2.1 Terminology

Electricity is the flow of electrons through a circuit. The force or pressure of moving electrons in a circuit is measured as voltage. The flow rate of electrons is measured as amperage. The power of a system is measured as watts.

A **volt** is the unit of force (electrical pressure) that causes electrons to flow through a wire. Volts are abbreviated V, or expressed by the symbol E. Electrical pressure is sometimes referred to as the electromotive force (EMF). Some common voltages used in light-duty electrical systems include 12v, 24v, 48v. Most homes use 120v and 240v systems.

An **ampere** or **amp** is the unit of electrical current flowing through a wire. Amps are abbreviated A or expressed by the symbol I (for intensity of current). Just as pipe is sized by the rate of water passing through it, a wire is sized according to the rate of electrons (amps) flowing through it. One amp of current flowing for one hour is referred to as an **amp-hour** (Ah). The term amp-hour is commonly used when describing battery capacity. (For more information on wire-sizing methods, refer to Chapter 9.)

A **watt** is a unit of electrical power equivalent to a current of one ampere under a pressure of one volt. Watts indicate the *rate* at which an appliance uses electrical energy or the rate at which electrical energy is produced. Since consumers need to gauge how much electricity they use, the **watt-hour**, an electrical unit of energy, is an important measurement. An appliance that consumes electrical energy at a rate of one watt for one hour will have consumed a quantity of electricity equal to one watt-hour.

To calculate watt-hours, there are two things you'll need to know:

- An appliance's rated watts.
- The estimated duration of time the appliance will be operated.

The term watt-hours probably sounds familiar, since utility companies bill their customers for the number of kilowatt-hours consumed. **Kilowatt-hours** of electricity are equal to 1,000 watt-hours and are abbreviated kWh.

Types of Current

There are two types of electrical current. **Alternating current** (AC) is electric current in which direction of flow reverses at frequent, regular intervals. This type of current is produced by alternators. In an alternator, a magnetic field causes electrons to flow first in one direction, then in the reverse direction. Electric utility companies supply alternating current.

Direct current (DC) is electric current that flows in one direction. Direct Current is the type of current produced by PV modules and stored in batteries.

<u>Equations:</u>

Power = Watts (W) = Volts (V) x Amps (A)
1,000W = 1 Kilowatt (kW)

Energy = Watt-hours (Wh) = Watts x Hours
1,000Wh = 1 Kilowatt-hour (kWh)

Amp-hours (Ah) = Amps x Hours

Problem: How much electrical energy is consumed if a 100-watt light bulb is used for 10 hours?

Solution: 100 watts x 10 hours = 1,000 watt-hours (or 1 kilowatt hour).

2.2 Matching Appliances to the System

Photovoltaic system designers adapt their systems by using the manufacturers' power ratings for appliances, in conjunction with a careful estimation of how long each appliance will be used. You can find an appliance's electrical rating and power requirements on the nameplate. To use the information on an appliance's nameplate and correctly match the electrical supply to the appliance's requirements, you must understand the terms discussed in this chapter, including watts, amps, volts, alternating current, and direct current.

When choosing an appliance for a PV system, there are two important rules that must be observed:

- The voltage of an appliance must match the voltage supplied to it. The power source, such as a battery, generator, or photovoltaic module, determines the voltage supplied.
- An appliance must be compatible with the type of current (AC or DC) that is supplied to it.

2.3 Electrical Circuits

An **electrical circuit** is the continuous path of electron flow from a voltage source, such as a battery or photovoltaic module, through a conductor (wire) to a load and back to the source. A simple electrical circuit is shown in Figure 2-1 as a schematic and a diagram. This example shows a single voltage source, a 12-volt battery, wired to a single load, a 12-volt, 24-watt light bulb, with a switch to turn the light on and off.

The switch controls the continuity of current flow. If the switch is turned off (an **open circuit**), the wire between the source and the load is disconnected, and the light will be off. If the switch is turned on (a **closed circuit**), the wire between source and load is connected, and the light will shine. Relay switching devices are often used as controls to open or close a circuit. Relays are rated by voltage, type of current (AC or DC), and whether the circuit is normally open or closed.

An electrical system can be compared to a water pumping system. A pump lifts two gallons of water per minute from a lower tank to an upper tank, increasing its height and pressure by 12 feet, the distance between the two tanks. The pressure created by the 12-foot height of the upper tank is like the 12-volt electrical pressure in the battery. The water falls at two gallons per minute from the upper tank and turns a water wheel, losing its height and pressure as it returns to the lower tank. The falling of water at two gallons per minute to turn the water wheel is like the two amp flow of electrons that powers the light and returns to the battery.

