate more power and move more water higher. Having students determine the best configuration is the goal of this project. This project is not designed to work with the KidWind Basic Wind Turbine.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

ESTIMATED TIME

We estimate that this project can be completed in 4–6 class periods. In the first 1–2 classes, students can design a set of blades that generates the most power possible (if they already have done this for a previous experiment, you can use those blades and skip this step). Students should also construct a system of reservoirs connected by tubes and pumps. In the next 1 or 2 classes, students can construct their wind farms and see how much water they can move. They will need at least one class period to refine their system, and then one class to write their report.

SUGGESTED PROJECT PLAN

1. Assign students a research project to gain a better understanding of the challenges faced by communities that do not have access to a reliable water supply, as well as how the development of water pumping technology has vastly improved human life as well as livestock and agricultural production. There are a great number of articles on how the windmill allowed the colonists to develop the American west.

2. Students need to understand current and voltage and what happens to these variables when you connect DC sources in series or parallel. If you have not covered these concepts before, you will need some additional time to do this.

3. If they have not already done so, students will need some time to construct a set of blades that can reliably generate enough power to activate the pump. See Appendix B for additional tips about designing blades.

4. Once students have a set of blades that will produce as much power as possible, they should start to configure them in arrays to maximize voltage or current in order to see how this affects the performance of the water pump in terms of water movement.

5. After students have constructed a functional wind farm, give them time to experiment to find an optimal configuration, collect data, and prepare their final report.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking questions and defining problems Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Engaging in argument from evidence Obtaining, evaluating, and communicating information	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3) ETS1.A Defining Engineering Problems ETS1.B Developing Possible Solutions ETS1.C: Optimizing the Design Solution	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter Structure and function Stability and change

PROJECT TIPS

1. The KidWind organization has developed a national competition, the KidWind Challenge, which offers students hands-on opportunities to apply their knowledge of renewable energy through friendly and challenging competitions. To learn more about the KidWind Challenge, visit **http://challenge.kidwind.org**

2. Develop a rubric with which to grade students' projects. Possible criteria include
   - Volume of water moved in 5 minutes
   - Height distance between the two containers where water was moved
   - Wind speed used to drive turbines.
   - How much water the system could move in 24 hours
   - Cost of materials (Can you do more with less?)
   - Design of pumping system (one pump, multiple pumps, staggered pumps)

   For additional ideas about developing a grading rubric, visit **https://www.kidwindchallenge.org**

3. There are three distinct objectives in this challenge. Students need to build turbines that produce as much power as possible, they need to configure them in arrays that combine this power to drive the pump as hard as possible, and lastly, they need to construct a reservoir system that can change in volume and height. Due to these distinct objectives, the project lends itself to large teams divided into smaller subsets that each work on a separate objective.

4. To test a wind farm you will need to build a bank of 2 or 3 fans so that students can set up their turbines with some space between them. If you are adventurous, you can have students set up

their wind farms outside at the start of class and see how much water they can pump in a class period. This can be challenging but very informative, as winds will be gusting, shifting, or potentially very low to non-existent. This can lead to some great conversations.

5. Students will need to determine the polarity of the wires before connecting their turbines. The polarity of the wires will change depending on the rotation of the turbine blades. This is an important step and is often the cause of systems not working.

6. Depending on the amount of time you allow students to experiment, you will see that they can come up with some very creative solutions. Student may try to drive multiple pumps from one reservoir or they may have multiple reservoirs at different heights, each with a pump, to drive the water higher and higher.

7. Adding an economic component for this challenge can be important. If a two turbine system with one pump can move as much as three with two pumps that would be a good point of discussion about efficient use of resources.

EQUIPMENT TIPS

1. Set up a safe testing area.
   - Clear the area of debris and materials.
   - Instruct your students to not stand in the plane of rotation of the turbine blades. Also tell them that they should not touch the blades while they are spinning. Blades can be moving very fast and can hurt if they hit someone.
   - Provide safety goggles for your students. Students should wear safety goggles when they are working with a turbine that is spinning.

2. For this project, students do not need to measure power output because they can watch the performance of the pump. However, including an Energy Sensor in the setup can make measuring power and energy output very simple and can also be helpful in determining the polarity of the output wires.

3. We recommend using KidWind Advanced Wind Turbines for this project, as they produce the most power. You can power the pumps if you use KidWind Basic or MINI Wind Turbines, however you may need more of them.

4. If collecting data with a LabQuest interface that can be used as a standalone device (e.g., LabQuest 2), we recommend using LabQuest as a standalone device when collecting data outside rather than connecting LabQuest to a computer. When using the LabQuest as a standalone device in bright sunlight, enabling High Contrast mode will make it easier to read the screen. To enable High Contrast mode, tap Preferences on the Home screen, then tap Light & Power. Select High Contrast.

Exploring Solar Panels

Using solar panels to generate electricity from the sun is becoming increasingly common. Solar panels can be used at many scales to generate power. A single, small panel can be used to charge electronic devices such as your cell phone. Large numbers of panels can function together to generate electricity for an entire neighborhood.

The amount of electricity that can be generated by a solar panel is affected by many variables. In this experiment, you will explore how the amount of current and voltage produced by a solar panel is affected by the distance to a lamp. You will then test your equipment in direct sunlight and calculate the efficiency of the photovoltaic cell when converting the energy from the sun into electrical energy.

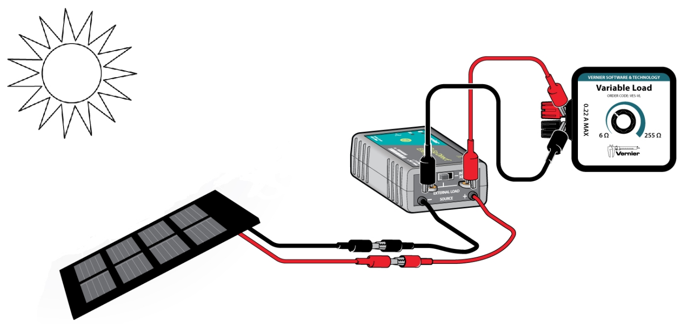

Figure 1

OBJECTIVES

- Understand how solar panels can be used to generate electricity.
- Predict variables that affect how much electricity is generated by a solar panel.
- Make observations and draw conclusions after testing your predictions.
- Calculate the efficiency of a solar panel.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Energy
Go Direct Light and Color
Vernier Variable Load
KidWind 2 V solar panel
2 wires with clips
protractor
75 W light bulb (or equivalent)
light bulb socket or lamp
sunshine
ruler

PRELIMINARY QUESTIONS

1. Solar cells can only generate power when the sun is shining on them. What elements does a system need in order to provide power overnight or other times when the sun is not shining?
2. List some examples you have seen of solar panels in use to provide power.

PROCEDURE

Part I Exploring solar panels

In this part of the experiment, you will use a lamp and a solar panel to learn more about how solar panels work. You will then take the equipment outside to determine how much current and voltage is produced by a solar panel.

1. Set the switch on the Energy Sensor to External Load. Launch Graphical Analysis. Connect the Energy Sensor to your Chromebook, computer, or mobile device.
2. Set up the equipment.
   a. Connect the solar panel to the Energy Sensor Source terminal wires.
   b. Connect the Variable Load to the Energy Sensor Load terminals.
   c. Set up the lamp with the light bulb as shown in Figure 2.

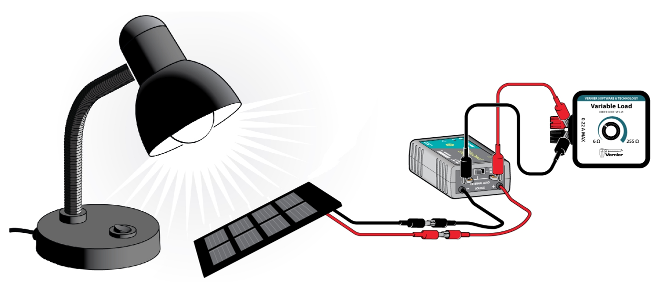

Figure 2

3. Check the current and voltage values and adjust the load.
   a. Turn on the light and place the solar panel close to the bulb.
   b. Note whether the current and voltage values are positive, negative, or zero.
   c. If the values are positive, the setup is correct. If the values are negative or zero, switch the wires connected to the Source terminal wires so they are connected to the opposite terminal wires.
   d. Adjust the load by turning the knob on the Variable Load until the resistance is approximately 10 Ω or equal to the resistance appropriate for your lamp.
4. Explore: Does distance between the solar panel and lamp affect current and voltage?
   a. Make a prediction about how distance between the solar panel and the light source affects current and voltage.
   b. Create a plan to investigate how distance affects how much current and voltage are produced. What are you purposefully changing in this investigation? What will you keep constant?
5. Carry out your plan. When you're ready, click or tap Collect to start data collection.

6. Examine the data.
   a. Click or tap the top graph to examine the voltage values. **Note**: You can also adjust the Examine line by dragging the line.
   b. Click or tap the bottom graph to examine the current values.
   c. What are the maximum current and voltage values that you find? Record these values in Table 1.

7. Determine the maximum power.
   a. Click or tap the vertical axis label of either graph. Select Power only.
   b. Click or tap Graph Tools, , and choose View Statistics.
   c. Record the maximum power in Table 1.

8. Take the equipment outside to a place that will receive sunshine for the duration of the experiment.

9. Explore: How are current and voltage affected by sunlight?
   a. Position the solar panel so it is facing toward the sun.
   b. Create a plan to investigate how current and voltage levels change in the presence of sunlight.
   c. Repeat Steps 6–8 to collect data for sunlight.

10. Answer the Data Analysis questions for Part I before you continue to Part II.

Part II Exploring solar panel efficiency

In this part of the experiment, you will use the Energy Sensor and a Light Sensor to determine the efficiency of the solar panel.

11. Click or tap File, , and choose New Experiment. Click or tap Sensor Data Collection. Connect the Go Direct Light and Color Sensor to your Chromebook, computer, or mobile device.

12. Zero the light sensor.
    a. Cover the light sensor so no light is reaching the sensor.
    b. Click or tap the Illuminance meter and choose Zero.

13. Verify the current and voltage values and adjust the load.
    a. Position the solar panel so it is facing toward the sun.
    b. Note whether the voltage values are positive, negative, or zero.
    c. If the values are positive, the setup is correct. If the values are negative or zero, switch the wires connected to the Source terminal wires so they are connected to the opposite terminal wires.
    d. Adjust the load by turning the knob on the Variable Load until the resistance is the lowest value possible.

14. Tilt the solar panel so it is facing directly toward the sun. Hold the Light Sensor facing toward the sun, next to the solar panel, as shown in Figure 3.

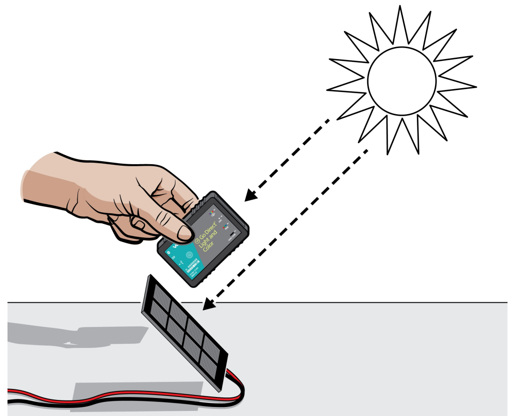

Figure 3

15. Click or tap Collect to start data collection.

16. Determine the mean power and light levels.
    a. Click or tap View, , and choose 2 Graphs.
    b. Click or tap the y-axis label of the top graph and select Power only. A graph of power *vs*. time is displayed.
    c. Click or tap Graph Tools, , for the top graph and choose View Statistics to determine the mean power value. Record the value in Table 2.
    d. Click or tap the y-axis label of the bottom graph and select Illuminance only. A graph of illuminance *vs*. time is displayed.
    e. Click or tap Graph Tools, , by the top graph and choose View Statistics to determine the mean light level. Record the value in Table 2.

17. Repeat data collection to collect a second trial and record the mean power and light levels. Keep the tilt of the solar panel and light sensor the same in both trials.

DATA TABLE

Part I Exploring solar panels

Table 1			
	Maximum current (mA)	Maximum voltage (V)	Maximum Power (mW)
Lamp			
Sunlight			

Part II Exploring solar panel efficiency

Table 2		
Trial	Average power (mW)	Average Illuminance (lux)
1		
2		
Average		

Table 3	
Average power (W)	
Number of cells on panel	
Area of each cell (cm^2)	
Total area of solar cells (m^2)	
Power output per square meter of solar cells (W/m^2)	
Power available from the sunlight (W/m^2)	
Panel efficiency (%)	

DATA ANALYSIS

Part I Exploring solar panels

1. What can you conclude about how distance affects how much voltage is produced based on your observation?
2. How do the current values that you recorded inside and outside compare to each other?
3. How do the voltage values that you recorded inside and outside compare to each other?
4. If you had to choose to collect data inside or outside in the sunshine, which would you choose? Why?

Part II Exploring solar panel efficiency

5. Calculate the average power and illuminance values for the two runs and record them in Table 2. Divide the average power by 1000 mW/W to convert the value to watts. Record the average power (in watts) in Table 3.
6. Examine the solar panel and record the number of solar cells on the panel in Table 3.

7. Determine the area of one cell in cm^2. Remember, the area of a rectangle is length × width. Draw a diagram of one cell and label any measurements that will help when calculating the area. Record the area in Table 3.

8. Calculate the total area of the cells in m^2 using the equation

$$\frac{\text{number of cells on panel} \times \text{area of one cell}}{10{,}000\ \text{cm}^2/\text{m}^2}$$

   Record the result in Table 3.

9. Determine the power output per square meter of the solar panel by dividing the average power output in watts by the total area of solar cells in m^2. Record this result in Table 3.

10. Determine the power per square meter available from the sunlight by dividing the average illuminance value by 93. This factor is a number that roughly converts illuminance to power per unit area, and is based on the temperature of the sun, among other things. Record this value in Table 3.

11. Calculate the average efficiency of the photovoltaic cells using the equation

$$\frac{\text{power output per square meter of the solar cells}}{\text{power available from the sunlight}} \times 100\%$$

12. Compare the efficiency you calculated with the results from other groups. Discuss possible reasons for differences.

EXTENSIONS

1. Explore the efficiency of solar panels under varying lighting conditions: 40, 60, and 100 W incandescent light bulbs, other types of light bulbs (e.g., LED), cloudy conditions, partial clouds, full sun.

2. In the data analysis of Part II, you divided average illuminance by 93. Research the origin of this number. Start by looking up what illuminance actually measures.

3. Research the theoretical limits of solar panel efficiency and the maximum efficiencies produced by commercial solar panel installations.

Exploring Solar Panels

The purpose of this experiment is to familiarize students with how solar panels work. If students need a basic introduction for learning how to use Vernier equipment, this is a good experiment with which to start.

The amount of electricity that can be generated by a solar panel is affected by many variables. In this experiment, students will compare light from the sun and light from a lamp to learn about how solar panels work. They will also calculate the efficiency of the panel they are testing.

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ESTIMATED TIME

We estimate that data collection and analysis can be completed in one, 45-minute class period.

RELATED SKILLS

- Zero sensors, if necessary.
- Use the Statistic tool to calculate statistics.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3) PS3.D Energy in Chemical Processes (HS-PS3)	Cause and effect Systems and system models Energy and matter

EQUIPMENT TIPS

1. This experiment was designed using a KidWind 2 V solar panel. KidWind products used in this experiment are available from Vernier Software & Technology. You may be able to use any solar panel, but we have only tested the experiment with the 2 V solar panel. Different solar panels will produce different power levels and may have different internal resistance values.

2. In the procedure, students are directed to set the Variable Load to 70 Ω or the internal resistance of their solar panel. The internal resistance is generally equivalent to the external resistance at which the solar panel produces the maximum power.

