	Center for Renewable Energy Advanced Technological Education

SOLAR PV: THE I-V CURVE

INSTRUCTOR'S GUIDE

Grade Level: High School, Technical College, Community College
Lesson Length: 2-4 hours, depending on coverage and emphasis
Author: Scott Liddicoat
Created: October, 2023

Learning Goals

Students will:

- Understand Standard Test Conditions for assessing solar PV module performance
- Apply and use Ohms law
- Understand how an IV curve is produced
- Construct I-V and Power curves manually
- Understand characteristic features of a standard I-V curve
- Determine solar PV module nameplate values from a standard I-V curve trace
- Measure electrical potential (Volts) and current (Amps) of a solar PV module under electrical conditions necessary to produce a successful I-V curve trace
- Acquire data with a spreadsheet and interpret resulting graphs
- Understand how Volts and Amps are affected by changes in irradiance and temperature.

Materials

- Student computing device
- LED floodlight
- Wood blocks
- 2 precut neutral density filter films
- Multimeter to measure DC Amps
- Classroom solar PV module
- Lab workboard with alligator clip wires
- Daystar solar irradiance meter
- Multimeter to measure DC Volts
- Decade variable resistance box

Introduction to the activity:

This laboratory activity must be practiced in advance with the equipment you'll use with your students. Doing so will ensure:

- you have the experience needed to plan, lead, and manage the activity
- safe and effective performance from your students.
- the timing of the activity matches your expectations.
- the teaching materials and instructions provided here match up with your equipment and specific classroom situation.

Practicing in advance will also provide you with information and inspiration on how to introduce, discuss, and conclude this activity with your students.

Also, work in advance with the Excel spreadsheets provided. If you use a version of Excel different than ours, you may have compatibility issues that need to be resolved ahead of time. You'll need to be aware of how to use basic spreadsheet and graphing features within Excel to best assist your students.

We recommend you use our equipment. All components were selected to fit the design of the lab. If you have a lot of experience with classroom equipment of this kind, you may be able to make the lab portion of this activity work with some modifications to our procedure. Remember that our copyright allows you to freely and easily edit the activity to correspond to your teaching approach.

In addition, you are always free to add or subtract student questions. You may choose to place images of you and your specific equipment into our instructional PowerPoint. We encourage you to make changes to our materials that improve your teaching of this activity.

There are three parts to **Solar PV: The I-V Curve**

Part One, I-V Curve Basics
Part Two, Producing I-V Curves in the Lab & The Effect of Irradiance
Part Three: The Effect of Temperature & The Temperature Coefficient

Part One, I-V Curve Basics

Plainly, **Part One** is designed to introduce students to the basics of an I-V curve trace: its importance, characteristics, characteristic shape, and the critical measurements taken (**Pmax, Vmp, Imp, Voc**, **Isc**) from an I-V curve produced under Standard Test Conditions (STC). Students learn most of this on their own as they work through **Part One, I-V Curve Basics**. An answer key to **Part One** follows.

Show What You Know, Part One

1. A *nameplate* provides the official power rating given to a solar PV module tested under standard testing conditions (STC). Enter the measurements for each of your labels (numbers 1, 2, 5, 7, 8, above) next to the asterisks in the solar PV module nameplate that follows.

CREATE

Create Energy™ Module Model: KW-22-296

Specification	Abbreviation	Measurement
Maximum Power	Pmax	* 296 W
Maximum Power Voltage	Vmp	* 32.5 V
Maximum Power Current	Imp	* 9.1 A
Open Circuit Voltage	Voc	* 40 V
Short Circuit Current	Isc	* 10 A

Standard Test Conditions: 1000W/m^2, 25.0 ºC, AM 1.5

WARNING! POTENTIAL ELECTRICAL HAZARD!

Solar module has full voltage even in low light.
Installation by a qualified technician only.

2. Why must every solar module produced be tested under standard testing conditions (page 2) as it comes off the production line? Explain your answer in convincing detail, below.

With standard testing:

- **consumers are provided one consistent metric with which solar modules may be compared and expected to perform.**
- **modules of the same rating from the same manufacturer can be expected to perform comparably and used together.**
- **solar installers have a consistent point of reference with which to make system calculations.**

3. Describe the most important idea, concept, principle, or fact you learned while completing this this part of the lesson. Explain why it is important for you (and probably other people) to know and understand.