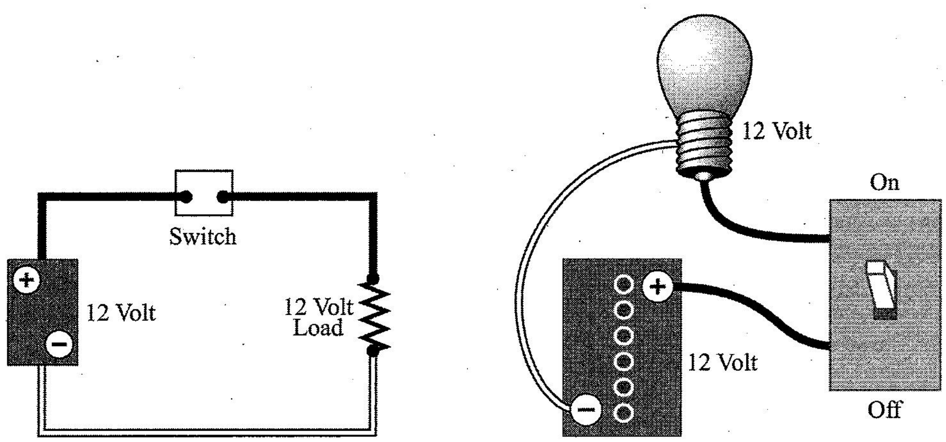


Figure 2-1
ELECTRICAL CIRCUITS

2.4 Series and Parallel Circuits in Power Sources

Photovoltaic modules and batteries are a system's building blocks. While each module or battery has a rated voltage or amperage, they can also be wired together to obtain a desired system voltage.

Series Circuits

Series wiring connections are made at the positive (+) end of one module to the negative (-) end of another module. When loads or power sources are connected in series, the voltage increases. Series wiring does not increase the amperage produced. Figure 2-2 shows two modules wired in series resulting in 24V and 3A.

Series circuits can also be illustrated with flashlight batteries. Flashlight batteries are often connected in series to increase the voltage and power a higher voltage lamp than one battery only could power alone.

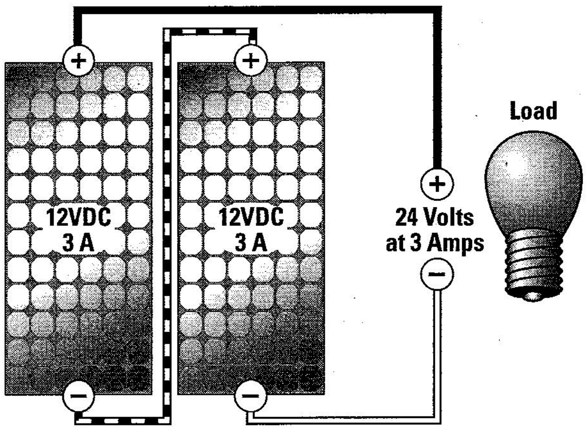


Figure 2-2

PV MODULES IN *SERIES*

Problem: When four 1.5V DC batteries are connected in series, what is the resulting voltage?

Solution: 6 volts

Parallel Circuits

Parallel wiring connections are made from the positive (+) to positive (+) terminals and negative (-) to negative (-) terminals between modules. When loads or sources are wired in parallel, currents are additive and voltage is equal through all parts of the circuit. To increase the amperage of a system, the voltage sources must be wired in parallel. Figure 2-3 shows PV modules wired in parallel to get a 12V, 6-amp system. Notice that parallel wiring increases the current produced and does not increase voltage.

Batteries are also often connected in parallel to increase the total amp-hours, which increases the storage capacity and prolongs the operating time.

