



Simplifying Electricity

Renewable power systems



MATRIX

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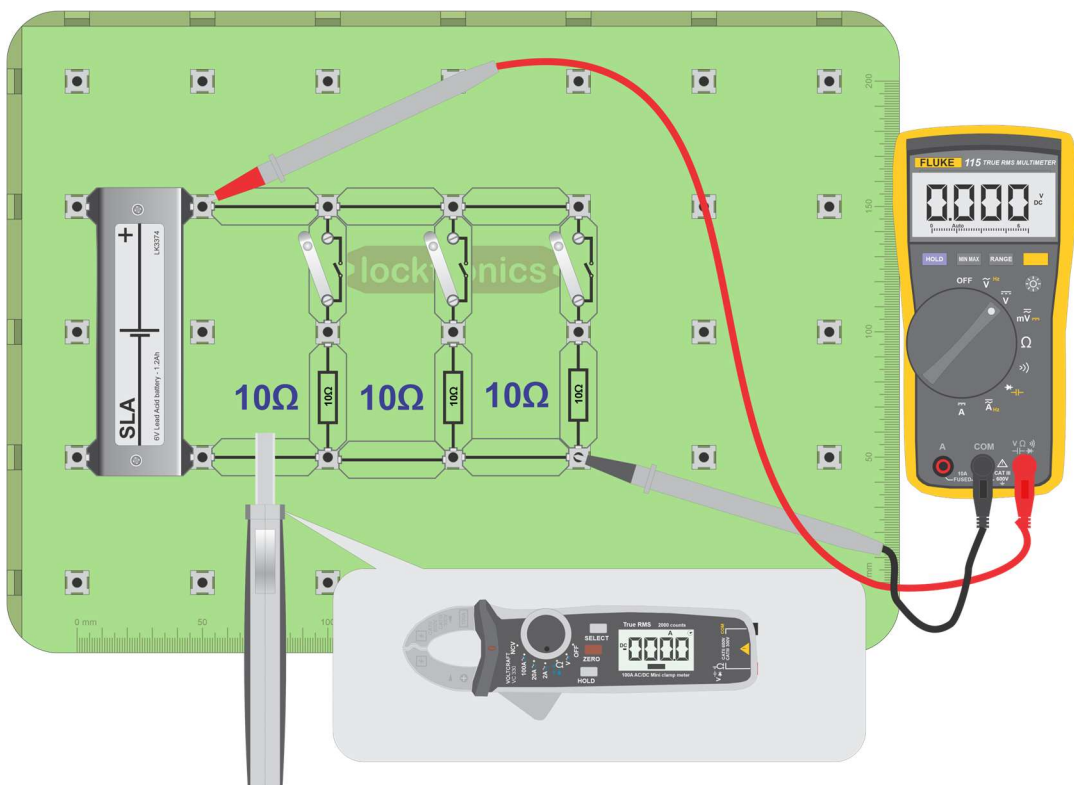
Worksheet 1

Testing Sealed Lead-Acid batteries

There are number of ways to test a battery, but, ultimately, the only sure way is to test its energy-storage capacity. This involves charging it and then discharging it, making measurements of energy intake and output as you do so.

The Sealed Lead-Acid battery (SLA) provided is a small one but it behaves just like the larger lead- acid batteries you find in vehicles.

The photograph shows a Voltcraft battery tester.



Over to you:

- Build the circuit shown above but leave the switches open for now.
- Configure the multimeter to measure DC volts.
- Configure the current clamp to measure DC amps and 'zero' it.
- Connected as shown, the meters measure the output voltage and current of the battery.

Worksheet 1

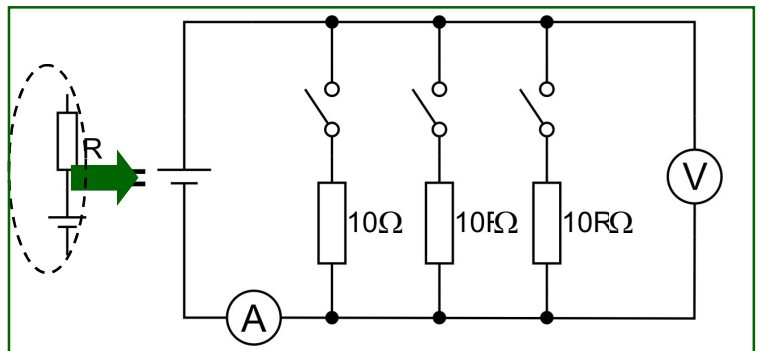
Testing Sealed Lead Acid batteries

Over to you continued ...

- Measure these and record them in the table in the Student Handout.
- Close the first switch briefly and measure output voltage and current again.
- Close the second and then third switch, briefly, and repeat the process.
- Note down all readings in the Student Handout.

So what?

- You made a battery tester and used it to measure elements of the performance of the SLA battery. The circuit diagram for this tester is shown opposite.
- Batteries are more complex than they may appear. To understand their behaviour, it helps to think of them as a combination of a battery and a series resistor, **R**. **R** is called the 'internal resistance'.
- For lead-acid cells the internal resistance of a battery becomes higher when the battery 'state of charge' (SOC) is low and as the battery ages.
- Many simple lead-acid battery testers show you the effects of this internal resistance.
- As the internal resistance increases, more of the voltage is dropped across it and the battery output voltage falls eventually to below an acceptable level.



Over to you again:

- Using the same circuit with all switches open, measure the initial output voltage.
- Close two switches and measure battery output voltage and current.
- Repeat this process after five minutes and then after ten minutes.
- Record your results in the table in the Student Handbook.

So what?

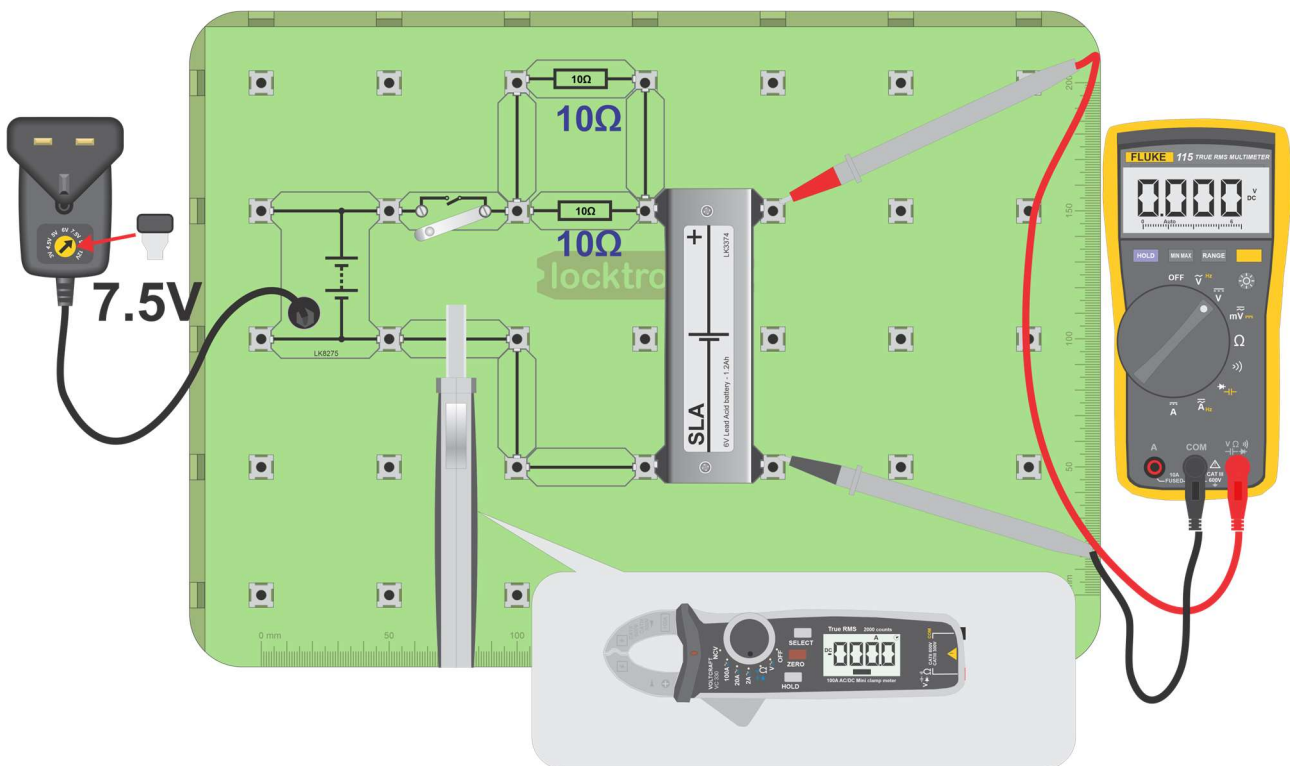
- The energy capacity of the battery, C, indicates how much energy it can store. It is measured in units called 'amp.hours, (Ah). This battery is rated at '6V 1.2Ah', meaning that, when fully charged, it should deliver a current of approximately 1.2A at 6V for 1 hour.
- As a rule of thumb, if this battery is fully charged, when you draw 1.2A for 10 minutes (i.e. two switches closed) the battery is probably satisfactory if the voltage stays above 5.5V.
- Simply measuring the output under no load is not a good enough test for lead-acid batteries.
- Using a quick and simple load test, like the one above, allows you to say with some degree of certainty that a battery is satisfactory.
- The only real way to test a battery with 100% certainty is to discharge it, charge it fully, and then discharge it whilst making sure that it supplies the rated current for the rated time.

Worksheet 2

Charging Sealed Lead Acid batteries

The car alternator is continually charging the lead-acid battery whilst, at the same time, its output is also used by the car's electrical system. Just like when testing lead-acid batteries, the proper charging process is more complex than it may at first seem. The current needed and charging time depend on the battery's initial SOC.

For this SLA battery, one recommended method is to charge it at 10% of its amp.hour rating for 24 hours. The amp.hour rating for the SLA used here is 1.2Ah, implying a charging current of 0.12A for 24 hours. The photograph shows a garage-based battery charger.



Over to you:

- Construct the circuit shown above.

Worksheet 2

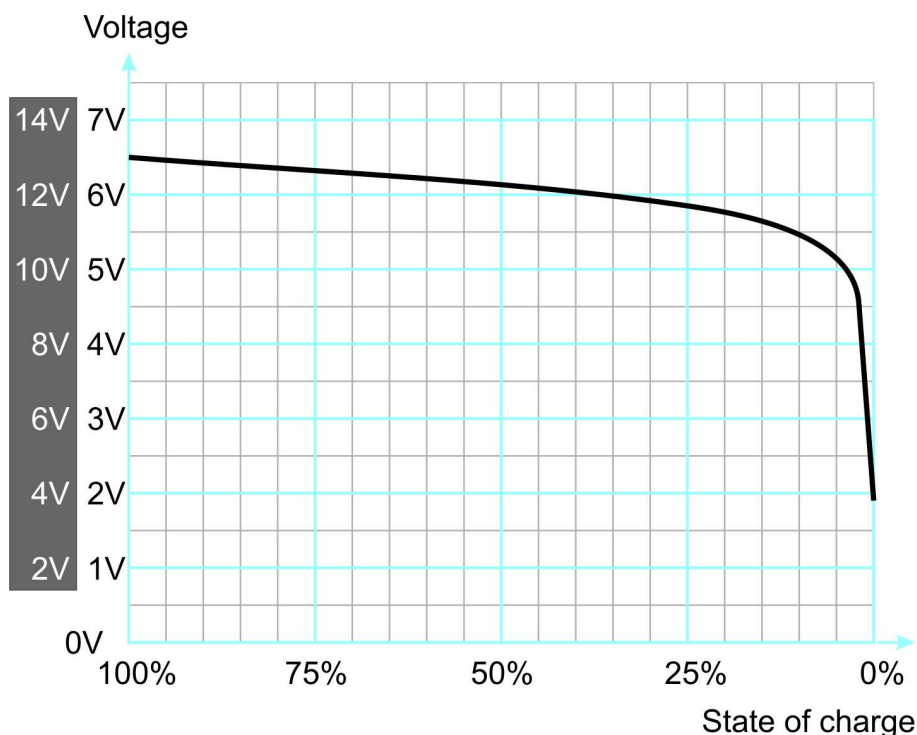
Charging Sealed Lead Acid batteries

Over to you continued...