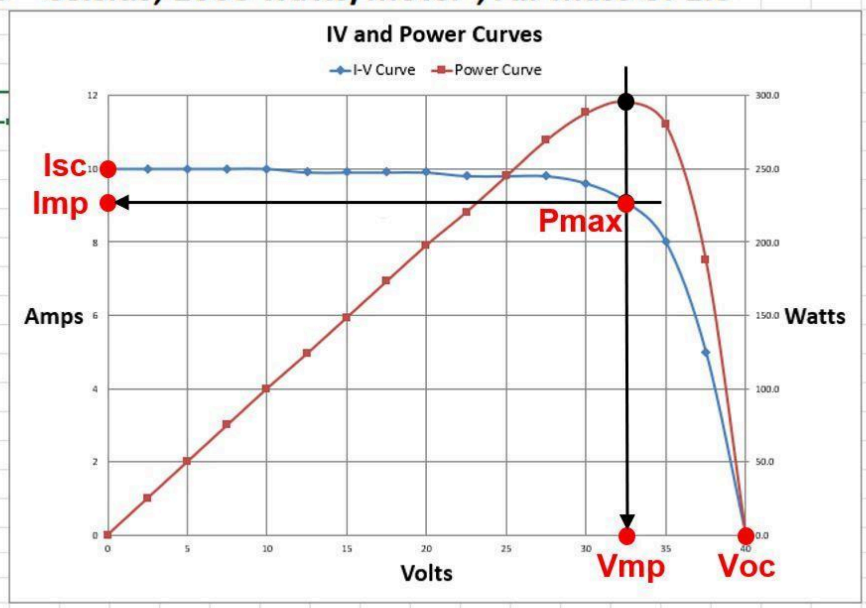
This is a reflection and judgement question. Student reasoning and reaction should be evident in a good answer. No two student answers should be the same.

4. Take a photo of your completed graph. Paste it into this document below. Arrange your photo so it is not split between two pages.

*** Paste your graph here**

STP conditions: 25 ° Celsius, 1000 watts/meter^2, Air mass of 1.5

	V	x	A	=	W
1	0	x	10	=	0.0
2	2.5	x	10	=	25.0
3	5	x	10	=	50.0
4	7.5	x	10	=	75.0
5	10	x	10	=	100.0
6	12.5	x	9.9	=	123.8
7	15	x	9.9	=	148.5
8	17.5	x	9.9	=	173.3
9	20	x	9.9	=	198.0
10	22.5	x	9.8	=	220.5
11	25	x	9.8	=	245.0
12	27.5	x	9.8	=	269.5
13	30	x	9.6	=	288.0
14	32.5	x	9.1	=	295.8
15	35	x	8	=	280.0
16	37.5	x	5	=	187.5
17	40	x	0	=	0.0
18		x		=	
19		x		=	
20		x		=	



Part Two, Producing I-V Curves in the Lab & The Effect of Irradiance

In **Part Two,** students construct I-V and Power curves of their own in the lab. Our PowerPoint (**I-V Curve Part 2 – Student Orientation**) is available to assist you in teaching students how to perform the lab. **I-V Curve Part 2 – Student Orientation** introduces students to their equipment. Then it visually takes them through the lab in slides that match their procedure, step by step.

First, students produce their own I-V curve at the highest irradiance possible in the lab using our readymade Excel spreadsheet. Then they make two additional I-V curves. Each additional trace is taken at about 50% less light than in the previous setting. Between performing the lab, developing and assessing their graphs, and answering the follow-up questions, students will learn how an I-V Curve trace is completed and the effect of irradiance on an I-V Curve trace.

Once again, the importance of critical I-V Curve measurements (**Pmax, Vmp, Imp, Voc**, **Isc**) is emphasized.

An answer key to **Show What You Know, Part Two** follows.

1. You should be familiar with the five solar PV module nameplate values from **Part One** of this activity. Determine the same five values from the I-V curves you produced for **Settings 1, 2, and 3** in your lab spreadsheet. Enter them into **Table 1** below, along with the irradiance measurement for each setting.