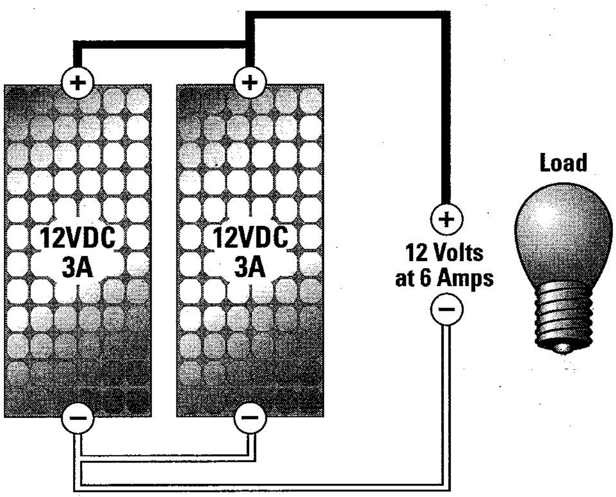


Figure 2-3

PV MODULES IN *PARALLEL*

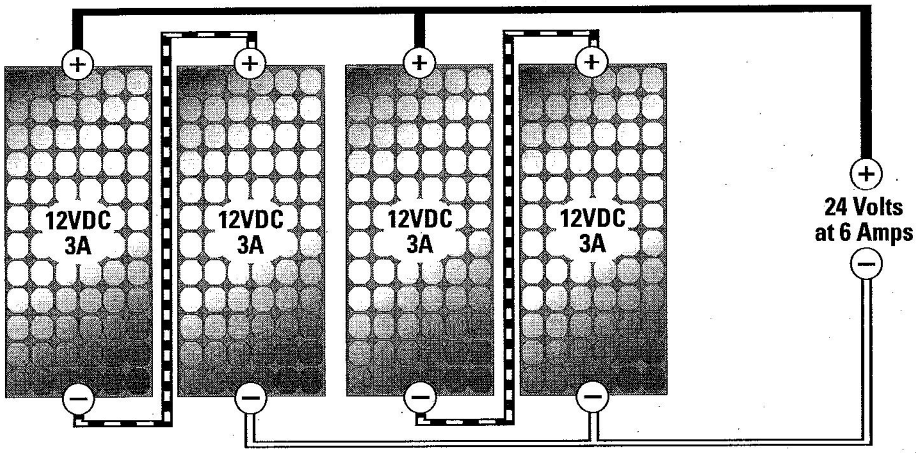


Figure 2-4
PV MODULES IN SERIES *AND* PARALLEL

Series and Parallel Circuits

Systems may use a mix of series and parallel wiring to obtain required voltages and amperages. In Figure 2-4, four 3-amp, 12V DC modules are wired in series and parallel. Strings of two modules are wired in series, increasing the voltage to 24V. Each of these strings is wired in parallel to the circuit, increasing the amperage to 6 amps. The result is a 6-amp, 24V DC system.

Batteries in Series and Parallel

The advantages of a parallel circuit can be illustrated by observing how long a flashlight will operate before the batteries fully discharge. To make the flashlight last twice as long, battery storage would have to be doubled.

In Figure 2-5, a series string of four batteries has been added in parallel to another string of four batteries to increase storage (amp-hours). The new string of batteries is wired in parallel, which increases the available amp-hours, thereby adding additional storage capacity and increasing the usage time. The second string could not be added in series because the total voltage would be 12 volts, which is not compatible with the six-volt lamp.

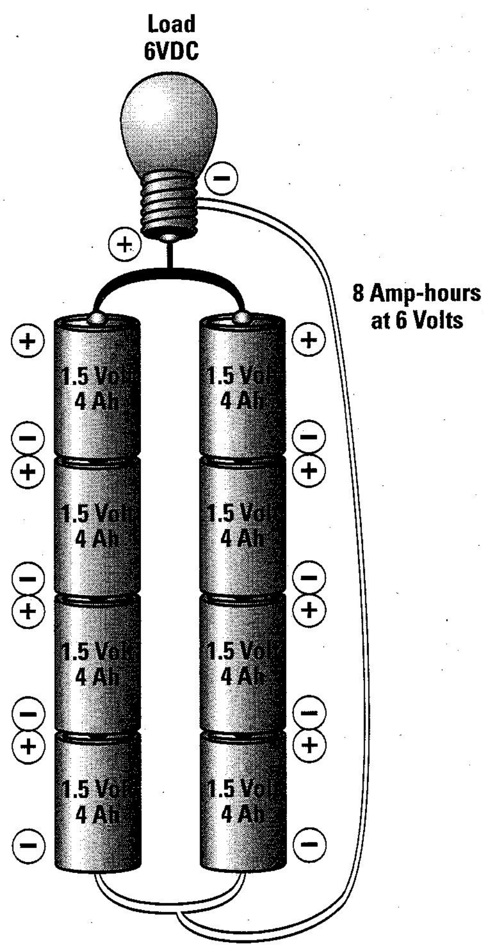


Figure 2-5
BATTERIES IN SERIES *AND* PARALLEL

High Voltage PV Arrays

So far in this chapter, we have only discussed input voltages up to 24V nominal. Today, most batteryless grid-tied inverters on the market require a high voltage DC input. This input window is generally in the range of 75 to 600VDC. Because of the inverter's high voltage input requirements, PV modules must be wired together in series in order to sufficiently increase the voltage. See Figure 2-6 for an example of a high voltage system.