- Measure the initial battery voltage with the switch open.
- Close the switch.
- Measure the charging current from the power supply and battery voltage.
- After five minutes, note the battery voltage and charging current again.
- Briefly, open the switch and measure the open-circuit voltage again.
- Close the switch and continue charging the battery.
- After ten minutes, and then after 15 minutes, repeat this process.
- Complete the table in the Student Handout with your measurements.

So what?

- As the *State of Charge (SOC)* increases, the open-circuit battery voltage rises. (It may be difficult to see much of a change in such a short time.) This voltage will also change as the battery settles once charging is finished.
- With a simple voltage source power supply, like the one used here, the current reduces as the SOC increases. (SLA batteries are quite robust and withstand erratic charging like this.)
- The graph gives typical SOC voltages for 6V and 12V SLA batteries.
- It shows how SOC changes with battery voltage and can be used to predict SOC from battery voltage.
- In practice, a 12V SLA battery usually reads an output voltage of around 12.7V and a 6V SLA battery around 6.4V.

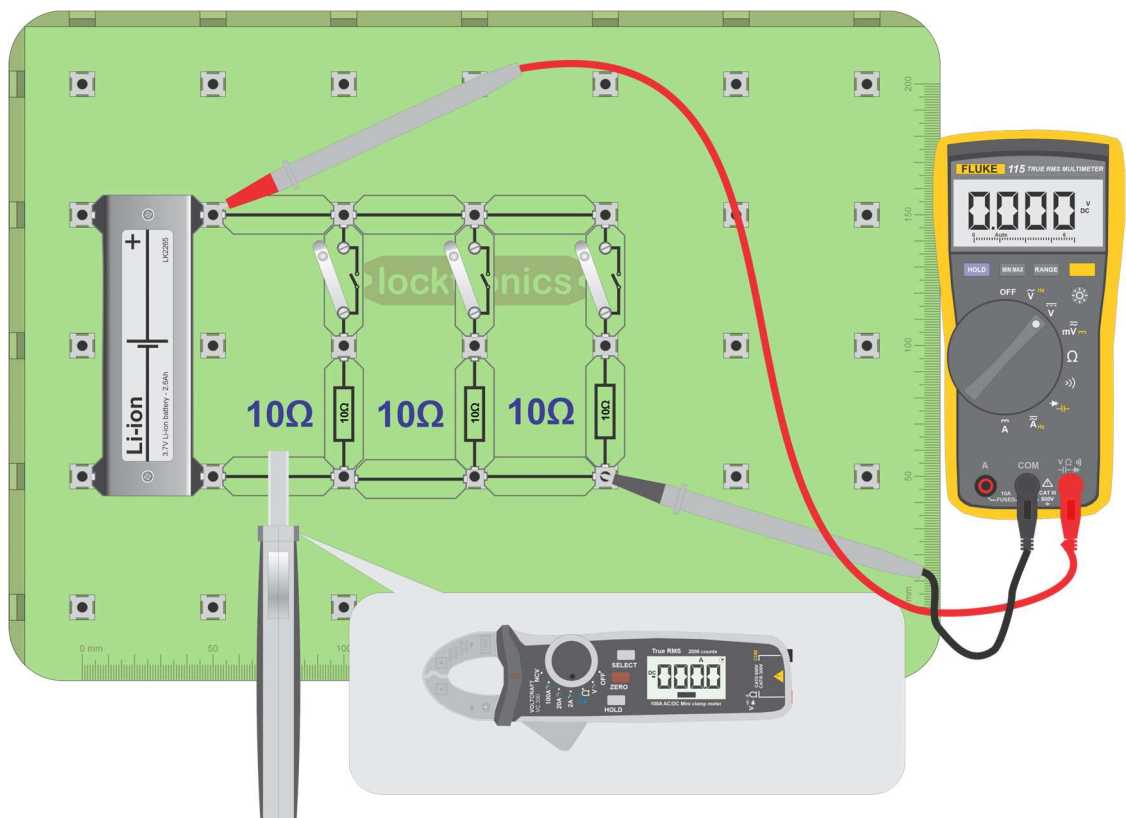


Worksheet 3

Testing Li-ion cells

In practice, lithium-ion (Li-ion) battery packs are made up of a large number of 'cells'. Testing the whole battery is difficult and so each cell, or group of cells, is monitored separately by the battery management system.

The photograph shows the interior of a Tesla battery with hundreds of small Li-ion cells identical to those in your kit. They are known as '18650' cells. In the kit, they are housed in a metal case because they can catch fire or explode if mistreated.



Do not discharge the batteries below 3.2V

Over to you:

- Construct the circuit shown above but leave the switches open for now.

Worksheet 3

Testing Li-ion cells



Over to you:

- Configure the multimeter to measure DC volts.
- Configure the current clamp to measure DC amps and 'zero' it.
- Measure the battery output voltage and current as shown.
- Close the first switch briefly and measure output voltage and current again.
- Close the second and then third switch, briefly, and repeat the process.
- Note down all readings in the Student Handout.

So what?

You should have noticed two obvious differences between the Li-ion and SLA batteries:

- their output voltage is very different - around 3.7V for the Li-ion cell compared to around 6.3V for the SLA battery;
- Li-ion cells have a much smaller internal resistance than the SLA batteries, allowing them to deliver huge power for their small volume.

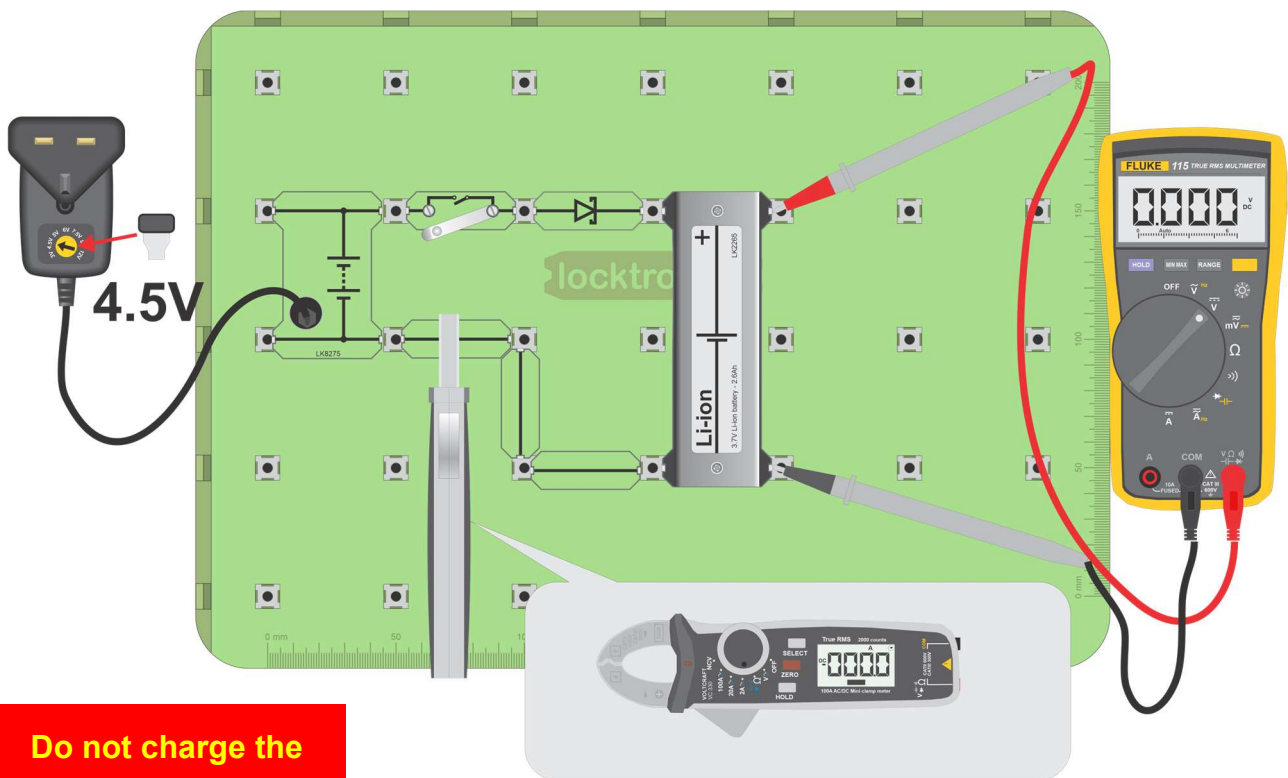
Worksheet 4

Charging Li-ion cells

Batteries convert chemical energy into electrical energy and vice-versa. They can be charged in a number of ways - slowly with a low current 'trickle' charge or quickly with a high current charge.

Charging time is becoming more important as the need to recharge cars mid-journey becomes a necessity.

The photograph shows a Tesla 2170 battery cell.



Do not charge the batteries above 4.2V

Over to you:

- Construct the circuit shown above.
- The circuit above delivers around 4.1V to the Li-ion battery. Check the voltage with your meter.

Caution: if you mistreat Li-ion batteries they can catch fire. Do not use any other charger than the one supplied with this kit and make sure you use the correct voltage and the Schottky diode in series.

Worksheet 4

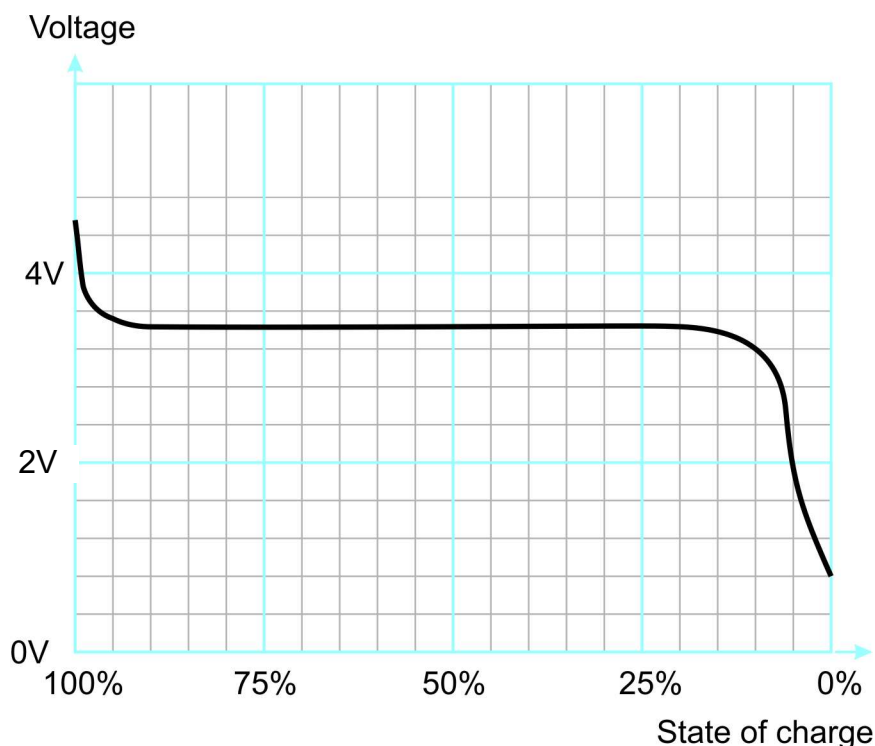
Charging Li-ion cells

Over to you continued...

- Measure the initial output voltage with the switch open.
- Close the switch.
- Measure the charging current from the power supply and battery voltage.
- After five minutes, note the output voltage and charging current again.
- Briefly, open the switch and measure the open-circuit voltage again.
- Close the switch and continue charging the battery.
- After ten minutes, and then after 15 minutes, repeat this process.
- Complete the table in the Student Handout with your measurements.

So what?