3. This experiment was designed using an energy sensor. It may also be done with a current probe and a voltage probe; students will need to create a calculated column in the data-collection app to calculate power. For more information, see **www.vernier.com/til/3184**

4. If you do not have a Vernier Variable Load, you can perform this experiment using the Vernier Resistor Board, available from Vernier Software & Technology (order code: VES-RB). Otherwise, students can wire combinations of resistors in series and parallel to create resistance values that match those in the Sample Results.

ANSWERS TO PRELIMINARY QUESTIONS

1. Answers will vary. Answers may include storage devices such as batteries or capacitors.

2. Answers will vary. Answers may include garden lights, emergency call stations, roof installations, and many others.

SAMPLE RESULTS

Part I Exploring solar panels

Table 1			
	Maximum current (mA)	Maximum voltage (V)	Power (mW)
Lamp	51.7	1.89	97.7
Sunlight	61.7	2.14	132

Part II Exploring solar panel efficiency

Table 2		
Run	Power (mW)	Illumination (lux)
1	126.4	118,800
2	125.8	118,200
Average	126.1	118,500

Table 3	
Average power (W)	0.1261
Number of cells on panel	12
Area of each cell (cm^2)	2.75
Total area of solar cells (m^2)	0.0033
Power per square meter (W/m^2)	38.21
Power from the sun (W/m^2)	1,580
Panel efficiency (%)	2.4

ANSWERS TO ANALYSIS QUESTIONS

Part I Exploring solar panels

1. Answers will vary.
2. Students should see that current values change quite a bit.
3. Voltage levels are higher outside in the sunlight, but there is not as much of a change compared to the increased current.
4. See Sample Results.
5. Students will likely choose outside in sunlight because the power output is greater.

Part II Exploring solar panel efficiency

1–7. See Sample Results.

8. Answers will vary.
9. Answers will vary and may include temperature, angle, and amount of sunlight.

Effect of Load on Solar Panel Output

Every power source has a characteristic internal resistance based on the materials out of which it is made and the physics of its operation. For example, a modern rechargeable AA battery generally has an internal resistance between 0.01 Ω and 0.10 Ω and a small generator such as those used for classroom wind energy experiments may have an internal resistance between 10 Ω and 100 Ω.

Solar panels, which operate in a very different way from either batteries or generators, have an internal resistance that depends on several variables, including temperature and the amount of light incident on the solar panel. In other words, the internal resistance of a solar panel it is not a fixed value; it fluctuates.

In general, the load and the internal resistance should be matched for optimal power output. However, in most cases it is not possible or cost-effective to vary the load according to changes in the internal resistance of a solar panel. Instead, engineers will choose a single resistance that is useful for the majority of the specified operating conditions.

In this experiment, you will vary the load resistance in a circuit connected to a small solar panel and graph the power output vs. resistance to determine the optimal load for your solar panel under your testing conditions.

OBJECTIVES

- Use the Energy Sensor to determine current, potential (voltage), resistance, and power.
- Determine how solar panel power output varies depending on the resistance (load) in a circuit for a given light source.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Energy
Vernier Variable Load
KidWind 2V/400mA solar panel
2 wires with clips
sunshine

PRELIMINARY QUESTION

What is an electrical load? Give some examples.

PROCEDURE

1. Set the switch on the Energy Sensor to External Load. Launch Graphical Analysis. Connect the Energy Sensor to your Chromebook, computer, or mobile device.

2. Set up the data-collection program.
   a. Click or tap Mode to open Data Collection Settings.
   b. Change Mode to Event Based.
   c. Select Selected Events as the Event Mode.
   d. Click or tap Done.
   e. Click or tap View, ⊞, and choose 1 Graph. Click or tap the vertical axis label and select Power only. Click or tap the horizontal axis label and select Resistance.

3. Set up the equipment.
   a. Connect the solar panel to the Energy Sensor Source terminal wires.
   b. Connect the variable load to the Energy Sensor Load terminals.

4. Perform the experiment.
   a. Gather up the equipment and take it outside to a place that will receive direct sunshine for the duration of the experiment.
   b. Orient the solar panel so it is facing directly toward the sun. Keep the solar panel in this orientation. **Caution**: Do not look directly at the sun.

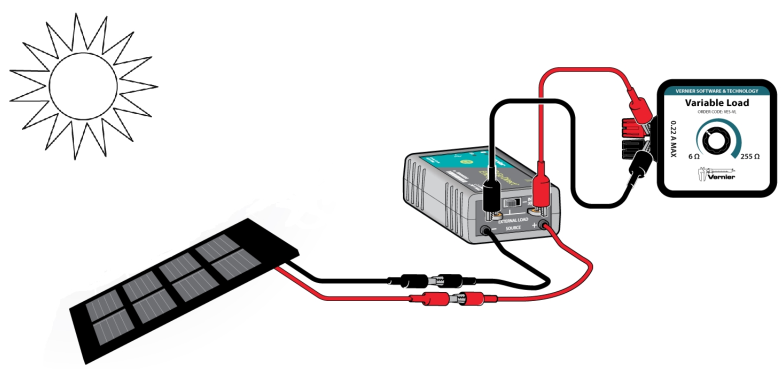

Figure 1

   c. Click or tap Collect to start data collection.
   d. Turn the knob on the variable load all the way counterclockwise.
   e. Click or tap Keep. A data point will be added to the graph.

5. Continue data collection.
   a. Turn the knob on the variable load very slightly clockwise. Check the resistance meter to make sure the resistance has changed by only 1–3 Ω.
   b. Click or tap Keep. The next data point will be added to the graph.

6. Repeat Step 5 until the resistance is about 20 Ω.

7. Once the resistance is about 20 Ω, collect an additional five data points at higher resistances, increasing by 5–10 Ω at a time. When you are done, stop data collection.

PROCESSING THE DATA

1. Examine the graph of power *vs*. resistance. Click or tap the graph to examine the data and find the greatest power output.
2. Export, print, or sketch your graph.

ANALYSIS QUESTIONS

1. What is the load resistance at the maximum power output in your data?
2. Do you think your collected data include the resistance at which your solar panel would produce the maximum power? Why or why not?
3. Based on the results of this experiment, what is the best resistance to use in future experiments with this solar panel?
4. If you were to use this solar panel for a future experiment under different conditions, would you use the same load resistance that you found in this experiment? Explain your reasoning.

EXTENSIONS

1. Find a way to test resistances smaller than or larger than the range of resistances of the Variable Load, and use them to more precisely determine the optimum load in direct sunshine for your solar panel.
2. Determine the resistance (load) that produces maximum power under various light conditions. Compare different indoor lights, bright sunlight, partial cloud cover, and full cloud cover. How does the optimal load resistance for a solar panel change with changing light conditions?
3. To relate the optimal resistance to the brightness of the light incident on the solar panel, perform the Extension 2 experiment while also collecting data with a light sensor or a pyranometer. Use transparent or translucent plastic or layers of window screening to change the amount of light reaching the solar panel.
4. Investigate the effect of temperature on the optimal load resistance.

Fill Factor and IV Curve of a Solar Panel

When considering a solar panel installation, engineers take into account a metric called the fill factor, or FF. This is one way of gauging the efficiency of a solar panel without measuring the irradiance from the sun at the location of the solar panel.

In this experiment, you will vary the load in the solar panel circuit to determine the fill factor. You will create a current-potential curve, also known as an IV curve (see Figure 1). The letter I is the standard symbol used to represent current in equations.

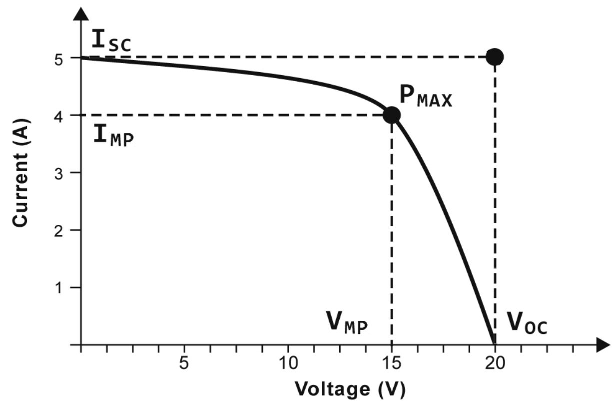

Figure 1

IV curves show the maximum current, maximum voltage, and maximum power a solar cell can generate. The rectangle formed by the graph axes and a vertical line from the open circuit voltage (V_{OC}) and a horizontal line extending from the short circuit current (I_{SC}) extends over a large area of the graph. A smaller rectangle is defined by the graph axes and the current and voltage at maximum power output (I_{MP} and V_{MP}). The fill factor is the area of the smaller rectangle divided by the area of the large rectangle:

$$\mathrm{FF} = \frac{I_{MP}V_{MP}}{I_{SC}V_{OC}}$$

The open circuit voltage V_{OC} is the voltage when the resistance is infinite (i.e., when there is no load connected to the system) and the circuit is open, therefore no current can flow. The short circuit current I_{SC} is the current when the resistance is approximately 0 Ω and the voltage is 0 V. This case is measured by closing the circuit with a plain wire instead of a load.

OBJECTIVES

- Use an Energy Sensor to determine current, potential (voltage), and power.
- Create an IV curve for a solar panel.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Energy
Go Direct Voltage
2 Vernier Variable Loads
KidWind 2 V solar panel
2 wires with clips
sunshine

PROCEDURE

1. Set the switch on the Energy Sensor to External Load. Launch Graphical Analysis. Connect the Energy Sensor and the Voltage Sensor to your Chromebook, computer, or mobile device.

2. Connect the solar panel to the Energy Sensor Source terminal wires by connecting the red wire of the solar panel to the red Source terminal wire and the black wire of the solar panel to the black Source terminal wire. **Note**: Wait to connect the Variable Loads.

3. Set up data collection.
   a. Click or tap Mode. Change the Mode to Event Based and the Event Mode to Selected Events.
   b. Click or tap Done.

4. Set up a graph.
   a. Click or tap View, ⊞, and choose 1 Graph. A single graph is shown.
   b. On the graph, click or tap the vertical (y) axis label and select Current only.
   c. Click or tap the horizontal (x) axis label and select Potential.

5. Determine the open circuit voltage (V_{OC}) of the solar panel.
   a. Orient the solar panel so it is facing directly toward the sun (see Figure 2). Keep the solar panel in this orientation. **Caution**: Do not look directly at the sun.
   b. Record the potential (voltage) reading in the data table as the value for V_{OC}. This reading should be made with no load.

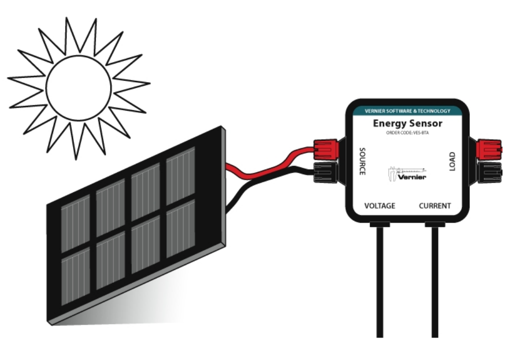

Figure 2

6. Collect data at high resistances.
   a. Connect two Variable Loads to the Energy Sensor Load terminals in series as in Figure 3.
   b. Turn both Variable Load knobs fully clockwise to the highest value.
   c. Click or tap Collect to start data collection.
   d. Click or tap Keep.
   e. Turn the knob of one Variable Load counterclockwise until the current has increased by 10–30 mA.
   f. Repeat parts d and e until the knobs of both Variable Loads are turned fully counterclockwise and the resistance is at its lowest limit.

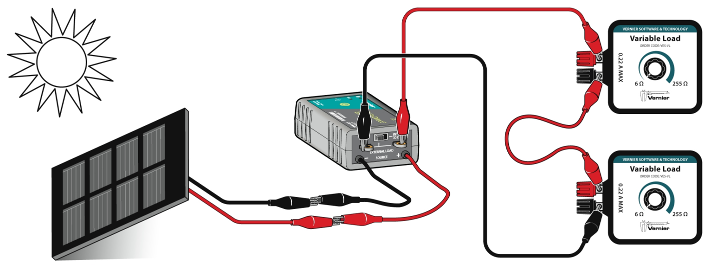

Figure 3

7. Collect data at low resistances.
   a. Connect two Variable Loads to the Energy Sensor Load terminals in parallel as in Figure 4. Figure 5 shows a close-up of how to connect the Variable Loads to the Load terminals. Clip one Variable Load to the Load terminal and the second Variable Load to the clip for the first Variable Load.
   b. Turn both Variable Load knobs fully counterclockwise to the lowest value.
   c. Tap Keep and wait 10 seconds for averaging to occur.
   d. Turn the knob of one Variable Load slightly clockwise and watch the voltage value. Look at the shape of your graph, and compare it to Figure 1. Try to collect additional data points that will fill in "empty" places on the IV curve.

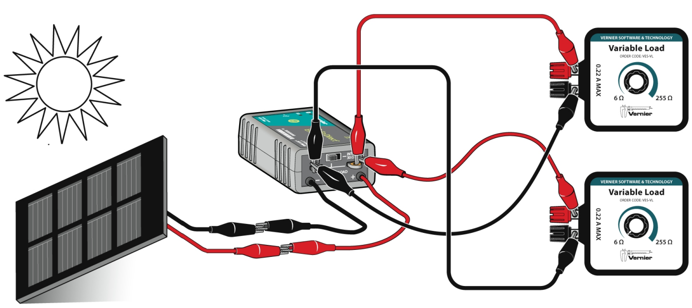

Figure 4 Parallel circuit setup

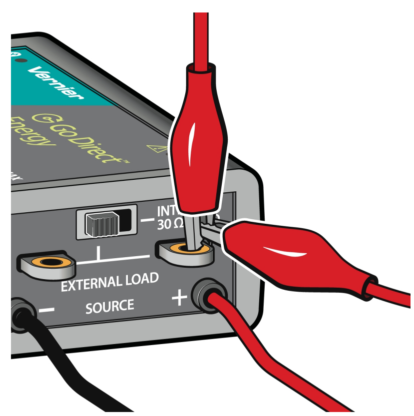

Figure 5 Close-up of connections on Load terminal

8. Determine the short circuit current (I_{SC}) of the solar panel.
   a. Disconnect both Variable Loads from the Energy Sensor.
   b. Connect the Energy Sensor Load terminals to each other with a wire in order to create a short circuit.
   c. Tap Keep.

9. If your data represent the full range of voltage and current values (data should include voltages close to 0 V), stop data collection and continue to the Processing the Data section. If you would like to collect additional data, repeat Steps 7 and 8 until you are satisfied with your data. Ask your instructor if you are unsure if you need to collect additional data.

DATA

V_{OC} (V)	I_{SC} (mA)	V_{MP} (V)	I_{MP} (mA)

PROCESSING THE DATA

1. Print or sketch a graph of current *vs.* potential. Label V_{OC} and I_{SC} on the graph, noting the numerical values.

2. Using the data table in the data-collection software, identify the point on the graph with the highest power output. Use this point to mark I_{MP} and V_{MP} on your graph.

ANALYSIS

Calculate the fill factor for your solar panel using the values you measured for V_{OC}, I_{SC}, V_{MP}, and I_{MP}. Compare your results to others in your class.

Effect of Load on Solar Panel Output

In Experiment 18A, students measure the power produced by a solar panel while changing the resistance. This will help them determine the ideal load resistance to use in future solar panel experiments in order to maximize power output. You will find that this experiment differs from the experiment included in earlier editions of this book. The original experiment has been edited and is included as Experiment 18B.

In Experiment 18B, students determine the fill factor of the solar panel by creating a current-potential curve, also known as an IV curve, for the solar panel. The fill factor is a way of gauging the efficiency of a solar panel without measuring irradiance or calculating the power produced per unit area of the panel. Fill factor is a term that is frequently used in the solar energy industry to characterize solar panels.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Zero sensors, if using the Vernier Energy Sensor.
- Create a graph using data collected during the experiment.