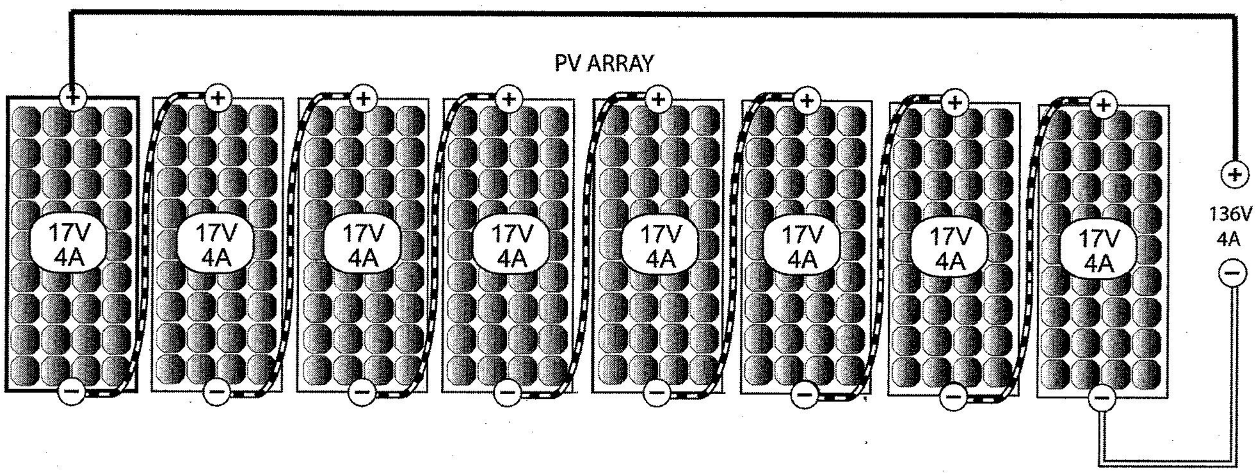


Figure 2-6
HIGH VOLTAGE ARRAY

2.5 Series and Parallel Circuits in Electric Loads

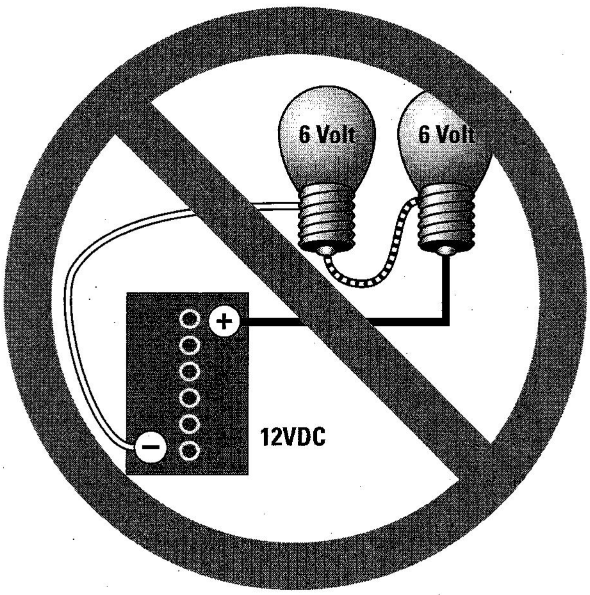


Figure 2-7
LOADS IN *SERIES*

Like the photovoltaic modules and flashlight batteries described in the previous sections, loads wired in series, parallel, or series/parallel configurations act similarly.

Loads in Series

Loads wired in series result in a voltage drop that is additive. The total voltage drop is equal to the sum of all the loads in the circuit. Current is equal through all loads in the circuit. Figure 2-7 shows two 6V light bulbs wired in series and supplied by a 12V battery. The voltage drop caused by each bulb is 6V; thus the total voltage drop is 12V, which is equal to the 12V pressure in the battery.