- The results depend on the state of charge of the cell.
- In general, the output voltage of a Li-ion cell varies less with SOC than it does for a SLA battery.
- The graph shows typical output voltage variation with SOC for Li-ion cells.
- At high SOC, the output voltage can be up to 4.5V.
- In the middle section, the curve is very flat at around 3.7V.
This makes it impossible to deduce the state of charge from voltage alone.
- The voltage really tails off in the last 10% of SOC.
In practice, we should not let Li-ion cells fall to below 20% of SOC.



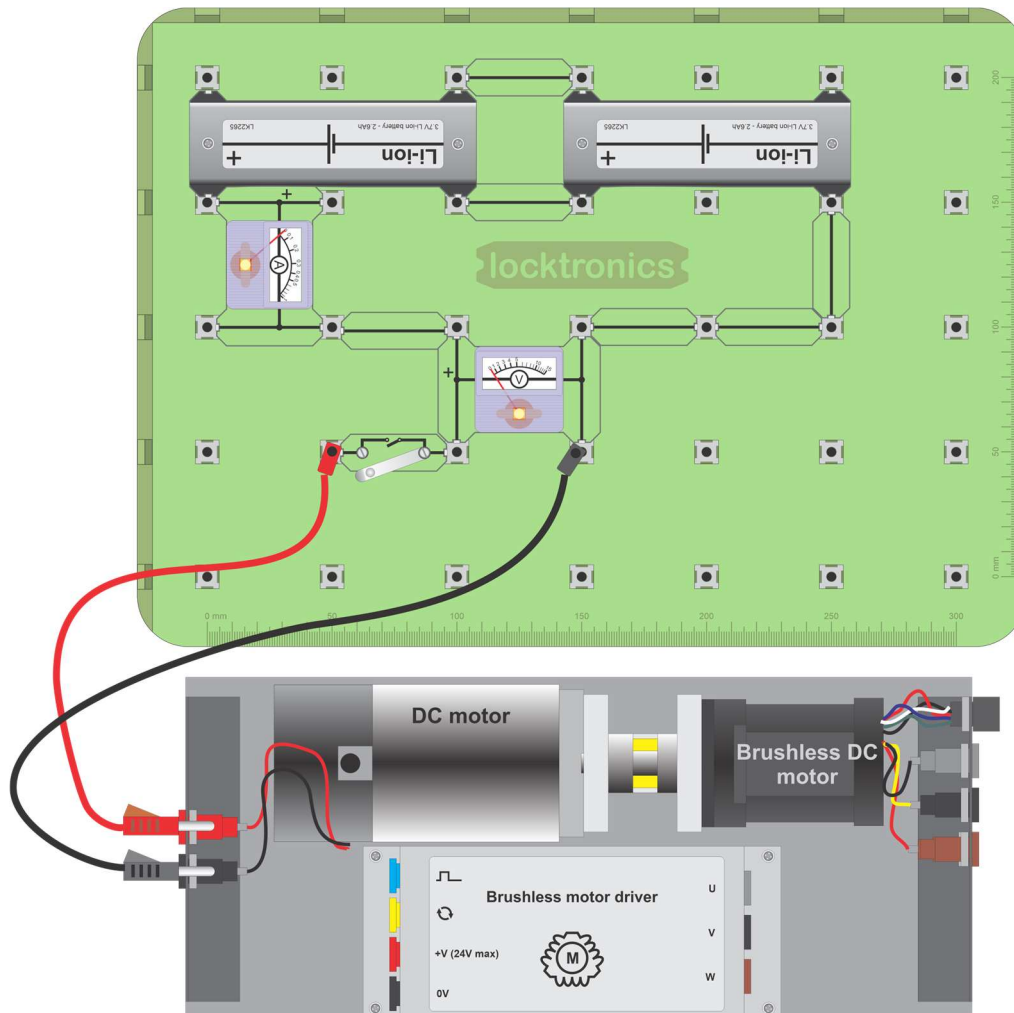
Worksheet 5

Building larger batteries

Larger batteries are made by connecting smaller batteries in series and / or parallel.

For example, a Tesla car battery is made up of 7,000 of the 18650 batteries like the one in your pack. The Tesla Powerwall uses the same batteries.

The photograph shows a Tesla powerwall.



Over to you:

- Using two 6V SLA batteries, build the layout shown above.
- Close the switch - the DC motor/Brushless motor coupled pair should rotate.
- Measure the battery output voltage and current and record them in the Student Handout.
- Calculate the power delivered to the motor.

Worksheet 5

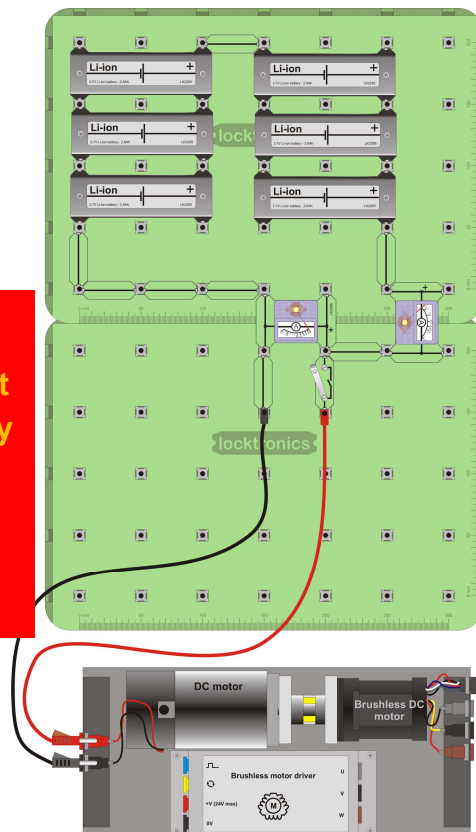
Building larger batteries

Try to match cells in parallel with others of a similar voltage: otherwise you just charge one cell with another.

Warning

Be careful to connect the cells the right way round!

Do not short-circuit them!



Over to you continued ...

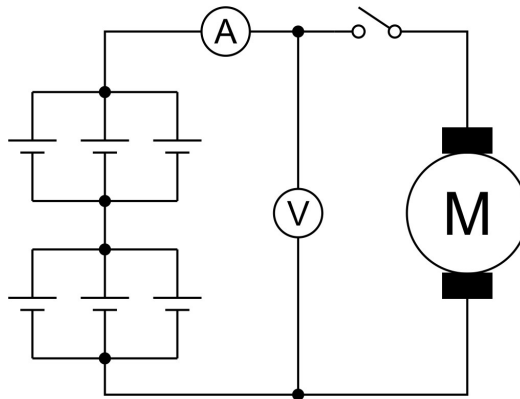
- Use six Li-ion cells, two sets of three, to build the battery shown above.
- Again, measure battery output voltage and current and calculate the power output.
- Record all your results in the Student Handout.

Worksheet 5

Building larger batteries

So what?

- The circuit you built is shown in the circuit diagram below. It is known as a '2 by 3' battery or, simply, a 2,3 battery, meaning that it is made up of two sets of three parallel cells, connected in series. The output voltage is twice the cell voltage, i.e. $2 \times 3.7V = 7.4V$.



- The following table shows you how to calculate the power rating of the larger battery:

Cell voltage	A	3.7	V
Individual cell current rating	B	2.6	Ah
Cells in parallel	C	3	
Groups of cells in series	D	2	
Combined power rating	$A \times B \times C \times D$	57.72	Wh

So what?

- Battery voltage and current capability can be changed by simply changing the number of batteries in series and parallel
- The Power rating of a battery is the voltage multiplied by the one hour current rating.
- Batteries are scalable. We can refer to a 2,3 battery as a 'module'. Then we can add other modules in series and parallel to build an even larger battery.

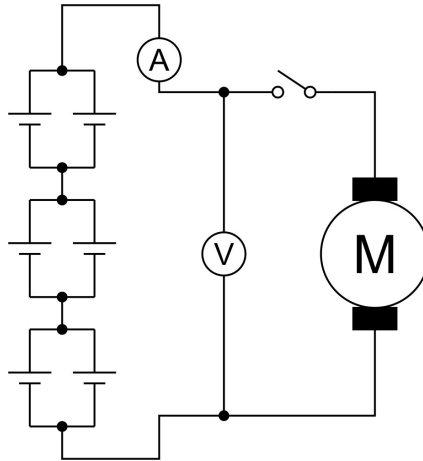
Warning - Be careful to connect the cells the right way round!

Worksheet 5

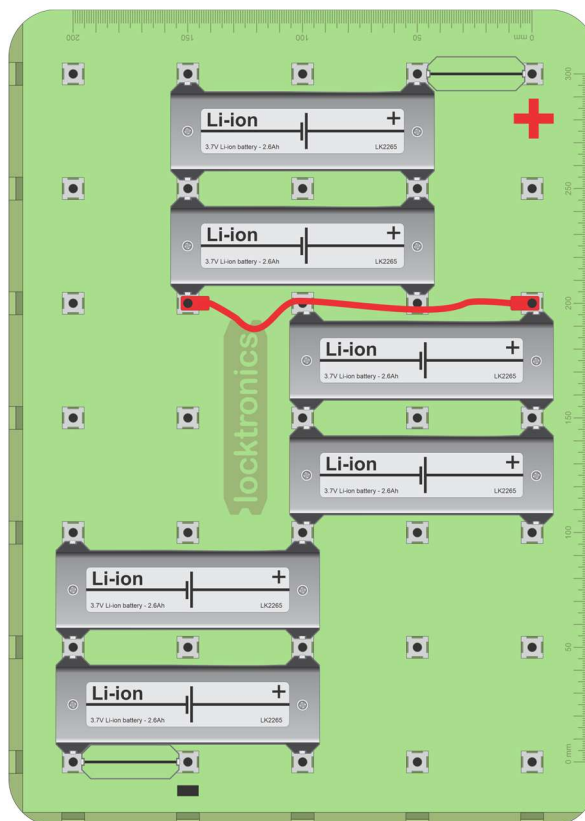
Building larger batteries

Challenge 1:

- Build the 3,2 battery module shown in the circuit below. You can use the diagram to help you.



- Measure the battery module output voltage and current and calculate the power delivered to the motor.
- Use the current clamp meter and multimeter to improve accuracy.
- Record all your results in the Student Handout.
- Calculate the power rating for the 3,2 battery using the table in the 2,3 calculation above.



A 3,2 battery module

Worksheet 5

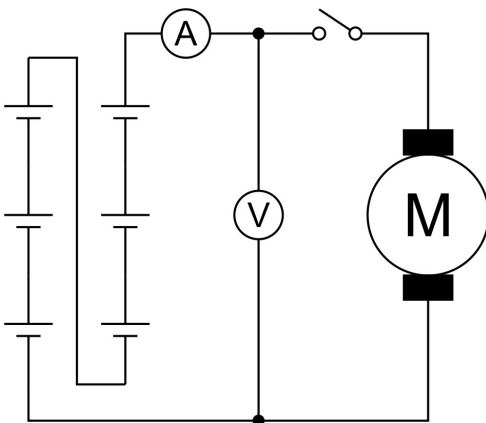
Building larger batteries

Challenge 2:

- Build the 6,1 battery module shown in the circuit below.

Warning - Be careful to connect the cells the right way round!

- Measure the battery output voltage and current and calculate the power delivered to the motor.
- Again, use the current clamp meter and multimeter to improve accuracy.
- Record all your results in the Student Handout.
- Calculate the power rating for the 6,1 battery



So what?