ESTIMATED TIME

We estimate that data collection for this experiment can be completed in one 45-minute class period. You may need to allow extra time for the Analysis.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3) PS3.D Energy in Chemical Processes (HS-PS3)	Cause and effect Systems and system models Energy and matter

EQUIPMENT TIPS

1. This experiment was designed using a KidWind 2 V solar panel. KidWind products used in this experiment are available from Vernier Software & Technology. You may be able to use any solar panel, but we have only tested the experiment with the 2 V solar panel. Different solar panels will produce different power levels and may have different characteristic resistance values and Fill Factors. Most solar panels are rated according to their open-circuit voltage (V_{OC}) and short-circuit current (I_{SC}). For example, the KidWind solar panel is often referred to as a "2V/400mA" panel, meaning that its V_{OC} is about 2 V and its I_{SC} is about 400 mA.

2. This experiment was designed using an energy sensor. It may also be done with a current probe and a voltage probe; students will need to create a calculated column in the data-collection app to calculate power. For more information, see **www.vernier.com/til/3184**

3. If you do not have a Vernier Variable Load, you can perform this experiment using the Vernier Resistor Board (order code: VES-RB). Students using the Vernier Resistor Board (or a collection of other resistors), can wire combinations of resistors in series and parallel to create a range of resistance values similar to those provided by the Vernier Variable Load. In order to produce a meaningful IV curve, students will need at least 10 different resistances ranging from 10 to 300 Ω.

DATA-COLLECTION AND ANALYSIS TIPS

1. The load resistance at which the solar panel produces the maximum power is very dependent on the irradiance incident on the solar panel and the wavelengths present in the incident light. It is somewhat dependent on the temperature of the solar panel. We recommend using sunlight for Experiment 18A, but it is instructive to try an overcast sky and various light bulbs as well. The results will be different.

2. The value measured for the short-circuit current (I_{SC}) depends significantly on the light level at the time it is measured. At low light levels, the I_{SC} you measure may be significantly less than the panel rating. However, even in low light settings, the open-circuit voltage (V_{OC}) and the shape of the IV curve will be about the same as they would be in bright light settings.

3. For best results when creating an IV curve, do this experiment on a clear day in bright light conditions, but not in full sunlight (e.g., conduct the experiment indoors with the equipment placed in sunlight through a window). Note that in very bright sunlight, you may have difficulty reaching low voltages on the solar panel (the plateau region of the IV curve). Under such conditions, you will need very low loads, maybe as low as 1–2 Ω, in order to reach low voltage values. The procedure instructs the student to connect two Variable Loads in parallel to decrease the overall resistance.

4. Experiment 18B, it is important that students collect data at high resistances and low resistances. If they collect data only at high resistances (for example, with the Variable Loads in series), it can appear that they have a full range of data (Figure 1), when in fact they do not (Figure 2).

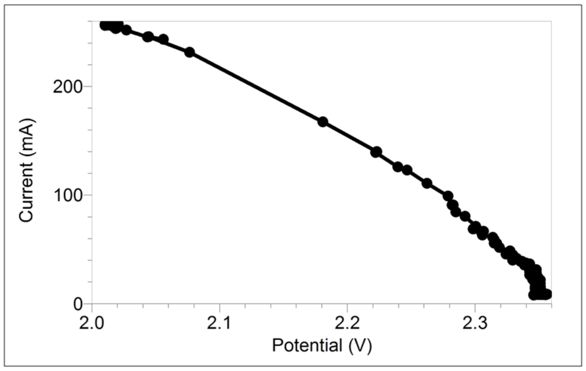

Figure 1

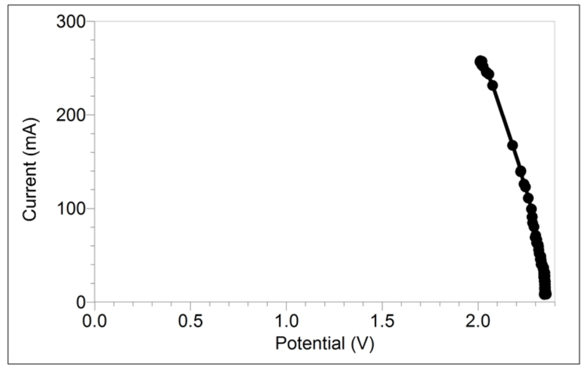

Figure 2

5. If using the LabQuest as a standalone device in bright sunlight, you will probably want to enable High Contrast mode to make it easier to read the screen. To turn on High Contrast mode, tap Preferences on the Home screen, then tap Light & Power. Select High Contrast.

ANSWER TO PRELIMINARY QUESTION

Experiment 18A (no Preliminary Question for 18B)

1. An electrical load is a component in a circuit that draws current to do work. A light, a resistor, and a motor are all examples of loads.

SAMPLE RESULTS

Experiment 18A

The Figure 3 power *vs*. resistance graph was collected in direct sunlight. The peak power is at a resistance of about 8.5 Ω.

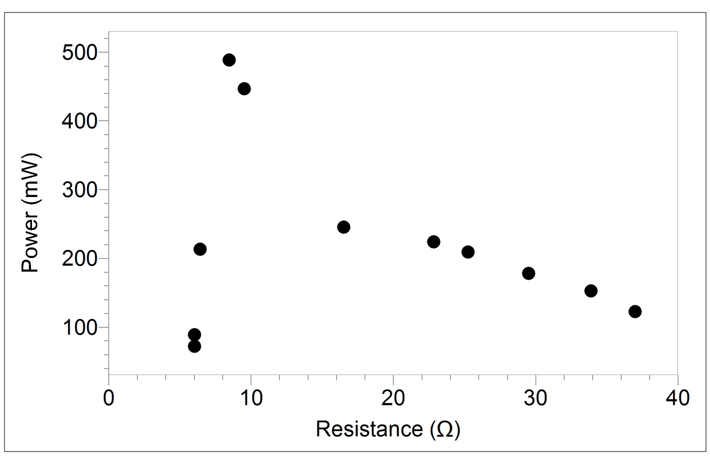

Figure 3 Sample data for Experiment 18A

Experiment 18B

Table 1 Sample Data for 18B			
V_{OC} (V)	I_{SC} (mA)	V_{MP} (V)	I_{MP} (mA)
2.42	345.9	1.82	305.5

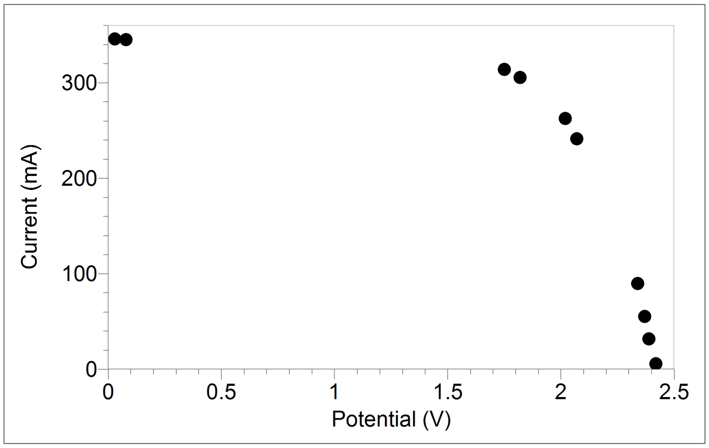

Figure 4 Sample data for Experiment 18B

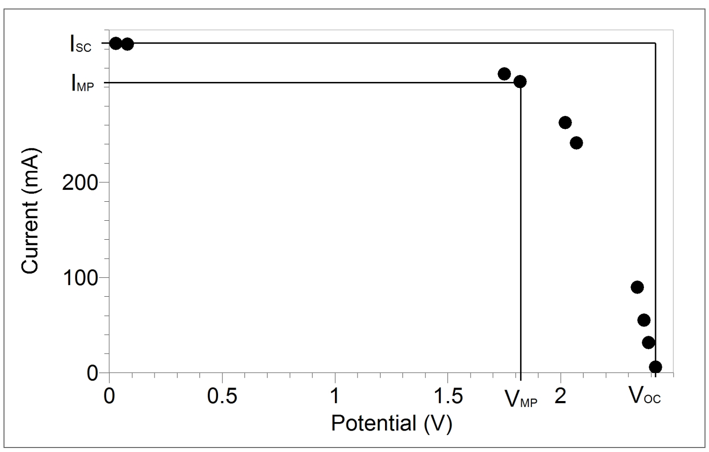

Figure 5

ANSWERS TO ANALYSIS QUESTIONS

Experiment 18A

1. Answers will vary. In our sample data, the maximum power output was at a load of about 8.5 Ω.

2. Answers will vary. In sunlight, it may be that the resistance at which maximum power is generated is lower than you have the means to create.

3. Answers will vary. In direct sunlight, expect a low value (under 10 Ω), but in indoor lighting the value will be higher.

4. It is good practice to match the electrical load to the characteristic resistance of the solar panel, for maximum efficiency. Since the characteristic resistance changes depending on the light source and brightness (irradiance) and with temperature, using the same load under different conditions will probably not result in efficient power production.

Experiment 18B

For the data in the Sample Results, the fill factor is 0.664. Answers will vary.

Variables Affecting Solar Panel Output

In this experiment, you will experiment with a small solar panel to explore factors that affect the power output of the panel.

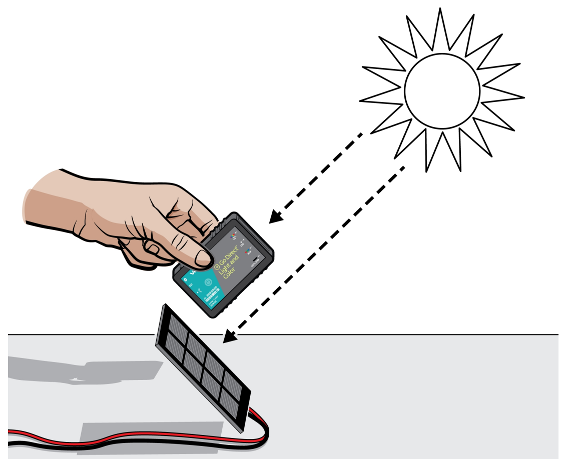

Figure 1

OBJECTIVES

- Use an energy sensor to measure current and voltage output.
- Explore variables that affect solar panel power output.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Energy
Vernier Variable Load
KidWind 2 V solar panel
2 wires with clips
additional sensors and materials to test and control variables (will depend on experiment design)

PRELIMINARY QUESTIONS

1. What variables might affect the power output of a solar panel?

2. How will you keep your non-experimental variables constant? Is it possible in all cases? Explain.

3. Do some variables matter more than others? For example, do you think angle or wavelength has a greater effect on power output?

PROCEDURE

1. Create a plan to collect data for the variable you are testing. You will make 3–5 modifications for your variable. For example, if you are testing the angle of the solar panel, you will collect data for 3–5 different angles.

2. Set up the equipment.
   a. Set the switch on the Energy Sensor to External Load. Launch Graphical Analysis. Connect the Energy Sensor to your Chromebook, computer, or mobile device.
   b. Connect any additional sensors you are using to your Chromebook, computer, or mobile device.

3. Change the data-collection parameters, if necessary for your plan.
   a. Click or tap Mode to open Data Collection Settings.
   b. Adjust the data collection settings based on your plan.
   c. Click or tap Done.

4. If you are testing a variable that requires sunlight, find a testing location that is in direct sunlight.

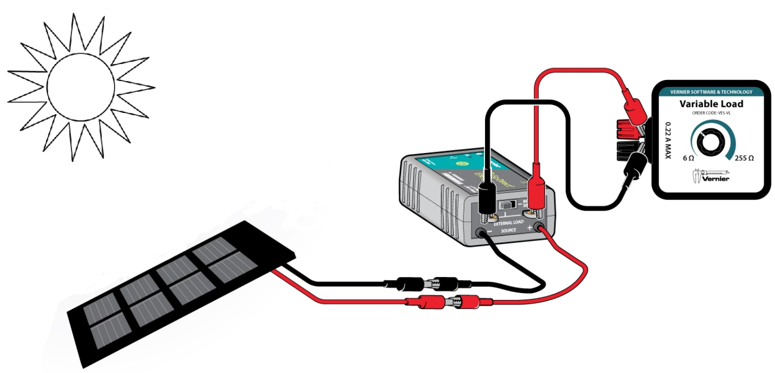

Figure 2

5. Check the current and voltage values and adjust the load.
   a. Position the solar panel so it is facing toward the sun. **Caution**: Do not look directly at the sun!
   b. Note whether the values are positive, negative, or zero. If the values are positive, the setup is correct. If the values are negative or zero, switch the wires connected to the Source terminal wires so they are connected to the opposite terminal wires.
   c. Adjust the load by turning the knob on the Variable Load until the resistance is approximately 10 Ω or equal to the ideal load for your solar panel under your conditions.

6. Collect data and determine the values that you need to fulfill your plan.
   a. Click or tap Collect to start data collection. When data collection is complete, graphs of voltage *vs*. time and current *vs*. time are displayed.

b. If you want to see a different graph, click or tap the axis labels of one of the graphs and select the variable you wish to display.
c. Analyze the graphs as necessary for your plan.

7. Repeat data collection until you have collected all the data that you need to test your variable.

DATA TABLE

If directed by your instructor, use the provided table to record your data. Use the blank columns for any additional variables you wish to include.

Angle (°)	Current (mA)	Voltage (V)	Illuminance (lux)	Power (mW)

PROCESSING THE DATA

Create a graph of power output *vs*. the variable you tested.

ANALYSIS QUESTIONS

1. Describe the relationship between power output and the variable you tested.
2. Share your results with the rest of the class. When you do this, describe your testing plan, the variable you tested, and your results. After you have heard all the results, use the information to write a paragraph explaining which variable has the greatest affect on power output.
3. Based on the class results, summarize important factors to consider if you are going to install solar panels to provide electricity to your home.

EXTENSIONS

1. Monitor power output of a solar cell throughout the day or over a longer time period such as a quarter or semester. Keep track of the cloud cover and angle of the sun.
2. Determine if dust on the solar panel affects power output. Can you use this information to determine if it is important to clean solar panels on a home?

Variables Affecting Solar Panel Output

Students use solar panels to test different variables and compare the power output as they make changes to the setup.

We suggest starting the experiment with a brainstorming session. Record students' ideas and have each group choose one or two different variables. This way, as a class, you will cover a wide variety of variables. If you would rather, simply assign variables to the groups. Options for variables include (among others)

- Wavelength of light
- Temperature of solar panel
- Angle in relation to horizon
- Orientation (N, S, E, or W)
- Time of day
- Irradiance or illumination
- Series or parallel circuit with different numbers of solar panels

You may decide that students should not choose temperature as their variable if you plan on also doing Experiment 20 "Effect of Temperature on Solar Panel Output."

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Zero sensors, if using the Vernier Energy Sensor.
- Create a graph using data collected during the experiment.
- Determine statistics (depending on student's plan).

ESTIMATED TIME

We estimate that data collection for this experiment can be completed in one to two 45-minute class periods. Provide time for students to analyze their data and then share it with the class.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3) PS3.D Energy in Chemical Processes (HS-PS3)	Cause and effect Systems and system models Energy and matter

EQUIPMENT TIPS

1. KidWind 2V/400mA Solar Panels may be purchased from Vernier Software & Technology (order code KW-SP2V). You may be interested in our Solar Energy Exploration Kit, which includes three solar panels, a box and hook-and-pile tabs for mounting the panels, and a few additional accessories (order code KW-SEEK).

2. This experiment was designed using an energy sensor. It may also be done with a current probe and a voltage probe; students will need to create a calculated column in the data-collection app to calculate power. For more information, see **www.vernier.com/til/3184**

3. If you do not have a Vernier Variable Load, you can perform this experiment using the Vernier Resistor Board, available from Vernier Software & Technology (order code: VES-RB). Otherwise, students can wire combinations of resistors.