Table 1.

Setting:	One	Two	Three
Irradiance:	*** W/m²**	*** W/m²**	*** W/m²**
Pmax	*** W**	*** W**	*** W**
Vmp	*** V**	*** V**	*** V**
Imp	*** mA**	*** mA**	*** mA**
Voc	*** V**	*** V**	*** V**
Isc	*** mA**	*** mA**	*** mA**

Data from different students will vary.

2. Open the Microsoft Excel spreadsheet titled **I-V Curve Part 2 - Blank Voc's and Isc's by Setting**. Into that spreadsheet, enter Irradiance, Voc, and Isc measurements from **Table 1** above where indicated. Examine the results from the data tables and graphs you produce.

Which variable, Electrical Potential (Volts) or Current (Amps) is impacted the most as light (irradiance) is decreased? Give your answer choice. Then explain how you made your choice by referring to the graphs you just produced.

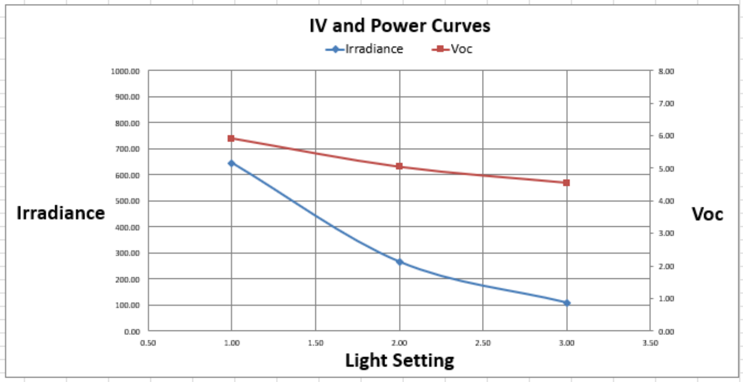
*** Amps**

*** As is visible from my graphs, as irradiance decreases, Amps (Isc) decreases in nearly the same proportion. Volts (Voc) decreases with irradiance as well. But not nearly as much.**

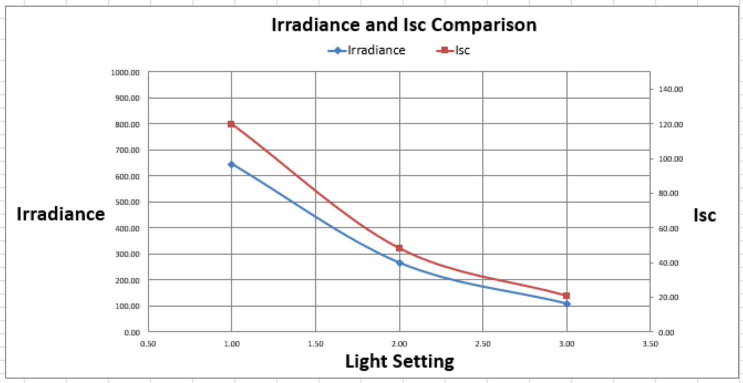
Take a snip or screenshot of your two completed graphs. Paste them into this document, below. Arrange your snip so it's not split between two pages.

*** Paste your graphs here ▼**

Light Setting	W/m^2	Voc
1	645.00	5.91
2	266.00	5.04
3	109.00	4.55



Light Setting	W/m^2	Isc
1	645.00	119.80
2	266.00	48.30
3	109.00	20.90



3. Confirm what you just learned and from the previous question in a different way. Go back to look at the **Setting 1, 2,** and **3** graphs you produced in the Microsoft Excel spreadsheet titled **I-V Curve Part 2 - Blank Data Tables and Graphs**.

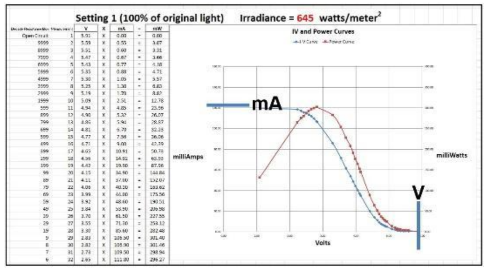
Which variable, Electrical Potential (Volts) or Current (Amps) is impacted the most as light is decreased? Give your answer choice. <u>Then explain how you made your choice by referring to the **Setting 1, 2,** and **3** graphs you produced during the lab</u>. [This is the same question asked in number 2, but refers you to different graphs for an explanation.]