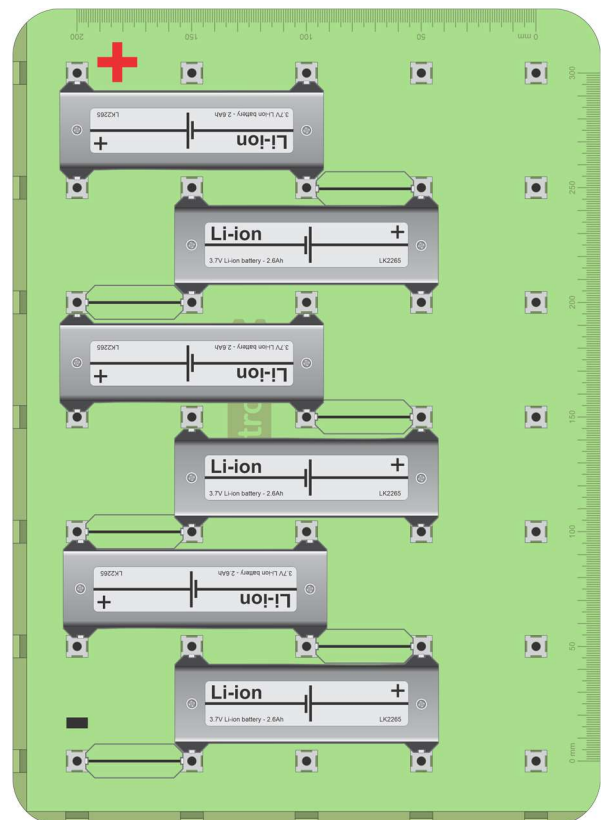
- You can build batteries with different output voltages, current and power capacities by varying the number of cells and their series / parallel configuration.
- You can keep the assembly in place as you will be using this for the next few experiments.

Challenge 3:

A Tesla model S battery pack contains 6,912 '16850' cells.

These are arranged in sixteen modules, or bricks, each containing 432 cells arranged with 72 cells in parallel, 6 groups of 72 batteries in series.

- What is the voltage of each brick?
- What is the total battery output voltage?
- What is the theoretical total power rating, in watt.hours, of the whole battery?
- Record your answers in the Student Handout.



Worksheet 6

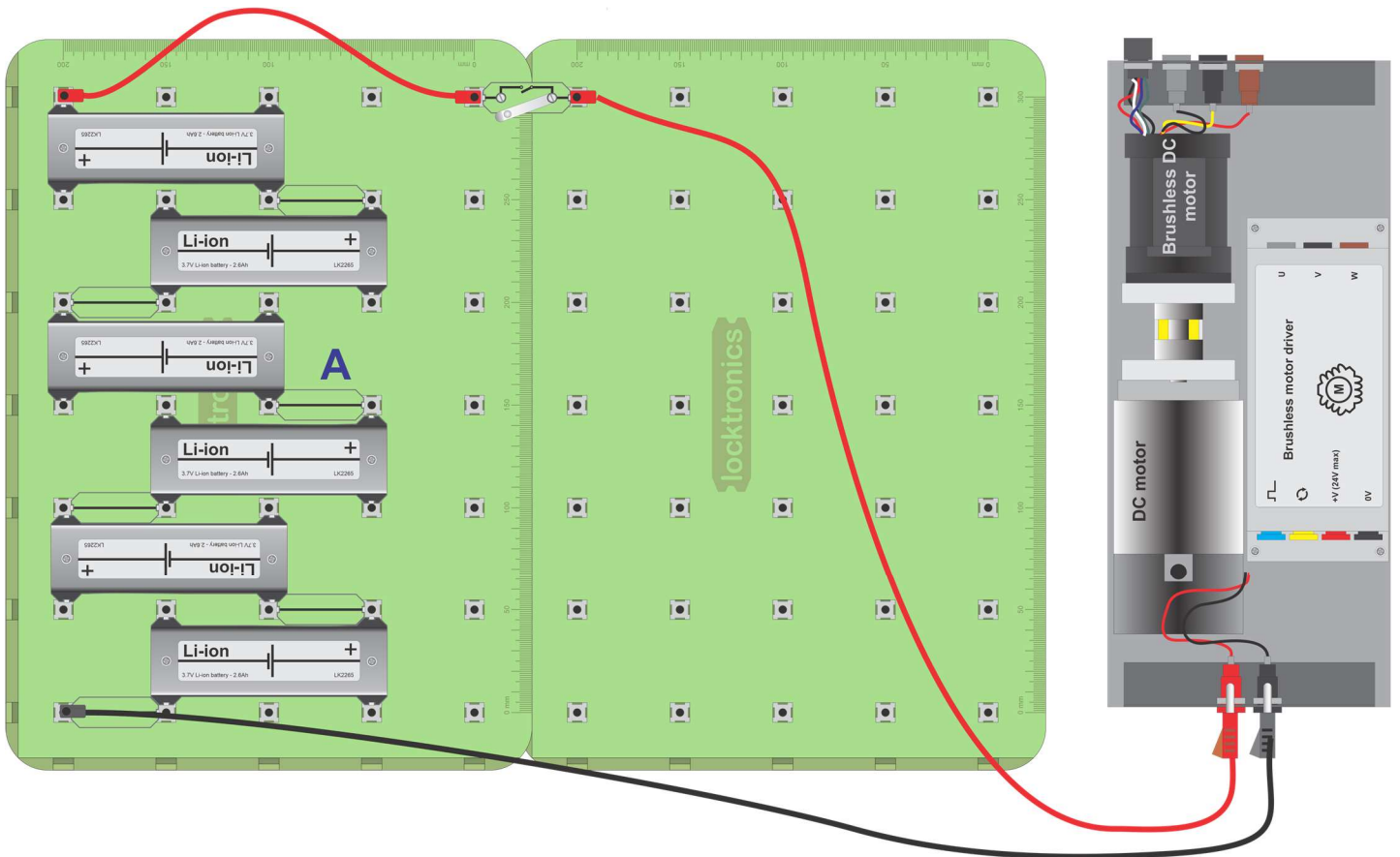
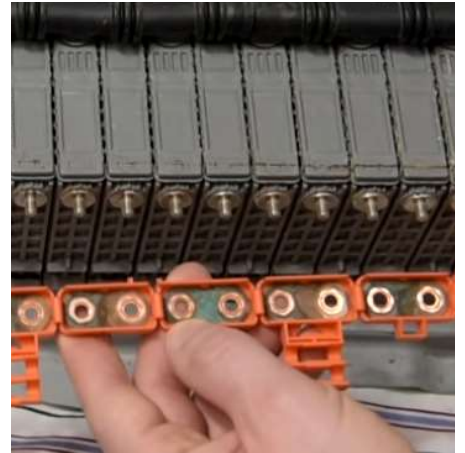
Li-ion battery faults

Resolving faults in battery packs is made easier by the reports (or clues) that on-board computers give.

There are two main causes of failure in a battery pack:

- bad cells;
- bad links between cells.

The photograph shows corrosion on the battery links in a Toyota Prius.



Over to you:

- Build the 6,1 battery as shown above but with the switch open for now.

Warning - Be careful to connect the cells the right way round!

- Measure the battery output voltage.
- Turn on the switch to power the motor.
- Measure the battery output voltage again.

Worksheet 6

Li-ion battery faults

Over to you continued ...

- Open the switch.
- Change the central link **A** for the fault component 'corrosion'.
- Measure the battery output voltage again.
- Turn on the switch to power the motor.
- Measure the battery output voltage again.
- Measure the voltage across the corrosion component.
- Record all your results in the Student Handout.

So what?

- The 'corrosion' component was used to simulate a fault. Corrosion on contact terminals adds resistance to the circuit. Bad or loose contacts can also behave like added resistance.
- Testing for corrosion or bad contacts is difficult in isolation. Battery voltages appear normal when tested with a multimeter. The effects are noticed only when a large current is drawn.
- In an electric vehicle, the battery management system constantly tests the voltage from battery cells.

Over to you:

- There are six Li-ion cells in your kit. The nominal output voltage for each is around 3.7V for SOC values between 15% and 90%.
- Measure the output voltage of each with a multimeter and record your results in the table in the Student Handout.
- If you see a voltage above 3.85V then the cell is likely to be in the top 5% of SOC. Discharge it for 10% of its SOC (see Appendix 3) and remeasure it.

So what?

- Battery voltages vary a great deal. In the case of the '18650' battery, the output voltage for a good cell can vary from 3.5 to 4V.
- An output voltage of below 3.5V for a charged Li-ion cell means that it is defective.

Worksheet 7

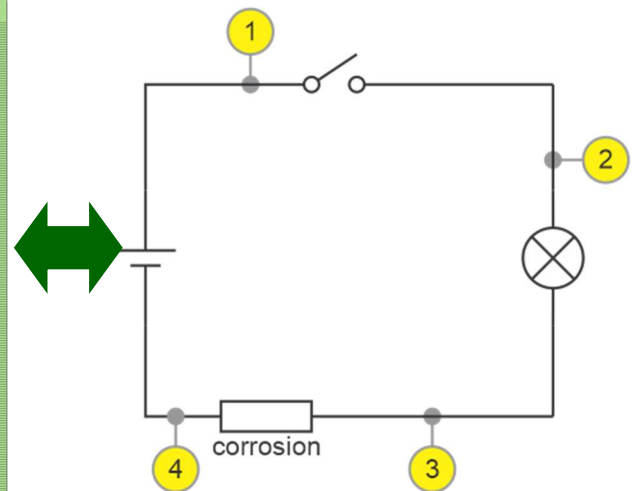
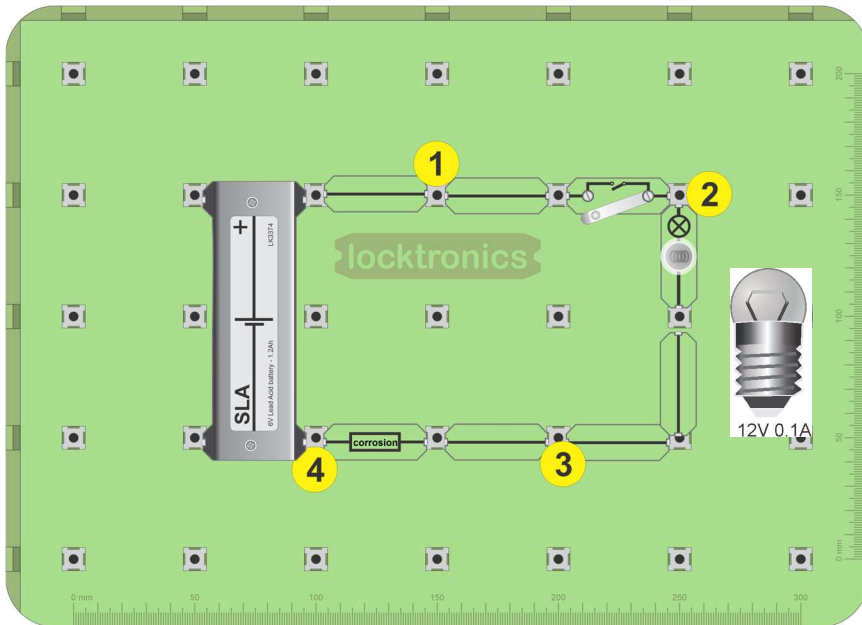
SLA battery faults

When chemicals from the battery leak onto the terminals, they can cause corrosion.

Corrosion on the negative terminal is often a sign of undercharging.

Corrosion on the positive side is often a sign of overcharging.

The photo shows a car battery with bad corrosion on one terminal.



Over to you:

- Build the layout shown above. It includes a 12V 0.1A filament lamp. The circuit diagram for this is shown alongside. The effect of corrosion is simulated by adding the 'corrosion' component in the earth path of the battery.

Worksheet 7

SLA battery faults

Over to you:

- Set up a multimeter to measure DC voltages.

Part 1:

- Connect the multimeter COMmon terminal to node 4.
- Measure the voltage across the battery, between nodes 4 and 1, with the switch open and then closed.
- Record the readings in the table in the Student Handout.

Part 2:

- Move the COMmon connection to node 3 .
- Measure the voltage across the battery between nodes 3 and 1, with the switch open and then closed again.
- Record the readings in the table in the Student Handout.
- Now answer questions 1 and 2.

Part 3:

- With the switch closed, measure the voltage dropped across the bulb.
- Open the switch and replace the 'corrosion' link with a normal link.
- With the switch closed, measure the voltage dropped across the bulb again.
- Record the readings in the table in the Student Handout and answer question 3.