4. When studying the effect of illuminance or irradiance levels, students will need to both measure and control the variable. Measurement of irradiance can be performed with the Pyranometer (order code PYR-BTA), which requires a Vernier interface in order to collect data (e.g. LabQuest 2 or LabQuest Mini). Illuminance data can be collected with the Light Sensor (order code LS-BTA; also requires an interface) or the Go Direct Light and Color Sensor (order code GDX-LC; does not require an interface). When using sunlight, controlling the illuminance or irradiance can be done with layers of window screening, differing transparent and translucent materials, or waiting for different times of day. When using an artificial light source, changing the distance between the light source and the solar panel is generally sufficient.

5. Investigating different combinations of solar panels connected in series and parallel is useful preparation if you plan to do Experiment 21 "Project: Build a Solar Charger".

DATA-COLLECTION AND ANALYSIS TIPS

1. Remind students to investigate only one variable at a time, keeping all other variables as constant as possible.

2. Depending on the variable tested, this experiment works best in bright sunlight. Some solar cells may be sensitive enough to do this experiment with a full spectrum bulb.

3. The illuminance or irradiance value will fluctuate due to obstructions of the sunlight. Students should record an average value if this is one of their variables.

4. If collecting data with a LabQuest interface that can be used as a standalone device (e.g., LabQuest 2), we recommend using LabQuest as a standalone device when collecting data outside rather than connecting LabQuest to a computer. When using the LabQuest as a standalone device in bright sunlight, enabling High Contrast mode will make it easier to read the screen. To enable High Contrast mode, tap Preferences on the Home screen, then tap Light & Power. Select High Contrast.

ANSWERS TO PRELIMINARY QUESTIONS

1. Answers will vary and may include angle, amount of sun, color of light hitting the panel, reflected light, and/or temperature.
2. Answers will vary. It will be challenging to keep the temperature of the solar panel constant, for example, and if students change the angle of the solar panel they are changing the irradiance on the panel by default.
3. Answers will vary.

SAMPLE RESULTS

The sample results were collected during an experiment to test the variable of angle. We collected data with an energy sensor and a light sensor.

Angle (°)	Current (mA)	Voltage (V)	Illuminance (lux)	Power (mW)
40	0.546	1.93	115100	1.054
30	0.540	1.90	109000	1.026
20	0.46	1.63	102000	0.750
10	0.434	1.53	98640	0.664
0	0.383	1.34	90180	0.513

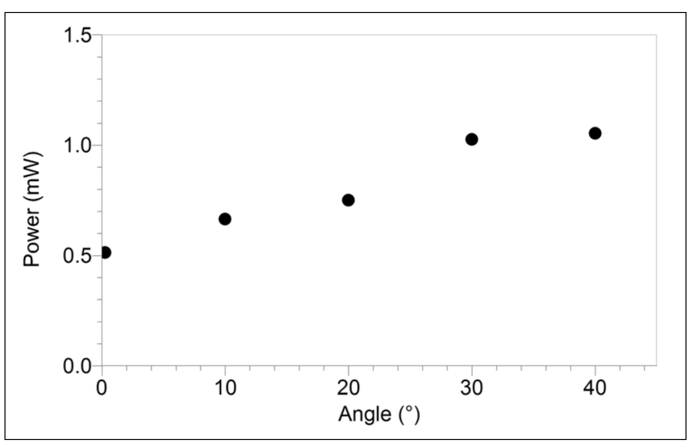

Figure 1 Effect of angle from horizontal on power output

ANSWERS TO QUESTIONS

1. Answers will depend on the variable tested by the student.

2–3. Answers will depend on class data.

Effect of Temperature on Solar Panel Output

Temperature affects a solar panel in multiple ways. As solar panels are made from silicon, one factor is the effect of temperature on the silicon. Higher temperatures mean increased thermal motion of the electrons in the material, resulting in a lower energy threshold for electrons to become mobile charge carriers, resulting in a current. Because it takes less energy to create current, the maximum voltage (V_{OC}) of the solar panel decreases as the temperature increases, while the maximum possible current (I_{SC}) increases.

Accompanying the change in the properties of the semiconductor, the characteristic resistance of the solar panel may change as well. The silicon generally decreases in resistance as temperature increases, but the metal contacts on the top and bottom of the solar panel will behave in the opposite way. The resistance of conductors generally increases as temperature increases.

With a minimum of four ways the properties of the solar panel are changing as temperature changes, it may seem challenging to predict how the maximum power output will be affected by changing in temperature. However, it is not necessary to have an understanding of solid state physics to determine the effect of temperature on the maximum power output of a solar panel. In this experiment, you will start with a cold solar panel, and let it warm up in the sun. As the solar panel warms, you will measure the power output using an Energy Sensor.

OBJECTIVES

- Use an Energy Sensor to measure power output while varying the temperature of a solar panel.
- Understand how temperature affects power output for a solar panel.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Energy
Go Direct Surface Temperature Sensor
Vernier Variable Load
KidWind 2 V solar panel
2 wires with clips
ice bath
clear tape
sunshine

PRELIMINARY QUESTIONS

1. Do you think a solar panel will generate more power in hot temperatures or cold temperatures (assume the same amount of light is hitting the panel)? Why?

2. Have you ever noticed other electrical devices that are affected by temperature? What changes do you notice? What happens when the devices get very hot or cold?

3. What happens to the resistance in a circuit when the temperature changes?

PROCEDURE

1. Connect sensors and set up data collection.
   a. Set the switch on the Go Direct Energy Sensor to External Load. Launch Graphical Analysis. Connect the Energy Sensor as well as the Surface Temperature Sensor to your Chromebook, computer, or mobile device.
   b. Click or tap Mode to open Data Collection Settings.
   c. Change Mode to Event Based.
   d. Change Event Mode to Selected Events. Click or tap Done.
   e. Click or tap View, ⊞, and choose 1 Graph.
   f. Tap the y-axis label and select Power only. Tap the x-axis label and select Temperature. A graph of power *vs*. temperature is displayed.

2. Continue setting up the equipment.
   a. Connect the solar panel to the Energy Sensor Source terminal wires. **Note**: Connect the red wire of the solar panel to the red Source terminal wire and the black wire of the solar panel to the black Source terminal wire.
   b. Connect the Variable Load to the Energy Sensor Load terminals. **Note**: Connect the terminals so that the red terminal of the Variable Load is connected to the positive (+) Load terminal and the black terminal of the Variable load is connected to the negative (–) Load terminal.
   c. Tape the sensor of the Temperature Sensor to the front of the solar panel.

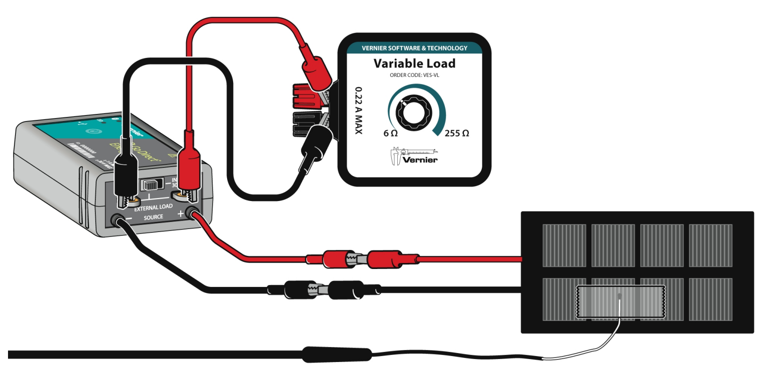

Figure 1

3. Adjust the load.
   a. Move the equipment to a place that will receive direct sunshine for the duration of the experiment.

   b. Position the solar panel so it is facing the sun. **Caution**: Do not look directly at the sun!
   c. Adjust the load by turning the knob on the Variable Load until the resistance is approximately 10 Ω or equal to the internal resistance of your solar panel.

4. Place the solar panel and Temperature Sensor in an ice bath. Monitor the temperature. When the temperature reading stabilizes (typically at a few °C), remove the solar panel from the ice bath and again position it so it is facing toward the sun.

5. Collect data. **Important**: Complete this step efficiently so you start data collection when the panel is close to the temperature of the ice bath.
   a. Click or tap Collect to start data collection.
   b. Click or tap Keep to record a data point.
   c. Monitor the temperature. When the temperature increases by 1°C, click or tap Keep.
   d. Repeat step c until the temperature has increased by 25°C, or until the temperature stops increasing.

6. Examine the power *vs*. temperature graph.
   a. Determine the starting power and temperature values and record the values in the data table.
   b. Determine and record the final power and temperature values.

DATA

	Power (mW)	Temperature (°C)
Starting		
Final		

PROCESSING THE DATA

1. Apply a linear fit to the power *vs*. temperature graph. Record the equation for the linear fit.
2. Print, export, or sketch the graph of power *vs*. temperature.

ANALYSIS QUESTIONS

1. Based on your data, write a statement that explains the relationship between the power output of a solar panel and its temperature.
2. Based on this experiment, what would the ideal conditions be for solar panel power production?
3. The International Space Station (ISS) is powered by 262,400 solar panels arranged in eight arrays, each 34 m by 12 m, which together can generate 84 to 120 kW of power[1]. Why is solar energy a good option for powering the ISS?

[1]https://www.edn.com/design/power-management/4427522/International-Space-Station--ISS--power-system

EXTENSIONS

1. Determine the I_{SC} and V_{OC} with the solar panel in an ice bath and after the solar panel has sat in full sun for at least 30 minutes. Create a power curve for the solar panel in each case and compare.
2. Repeat the experiment, but taking the temperature of the solar panel from the back instead of the front. Is there a difference in your results?
3. Repeat the experiment with a different load. Is there a difference in your results?
4. Determine the optimal load for the solar panel while it is held at ice-water temperature and again when the solar panel has been in the sun for at least 30 minutes and the temperature is stable and warm. Compare your results.

Effect of Temperature on Solar Panel Output

The physics of the effect of temperature on solar panels is complex, as several factors are at work. Visit **www.pveducation.org** for an excellent introduction to solar panels. This resource explains the factors involved in detail.

In this experiment, students monitor the power production of a solar panel as its temperature increases. They should discover a fairly linear relationship between power production and temperature.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Change data-collection parameters.
- Zero sensors, if using the Vernier Energy Sensor.
- Change what is plotted on graphs.
- Create a graph using data collected during the experiment.

ESTIMATED TIME

We estimate that data collection for this experiment can be completed in one to two 45-minute class periods.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3) PS3.D Energy in Chemical Processes (HS-PS3)	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter

EQUIPMENT TIPS

1. The KidWind solar panels sold by Vernier Software & Technology are resistant to water, and will operate while submerged even if the wires and alligator clips become wet. We recommend drying the solar panels thoroughly before storage.

2. This experiment was designed using an energy sensor. It may also be done with a current probe and a voltage probe; students will need to create a calculated column in the data-collection app to calculate power. For more information, see **www.vernier.com/til/3184**

3. The Surface Temperature Sensor can be submerged in water. It has not been tested in other liquids.

DATA-COLLECTION AND ANALYSIS TIPS

1. This experiment works best in bright sunlight. Some solar cells may be sensitive enough to do this experiment with a full spectrum bulb. If you are using a lamp, keep an eye on the solar panel to ensure that it does not get damaged from heat. We recommend a 75 or 100 W or equivalent light bulb, 15–25 cm from the solar panel.

2. Students need to cool their solar panels in an ice bath. Ideally, the ice bath should be located close to the data-collection site so that students can start data collection soon after removing the panel from the ice bath.

3. If collecting data with a LabQuest interface that can be used as a standalone device (e.g., LabQuest 2), we recommend using LabQuest as a standalone device when collecting data outside rather than connecting LabQuest to a computer. When using the LabQuest as a standalone device in bright sunlight, enabling High Contrast mode will make it easier to read the screen. To enable High Contrast mode, tap Preferences on the Home screen, then tap Light & Power. Select High Contrast.

ANSWERS TO PRELIMINARY QUESTIONS

1. Answers will vary.

2. As students may not have had experience with electronics in temperature extremes, answers will vary. Modern electrical devices with integrated circuits generally do not perform well in very hot conditions as this can affect the circuits and degrade performance.

3. As the temperature decreases, the resistance in a circuit usually decreases.

SAMPLE RESULTS

In the sample data shown, the equation for the linear fit of the data is

$$P = (-3.69\ \text{mW/°C})T + 552.82\ \text{mW}$$

where P is the measured power and T is the measured temperature.

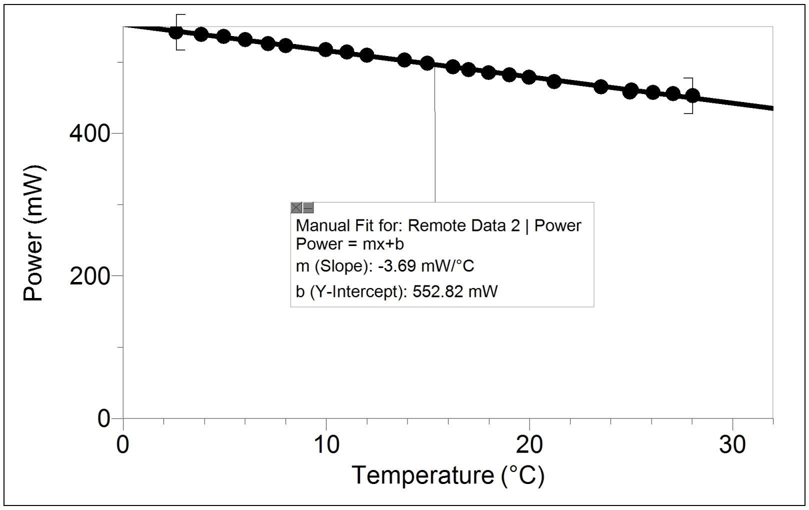

Figure 1 Relationship between power and temperature

	Power (mW)	Temperature (°C)
Starting	541.2	2.6
Final	452.6	28.0

ANSWERS TO ANALYSIS QUESTIONS

1. As temperature increases, power output decreases.
2. The ideal conditions would be very cold and no clouds or haze.
3. Answers will vary, but should connect the idea that there is no atmosphere between the sun and the solar panels on the International Space Station (ISS) and the fact that it is very cold in space. Also, floating in space means that it is easy to orient the solar panels to face directly toward the sun, while this is not necessarily easy on a roof-mounted system, for example.

Project: Build a Solar Charger

Generating electricity from fossil fuels comes with many environmental and social problems related to pollution and climate change. But in order to have a high percentage of renewable sources in our electricity mix, we need an affordable way to store large quantities of energy so it is available when electricity demand surpasses generation from the sun. We are used to getting electricity whenever we want it—not waiting for the sun to shine if we want power!

In this project, you will design a solar-powered charging system for rechargeable AA or AAA batteries. You will build a small solar array, combining at least two solar panels, to charge your batteries. Your group will work together to design, test, and optimize your system for charging batteries.

You must be careful not to overcharge your batteries. As a general rule, it is safe to trickle charge at a 10% rate, meaning your input current can be up to 10% of the battery's rated capacity. This is called a C/10 rate. For example, if a battery is rated at 2100 mAh, the C/10 rate would be 210 mA.

Consider the following points as you develop your plan:

- Note the storage capacity of each battery you are using.
- Determine the maximum current output of a single solar panel from your array. This is also known as the short-circuit current (I_{SC}).
- Arrange your solar panels in a circuit so that the maximum current does not exceed 10% of the rated capacity. The maximum voltage of your solar array can be slightly greater than the total voltage of your batteries.
- You may need to use a Vernier Variable Load or a resistor in series with your solar panels to limit the current flowing from the panels into the batteries.