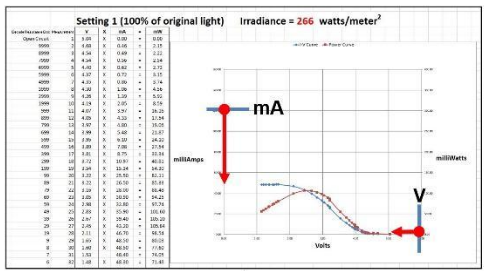
*** Amps**

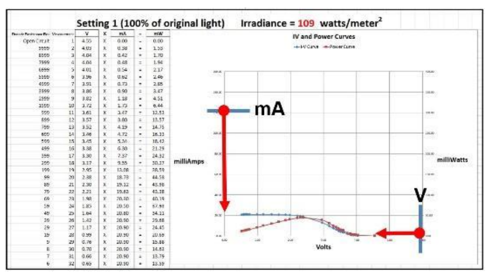
*** I used Isc and Voc data points from these graphs to produce the graphs from the previous question. It makes sense they should reveal the same trends. As is visible from my graphs, as irradiance decreases, Amps (Isc) decreases a lot. However, the proportional Amps decrease with the decrease in irradiance is not quite as obvious. Volts (Voc) decreases with irradiance as well. But not nearly as much.**

Take snips or screen shots of your three completed graphs. Paste them into this document, below. Arrange your photos so none of them are split between two pages.

*** Paste your graphs here ▼**







4. Compare your **Setting One** measurements from Post-lab question number 1, **Table 1,** to your module's nameplate values at STC shown in **Table 2**, below.

Table 2.

Specification	Your module at STC
Pmax	**1.2** W
Vmp	**6.0** V
Imp	**200** mA
Voc	**7.2** V

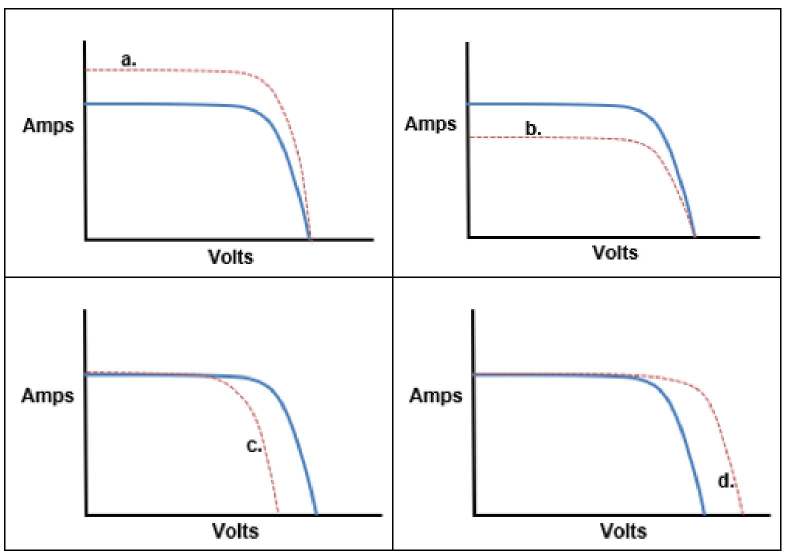
Isc	**210** mA

Plainly, your lab measurements from **Setting 1** don't match the nameplate values for your classroom module. Provide at least two different reasons why these values don't match.

4a. We did not perform our lab under Standard Testing Conditions (STC).

4b. Our lab equipment is relatively unsophisticated in comparison to the equipment used by module manufacturers in a quality control lab.