The two lights in Figure 2-7 are wired in series and are jointly controlled. If one light burns out, the circuit will be open, and all loads in the circuit will lose power. For this reason it is not recommended to wire loads in series.

Loads in Parallel

What happens when loads are wired in parallel? Remember how the batteries added to the flashlight in Figure 2-5 did not increase the voltage supplied to the lamp? As loads are added in parallel, the voltage drop for each remains equal to the source voltage. Current drawn from the source is increased with each load added in parallel. See Figure 2-8.

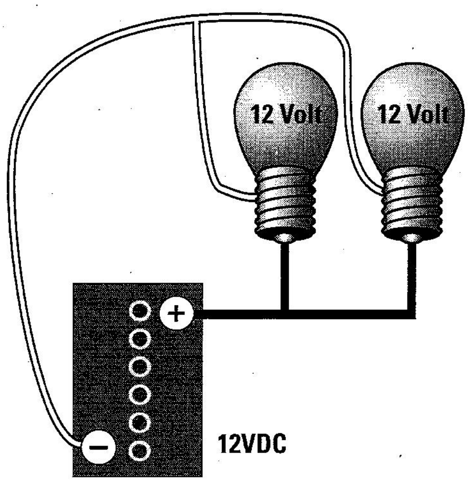


Figure 2-8
LOADS IN *PARALLEL*

Electrical circuits are commonly wired with all the loads in parallel for the following two reasons:

- Each load can be controlled individually.
- Adding more loads does not affect the operating voltage of any other load.

2.6 Series and Parallel Wiring Exercises

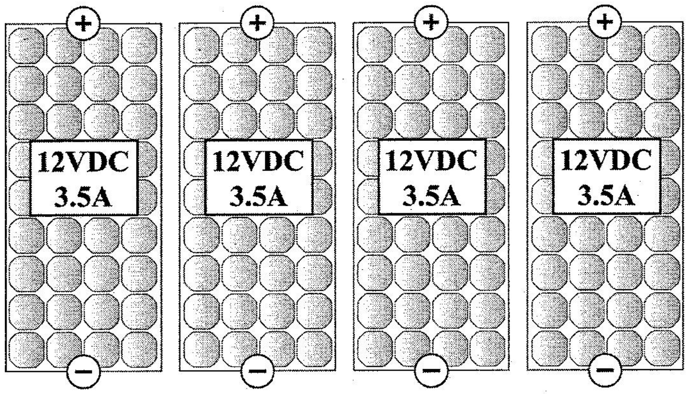
Use the following worksheets to practice series and parallel wiring for 12-, 24-, and 48-volt systems. Enter your answers in the blanks on each page or copy these pages for future practice. Draw lines to make your connections. The answers are listed in Section 2.7.

Instructions:

1. Connect the photovoltaic modules (array) either in series or parallel or series/ parallel to get the desired system voltage.
2. Calculate total module output for volts and amps.
3. Connect the array to a charge controller.
4. Connect batteries either in series or parallel to get the desired system voltage.
5. Calculate total battery bank voltage and amp-hour capacity.
6. Connect the battery bank to the charge controller.

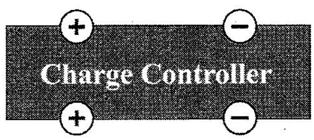
Exercise A: DESIGN A 12V SYSTEM WITH FOUR 12V PV MODULES