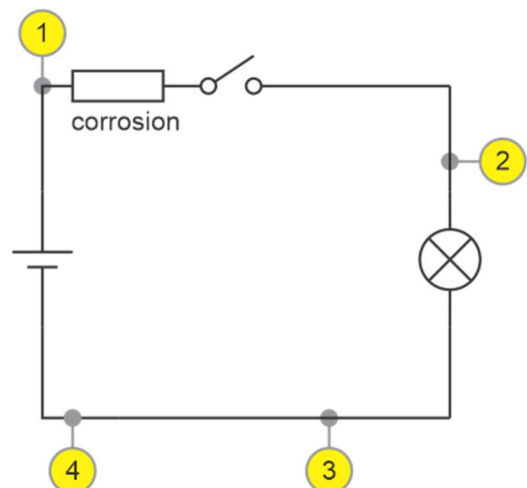
So what?

- Corrosion is the equivalent to a resistor in the circuit.
- You need to be careful about what you assume is the 0V line or earth.
- Always make sure you know what the exact battery voltage is.

If you know that the battery voltage is 12.7V and you see under 12V in a circuit then it could be a sign of problems.

Challenge:

- Build the circuit opposite, which has corrosion in the 6V line.
- Use a multimeter to investigate the effect of corrosion.
- Record the results of your investigation in the Student Handout.
Describe how you would check whether there is corrosion on the battery?



Worksheet 8

Battery management

Batteries are all different, physically and therefore electrically. That's the result of a manufacturing process which is not exact.

This raises problems that need managing by the electronics systems that supervise charging.

The photograph shows the insides of a Tesla Powerwall.



Over to you:

There are six Li-ion cells in your kit. The nominal voltage is around 3.7V for each, provided that the SOC is between 15% and 95%.

- Measure the output voltage of each with a multimeter and record your answers in the table in the Student Handout.
- If you see a voltage above 3.8V then that cell is likely to have a SOC above 95%. Discharge it until the SOC falls by around 10%, (see Appendix 3). Then measure its voltage again.

So what?

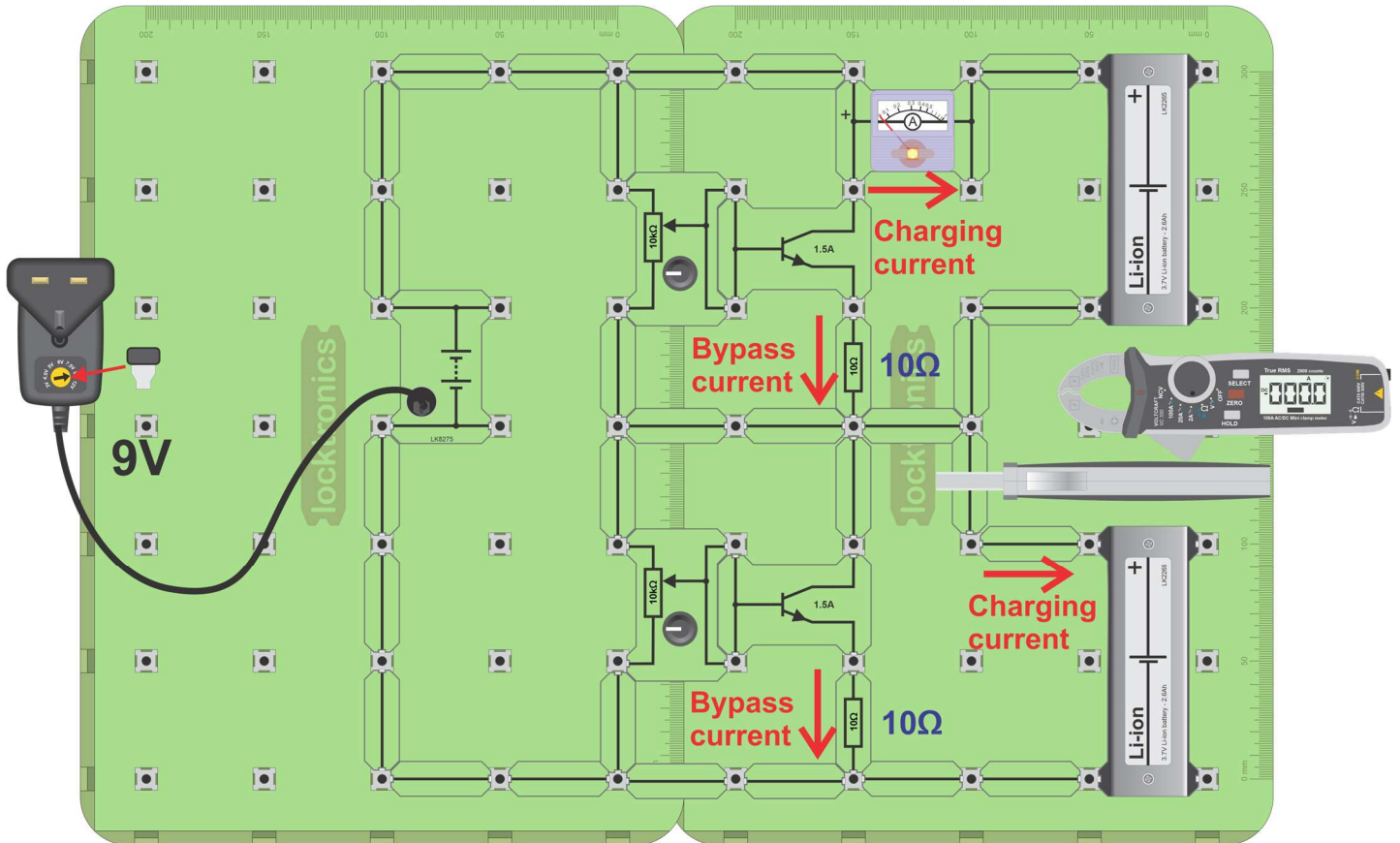
- The actual output voltage of a Li-ion '18650' cell will vary between 3.5 and 3.9V.
- Providing that it is properly charged, with a SOC between 5% and 95%, any cell with an output voltage outside this range can be assumed to be out of specification.
- One bad cell in a battery pack can affect the performance of the entire battery pack.
- Where it is necessary to charge many batteries connected in parallel, batteries of similar output voltages are chosen.

Over to you continued ...

- Select two cells from your collection, one with high voltage and one with low voltage.
- Note their voltages in the Student Handout.
- Build the circuit shown on the next page.
- Using the current clamp meter to monitor performance, adjust each potentiometer until the current charging each cell is 0.7A.
- Measure the bypass current in each circuit.

Worksheet 8

Battery management

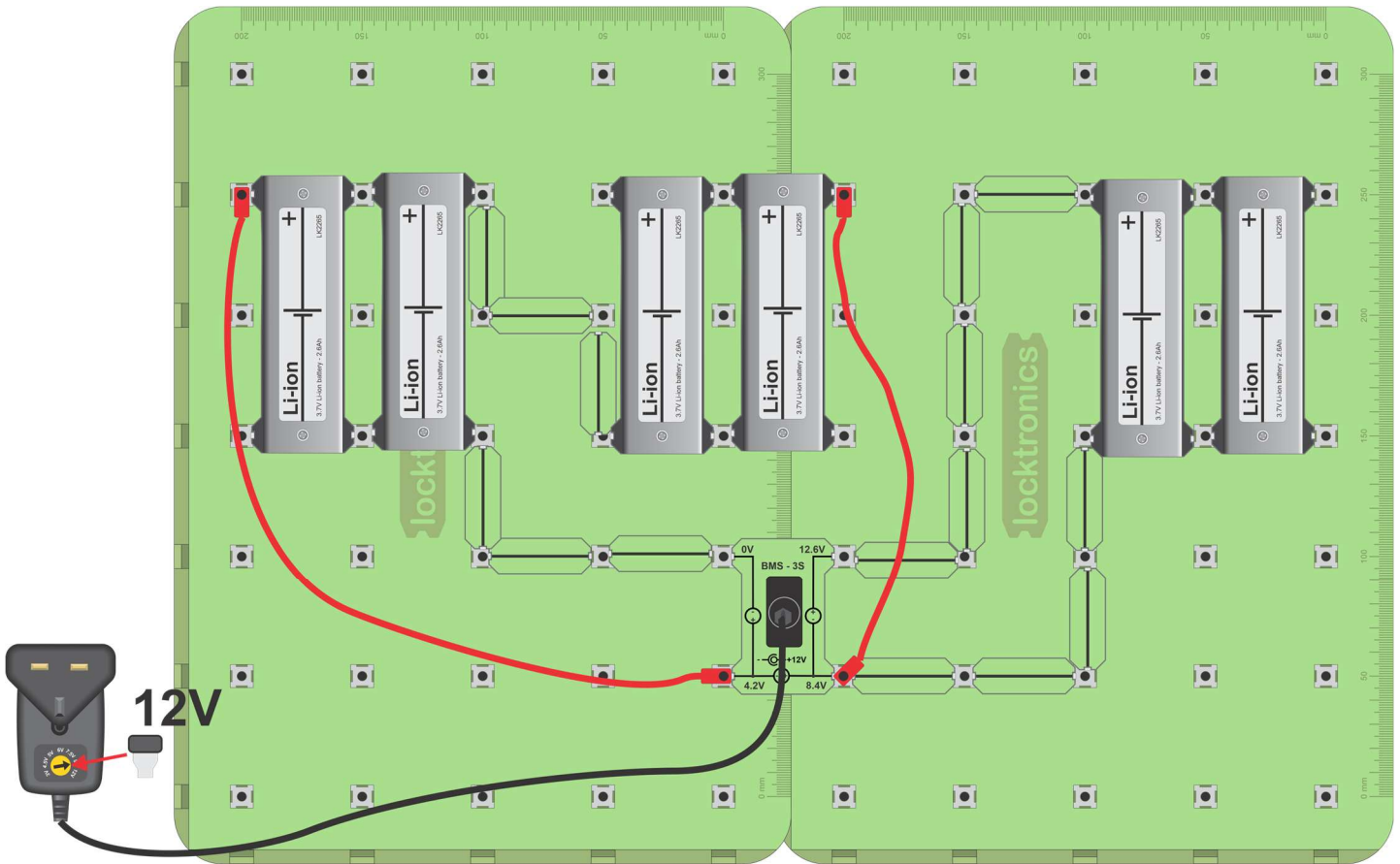


So what?

- This circuit allows you to vary the charging current for each cell.
- In a battery management system, a computer measures the voltage and current for each battery - or for each set of batteries in parallel.
The computer then uses a transistor to bypass current for batteries that are fully charged so that they do not overcharge.
- It then uses a similar circuit to vary the amount of current charging each battery to ensure that the batteries are not over or under charged.

Worksheet 8

Battery management



Over to you:

- Build the circuit shown above. The Battery Management System (BMS) allows you to charge three pairs of batteries together.
- Measure the voltage and current of each pair of batteries and make a note in the handout.

So what?

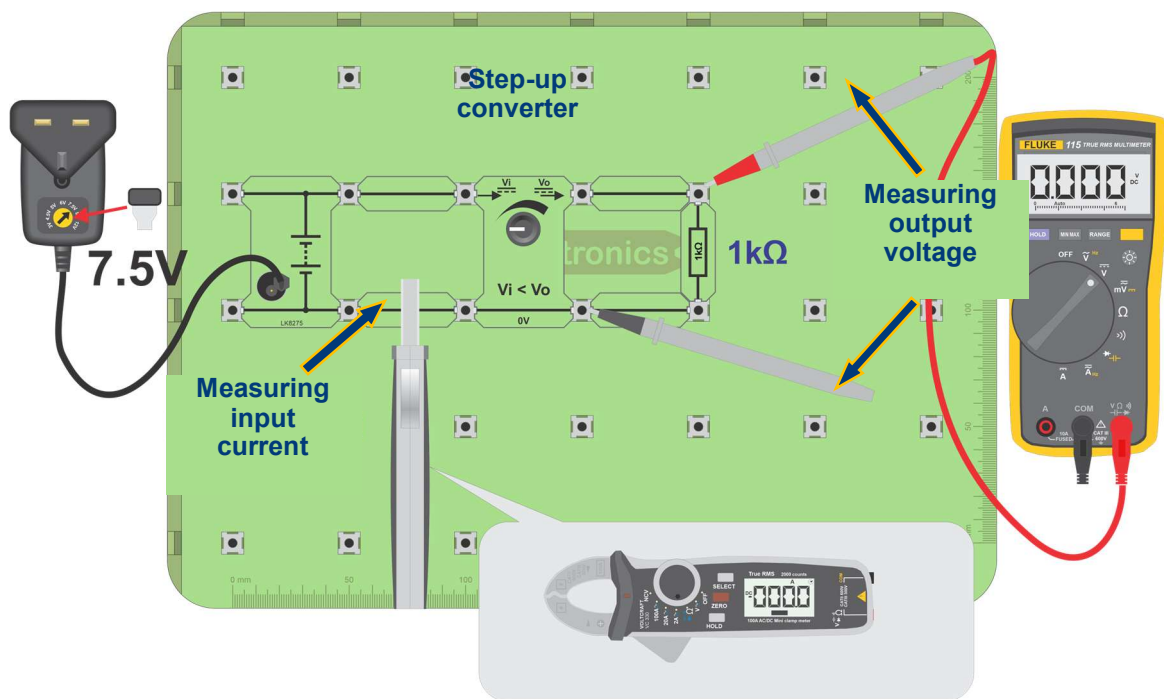
- Battery Management Systems vary in their complexity. The Locktronics BMS charges all batteries at the same rate until the voltage across one pair of batteries reaches 4.2V. Then it stops charging all batteries.
- This unsophisticated system is safe, but it does not allow all batteries to reach their maximum capacity.