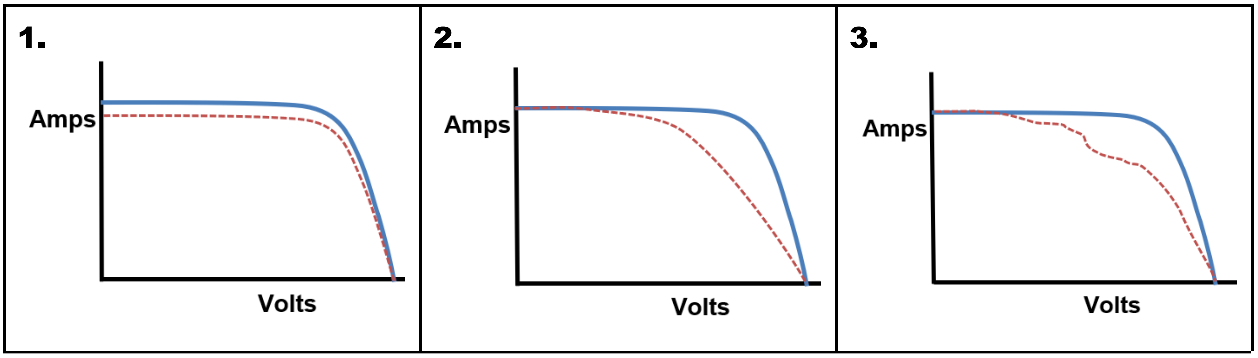
5. Each of the solid, blue I-V curves shown below are identical. They represent an I-V curve trace from a solar array in Madison, Wisconsin. The other I-V curves (shown in dashed, brown) represent four different locations from around the United States.



Assume all factors other than location are exactly the same. Which location choice, a, b, c, or d, shows how the very same system would usually perform in Phoenix, AZ? Give your answer choice. Then explain how you made your choice and why it makes sense.

<u>a</u> is the correct choice. Phoenix usually has stronger sunlight available than Madison, WI. Another way to say this is that Phoenix usually has higher irradiance measurements. We learned in our lab that irradiance has a much greater effect on current (Amps) than on electrical potential (Volts). Specifically, the higher the irradiance, the greater the Amps (or the lower the irradiance, the lower the Amps). For this reason, a is the correct choice. The dashed, brown curve in <u>a</u> (Phoenix) clearly shows the Amps to be higher than Madison, WI.

6. Each of the blue I-V curves shown below are identical. They show an I-V curve trace from a solar array in Green Bay, Wisconsin upon installation. The I-V curves shown in dashed brown represent situations that might occur over time in contrast to the original, solid, blue curve traces. Match each of the three pairs of graphs (numbered) to the description that best fits each one, below. Each number choice is used once.



6a. Over time, the solar array becomes uniformly covered in dust and dirt.
***   1**

6b. Over time, trees grow up and the solar array becomes partially shaded.
***   3**

6c. The modules in the solar array age after many years.
***   2**

7. Describe the most important idea, concept, principle, or fact you learned while completing this this part of the lesson. Explain why it is important for you (and probably other people) to know and understand.

This is a reflection and judgement question. Student reasoning and reaction should be evident in a good answer. No two student answers should be the same.

Part Three: The Effect of Temperature & The Temperature Coefficient

In **Part Two** of this lab activity, students produced three I-V curves, each at a different level of irradiance. From the graphs they produced, students were able to easily determine that Amps, rather than Volts, is primarily affected by irradiance.

For a variety of reasons it's harder to perform a classroom experiment that shows the effect of <u>temperature</u> on Volts and Amps for a solar PV module. So we've produced a self-paced video making that relationship easy to see and understand. Students will watch a twelve minute video titled **Solar PV: Volts and Amps vs. Temperature.** The video will describe and students will observe an experimental setup. They'll watch Volts and Amps measurements being taken as two solar modules warm up from 15°C to 55°C. During that time they'll record data into an Excel® spreadsheet.

Working with the data students record from the video they produce two graphs that enable them to answer this question: Which electrical measure, electrical potential (Volts) or current (Amps), is affected most by the temperature of a solar module?

Preparing to watch the video:

But before starting the video, students should prepare to record data by opening the Excel® spreadsheet titled **I-V Curve Part 3 - Blank Data Table and Graph**. They'll begin recording data into the spreadsheet at about the 5:30 mark on the timeline.

Prior to 5:30, students review background information provided in the video by answering the questions that follow (1-9). Remind students to top the video for as long as needed to write a good, complete answer to each question.