DESIGN REQUIREMENTS AND CONSTRAINTS

- Design and construct a system that charges AA or AAA batteries using solar panels
- Must use rechargeable batteries (NiMH recommended)
- Must not exceed 10% charging rate (C/10)
- Must power the charger using small solar panels
- Must use a diode between solar panels and batteries
- May use a resistor to limit current
- Can use multiple solar panels
- Can use multiple batteries (between 1 and 4 batteries)
- Batteries must be connected in series
- Solar panels can be connected in series and/or parallel
- Construction materials must be readily available (recycled materials are encouraged)
- Instructor must approve your design and circuit before you close the circuit and expose solar panels to sunlight
- Do not exceed the project budget

DELIVERABLES

- Detailed system specifications (so the unit can be replicated exactly)
- Maximum voltage output of solar array (in volts)
- Maximum current output of solar array (in milliamps)
- Total battery storage capacity (in milliamp-hours)
- Approximate system charging rate (total battery capacity/array maximum current)
- Method to determine battery state of charge (% charged)
- Approximate system budget

Project: Build a Solar Charger

In this project, each group will design a solar-powered charging system for rechargeable AA or AAA batteries. We recommend that students build a small solar array, combining at least two solar panels to charge batteries. Groups will work together to design, test, and optimize their system for charging batteries.

Students must be careful not to overcharge the batteries. As a general rule, it is safe to trickle charge at a 10% rate, meaning your input current can be up to 10% of the battery's rated capacity. This is called a C/10 rate. For example, if a battery is rated at 2100 mAh, the C/10 rate would be 210 mA.

Having students design and implement the best configuration of solar panels for charging their batteries is the goal of this project. When preparing equipment and coaching students consider these points:

- Note the storage capacity of each battery being used. This may be on the side of the battery or can be found online by searching for the battery specifications. Capacity is measured in milliamp-hours (mAh).
- Find the maximum current output of a single solar panel from the array. This is also known as the short-circuit current (I_{SC}). Determine what happens to voltage and current output when you connect multiple panels together in series and in parallel.
- Arrange solar panels in a circuit so that the maximum current does not exceed 10% of the rated battery capacity. The maximum voltage of the solar array can be slightly greater than the total voltage of your batteries.
- You may need to use a Vernier Variable Load or a resistor in series with your solar panels to limit the current flowing from the panels into the batteries. You many need to help students select the correct load.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

ESTIMATED TIME

We estimate that this project can be completed in three class periods. In the first class, students can perform basic tests with solar panels to measure voltage and current output under various conditions. They can also begin calculations to determine how many panels could safely be connected in series and parallel circuits in order to charge batteries. In the second class period, students can design and construct their battery charging systems. Students can analyze the results and refine their designs in the third class period.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking questions and defining problems Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Engaging in argument from evidence Obtaining, evaluating, and communicating information	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3) ETS1.A Defining Engineering Problems ETS1.B Developing Possible Solutions ETS1.C: Optimizing the Design Solution	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter Structure and function Stability and change

TIPS

1. It is helpful for students to have completed Experiments 17, 18, and 19 from this book before doing this project.
2. If students have not combined multiple solar panels in series or parallel before, you my need to instruct them on what those terms mean and how to make the connections.
3. The KidWind Solar Energy Exploration Kit (order code: KW-SEEK) includes three solar panels and a box for mounting them and for storing them when not in use. It is a convenient way to have student groups use multiple solar panels.
4. Omit any requirements in the student handout that you do not want to use. For example, you may or may not want to include specific budget requirements, or you may wish to restrict all groups to charging the same size or brand of battery.

Exploring Passive Solar Heating: Baseline Cooling Curve

To reduce the amount of electricity used to heat and cool buildings, people are working to refine passive solar design features that allow buildings to heat and cool without the need for a system that relies on electricity.

A well-designed passive solar building retains heat in the winter in order to be comfortably warm and, during the summer, eliminates heat so that it remains cool. This heating and cooling is done without the use of pumps or fans and instead relies on insulation and shade, amongst other features.

In this experiment, you will monitor temperature of a model home and determine the cooling rate of the interior after the model home has been heated by a lamp. Once you have this baseline data, you can compare it to future experiments after making modifications to your model home.

OBJECTIVES

- Measure the temperature of a model home as it cools.
- Compare results to Newton's Law of Cooling.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Surface Temperature Sensor
model home
lamp with 100 W (or equivalent) light bulb

PROCEDURE

1. Launch Graphical Analysis. Connect the Go Direct Surface Temperature Sensor to your Chromebook, computer, or mobile device.

2. Set up the data-collection mode.
   a. Click or tap Mode to open Data Collection Settings.
   b. Change End Collection to 300 s.
   c. Click or tap Done.

3. Record the room temperature in the data table.

4. Obtain a model home. Insert the Temperature Sensor into the hole provided. Position a lamp with its bulb about 3 cm away from the model home’s window.

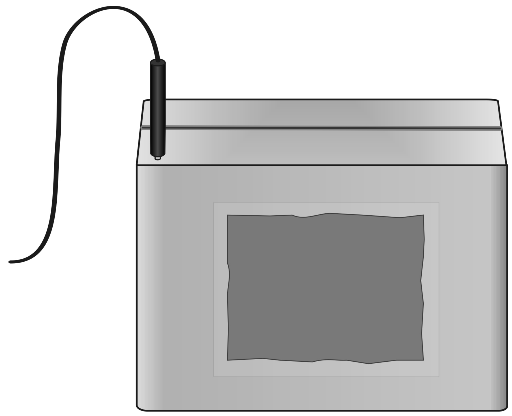

Figure 1

5. Turn on the lamp and allow it to warm the model home.

6. Turn off the lamp when the internal temperature of the model home is 7.0°C greater than room temperature.

7. When the temperature drops to exactly 6.0°C greater than room temperature, click or tap Collect to start data collection.

8. After data collection is complete, observe the graph. Determine the initial cooling rate.
   a. Select the first 20 seconds of data on the graph.
   b. Click or tap Graph Tools, , and choose Apply Curve Fit.
   c. Select Linear as the curve fit. Click or tap Apply. The linear-regression statistics for these two data columns are displayed for the equation in the form

   $$y = mx + b$$

   where x is time, y is temperature, m is the slope, and b is the y-intercept.
   d. Record the value of the slope, m, as the initial cooling rate.

9. Determine the final cooling rate.
   a. Select the last 40 seconds of data on the graph.
   b. Click or tap Graph Tools, , and choose Apply Curve Fit.
   c. Select Linear as the curve fit. Click or tap Apply.
   d. Record the value of the slope, m, as the final cooling rate.

10. Print or sketch your graph with the linear fits, as directed by your instructor.

DATA TABLE

Room temperature (°C)	
Initial cooling rate (°C/s)	
Final cooling rate (°C/s)	

DATA ANALYSIS

1. Newton's Law of Cooling says that the cooling rate at which thermal energy moves from one body to another is proportional to the difference in temperature between the two bodies. This can be written as

   $$\text{cooling rate} = -kT_{\text{diff}}$$

   From this simple assumption, Newton showed that the temperature change of a cooling object is exponential and can be modeled by the equation

   $$T_{\text{diff}} = T_0 e^{-kt}$$

   where T_0 is the initial temperature difference. Apply an exponential curve fit to the full set of collected data and write the equation.

2. Compare your data to the data collected by other groups. What similarities and differences between the model homes can explain how your results compare with those of other people in the class?

3. Imagine if data collection had continued for another 300 seconds. Would the temperature ever stop decreasing? When and why?

4. List some building design features that help capture solar energy and retain heat.

EXTENSIONS

1. Based on what you learned from this lab, design your own model home. You can experiment with color, insulation, reflective material, surface area, and more as you try to design a more efficient system for heating a home using energy from the sun.

2. Create a competition with the class. The winner builds a home that has the least change between the warmest temperature and the final temperature over the same time span.

3. Look into factors that help keep a home cool in the summer. Use this information to make adjustments to your model home.

Exploring Passive Solar Heating: Baseline Cooling Curve

In this experiment, students will collect baseline data for the cooling of a building that has been heated by the sun. This experiment is an excellent introduction to passive solar heating, which is explored further in Experiment 23 "Variables Affecting Passive Solar Heating."

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Change data-collection parameters.
- Use the Linear Fit tool in the data-collection app.

ESTIMATED TIME

We estimate that data collection and analysis can be completed in one to two 45-minute class periods. Students are asked to compare results, which could take some additional time.

EQUIPMENT TIPS

1. Cut a window in one side of the box you are using for the solar home. Leave enough material in the side of the box so the material for the "window" can be attached. The window can be made of any transparent material.

2. Create a hole for a Temperature Sensor at the top of the front side, where the probe will be out of direct light. Place a piece of black construction paper on the floor, if possible. Tape the box shut and use tape to seal the edges of the window to reduce heat loss.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking questions and defining problems Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Engaging in argument from evidence Obtaining, evaluating, and communicating information	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3) ETS1.A Defining Engineering Problems ETS1.B Developing Possible Solutions ETS1.C: Optimizing the Design Solution	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter Structure and function Stability and change

DATA-COLLECTION AND ANALYSIS TIPS

1. The sensor of the Surface Temperature Sensor should be measuring the temperature of the air in the model home, not the model home "walls." Instruct students to make sure the sensor (the black tip of the wire) is suspended in the air.
2. In order for students to be able to compare their data, the model homes should be the same shape, size, and materials. If this is not possible, students can use the discrepancies as discussion points for why they see differences in data.
3. Although longer data-collection periods give better results, this experiment can be done with total running times as short as 40 minutes.

SAMPLE RESULTS

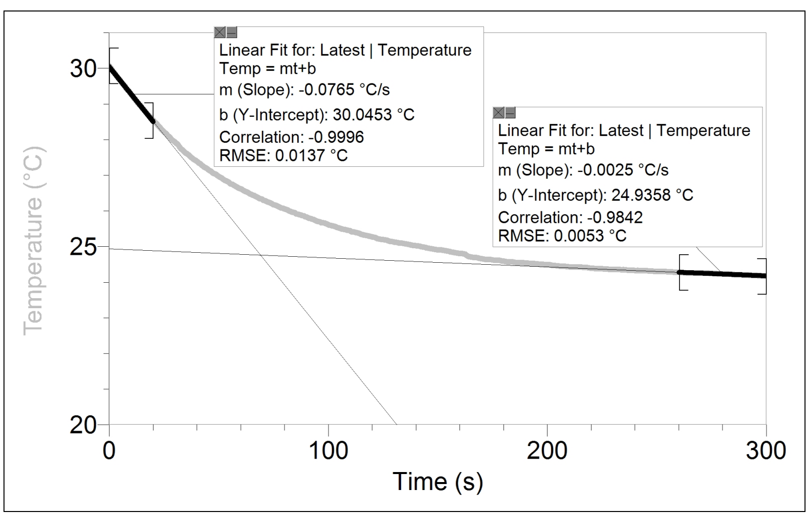

Figure 1

Room temperature (°C)	23.0
Initial cooling rate (ºC/s)	–0.0765
Final cooling rate (ºC/s)	–0.0025

ANSWERS TO ANALYSIS QUESTIONS

1. The expression for the curve in the Sample Results is: $5.84e^{-0.0139t} + 24.1282$

2. Answers will vary. Students will compare their data with the data collected by the other groups.

3. Answers will vary. Students should realize that the solar homes will not cool indefinitely. The temperature will eventually reach that of the room.

4. Some examples of design features of that help passive solar houses capture solar energy and retain heat include the following:
   - insulation
   - large south-facing windows
   - multiple-paned windows
   - insulated drapes or window shades
   - thermal mass (such as concrete, stone, or water)

Variables Affecting Passive Solar Heating

Buildings can be designed to retain heat in the winter while also helping them to remain cool in the summer. Insulation and heat storage are important factors in such a system. A *thermal mass*, a material that absorbs and stores heat, is one example of a design feature that can be used to help control the temperature in a building.

In this experiment, you will examine the effectiveness of different design features. Two model homes, one that will act as a control and one that you modify, will be heated by a light bulb. Temperature sensors will monitor their temperatures throughout a simulated day and night.

OBJECTIVES

- Use Surface Temperature Sensors to measure temperature.
- Design, build, and test a model solar home.
- Compare your results to the data collected by other groups.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
2 Go Direct Surface Temperature Sensors
2 model solar homes
solar home "windows"
2 pieces of cardboard to cover the windows
lamp with 100 W bulb
ring stand
utility clamp
tape
ruler
materials to test variables (will depend on experiment design)

PRELIMINARY QUESTIONS

1. List three or four design factors, other than the presence of a thermal mass, that affect the ability for a home or building to retain heat.
2. If you build a building so as to increase passive solar heating, what can you do to help reflect or reduce heating in the summer when you want to keep the interior cool?
3. Sketch a graph of the temperature inside the solar home that is the control during one day-night heating-cooling cycle. On the same graph, sketch your prediction of the temperature inside the house that you are designing.

PROCEDURE

Part I Initial data collection

1. Obtain two solar homes that are matched in size and shape.
2. Create a plan to modify the model home for the variable you are testing, and then make the necessary modifications. Tape both model homes closed.
3. Position the two solar homes 20 cm apart, with the window sides facing each other (see Figure 1). Position a lamp so that it will shine down between the model solar homes. The lamp bulb should be 10 cm above the table top and equidistant from the two model homes. Do not turn on the lamp yet.

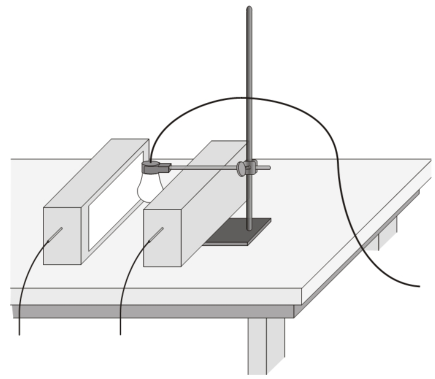

Figure 1

4. Launch Graphical Analysis. Connect the Go Direct Surface Temperature Sensor to your Chromebook, computer, or mobile device.
5. Set up the data-collection mode.
   a. Click or tap Mode to open data-collection settings
   b. Change Time Units to min.
   c. Change Rate to 1 sample/min and End Collection to 80 minutes. Click or tap Done.
6. Read the room temperature and record it in the data section.
7. Position Sensor 1 in the model solar home that is the control and Sensor 2 in the model solar home that you modified. In both cases, make sure the sensor is in the same relative location and that is not in direct light from the lamp.

   You will collect data for 80 continuous minutes. Once you have started data collection, you will turn the light on and leave it on. After 40 minutes have passed, you will turn the light off and cover the windows of the model solar homes. You will then collect "not-lighted" data for 40 more minutes.
8. Click or tap Collect to start data collection. Turn on the light.
9. After 40 minutes, turn off the light and cover the window of each model solar home with a piece of cardboard. Data collection will end after 80 minutes.
10. Record the maximum and final temperature values for both sensors.
    a. When data collection is complete, a graph of temperature *vs*. time is displayed. Click or tap the graph to examine the temperature and time values of both sensors. **Note**: You can also adjust the Examine line by dragging the line.
    b. Click or tap the point where the maximum temperature was recorded for Sensor 1. Record the maximum temperature value for Sensor 1 (to the nearest 0.1°C).
    c. Now click or tap the point where the maximum temperature was recorded for Sensor 2. Record the highest temperature value for Sensor 2 (to the nearest 0.1°C).
    d. Record the temperature at 80 minutes (round to the nearest 0.1°C).

11. Sketch or print copies of your graph as directed by your teacher. Label the two curves.

12. Complete Processing the Data and Analysis Questions for Part II and then continue to Part II.

Part II Design challenge

13. Using the information you gained in this and other experiments, design and build a model solar home that cools more slowly than the one you tested in Part I.
    - Begin with a model solar home like the one used in Part I.
    - You may add no more than 3 cm to the thickness of the walls.
    - You may use no more than 600 mL of thermal mass.
    - Your home must have a window with an area of at least 150 cm^2.