PV Array



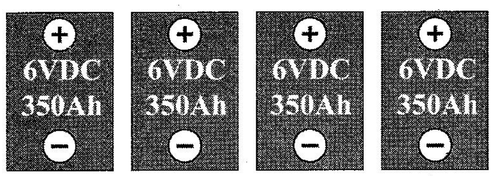
Total Volts = ____________

Total Amps = ____________



Total Volts = ____________

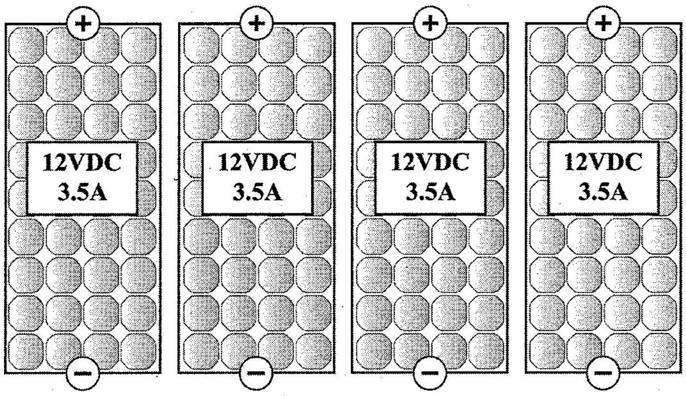
Total Amp-Hours = ________



Battery Storage

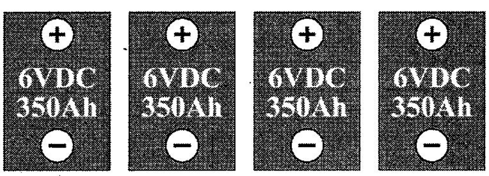
Exercise B: DESIGN A 24V SYSTEM WITH FOUR 12V PV MODULES

PV Array



Total Volts = __________

Total Amps = _______



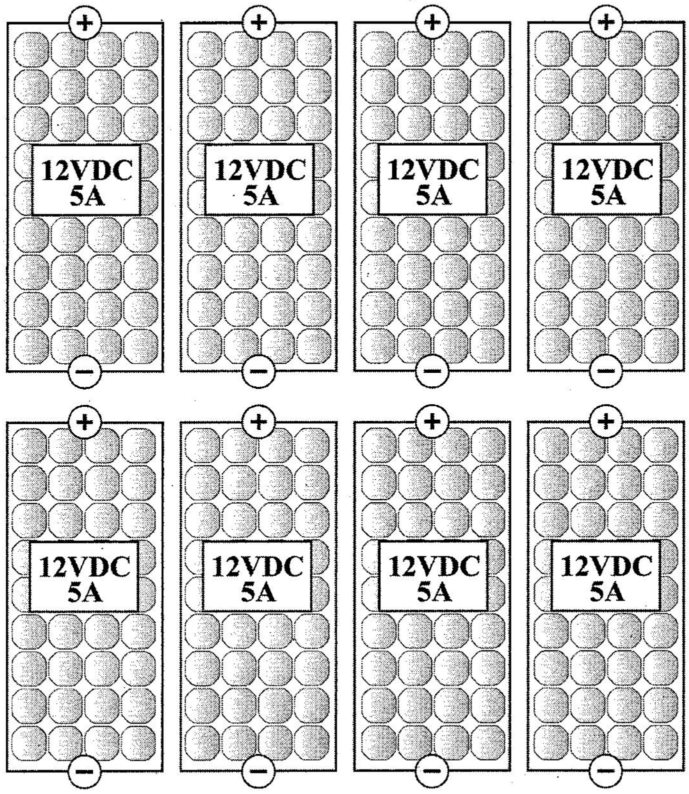
Battery Storage

Total Volts = __________

Total Amp-Hours = _______

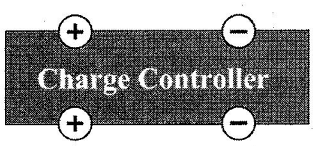
Exercise C: DESIGN A 48V SYSTEM WITH EIGHT 12V PV MODULES