During the video:

1. Which variable is the independent variable—the one variable that causes the other variables to change?

*** Temperature**

2. Which variables are the dependent variables—the variables that depend on, or are affected by changes in the independent variable?

*** Volts and Amps**

3. What type of electricity is produced from a solar module?

*** Direct Current, or DC electricity**

4. What is the azimuth of the solar modules?

*** Approximately 170°**

5. What is the altitude of the sun?

*** Approximately 65°**

6. What is the tilt angle of the solar modules?

*** Approximately 25°**

7. Why were this azimuth and tilt angle selected?

*** The sun's rays will be roughly perpendicular to the surface of the solar PV modules ensuring the strongest solar radiation possible.**

8. What is the measured irradiance (light intensity) value?
*** 1030 Watts/meter ^{2}**

9. Why won't the irradiance change very much during the demonstration?
*** The sky is cloudless and clear.**

10. Place measured **Voc** and **Isc** values from the video into your Excel® spreadsheet titled **I-V Curve Part 3 - Blank Data Table and Graph**.

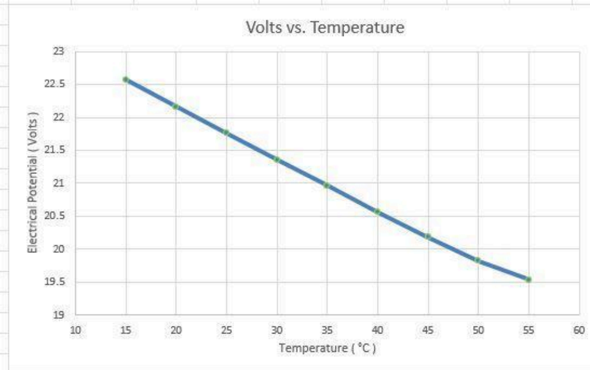
After the Video:

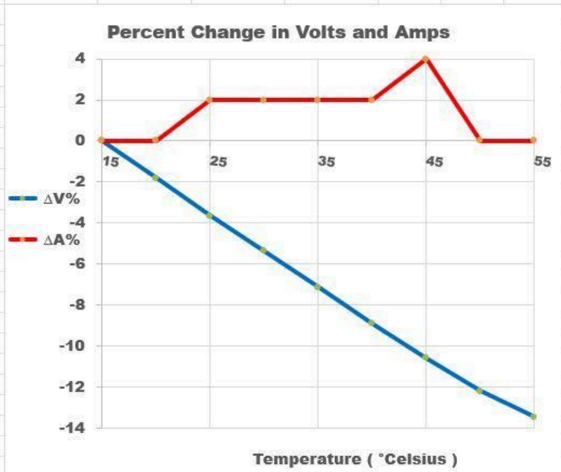
Students follow these directions to produce the two graphs that follow:

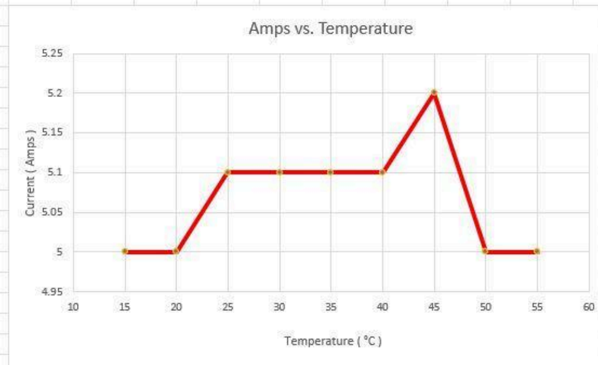
11. Calculate the change in Volts (∆**V**) and change in Amps (∆**A**) from your data.
    - Subtract your first **Voc** measure (at 15°C) from each successive measurement of **Voc**. Record your answer in the data table.
    - Subtract your first **Isc** measure (at 15°C) from each successive measurement of **Isc**. Record your answer in the data table.

12. Calculate the percent change in Volts (%∆**V**) and percent change in Amps (%∆**A**) from your data.
    - Divide each change in Volts (∆**V**) by your original Volts measurement (**Voc** at 15°C). Multiply your answer by 100 to turn it into a percent. As you post your calculated percent into the data table the percent change in Volts graph will assemble itself.
    - Divide each change in Amps (∆**A**) by your original Volts measurement (**Isc** at 15°C). Multiply your answer by 100 to turn it into a percent. As you post your calculated percent into the data table the percent change in Amps graph will assemble itself.