Worksheet 9

Voltage converters

A key difficulty in green energy system is that wind turbines, solar panels, batteries and the energy grid all operate at different voltages. To get round this modern energy systems make use of voltage upconverters and down converters. These are blocks of electronics that efficiently convert one voltage to another.

The photograph shows a domestic solar panel inverter



Over to you:

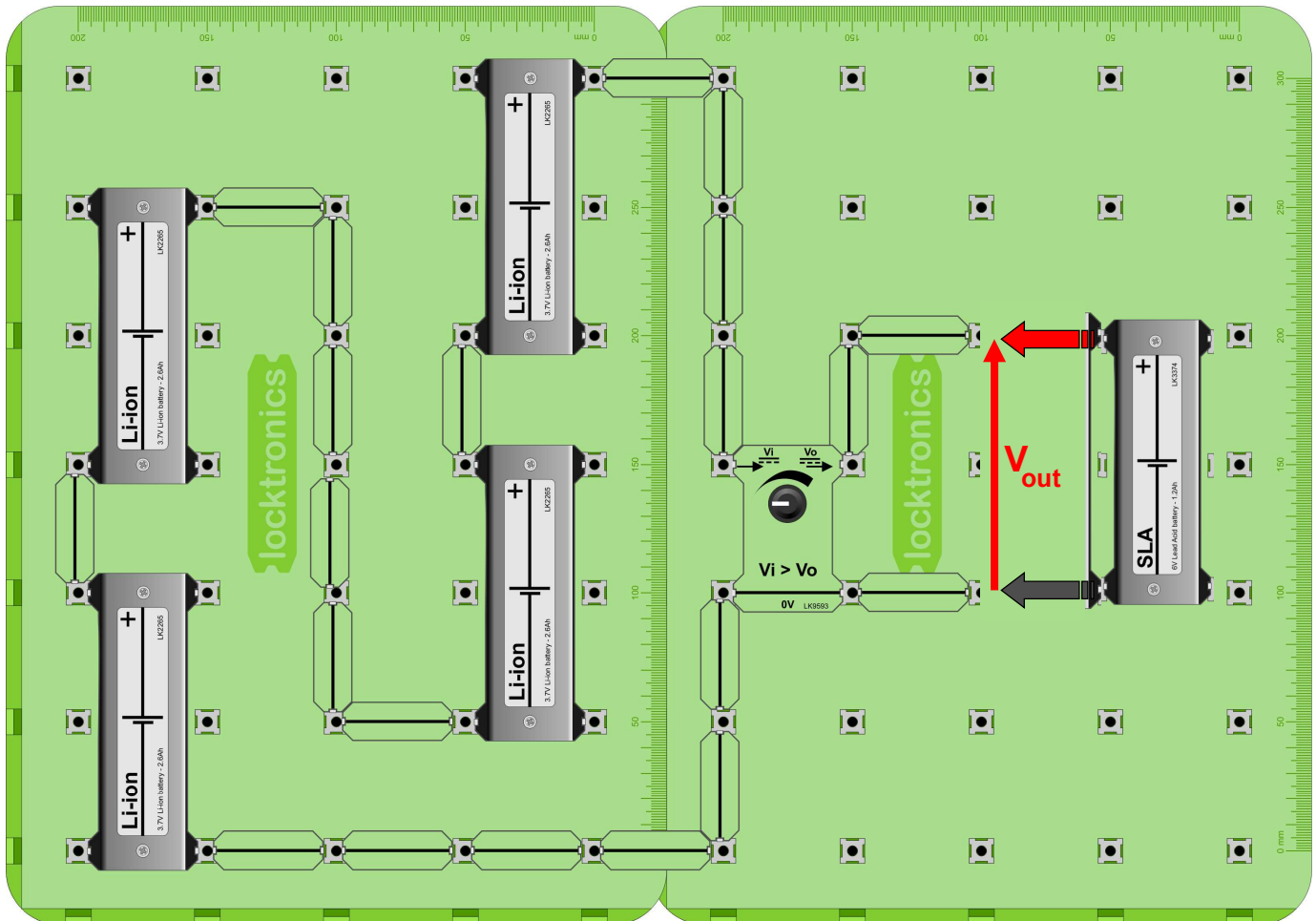
- Build the layout shown above.
The circuit converts the 7.5V output of the power supply to a voltage between 12V and 20V, depending on the position of the step-up converter potentiometer.
- Rotate the potentiometer fully anti-clockwise.
- Use the multimeter to measure the input and output voltages of the step-up converter.
- Use the current clamp-meter to measure input and output currents of the step-up converter.
- Rotate the potentiometer half way round and measure the same quantities again.
- Then do the same when the potentiometer is rotated fully clockwise.
- Calculate the power in and out of the step-up converter for all three positions.

Worksheet 9

Voltage converters

So what?

A 'DC-to-DC converter' or 'inverter' converts one DC voltage to another and can reverse its polarity. The voltage conversion inevitably includes a loss of energy, i.e. an efficiency of less than 1. This circuit has high losses. In domestic installations, the loss would be less than 5%.



Over to you:

- Build the circuit shown above using four Li-ion cells in series.

Warning - Be careful to connect the cells the right way round!

- Adjust the potentiometer in the step down-converter so that its output voltage, V_{OUT} , is 7V.
- Now connect a single SLA battery to the output.
- This circuit converts the 15V or so output of the Li-ion battery to a voltage suitable for charging the SLA battery. In the same way as before, take measurements to allow you to calculate the power in and out of the step-down converter.
- Hence, calculate the efficiency of the step-down converter.

So what?

- Modern electric systems make use of upconverters and downconverters.
- In every stage efficiency of conversion of energy is less than 100%.

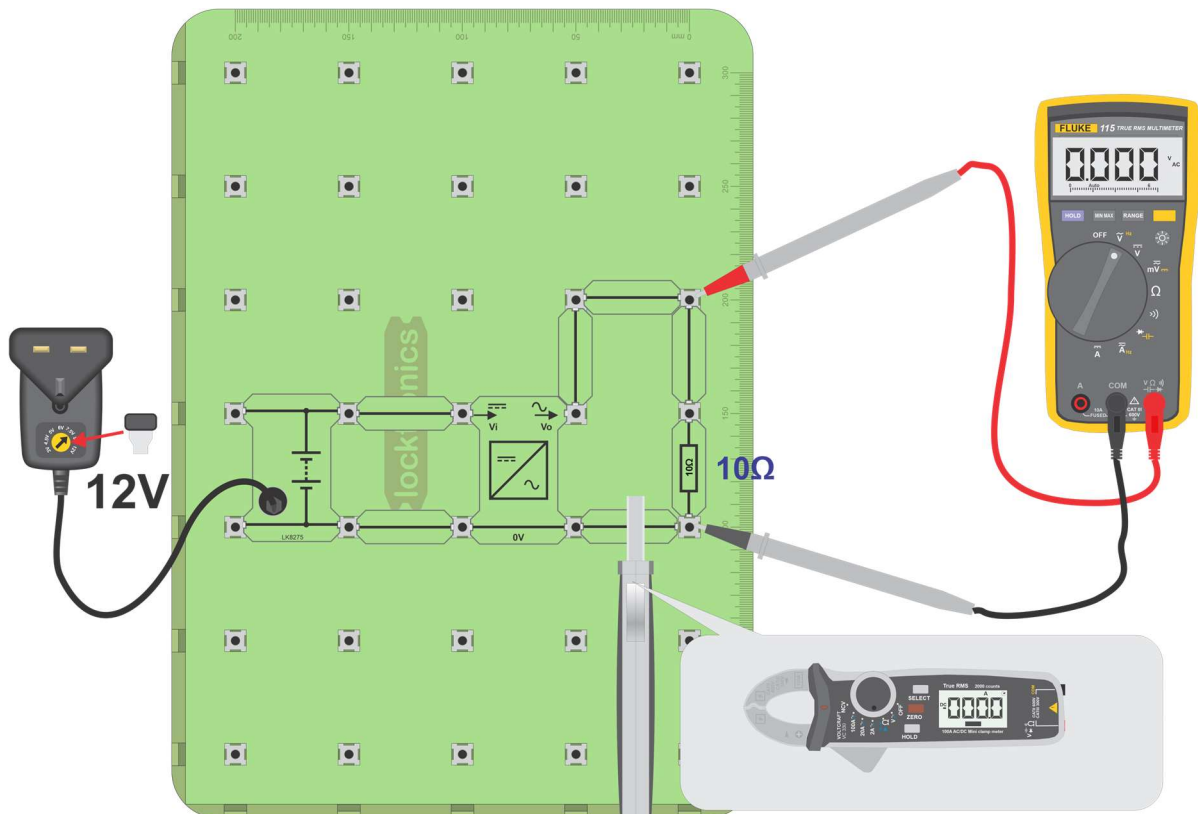
Worksheet 10

Voltage inverters

Solar panels give out direct current (DC) energy. The electricity from a wind turbine is converted from three phase Alternating Current (AC) to DC by the bridge rectifier. The power from the electricity grid is AC and most domestic appliances use AC. What is needed is a unit that converts DC to AC - the inverter.



The photograph shows a 24V DC to 240V AC inverter.