14. Repeat Steps 6–11.

15. Complete Processing the Data and Analysis Questions for Part II.

DATA TABLE

Part I Initial data collection

Room temperature (°C):

	Sensor 1 (control)	Sensor 2 (modified)
Maximum temperature (°C)		
Temperature at 80 minutes (°C)		
Temperature change (°C)		

Part II Design challenge

Room temperature (°C):

	Sensor 1 (control)	Sensor 2 (modified)
Maximum temperature (°C)		
Temperature at 80 minutes (°C)		
Temperature change (°C)		

PROCESSING THE DATA

Part I Initial data collection

1. In the space provided in the data table, subtract to find the temperature changes.

2. Share your results with the rest of the class.

Part II Design challenge

3. In the space provided in the data table, subtract to find the temperature changes.

ANALYSIS QUESTIONS

Part I Initial data collection

1. Describe the modifications to your model home.
2. Which model solar home cooled more?
3. How are the "control" and the "modified" curves similar? How are they different?
4. How does the graph compare to the sketch you made in the preliminary questions?
5. Which model solar home heated more slowly?
6. Which model solar home cooled more slowly?

Part II Design challenge

7. Explain why you chose the materials you did.
8. Compare the results with your Part I results and then compare your results with the Part II results from the other groups.

EXTENSIONS

1. Run the experiment for two or more consecutive "daily" cycles of four hours or longer.
2. Design an experiment to test other types of thermal mass, such as stones or phase-change materials.
3. Design an experiment to test other variables affecting a solar home, such as color, window material, window size, and insulation type.
4. What design factors about your school allow it to take advantage of passive solar heating? Are there things you could do at your school to improve passive heating as well as to reduce the need for using electricity to cool the building in the summer?

Variables Affecting Passive Solar Heating

We recommend preceding this experiment with Experiment 22 "Passive Solar Heating: Baseline Cooling Curve." Then, once students have had the experience of using a model solar home, they can brainstorm ways to improve the design and variables they can measure. Record students' ideas and either have the groups pick different variables or assign variables to the groups. This way, as a class, you will cover a wide variety of variables.

Students can enjoy turning this lab into a competition. In Part II, they are instructed to alter their model homes to see which group can produce the best model solar home, as determined by the least change in temperature from the warmest temperature to the lowest final temperature (i.e., which model home retains heat the best).

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Change data-collection parameters.
- Examine data to determine values.

ESTIMATED TIME

We estimate that data collection for Part I can be completed in one 90-minute class period. If you have 45-minute class periods, students can start data collection and let it run after they leave. Students will need additional time to share results. Then, give your students some class time for design and test purposes in preparation for Part II. Data collection for Part II takes the same amount of time as Part I. You can skip Part II if you do not have time.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking questions and defining problems	PS3.A Definitions of Energy (HS-PS3)	Patterns
Developing and using models	PS3.B Conservation of Energy and Energy Transfer (HS-PS3)	Cause and effect
Planning and carrying out investigations	ETS1.A Defining Engineering Problems	Scale, proportion, and quantity
Analyzing and interpreting data	ETS1.B Developing Possible Solutions	Systems and system models
Using mathematics and computational thinking	ETS1.C: Optimizing the Design Solution	Energy and matter
Constructing explanations and designing solutions		Structure and function
Engaging in argument from evidence		Stability and change
Obtaining, evaluating, and communicating information		

EQUIPMENT TIPS

1. Construct a classroom set of model solar houses using identical cardboard boxes. This is especially important if you want students to compare results. Boxes with 20–30 cm edges work well. A window should be cut in one side and a 4 cm frame should be kept for attachment of a transparent window pane. The window pane can be made of any transparent material. Tape all cut edges to reduce heat loss. Place a hole for a Temperature Sensor in the top or side of the box. The location of the hole depends on the shape and design of your home. Cut the hole in a place where the probe will be positioned out of direct light.

2. An alternate model solar home is a triangular version cut from cardboard. Use three rectangular (15 × 25 cm) pieces for sides and two triangular (15 cm edge and 60° angle) pieces for ends. Cut a window in one of the rectangular pieces, leaving a 3 cm window frame for attaching the window.

3. Thin sheets or rolls of polystyrene, appropriate for use in this experiment, can be purchased at building-supply stores. Consider providing a roll of aluminum foil for student use.

4. Plastic bottles or zip-type plastic bag of room-temperature water can be used as a thermal mass. Advise your students to position the thermal mass near the window.

5. Have plenty of wide tape available for taping the boxes closed.

6. If you cannot find 100 W equivalent bulbs, look for some other bulb that produces heat. A heat lamp could work well, but you may want to adjust the distance between the bulb and the model homes. Compact fluorescent and LED bulbs are generally not sufficient for this activity.

DATA-COLLECTION AND ANALYSIS TIPS

1. Although longer data-collection periods give better results, this experiment can be done with total running times as short as 40 minutes.

2. The student version of this experiment is written assuming this experiment is conducted in a classroom. However, we tested the experiment in direct sunlight and it worked very well (see

Sample Results). If you have the ability to collect data in the outdoors, it can help students make real world connections to the experimentation process.

ANSWERS TO PRELIMINARY QUESTIONS

1. Answers will vary. Possible answers include: a high number of equator-facing windows (south in the northern hemisphere and north in the southern hemisphere), double-paned windows, insulation, trees that lose their leaves in the winter.
2. Answers will vary. Possible answers include: roof overhangs or awnings, trees with leaves in the summer to shade the equator side of the building, system for air flow that allows hot air to escape (e.g., vents that can be open and closed), blinds that don't allow in sunlight that can be closed in the summer.
3. Answers will vary. Students will draw a prediction for how the data will appear.

SAMPLE RESULTS

To collect sample data, we investigated the effect of the presence of a thermal mass. Student results will vary.

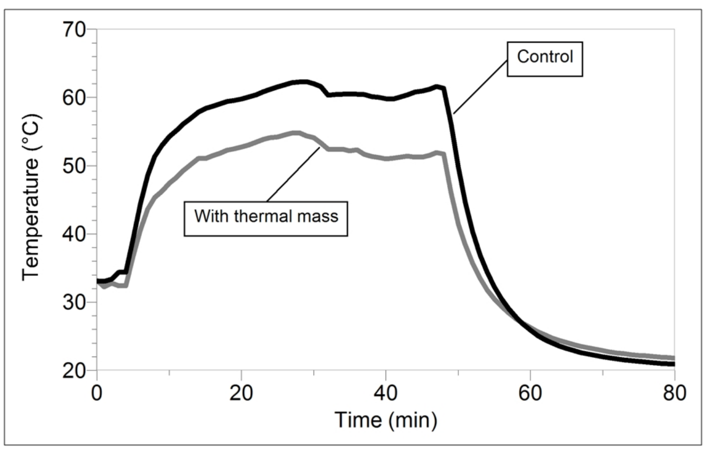

Figure 1 Effect of the presence of a thermal mass on the temperature inside a model home during a simulated cycle of daytime and nighttime

	Sensor 1 No thermal mass	Sensor 2 With thermal mass
Maximum temperature (°C)	62.3	54.8
Temperature at 80 minutes (°C)	20.9	21.8
Temperature change (°C)	41.4	33.0

ANSWERS TO ANALYSIS QUESTIONS

Note: Answers are provided based on the Sample Results. Students answers will depend on their results and modifications.

Part I

1. The data in Sample Results were collected using a control and a model home with a thermal mass.
2. See Sample Results. The model solar home with no thermal mass (the control) cooled more.
3. The curves have the same basic shape. Both curves initially rise rapidly, both have a section of less rapid rise, and both level off. Both curves drop rapidly after being removed from the sunlight and both have a section of less rapid drop.

   The "with thermal mass" curve levels off at a lower temperature. It also shows less temperature change from the maximum temperature to the final temperature.
4. Answers will vary and will depend on the student's prediction.
5. The "with thermal mass" model home heated more slowly, and its maximum temperature was lower than that of the "control" model home.
6. The "with thermal mass" model home cooled more slowly, and its final temperature was higher than that of the "control" model home.

Part II Design challenge

7. Answers will vary.
8. Answers will vary.

Exploring Solar Collectors

Using the sun to heat water is not a new idea. Humans have been harnessing the thermal energy of the sun for centuries. Today, solar thermal systems are found on rooftops around the world, providing affordable, pollution-free hot water for millions of people.

In most US homes, water is heated using electricity, natural gas, or oil. Since most of our electricity is generated from fossil fuels, it is safe to say that most water in the United States is heated using energy from fossil fuels. The burning of fossil fuels releases pollution into the environment and is believed to contribute to global climate change.

Since it takes a large amount of energy to heat water, it can be a significant portion of our energy bills. Replacing a traditional water heater with a device that can heat water using energy from the sun is not only good for the environment, it can also be a great way to save money on your energy bill.

Solar collectors take advantage of the greenhouse effect in order to heat water. Have you ever noticed how surprisingly warm it is inside a car that has been parked in the sun? Sunlight easily passes through the glass windows and is converted into heat when it hits the interior of the car. Some of that heat passes back through the glass, but a lot of it gets trapped inside. In a solar collector, this trapped heat warms the water that is circulating through the system.

A solar collector system used to heat water generally includes the following parts:

- A solar collector positioned to face the sun so it can catch and absorb sun light
- A transparent cove
- A heat insulating backing for the solar collector
- A fluid, either water or antifreeze, flowing through the collector, usually in tubes
- An insulated tank to store the heated water
- (optional) A pump and controls to move the water through the system
- (optional) A back-up energy source (electric or natural gas)

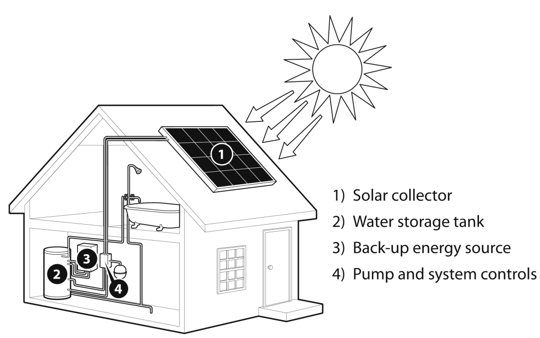

Figure 1 Solar collector system

The KidWind Solar Thermal Exploration Kit that you will use in this experiment is a model of what is called an *active* or *forced circulation* system. This type of solar water heater requires a pump to move water from the storage tank to the collector. Most solar water heaters in the United States are forced circulation systems because this type of system works well even when temperatures drop below freezing. Passive systems that do not use an electric pump are also common, but are not practical for colder climates where the water may freeze.

The color of the solar absorber affects the ability of the solar collector to take advantage of the greenhouse effect. Every color reflects a certain amount of light while absorbing the rest as heat energy. In this experiment, you measure the reflectivity of various colors using a light sensor, and then compare these values to the reflection value of aluminum foil. Aluminum foil will arbitrarily be assigned a reflectivity of 100 percent. You will calculate percent reflectivity using the relationship

$$\%\ \text{reflectivity} = \frac{\text{value for paper}}{\text{value for aluminum}} \times 100$$

After determining the best color for the background of the solar collector, you will set up a solar collector and measure the change in water temperature during data collection.

OBJECTIVES

- Use a light sensor to measure reflected light.
- Use a temperature sensor to measure changes in temperature.
- Calculate percent reflectivity of various colors.
- Use results to design and set up a solar collector.
- Determine the temperature change of the water in a solar collector.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Light and Color
Go Direct Surface Temperature
KidWind Solar Thermal Exploration Kit
ring stand
2 utility clamps
lamp and 100 W (or equivalent) light bulb
2 pieces of paper of different colors
aluminum foil
tape
ruler

PRELIMINARY QUESTIONS

1. One of the many advantages of using a solar water heating system to heat water for your home is that it can be retrofitted to older buildings. Identify two other advantages and also two disadvantages of using solar collectors for heating water.

2. What design factors, other than color, affect the efficiency of a solar collector?

3. What colors will you test for reflectivity and absorption? Predict the rank of the pieces of paper, in terms of the paper's reflectivity, from least to greatest. Create a second list that ranks the paper's ability to absorb heat, from least to greatest.

PROCEDURE

Part I Light reflectivity and heat absorption

1. Launch Graphical Analysis. Connect the Go Direct Light and Color Sensor as well as the Go Direct Surface Temperature Sensor to your Chromebook, computer, or mobile device.

2. Set up the data-collection mode.
   a. Click or tap Mode to open Data Collection Settings.
   b. Change Time Units to min.
   c. Change Rate to 6 samples/min and End Collection to 10 minutes.
   d. Click or tap Done.

3. Set up the equipment for data collection.
   a. Tape the cable of the Temperature Sensor to the table surface.

Figure 2

   b. Bend the tip of the Temperature Sensor to make sure that sensor the does not touch the tabletop during data collection (or you will measure the temperature of the table).
   c. Place one of your pieces of paper over the Temperature Sensor.
   d. Use a utility clamp and ring stand to fasten a Light Sensor 5 cm above the paper (see Figure 3).

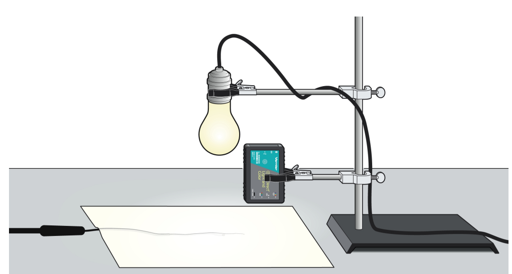

Figure 3

4. Switch on the light bulb and click or tap Collect to start data collection.

5. When data collection is complete, turn off the lamp and determine and record the mean light reflection value and the minimum and maximum temperature readings.
   a. Click or tap Graph Tools, , for the temperature graph and choose View Statistics. Record the minimum and maximum temperature readings (round to the nearest 0.1°C).
   b. Click or tap Graph Tools, , for the illuminance graph and choose View Statistics. Record the mean light reflection value in your data table (round to the nearest whole lux).
6. Repeat Steps 4–5 two times (once for the second piece of paper you are testing and a second time for a piece of aluminum foil).
7. Complete the Processing the Data and Analysis Questions sections for Part I before continuing to Part II.

Part II Solar collector

8. Disconnect the Light Sensor from your computer, Chromebook, or mobile device. Leave the Temperature Sensor connected. Click or tap File, , and choose New Experiment. Click or tap Sensor Data Collection.
9. Click or tap Mode to open data collection settings.
   a. Change Time Units to min.
   b. Change Rate to 6 samples/min and End Collection to 20 minutes.
   c. Click or tap Done.
10. Set up the solar collector in a sunny place.
    a. If your tray is a color other than the color you determined during Part I, line the tray with paper to change its color.
    b. Arrange the tubing in the box so water will flow through it. If necessary, tape down the tubing to hold it in place (see Figure 4).
    c. Put the cover on the solar collector.
    d. Connect the tubing to the water pump and secure the pump to the bottom of the water storage container.
    e. Add water to the storage container.
    f. Place the free end of the tubing into the water.
    g. Position the Temperature Sensor in the water storage container. If necessary, tape it in place.
    h. Connect the solar panel to the wires from the pump (red to red and black to black) using the alligator clips. **Note**: If the solar panel is receiving sunlight, the pump will start working when the panel and pump are connected. Cover the solar panel before you connect the wires and then uncover it when everything is in place.

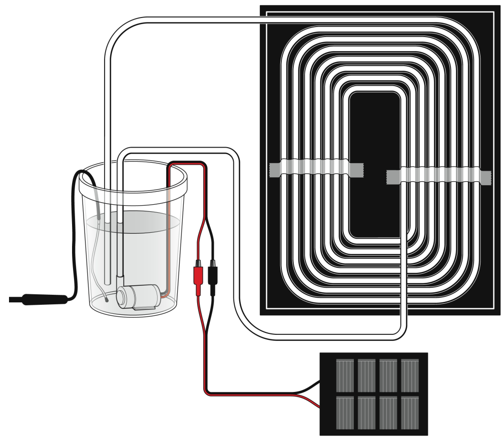

Figure 4

11. Click or tap Collect to start data collection.

12. When data collection is complete, a graph of temperature *vs*. time is displayed. Determine the starting temperature and maximum temperature. Record these values in the data table.

