To our teachers:

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SAVING TODAY IS solarWise TOMORROW WISE	**Wisconsin Public Service** **SolarWise for Schools** **and the** **Center for Renewable Energy** **Advanced Technological Education**	CREATE

ENERGY STORAGE:
BATTERIES IN SERIES AND PARALLEL

INSTRUCTOR'S GUIDE

Grade Level:	High School, Technical College, Community College
Lesson Length:	2-3 class hours, depending on coverage and emphasis
Author:	Scott Liddicoat
Created:	October, 2023

Learning Goals:

- Students will understand that the electricity produced with a solar photovoltaic system is generated renewably.
- Students will interpret the arrangements of battery wiring diagrams in various series and parallel configurations.
- Students will wire batteries in various series and parallel configurations.
- Students will predict the electrical potentials (Volts) of batteries arranged in various series and parallel configurations.
- Students will measure the electrical potentials (Volts) of batteries arranged in various series and parallel configurations.
- Students will state the electrical potential (Volts) and capacity (Amp-hours) relationships that emerge from working with batteries arranged in various series and parallel configurations.

Materials, Resources, and Technology Required:

- 12 fully charged rechargeable batteries
- 12 battery holders with pin contact extensions
- 3 wood battery holder holders
- Numerous alligator clip colored wires

- 6 V incandescent bulb with screw in base
- 1 Telegraph key circuit connector switch
- 1 Multimeter

Tips for Teaching this Lesson:

This lab-based activity is plainly a basic, but critical introduction to batteries, battery connections, and battery terminology. Its primary objectives are to reveal to students the Volts and Amp-hours relationships that occur when batteries are wired in series and parallel arrangements. The Volts relationships emerge in the lab activity part of the lesson. The Amp-hours relationships emerge as students perform the Lesson Summary Questions.

Regardless of your background or training, you need to perform this lab activity as a student before using it in your classroom. This will give you information on possible difficulties, timing, and the length of time you want to schedule for it.

Prior to performing this lesson you should consider using our video series, "Understanding Battery Technology" to introduce battery structure and function.

- **Lithium Basics These need to be swapped off my site and go to CREATE.**
5:25
https://www.youtube.com/watch?v=JjnTDQ_QfpE

- **Understanding Battery Technology**
Chapter 0: Introduction
3:00
https://www.youtube.com/watch?v=0xIsDWIIOB8

- **Understanding Battery Technology**
Chapter 1: The Pickle Battery
10:16
https://www.youtube.com/watch?v=8be8YXzu0bY

- **Understanding Battery Technology**
Chapter 2: The Primary (non rechargeable) Battery
7:35
https://www.youtube.com/watch?v=Bok2I_zs1X4

- **Understanding Battery Technology**
Chapter 3: The Secondary (rechargeable) Battery
12:12
https://www.youtube.com/watch?v=I8AjoJXunIU

Batteries in Series and Parallel is designed to be user friendly, flexible, and (more or less) inquiry based. Depending on your preferences, grade level, and student aptitude, you may use it entirely self-paced, entirely teacher-paced, or somewhere between. For a variety of good reasons, it is probably best to have students work through this activity in cooperative lab groups.

Our recommendation is to provide each group of students with a hard copy of the lesson they can mark up, and on which they may take data, and answer questions. Students may then transfer information and answers to the **Student Digital Response Guide** (included with your lesson materials) for submission. Alternately you may have students submit their original paper document for grading.

The student materials for this lesson are designed to be Section 508 compliant. Section 508 of the Rehabilitation Act requires federal agencies to ensure that their information and communication technology (ICT) is accessible to people with disabilities unless certain exceptions apply. Specifically, Section 508 requires federal agencies to ensure that ICT they develop, procure, maintain, or use allows employees with disabilities and individuals with disabilities who are members of the public to have access to and use of information and data. This access should be comparable to that available to employees and members of the public without disabilities.

As always, you are welcome to revise this lesson to your liking.

Answers in the following Answer Key have been composed to assist teachers in their understanding. They are not necessarily intended to be representative student answers.

Lesson Summary Questions Answer Key

Question 1a. Write down your teacher's definition of a circuit wired in series, or research one that you understand well.

A series circuit is one in which the batteries are arranged in a single path. Electrons flow only through the single circuit pathway.

Question 1b. Write down your teacher's definition of a circuit wired in parallel, or research one that you understand well.

A parallel circuit is one in which batteries are connected across the same two points. The batteries are arranged in separate circuit "branches." Current flows may flow through any of the branches.