Over to you:

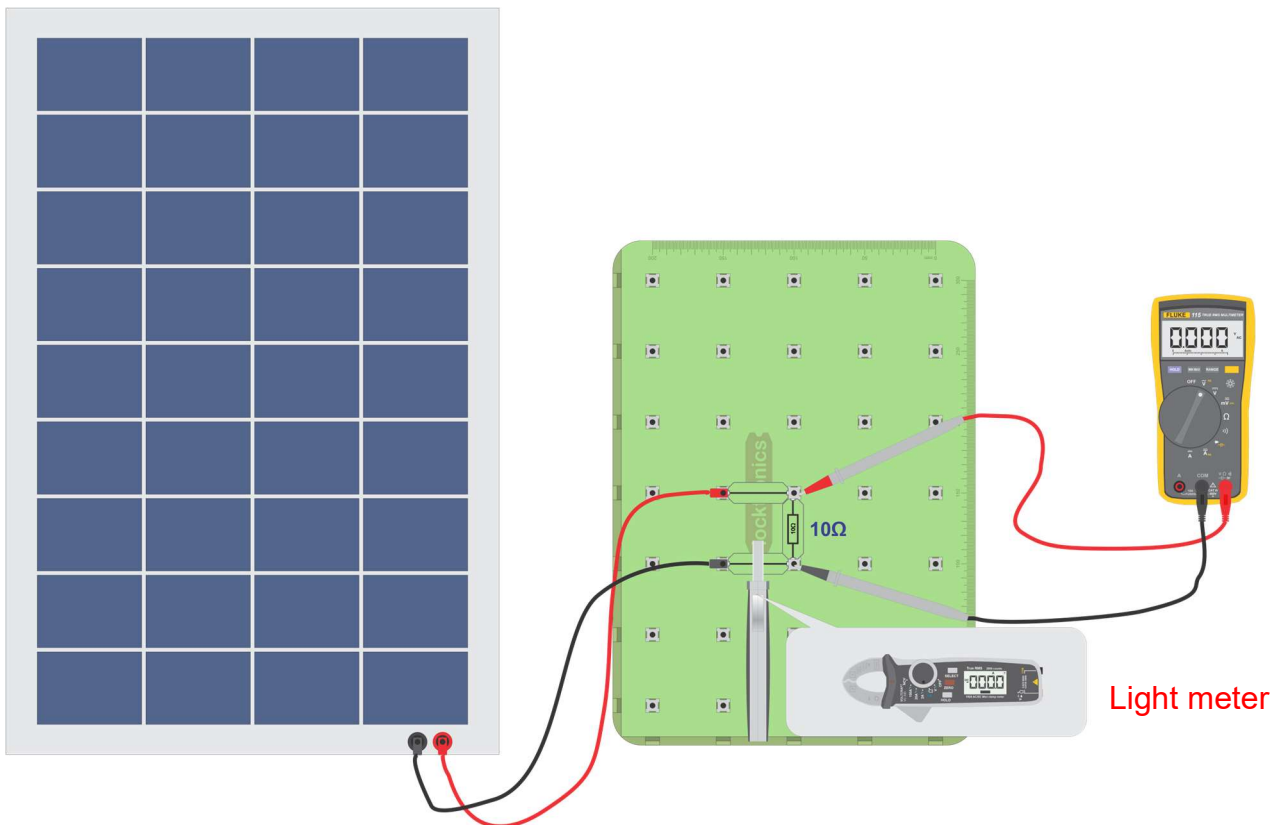
- Build the layout shown above.
The circuit converts the 12V power supply output to AC.
- Use the multimeter to measure the input and output voltages of the inverter.
- Use the current clamp-meter to measure input and output currents of the inverter.
- Calculate the power in and out of the inverter.
- Look at the output on an oscilloscope. What frequency does it produce?
- What is the efficiency of modern domestic 240VAC inverters?

Worksheet 11

Solar panels

Solar panels give out direct current (DC) energy. Like batteries the voltage and current that a bank of panels produces can be customised by wiring them in series and in parallel. To be useful they need to integrate into the AC network in the home or office.

The photograph shows a domestic solar panel installation.



Over to you:

- Build the layout shown above. This is simply the solar panel feeding a 10ohm resistor.
- Use the light meter, the current clamp meter and the multimeter to investigate the performance of the solar panel.
- Fill in the table below with your findings.

Worksheet 11

Solar panels

Inside

Make the following measurement of the solar panel's performance by measuring the luminous flux per unit area (lux), the voltage and the current produced in each situation

- With the solar panel in the lab, flat on the bench,
- With the solar panel facing the window
- With the solar panel outside flat on the floor
- With the solar panel at 90 degrees to the Sun's rays.

	Luminous flux (lux)	Voltage (V)	Current (I)	Power (W)
On the bench				
Facing the window				
Outside				
Outside at 90 degrees to sun's rays				

So what?

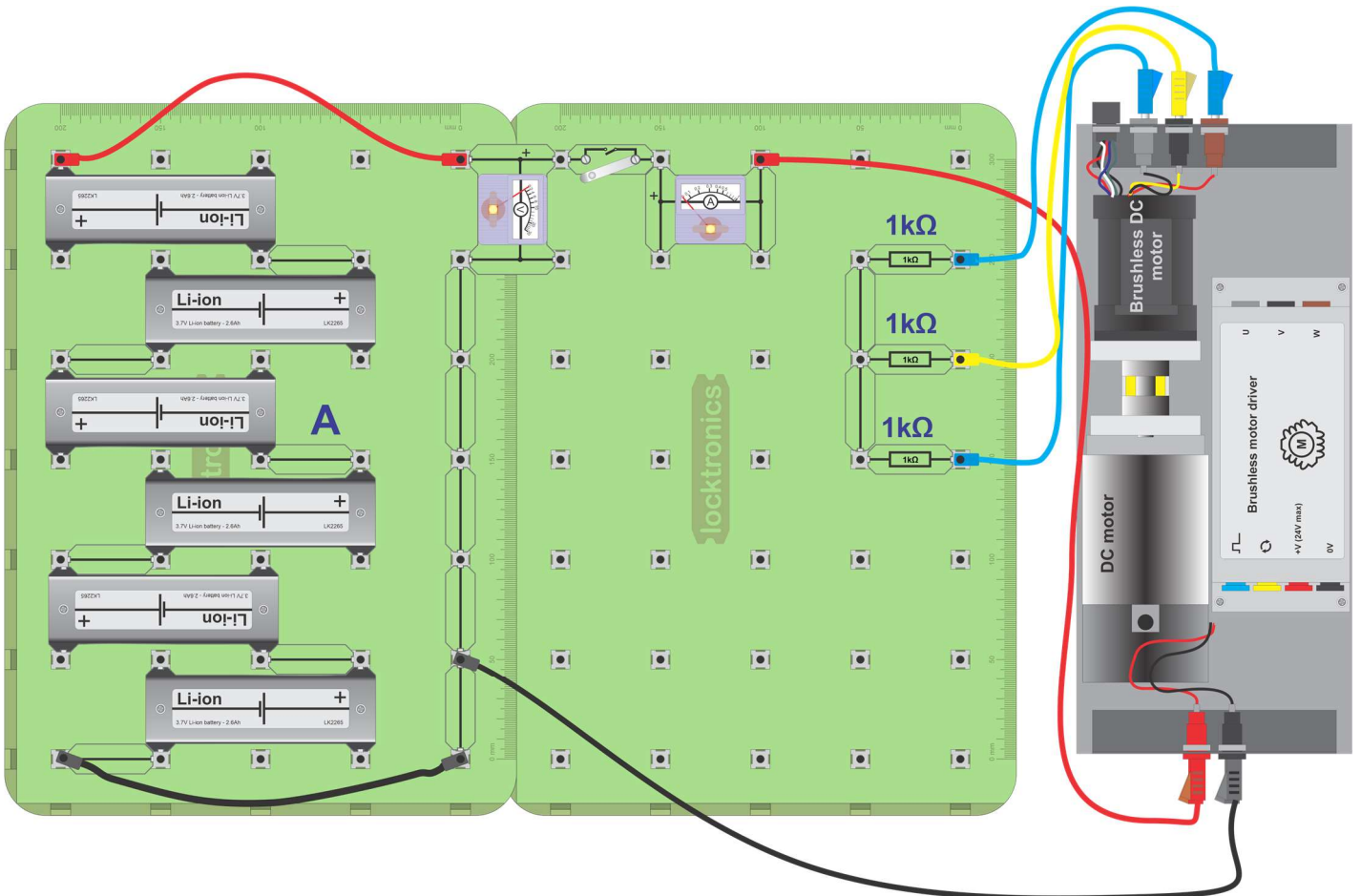
- Solar panels generate electricity by converting light energy to electrical energy.
- The factors that affect the amount of energy are the light intensity and the angle of the light on the panel surface.
- Our eyes are not always good at resolving the amount of light energy around us.
- The panels are optimised for sunlight.
- Sunlight has much greater energy than room lighting.
- To get a really good performance from the panel you will need to be outdoors

Worksheet 12

Wind turbines

Wind turbines are actually three-phase AC generators. Smaller turbines use a permanent magnet rotor and a three phase wound stator to produce electricity. Three phase is used because it is more energy efficient than single phase.

Photograph shows a small three phase wind turbine with nacelle and blades removed.



Over to you:

- Build the circuit shown above. Here we are powering the three phase generator with 24V.

Warning - Be careful to connect the cells the right way round!

Wind turbines

Over to you continued ...

- Use an oscilloscope to look at the waveforms coming from the three-phase generator. Your oscilloscope probably has only two inputs. To see the relative timing of the three waveforms, keep one waveform on channel 1 all the time and use channel 2 to examine the other two waveforms, in turn.

Connect the oscilloscope probe across one of the 1kΩ resistors with the ground connection of the oscilloscope attached to the connecting links.

Oscilloscope settings:

Timebase - 10ms/div

Voltage range - ±10V DC

Trigger mode - Auto

Trigger channel - ch A

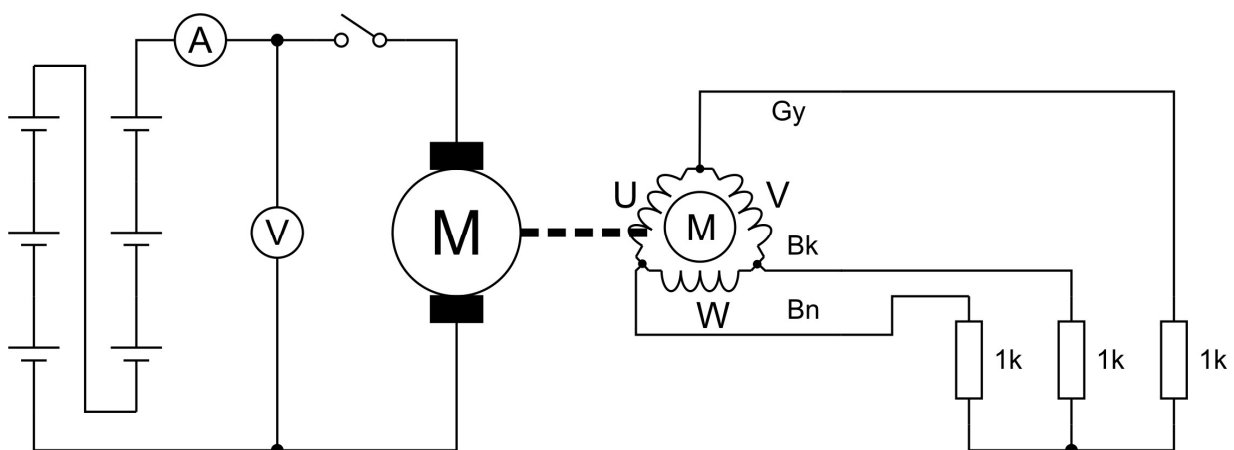
Trigger direction - Rising

Trigger threshold - 5V

- Use the axes provided in the Student Handout to sketch the waveforms across the three resistors.
- Reduce the supply voltage to the DC motor by using just three Li-ion batteries.
- Sketch one of the waveforms again.

So what?