Temp °C	Volts	ΔV	ΔV%	Amps	ΔA	ΔA%
15.0	22.57	0.00	0.00	5.0	0.00	0.00
20.0	22.16	-0.41	-1.82	5.0	0.00	0.00
25.0	21.76	-0.81	-3.66	5.1	0.10	2.00
30.0	21.36	-1.21	-5.36	5.1	0.10	2.00
35.0	20.96	-1.61	-7.13	5.1	0.10	2.00
40.0	20.56	-2.01	-8.91	5.1	0.10	2.00
45.0	20.18	-2.39	-10.59	5.2	0.20	4.00
50.0	19.82	-2.75	-12.18	5.0	0.00	0.00
55.0	19.53	-3.04	-13.47	5.0	0.00	0.00







Show What You Know, Part Three

1. Which electrical measure, Volts or Amps, is more responsive to changes in temperature? Give your answer choice. Then convincingly explain your answer with specific references to your data, or specific references to your graph (or even better, specific references to both).

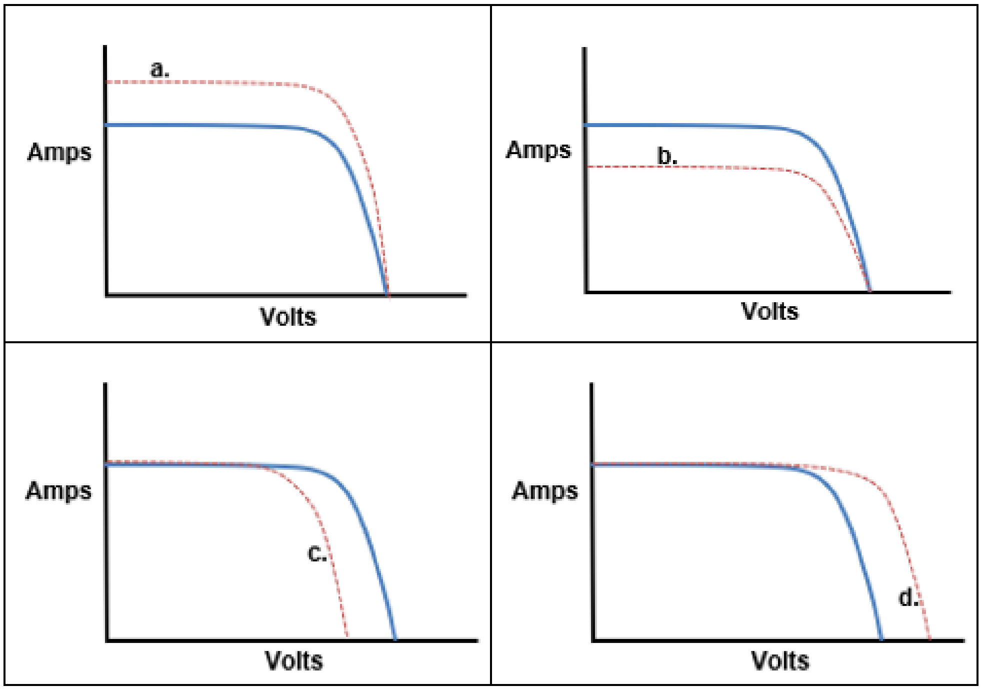
*** Volts is more responsive to temperature.**

From the video script:

"Amp readings from our modules changed little during the 40° of temperature change, and the changes were irregular. It's easy to see this when graphing the percent change in Amps versus temperature. It's likely that the few changes we saw were in response to slight changes in sunlight hitting our modules.

However, changes in Electrical Potential—Volts—on our modules tell a different story. Changes in volts were continuous, regular, and substantial over our 40° of temperature change. Once again, it's easy to see this when graphing the percent change in Volts versus temperature. With this knowledge, Solar PV installers always use temperature extremes expected at their installation site to calculate voltage extremes expected from an array they install."

2. Each of the solid blue I-V curves shown below are identical. They represent an I-V curve trace from a solar array in Madison, Wisconsin. The other I-V curves (shown in dashed brown) represent four different locations from around the World.