DATA TABLE

Part I Light reflectivity and heat absorption

Color	____________	____________	Aluminum
Starting temperature (°C)			
Final temperature (°C)			
Change in temperature (°C)			
Reflection value (lux)			
Percent reflectivity (%)			100

Part II Solar collector

Color	
Starting temperature (°C)	
Maximum temperature (°C)	
Change in temperature (°C)	

PROCESSING THE DATA

Part I Light reflectivity and heat absorption

1. Subtract to find the change in temperature for each color paper.

2. Calculate the percent reflectivity of each color paper using the relationship:

$$\% \text{ reflectivity} = \frac{\text{value for paper}}{\text{value for aluminum}} \times 100$$

Part II Solar collector

3. Subtract to find the change in temperature.

ANALYSIS QUESTIONS

Part I Light reflectivity and heat absorption

1. Which color paper had the largest temperature increase?

2. Which color paper had the smallest temperature increase?

3. Solar collectors can be used to absorb the sun's energy and change it to heat. What color would work best for solar collectors? Explain.

4. Which color paper has the highest reflectivity?

5. Which color paper has the lowest reflectivity?

6. What relationship do you see between percent reflectivity and temperature change?

Part II Solar collector

7. Sketch or print your graph. Describe what happened to the temperature of the water during data collection. Did the water heat up at a consistent rate?

8. Compare your results to the data collected by other groups. Which variables account for differences between your data and the results of the other groups?

9. If you were going to re-design your solar collector to try to make it heat water more quickly, what would you do?

EXTENSIONS

1. There are two general categories of solar collector: flat plate collectors and evacuated tube collectors. Research the two categories and explain why you would chose to install one over the other based on their differences.

2. Other than heating water for use in a home, what else do people use solar collectors for?

3. Research what would be involved in retrofitting your own home to use a solar collector to heat air, water, or generate electricity. Consider installation costs and cost savings over time.

4. Collect data for the solar water heater for longer than 20 minutes. How hot does the water get after an hour? Eventually, does the temperature stop rising?

5. Makes changes to your solar collector and collect data again to see if you get a greater increase in temperature.

6. Measure the mass of water heated in the solar collector and use the specific heat capacity of water to calculate the amount of energy used to heat the water.

$$\Delta Q = mc\Delta T$$

   where Q is the heat supplied, m is mass, c is specific heat capacity of water, and ΔT is the change in temperature.

Exploring Solar Collectors

In this experiment, students explore solar thermal systems for water heating. Solar collector systems are becoming a popular option for homeowners and businesses to heat domestic water, as they have proven to be highly efficient and cost-effective.

In the Electronic Resources you will find multiple versions of each student experiment—one for each supported data-collection program (Graphical Analysis 4, Logger *Pro*, or LabQuest App). Deliver to your students the version that supports the software and hardware they will use. Sign in to your account at **www.vernier.com/account** to access the Electronic Resources. See Appendix A for more information. **Note**: The printed book and the PDF of the entire book (found in the Electronic Resources) include only the Graphical Analysis (Go Direct sensors) versions of the experiments.

RELATED SKILLS

- Change data-collection parameters.
- Use the Statistics tool to calculate statistics.

ESTIMATED TIME

We estimate that data collection and analysis can be completed in one to two 45-minute class periods.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models	PS3.A Definitions of Energy (HS-PS3)	Patterns
Planning and carrying out investigations	PS3.B Conservation of Energy and Energy Transfer (HS-PS3)	Cause and effect
Analyzing and interpreting data	ESS3.C Human Impacts on Earth Systems (HS-ESS3)	Scale, proportion, and quantity
Using mathematics and computational thinking		Systems and system models
Constructing explanations and designing solutions		Energy and matter

EQUIPMENT TIPS

1. Arrange the tubing in the box so the water flowing through the tubing is exposed to as much light as possible. Tape can be used to hold the tubing in place. Clear tape such as packing tape will allow sunlight to pass through and reach the water.

2. Cover the solar collector box with the clear acrylic sheet. The first time you use it, you will need to remove the protective coating(s) from the acrylic. Tape down one side to create a hinge or tape all edges for a tighter seal.

3. The tubing and electric water pump should be connected in such a way that the pump pumps water out of the storage container, through the solar collector, and back into the container. To set the pump up, connect one end of the tubing to the pump and place it at the bottom of the storage container (if necessary, use tape to secure it to the bottom). The two wires from the pump should be facing up. Place the "free" end of the tubing from the solar collector into the storage container to complete the circulation loop.

4. The Surface Temperature Sensor can be taped to the inside of the storage container to keep it from getting in the way.

5. When you add water to the container, add at least enough water to submerge the pump.

6. The system will still work if the alligator clip connections get wet. We recommend letting all components dry thoroughly before storing them.

7. Connect the solar panel alligator clips to the pump wires (red to red and black to black). **Note**: As soon as you connect the solar panel to the pump (assuming the solar panel is exposed to sunlight), the pump will turn on and start pumping. If everything is connected, but the pump does not seem to be working, double-check the connections. Make sure the set of connected red alligator clips and connected black alligator clips do not touch each other, as that would make a short circuit and prevent the pump from working. You can test to make sure the pump works by connecting it to a 1.5 V battery cell (such as a AA battery). If the pump operates using the battery, it should also operate on the power from the solar panel.

8. To stop the pumping, shade the solar panel. The panel will stop producing electricity, and the pump will stop with the electricity stops.

DATA-COLLECTION AND ANALYSIS TIPS

1. Heavy construction paper works well in this experiment. Try to obtain pieces with the same texture and thickness.

2. There are many options for choosing which colors of paper to test, depending on your own preference and material availability. Considering setting groups up so each group compares black and white paper to aluminum foil. Alternately, have students choose two colors from a selection of colors that you provide, and then share their information with the class. Then, allow students to choose the best color for their solar collector based on the data from the entire class.

3. If, instead of collecting reflectivity data for different colors of paper, you want to collect solar collector data twice, use the Part II procedure to collect data for trays of different colors.

ANSWERS TO PRELIMINARY QUESTIONS

1. Answers will vary. Possible advantages: fewer emissions than associated with using fossil fuels as a heating source, reduced costs in the long run. Possible disadvantages: high initial costs,

owner has to maintain, households with high demand for hot water can have a challenge meeting their needs, and it isn't always sunny.

2. Answers will vary. Possible answers include surface area, temperature of the collector, material that the collector is made out of, angle of exposure to sunlight, and the amount of sunlight the collector receives.

3. Answers will vary.

SAMPLE DATA

Part I Light reflectivity and heat absorbance

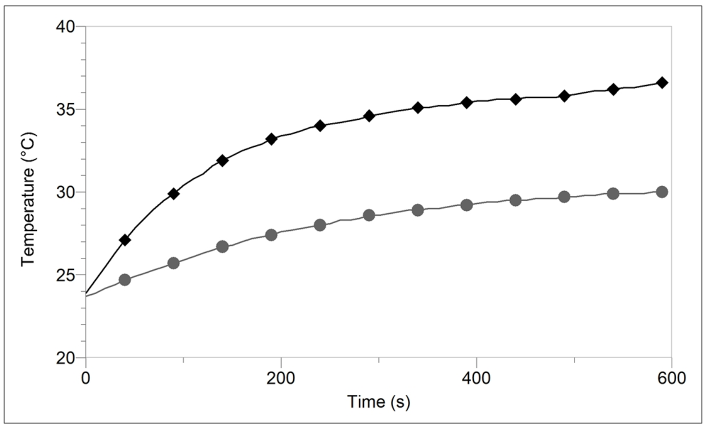

Figure 1 Sample data for black paper (black line, diamond markers) and white paper (gray line, circle markers)

Color	white	black	aluminum
Starting temperature (°C)	23.7	23.9	23.4
Final temperature (°C)	30.0	36.6	28.0
Change in temperature (°C)	6.3	12.4	4.8
Reflection value (lux)	1769	372	2558
Percent reflectivity (%)	44.7	18.4	100

Part II Solar collector

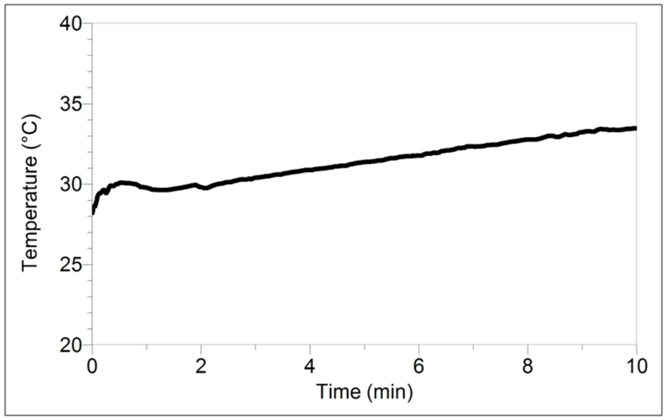

Figure 2 Temperature of water in a solar collector exposed to direct sunlight

Color	black
Starting temperature (°C)	28.20
Maximum temperature (°C)	33.46
Change in temperature (°C)	5.26

ANSWERS TO ANALYSIS QUESTIONS

Part I Light reflectivity and heat absorbance

Note: All answers based on Sample Results. Student responses will vary.

1. Black paper had the largest temperature increase.
2. White paper had the smallest temperature increase.
3. Black would work best for a solar collector since it absorbs radiant energy best and reflects the least.
4. White paper has the highest reflectivity.
5. Black paper has the lowest reflectivity.
6. The lower the reflectivity, the greater the temperature change.

Part II Solar collector

7. Answers will vary.
8. Answers will vary. Possibilities for differences between groups light/shade received during data collection, different seals on the trays, and different tubing patterns.
9. Answers will vary.

Variables Affecting Solar Collectors

Light is composed of *photons* or bundles of radiant energy. When photons strike matter, they are absorbed, and then one of the following happens: the energy is re-emitted, or it stays within the matter in a different form. Re-emitted light can be reflected, scattered, or transmitted, depending on the direction of the re-emission. In the case of absorption, there are additional possibilities. As an example, in photovoltaic panels, the absorbed energy is converted into electricity. In a solar water heating system, the absorbed energy is converted into thermal energy (vibration and other particle motion) in the solar collector.

The ability of a solar collector to absorb photons is affected by various factors. In this experiment, you will choose one variable and test it using the KidWind Solar Thermal Exploration Kit. You will use a temperature probe to measure the change in temperature of the water as a way of measuring the absorption of light energy by the solar collector.

OBJECTIVES

- Use a Surface Temperature Sensor to measure the change in temperature of the water in a solar collector.
- Create a plan to test a variable that affects solar collectors.
- Collect data and draw conclusions based on results.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Surface Temperature Sensor
KidWind Solar Thermal Exploration Kit
materials to test variable (will depend on experiment design)

PRELIMINARY QUESTIONS

1. What are the benefits of using the sun to heat water? Think about global, social, and environmental issues that can be reduced by using the sun as an energy source.

2. List four variables that affect how effective a solar collector can be at heating water. For each variable you list, explain how it will affect the effectiveness of the solar collector.

3. Which variable will you test for this experiment? Predict the results of your tests using a graph or describe the results in a paragraph.

PROCEDURE

1. Create a plan to collect data for the variable you are testing. You will modify the solar collector 2–4 times. For example, if you are testing tubing length, you will collect data for 2–4 different lengths.

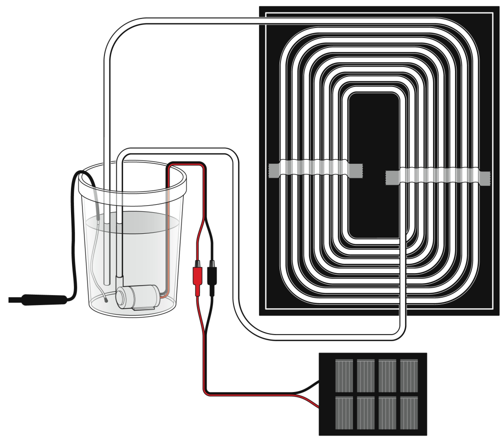

Figure 1

2. Launch Graphical Analysis. Connect the Surface Temperature Sensor to the data-collection interface, and then connect the interface to your Chromebook, computer, or mobile device.

3. Set up the data-collection mode.
   a. Click or tap Mode to open Data Collection Settings.
   b. Change the data-collection rate and duration to values that are appropriate for your plan.

4. Set up the Solar Thermal Exploration Kit to test your first modification. **Note**: Figure 1 shows a generalized setup. Your setup may differ depending on the variable you are testing.

5. Click or tap Collect to start data collection.

6. When data collection is complete, a graph of temperature *vs*. time is displayed. Click or tap the graph to examine the data. Determine the starting and maximum temperatures, as well as any other data that you need. Record these values in the data table. **Note**: You can also adjust the Examine line by dragging the line.

7. Repeat data collection until you have collected all the data you need to test your variable.

DATA TABLE

Variable (length, color, material, etc)	Starting temperature (°C)	Maximum temperature (°C)	Change in temperature (°C)

PROCESSING THE DATA

Calculate the change in temperature for each of your modifications.

ANALYSIS QUESTIONS

1. Is there a noticeable difference in temperature change for the different modifications? If so, which system had a greater temperature change?
2. Do your results match your prediction? Explain why or why not.
3. Imagine someone is designing a solar collector and they have asked you for your advice. Use your results to give them advice about how to design the element of the solar collector that you tested.
4. If you could design an ideal solar collector, what design choices would you try to incorporate? What else could you do to improve efficiency that you did not test in this experiment?

EXTENSIONS

1. Share your results with the class. Then, summarize the group findings in a report.
2. Use the collected data to design a more efficient solar collector and test what you predict will be the best combination.

Variables Affecting Solar Collectors

We suggest starting the experiment with a brainstorming session. Record students' ideas and have the groups pick different variables. This way, as a class, you will cover a wide variety of variables. If you would rather, simply assign variables to the groups. Options for variables to explore (among others) include

- Tray color
- Light intensity: use reflective materials, change the time of day of the experiment, change the angle of the collector, or change the light intensity another way.
- Insulation of solar collector and water storage container
- Use of the greenhouse effect: test presence of cover or lack thereof, cover material, and/or thickness of the cover
- Rate of water pumping
- Length of time of data collection or exposure to light
- Use of a capacitor to sustain water flow if solar panel stops working
- Tube design: pattern, length of tubing, and/or material and color of tubing (e.g., compare tubes made from aluminum, copper, plastic, and rubber)

We suggest that students perform Experiment 24, "Exploring Solar Collectors," before doing this experiment; they will gain familiarity with solar collectors that will help them to develop a good plan to test their variable for this experiment.

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RELATED SKILLS

Students will need to change data-collection parameters.

ESTIMATED TIME

We estimate that data collection can be completed in two to four, 45-minute class periods. Data collection lasts 20 minutes. If you have 45-minute class periods, you could use the following schedule:

Day 1: Introduce the experiment. Ask students to pick a variable and create a testing plan.

Day 2: Collect two runs of data (efficiency will be key!). To save time, you could have two or more groups test a single variable and share their data (e.g., Group 1 tests tubing lengths of 8 m and 6 m; Group 2 tests tubing lengths of 4 m and 2 m.)

Day 3 (optional): Collect additional data

Day 3 or 4 (optional): Analysis

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3) ESS3.C Human Impacts on Earth Systems (HS-ESS3)	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter

EQUIPMENT TIPS

Arrange the tubing in the box so the water flowing through the tubing is exposed to as much light as possible. Tape can be used to hold the tubing in place. Clear tape such as packing tape will allow sunlight to pass through and reach the water.

DATA-COLLECTION AND ANALYSIS TIPS

Students are instructed to pick an appropriate data-collection rate and duration. They should pick a time that allows them to see a temperature change. In good conditions, a data-collection duration of 20 minutes will generally work well. We suggest data-collection rates of 5 to 10 samples/minute.

ANSWERS TO PRELIMINARY QUESTIONS

Answers will vary.