PV Array



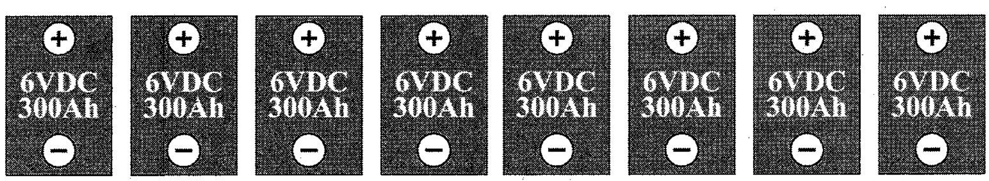
Total Volts = ________

Total Amps = ________



Total Volts = __________

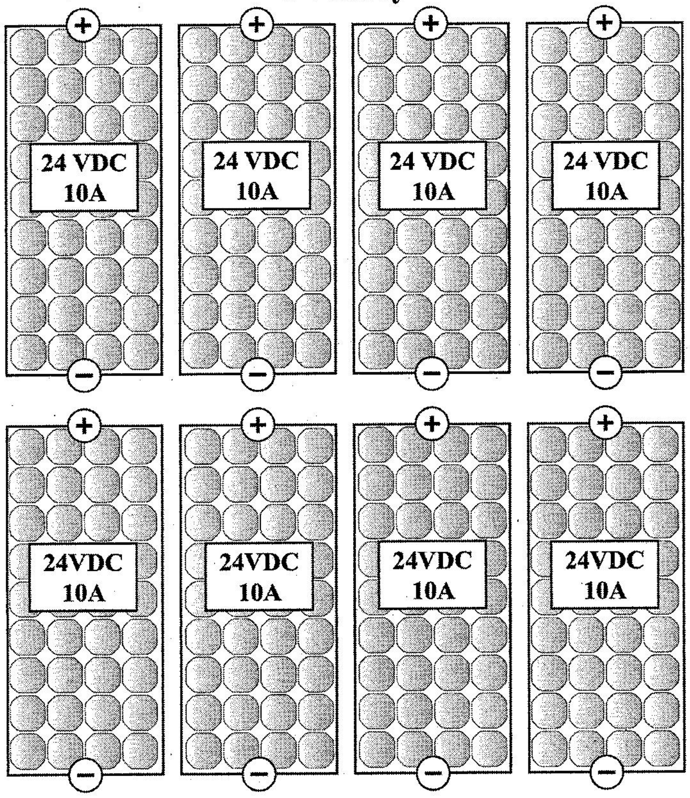
Total Amp-Hours = ______



Battery Storage

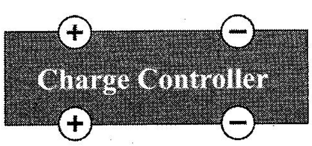
Exercise D: DESIGN A 48V SYSTEM WITH EIGHT 24V PV MODULES

PV Array



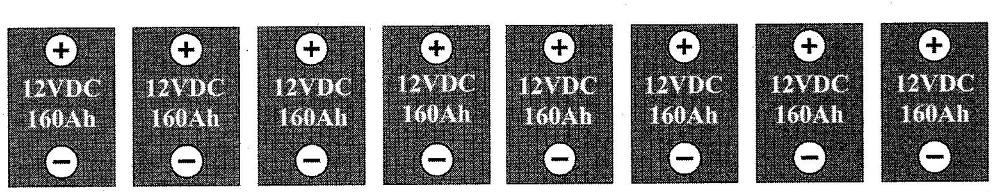
Total Volts = ____________

Total Amps = ____________



Total Volts = ____________

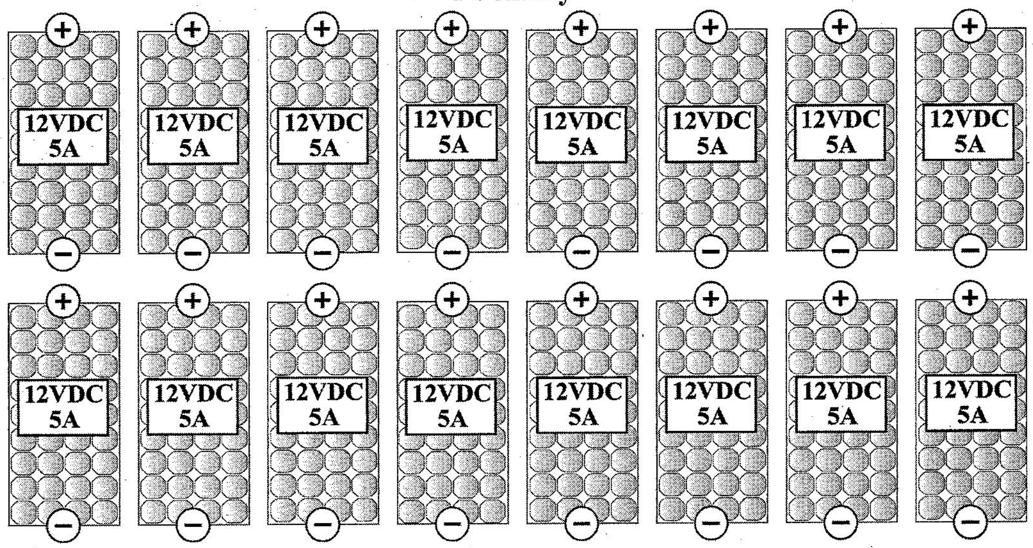
Total Amp-Hours = ________



Battery Storage

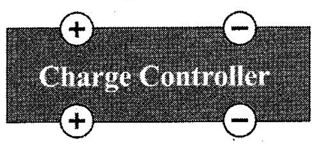
Exercise E: DESIGN A 48V SYSTEM WITH SIXTEEN 12V PV MODULES