Table 1. Rechargeable Battery Measurements **[Example Data]**

Lab Setting:	Wiring Configuration:	Electrical Potential (Volts) **Prediction:**	Electrical Potential (Volts) **Measurement:**
1.	**1B**	*	1.44
2.	**2S**	*	2.87
3.	**3S**	*	4.31
4.	**4S**	*	5.74
5.	**1B**	*	1.44
6.	**2P**	*	1.43
7.	**3P**	*	1.43
8.	**4P**	*	1.43
9.	**2P2S**	*	2.84
10.	**2P3S**	*	4.25
11.	**2P4S**	*	5.68
12.	**3P2S**	*	2.83
13.	**3P3S**	*	4.26
14.	**3P4S**	*	5.68

Question 2a. Using what you've just learned, write a clear general statement that explains what happens with electrical potential (Volts) when batteries are configured (wired) in a series circuit.

The electrical potential (output Volts) of batteries connected in a series circuit is the sum of the individual Volts of each battery wired in the series string (assumes batteries have matching Volts and Amps ratings and are very close to the same level of charge).

Question 2b. Using what you've just learned, write a clear general statement that explains what happens with electrical potential (Volts) when batteries are configured (wired) in a parallel circuit.

The electrical potential (output Volts) of batteries connected in a parallel circuit is the same as each of the individual batteries wired in the parallel circuit (assumes batteries have matching Volts and Amps ratings and are very close to the same level of charge).

Common household single use, disposable batteries:

3. **4** parallel strings of **3** batteries in series.
4.5 volts **4** amp-hours **18** watt-hours

4. **3** parallel strings of **4** batteries in series.
36 volts **1.5** amp-hours **54** watt-hours

5. **3** parallel strings of **5** batteries in series.
7.5 volts **6** amp-hours **45** watt-hours

6. **2** parallel strings of **4** batteries in series.
6 volts **30** amp-hours **180** watt-hours

7. **6** parallel strings of **2** batteries in series.
3 volts **9** amp-hours **18** watt-hours

8. **2** parallel strings of **6** batteries in series.

54 volts **1** amp-hours **54** watt-hours

Lead-acid batteries, formerly the first choice for solar PV storage:

9. **3** parallel strings of **4** batteries in series.
48 volts **450** amp-hours **21,600** watt-hours

10. **4** parallel strings of **2** batteries in series.
12 volts **900** amp-hours **10,800** watt-hours

11. **5** parallel strings of **2** batteries in series.
24 volts **750** amp-hours **18,000** watt-hours

12. **2** parallel strings of **4** batteries in series.
24 volts **450** amp-hours **10,800** watt-hours

Solar PV modules:

13. **2** parallel strings of **4** modules in series.
120 volts **20** amps **2400** watts

14. **3** parallel strings of **8** modules in series.
320 volts **36** amps **11,520** watts

15. **2** parallel strings of **7** modules in series.
280 volts **24** amps **6720** watts

Rechargeable Lithium Ion Batteries:

16. **1** parallel strings of **5** batteries in series.
18 volts **1.5** amp-hours **27** watt-hours

17. **2** parallel strings of **5** batteries in series.
18 volts **6** amp-hours **108** watt-hours

18. **3** parallel strings of **5** batteries in series.
18 volts **12** amp-hours **216** watt-hours

19. **1** parallel strings of **8** batteries in series.
28.8 volts **3.5** amp-hours **100.8** watt-hours

20. **1** parallel strings of **6** batteries in series.
21.6 volts **5.0** amp-hours **108** watt-hours

21a. **48** volts **200** amp-hours **9.6** kilowatt-hours

21b. **48** volts **400** amp-hours **19.2** kilowatt-hours

22a. **44.4** volts **216** amp-hours **9.6** kilowatt-hours

22b. **399.6** volts **216** amp-hours **86.3** kilowatt-hours

Question 23a. Consider what you just learned in completing Lesson Summary Questions 3-22. Write a clear general statement that explains what happens with battery capacity (Amp-hours) when batteries are configured (wired) in a series circuit.

The Amp-hour capacity of batteries connected in a series circuit is the same as each of the individual batteries wired in the series circuit (assumes batteries have matching Volts and Amps ratings and are very close to the same level of charge).

Question 23b. Consider what you just learned in completing Lesson Summary Questions 3-22. Write a clear general statement that explains what happens with battery capacity (Amp-hours) when batteries are configured (wired) in a parallel circuit.

The Amp-hour capacity of batteries connected in a parallel circuit is the sum of the individual Amp-hour capacities of each battery wired in the parallel circuit (assumes batteries have matching Volts and Amps ratings and are very close to the same level of charge).

The battery sub-module used in a popular EV contains 864 individual battery cells rated at 3.7 Volts (nominal) and 3.0 Amp-hours. These cells are configured in 72 parallel strings of 12 cells wired in series (72 P, 12 S). What are the Volts, Amp-hours, and kiloWatt-hours for one EV sub-module?

a. **3.7 V**olts**, 3.0** Amp-hours**, 0.011** kiloWatt-hours
b. **266.4 V**olts**, 36** Amp-hours**, 9.6** kiloWatt-hours
c. **44.4 V**olts**, 216** Amp-hours**, 9.6** kiloWatt-hours
d. **3197 V**olts**, 2597** Amp-hours**, 8287** kiloWatt-hours