SAMPLE RESULTS

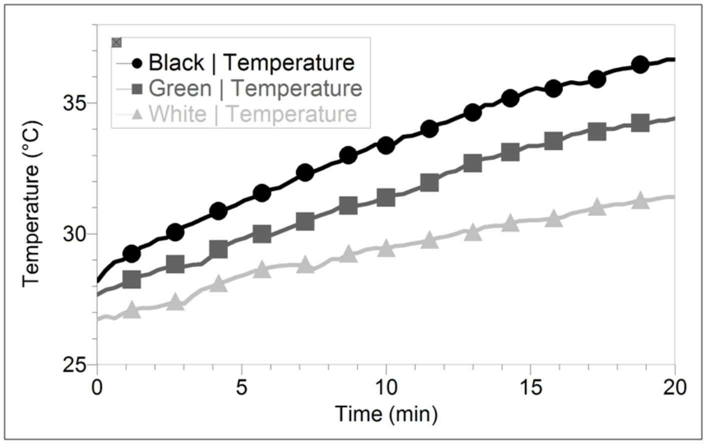

Figure 1 Effect of background color on the temperature of water in a solar collector

Background color	Starting temperature (°C)	Maximum temperature (°C)	Change in temperature (°C)
Black	28.2	36.7	8.5
Green	27.7	34.4	6.7
White	26.7	31.4	4.7

ANSWERS TO ANALYSIS QUESTIONS

1–4. Answers will vary based on the variable tested and data collected.

Project: Solar Cooker

Solar cookers convert sunlight into thermal energy. They are a low-cost, pollution-free method of food preparation. Under normal conditions, solar cookers can reach temperatures of 80–120°C (175–250°F). Since food cooks at around 80–90°C (175–195°F), solar cookers are hot enough to fully cook food, but not to burn or dry it out.

Globally, solar cookers play an important role. They benefit millions by providing a smoke-free method of cooking that does not rely on wood, charcoal, or other fuels. They provide a means for pasteurizing water during emergencies and disinfecting medical supplies. What other benefits do solar cookers provide?

In this project, you will design a solar cooker that will cook a food item. It needs to fit within the design requirements and restraints. During the project, you will work with your group to design, test, and then optimize the solar cooker design. At the end of the project, you will submit the set of deliverables listed below.

DESIGN REQUIREMENTS AND CONSTRAINTS

- Placement profile: 1 cubic meter
- Must be able to load and retrieve food easily
- Construction materials should not emit any noxious fumes when heated
- Construction materials must be readily available (recycled materials are encouraged)
- Do not exceed the project budget

DELIVERABLES

- Prototype
- Detailed design specifications (so the unit can be replicated exactly)
- Daytime temperature log (8 hours)
- Maintenance requirements
- Projected cooking time
- Social and environmental impact statement on the benefit of your design

Project: Solar Cooker

There are three common types of solar cookers: box, panel, and curved concentrator. Box cookers have transparent tops for sunlight penetration, dark bottoms for heat absorption, and reflective sides to reflect the heat back toward the cooking pot. They can accommodate multiple pots and typically reach temperatures around 70–135°C (160–275°F). Panel cookers are built from a series of reflective panels arranged in an open profile in such a way as to direct sunlight onto a dark cooking pot. Instead of covering the entire device with a transparent top to retain heat, the cooking pot is typically placed under an inverted glass bowl or sealed in a clear, heat-resistant cooking bag. Panel cookers are the simplest and cheapest to make, but their temperature range is the lowest of the three designs. A curved concentrator is built from a 360° parabolic reflector with the food placed at the focal point of the parabola. Curved concentrators can achieve very high temperatures, but they are difficult to construct, require frequent repositioning to keep the food at the focal point, and can cause serious eye damage from misdirected reflections.

Students should consider four major factors during the design process:

- Sunlight concentration–A shiny, reflective surface concentrates the sun's light into the cooking area. The more concentrated the energy, the better the heating capability.
- Light absorption–A dark surface on the bottom of a box cooker and/or the placement of food inside a dark pot improves the conversion of sunlight into thermal energy.
- Insulation–A sealed cooker reduces convection losses to cooler outside air, especially on windy days. Tight-fitting lids on cooking pots help retain heat and moisture.
- Transmissivity–A sheet of transparent material across the top of the cooker allows the transmission of visible light, and traps infrared thermal radiation from heated surfaces.

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ESTIMATED TIME

We estimate that data collection can be completed in 3 to 7 class periods.

At a minimum, this activity requires 1 to 2 days to design and build the solar cooker and 1 day to collect temperature data. If you are short on time, students can cook their food items simultaneously while collecting temperature data, however they will have anomalies in their temperature profiles whenever they open their solar cookers to add or retrieve food. Ideally, you should give students the opportunity to rework their designs based on initial data results (2 to 3 additional class periods). This is an excellent experience for learning that things do not always operate as you expect.

NEXT GENERATION SCIENCE STANDARDS (NGSS)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking questions and defining problems Developing and using models Planning and carrying out investigations Analyzing and interpreting data Using mathematics and computational thinking Constructing explanations and designing solutions Engaging in argument from evidence Obtaining, evaluating, and communicating information	PS3.A Definitions of Energy (HS-PS3) PS3.B Conservation of Energy and Energy Transfer (HS-PS3) ETS1.A Defining Engineering Problems ETS1.B Developing Possible Solutions ETS1.C: Optimizing the Design Solution	Patterns Cause and effect Scale, proportion, and quantity Systems and system models Energy and matter Structure and function Stability and change

SUGGESTED PROJECT PLAN

1. Assign students a research project in which they are expected to research the purpose of a solar cooker. Students should be able to define the problems addressed by solar cookers, including global, social, and environmental issues that can be reduced by using the sun as an alternative energy source.
2. Help students conduct tests or research to determine the angle of the sun for optimum solar energy. (**Note**: This value will vary depending on the time of year.)
3. Give students time to design and build a solar cooker based on the design requirements. (The student version includes a list or requirements and constraints, but you may have additions.) Consider providing materials or setting a budget to limit how much students can spend on materials.
4. Set up solar cookers and allow students to create temperature profiles with their solar cookers for one 8-hour day.
5. Provide time for students to optimize their original designs based on their temperature data, and then collect a second 8-hour temperature profile.
6. Have students make predictions as to the time of day and amount of time required to cook an item of food that you specify, and then proceed with cooking the food item.
7. Give students an opportunity to develop and present a social and environmental impact statement on the benefit of their design.

PROJECT TIPS

1. Consider developing a rubric with which to grade students' projects. Possible criteria include
   - Maximum cooking temperature
   - Heat retention
   - Ease of construction

- Ease of operation
- Placement profile (size; location)
- Method of storage
- Durability
- Aesthetics
- Material availability

2. An important part of the engineering design process is giving students the opportunity to optimize their designs. Plan for enough time for this project so that students can test their designs, redesign, and then test again.

3. The quality of construction has a significant impact on the effectiveness of a solar cooker. If students use aluminum foil sheets, they should be sure to use the shiny side and affix it to the cooker with a minimum of wrinkling. All leaks should be sealed to aid in heat retention. A rigid glass cover allows greater sun penetration than a flexible cover of plastic wrap. To speed cooking, the food container should be slightly elevated above the bottom of the cooker.

4. The foods you choose to cook will somewhat affect your success. Marshmallows and hot dogs work very well, because they can be threaded onto a wooden skewer for suspension within the cooker. Rice is also good, because students will notice a definite change in the structure of the grains as they expand. Be aware that foods will take longer to cook due to the lower temperatures in a solar cooker.

5. Foods will cook better at noon when the sun is high in the sky than later in the afternoon when the sun is lower. The most intense cooking generally occurs between 10:00 am and 2:00 pm.

EQUIPMENT TIPS

1. The recommended safe operating range for the Surface Temperature Sensor is –25° to 125°C (–13° to 257°F). The maximum temperature the sensor can tolerate without damage is 150°C (300°F). If your solar cooker is generating temperatures outside this range, you should substitute the Vernier Wide-Range Temperature Probe (order code: WRT-BTA) or the Thermocouple (order code: TCA-BTA) for data collection.

2. When setting up the data-collection parameters for this project, we suggest setting the data-collection duration to 480 minutes and the data-collection rate to 4 samples/minute. If you would like students to collect data at a higher rate, be aware of the limits for total number of points that your interface can collect. For more information, see **www.vernier.com/interfaces**

Appendix **A**

Electronic Resources

The Electronic Resources for this book contain the following files. To download the Electronic Resources, create an account or log in at **vernier.com/account**

Renewable Energy with Vernier.pdf–A searchable PDF of the entire book.

_Intro and Appendices

- **Appendices**–Contains a file for each of the Appendices in this book.
- **Intro.pdf**–Includes the Table of Contents and the Vernier Equipment chart for this book. Use the Vernier Equipment chart to identify which experiments can be done with a particular sensor.

Instructor–Contains a PDF of each of the Instructor Information files for this book.

Student–In the folder for each data-collection program, you will find folders containing the PDF and Word files of each of the experiments.

- **Graphical Analysis**–Supports Graphical Analysis 4 app on computers, Chromebooks, and iOS and Android devices.
  - **Go Direct**–Use these files when collecting data with Go Direct sensors connected via Bluetooth or USB.
  - **LabQuest**–Use these files when collecting data with LabQuest sensors connected to an interface from the LabQuest family of interfaces (e.g., LabQuest 2 or LabQuest Mini).
- **LabQuest App**–Use these files when collecting data with LabQuest sensors and LabQuest interface running LabQuest App (e.g., original LabQuest or LabQuest 2).
- **Logger *Pro***–Use these files when collecting data with LabQuest sensors and Logger *Pro* 3 running on a computer.

More Power: Designing Wind Turbine Blades

KidWind turbines were created specifically to allow students to experiment with blade design variables. They can also be used to light bulbs, spin motors, lift weights, or charge batteries if you have a good fan and well-designed blades.

When designing blades, one question to always keep in mind is, “How much drag are my blades encountering?” Blades that experience less drag will, generally, spin more quickly. The faster the blades spin, the more power will be generated.

Regardless of how well your blades are designed, the wind turbine needs to receive plenty of wind. We suggest a fan with a diameter of at minimum 14–18 inches (35–45 cm). A standard 20-inch (50-cm) box fan works well.

BASIC BLADE DESIGN

Blade length

Students tend to think that more blade area equals more power. This is sometimes true, but it can be very hard to make longer blades without adding drag. Try shortening blades by a few centimeters.

When deciding how long the blades should be, compare the turbine diameter to the diameter of the fan. Blades that extend beyond the diameter of the fan are adding drag without catching additional wind.

Blade shape

Blades that start as close as possible to the Wind Turbine Hub will catch more wind. Minimize the space between the base of the blade and the Hub. **Important**: Leave enough of the dowel exposed that you can securely insert the dowel into the Hub.

Are the blade tips thin and narrow or wide and heavy? Wide tips add drag.

Blade pitch

Pitch dramatically affects power output. Students tend to set the angle of blades to about 45° the first time they set up a turbine. Try making the blades more perpendicular to the wind flow (closer to 15 or 20°).

Number of blades

Typically, 3 or 4 blades give the best results. However, depending on other factors, such as shape and pitch, as few as 2 blades or as many as 6 blades will work well.

Blade material

To reduce the weight of the blades, use less material or lighter material. Also note that smoother blade surfaces experience less drag. A blade with lots of tape or rough edges will have more drag.

ADVANCED BLADE DESIGN

Two primary forces act on wind turbine blades as they rotate: lift and drag. These forces are in constant competition; lift is the force that propels the blade, while drag is the force that slows it. When you are optimizing blades, try to maximize lift and minimize drag.

Lift is primarily produced as a result of the angle of attack of the blade. This angle deflects the air molecules as the blade passes through the air. The deflected air, in return, pushes the blade so that the system rotates.

Large-scale wind turbine blades are airfoil shaped, much like airplane wings. The shape is designed to decrease drag by minimizing turbulence and increase lift using air pressure differences. Large-scale blades are also designed to taper and twist slightly toward the tip. The varying pitch increases the angle of attack near the blade root where linear velocity is slowest; blades designed in this manner are able to optimize the balance between lift and drag at all points on the blade.

Most large-scale turbines have three blades. Advanced students may be interested in investigating 2- and 4-blade configurations for comparison and researching why a 3-blade configuration is standard.

Tips for advanced blade design

- Bend card stock into an airfoil shape. Glue the dowel inside the blade.
- Tape bent card stock to a flat piece of corrugated plastic or balsa wood to produce an airfoil shape.
- Take a block of foam and form it into an airfoil shape. Try to incorporate both a taper and a twist into the design.
- Carve and sand a piece of soft wood into an airfoil.
- Cut blades out of some form of cylinder. Try a cardboard tube, a paper or plastic cup, etc.
- Soak card stock in water for a few minutes. Form it into the desired shape and clamp or tape it in place until it dries and holds that shape.
- Print blades using a 3D printer.

Equipment and Supplies

A list of equipment and supplies for all experiments is included in this appendix. The amounts listed are for eight groups of students. The materials have been divided into nonconsumables and consumables. Most nonconsumable materials may be used many years without replacement. Most consumables will need to be replaced each year. Due to the open-ended nature of the Projects in this book, please see the specific Instructor Information for the project for suggestions about materials and equipment that you and/or your students will need. Note that this appendix does not include the Vernier products that are used in this book.

NONCONSUMABLES

Item	Amount	Experiment
balance	2–4[1]	2, 6
battery holder (to hold two D-cell batteries)	8	4, 5
box (size varies, see experiment)	8	1, 22, 23
camera, digital[2]	8	11
can, small (such as an aluminum beverage can)	8	2
cardboard (size varies)	see experiment	13, 23
compass, magnetic	8	4, 5
drill (hand drill)	8[3]	7
fan[4]	3	1 (optional), 6, 8, 9, 10, 11, 12, 13, 14
graduated cylinder, 50 mL	8	2
hot glue gun	8	6, 8, 9, 10, 11, 12, 13, 14
LED, red	8	4, 7

[1]Groups can share balances.

[2]Only needed if analyzing data in Logger *Pro*. Cell phone cameras work well.

[3]One drill per group is ideal, but drills may be shared between two groups.

[4]We recommend setting up a few testing stations with fans around the room. Generally having each group have their own fan is not advised because (a) it's too loud and (b) the air flow is too chaotic.

Item	Amount	Experiment
light bulb socket or lamp	8	1, 17, 22, 23, 24
light bulb, 7.5 V, and socket	8	4
light bulb, 60 W incandescent or equivalent	8	1
light bulb, 75 W incandescent or equivalent	8	1, 17
light bulb, 100 W incandescent or equivalent	8	1, 22, 23, 24
light bulb, small, incandescent (holiday-light style)	8	7
meter stick	8	6
paper (various colors)	16 pieces	24
pencil	8	2
plastic, glass, or some other transparent material (for model home window)	varies	22, 23
protractor	8	17
resistor, 100 Ω	8	7
ring stand	8	1, 2, 23, 24
ring, 10 cm (4"), for ring stand	8	2
ruler, metric	8	10, 11, 12, 13, 14, 17, 23, 24
safety goggles	1 pair per student	2, 6, 8, 9, 10, 11, 12, 13, 14
scissors	8	6, 8, 9, 10, 11, 12, 13, 14
stirring rod	8	2
stopwatch or timer	8	6
utility clamps	16	1, 2, 23, 24
wires with clips	16	4, 5, 17, 18A, 18B, 19, 20

CONSUMABLES

Item	Amount	Experiment
aluminum foil	1 roll	23 (optional), 24
battery, 3-V, coin-cell	8	4
battery, D-cell	16	4, 5
candle	8	2
gel chafing fuel	8 canisters	2
hot glue (for hot glue gun)	1 box or bag	6, 8, 9, 10, 11, 12, 13, 14
ice	1 bag	20
matches	8 boxes or matchbooks	2
tape (clear tape needed for Experiment 20)	several rolls	6, 7, 23, 20, 24
water	see experiment for details	2, 20

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