PV Array



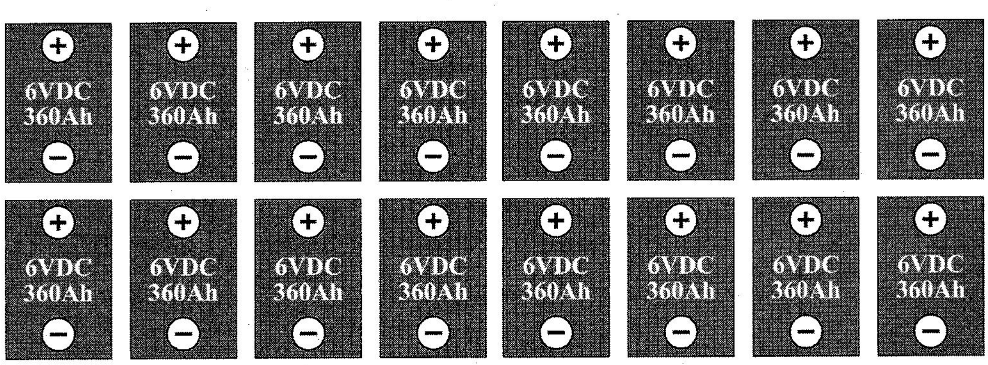
Total Volts = ___________

Total Amps = _______



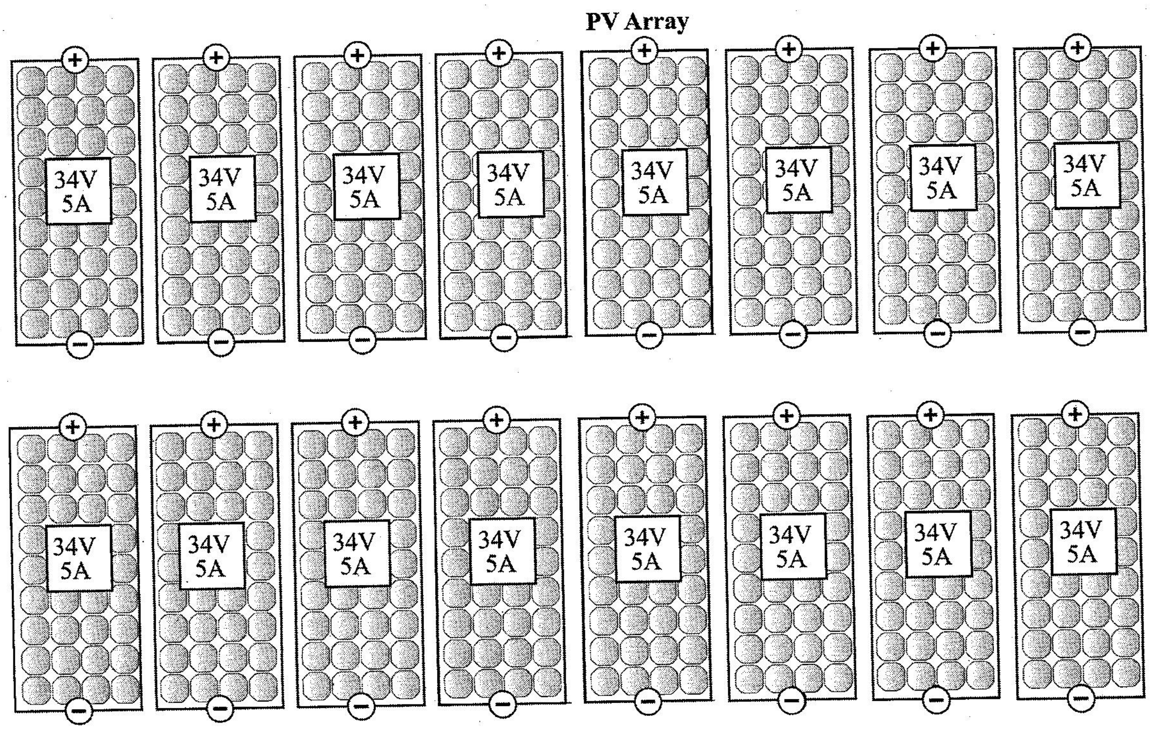
Total Volts = ___________

Total Amp-Hours = _______



Battery Storage

Exercise F: DESIGN A GRID-TIED SYSTEM WITH 2 SERIES-STRINGS USING SIXTEEN 34V PV MODULES



Total Volts = __________

Total Amps = __________