Assume all factors other than location are exactly the same. Which location choice, a, b, c, or d, shows how the very same system would usually perform at the Amundsen-Scott Antarctic South Pole Weather Station? Give your answer choice. Then explain how you made your choice and why it makes sense.

*** The answer is letter choice d, showing higher electrical potential (Volts). The Amundsen-Scott Antarctic South Pole Weather Station is always cold. As we learned from our video, the lower the temperature, the higher the Volts. Amps are affected little by temperature. Higher Volts X Amps = higher Watts (higher electrical power).**

3a. Calculate the **Temperature Coefficient of Voc** from the data in the video. If you're not sure how to do this, ask for assistance from your teacher. Show how you calculated the **Temperature Coefficient of Voc**, along with your answer, below. [If you prefer, you may neatly perform the calculation on paper, take a photo, and insert it below.]

*** The Temperature Coefficient of Voc is the percent Voc is expected to change for every degree of Celsius temperature increase. Calculating the Temperature Coefficient of Voc <u>from our data</u>:**

As the module warmed in temperature from 15°C to 55°C, our temperature increase (∆T) was:

- **55°C - 15°C = 40°C temperature increase**

As the module warmed from 15°C to 55°C, Voc decreased from 22.57 V to 19.53 V:

- **22.57 V - 19.53 V = -3.04 V (negative number because Voc decreased as we increased from 15°C to 55°C)**

As the module warmed from 15°C to 55°C, the Voc change in percent was:

- **(-3.04 ~~V~~ / 22.57 ~~V~~) X 100 = -13.47 %**

To calculate the Temperature Coefficient of Voc, divide by ∆T:

- **-13.47 % / 40°C = -0.34 % / °C**

3b. How does your calculated **Temperature Coefficient of Voc** compare to the manufacturer's **Temperature Coefficient of Voc** for the module? In your answer, you must quote the manufacturer's **Temperature Coefficient of Voc**. Use complete sentences in your answer as well.

*** Our Temperature Coefficient of Voc compares favorably to the manufacturer's Temperature Coefficient of Voc for the module:**

- **-0.34 % / °C (calculated) -0.36 % / °C (manufacturer's actual)**

4a. You buy ten solar PV modules, each of which is rated at100 Watts under Standard Test Conditions. The modules have a Voc of 22.0 and a **Temperature Coefficient of Voc** of - 0.40 % / °C. You plan to connect the ten modules in series for your rooftop array. You also plan to purchase an inverter that has a maximum input of 250 Volts DC. Producing above 250 Volts DC will harm or destroy this inverter.

You check the weather records where you plan to install your modules. Calculate the increase in Volts expected on a day when the temperature drops to the 100 year record low of 5°C.

If you're not sure how to do perform this calculation, ask for assistance from your teacher. Show how you calculated your answer below. [If you prefer, you may neatly perform the calculation on paper, take a photo, and insert it below.]

*** Since the 100 year temperature low is 5°C, we must plan for a maximum Volts condition at that temperature.**

At a Standard Test Condition of 25°C, the 10 modules wired in series will give us an array electrical potential (Volts measurement) of:

- **10 ~~modules~~ X 22.0 Voc / ~~module~~ = 220 Voc**

From a Standard Test Condition of 25°C to 5°C gives us a ∆T of:

- **25°C - 5°C = -20°C (negative number because temperature decreased)**

To calculate the percent increase in Volts expected from decreasing the temperature at 25°C to 5°C:

- **-20~~°C~~ X -0.40 % / ~~°C~~ = 8 %**

The array's maximum electrical potential (Volts) at the 100 year temperature low:

- **220 Volts X 1.08 % = 237.6 Volts**

4b. Will the inverter you plan to buy handle the expected increase in Volts at 5°C?

*** Yes, my 250 Volt maximum input inverter will comfortably handle the electrical potential of 237.6 Volts expected at 5°C.**

5. Describe the most important idea, concept, principle, or fact you learned while completing this this part of the lesson. Explain why it is important for you (and probably other people) to know and understand.

This is a reflection and judgement question. Student reasoning and reaction should be evident in a good answer. No two student answers should be the same.