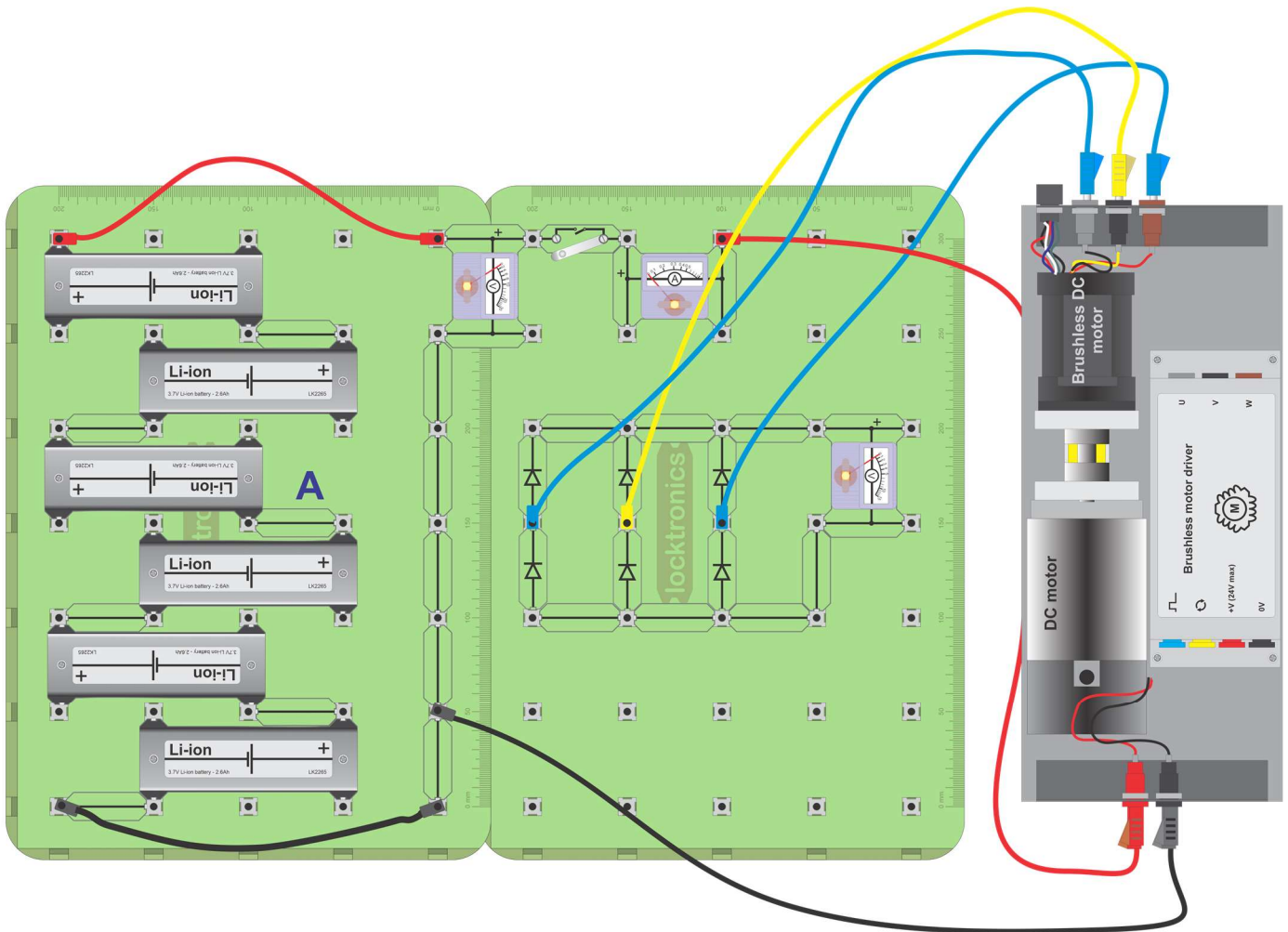
- The three-phase outputs all have different timings on the oscilloscope. The windings in the three-phase generator are spaced 120° apart. The peaks of the waveforms occur spaced at 33% of the time period of the waveform. Hence we say that “the waveforms are 120° apart”.
- The output of the three-phase generator depends on the speed of the DC motor.



You built the circuit shown in the diagram above. In reality, it is two separate circuits. Each has its own earth or ground. They are not connected and can be at different voltages.

Worksheet 13

Three-phase rectifiers



Over to you:

- Build the circuit shown above.

Warning - Be careful to connect the cells the right way round!

- Use an oscilloscope to look at the waveforms coming from the three-phase generator.

Oscilloscope settings:

Timebase -10ms/div

Voltage range - $\pm 10V$ DC

Trigger mode - Auto

Trigger channel - ch A

Trigger direction - Rising

Trigger threshold - 5V

- Use the axes provided in the Student Handout to sketch the waveforms across the banks of diodes.

Worksheet 13

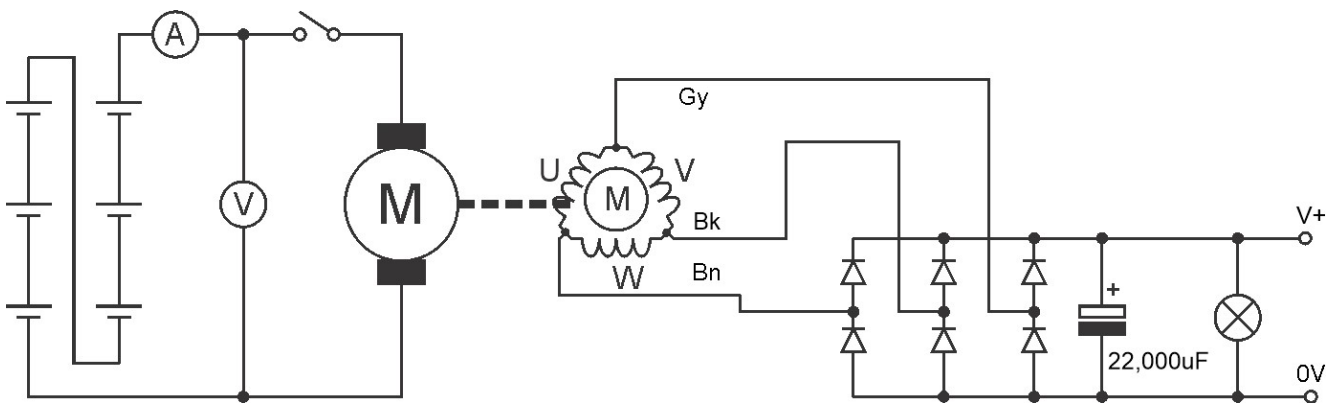
Three-phase rectifiers

So what?

- The diodes rectify the three phase voltage signal into a single DC waveform.
- The DC waveform has some ripple on it. When the output of a bridge like this is connected to a battery, the battery removes the ripple.

Over to you:

- Add a large 2200 μ F capacitor to the rectifier output.
- Connect a LED bulb across the rectifier output. The circuit looks like the one below.



- Close the switch and run the DC motor.
- Open the switch to stop the DC motor.
- How long does the bulb stay lit?
- With a multimeter on DC voltage setting, measure the **initial** voltage between the two earths - this voltage will decline rapidly.

So what?

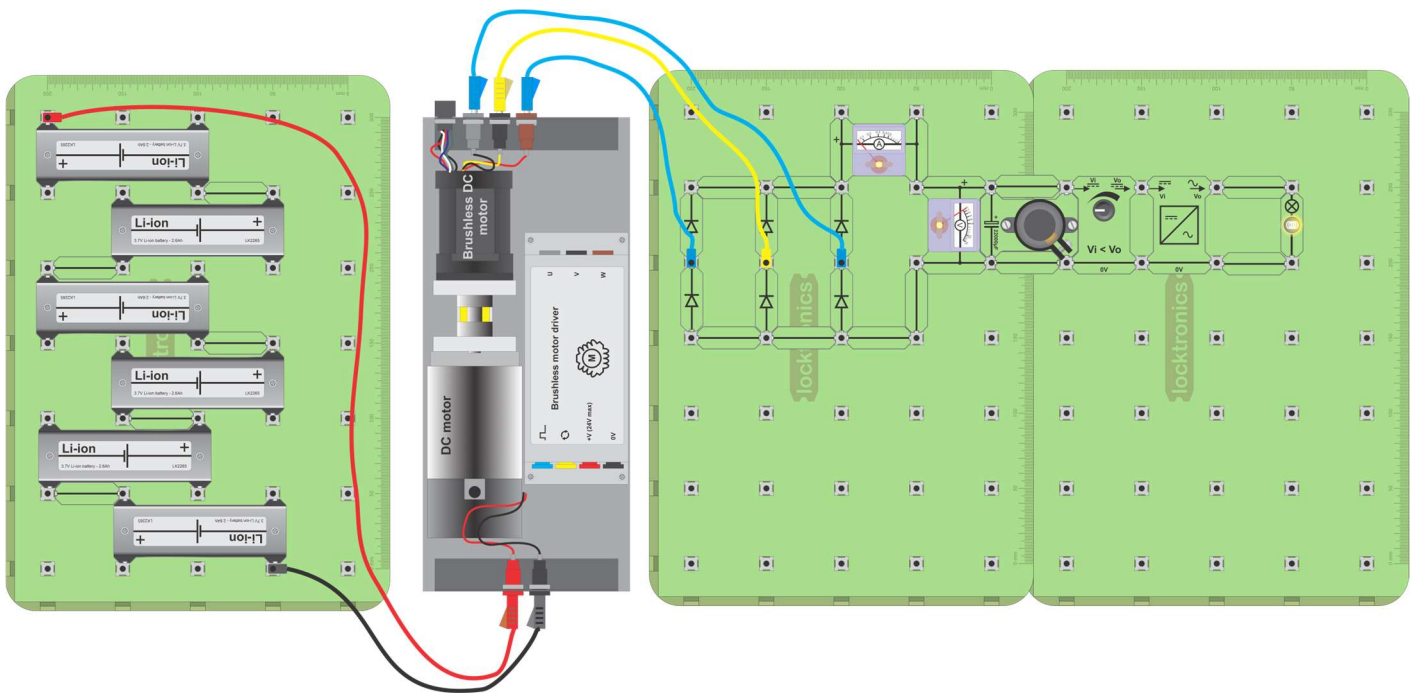
- The capacitor is discharging because of only one LED bulb. Without that in place it would stay charged for much longer.
- You need to be very careful of capacitors in the high voltage side of electric vehicles - even when batteries are removed they may still contain enough charge to kill.
- There is no electrical link between the ground of each side of the circuit. That means there could be a significant voltage between the two grounds.

Worksheet 14

Using wind power to provide AC

The output from wind turbines varies in amplitude and frequency - we can't just connect it to the domestic AC system. First we rectify it to DC, then smooth it with a large capacitor, then we use an upconverter or downconverter to regulate its voltage, then we create AC. In practice each module is computer controlled with a feedback system to cater for variations in output.

The photograph shows a small domestic wind turbine.

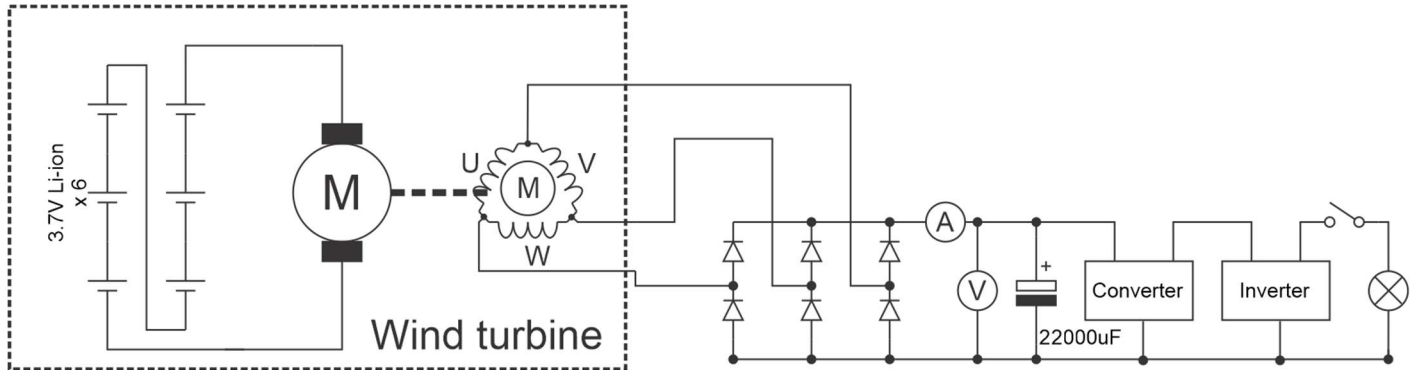


Over to you:

- Build the layout shown above. The six Li-ion batteries produce around 24V when charged. This powers a DC motor mechanically coupled to a brushless DC motor which makes three phase electricity. You can vary the speed of the DC motor / brushless DC motor by tapping into the battery chain at different points.
- This battery/DC motor / brushless DC motor allows you to mimic the action of a wind turbine.
- You should get around 6V RMS across the large capacitor.
- Adjust the potentiometer on the voltage upconverter until current starts to flow. This should be when the DC output from the upconverter is around 12V.

Worksheet 14

Using wind power to provide AC



So what?

The diagram above shows you the schematic of your system

To create AC the voltage needs to first be rectified, then regulated to a set voltage, then inverted to AC.

Over to you:

Calculate the efficiency of the system at each stage:

- Power in to the motor DCV in DCI in
- Power generated after the rectifier ACV AC I
- Power into and out of the voltage converter DC Vin DC I in DC Vout DC I out
- Power into and out of the inverter. DC Vin DC I in AC Vout AC I out

Research what typical efficiencies you would find in commercial units.

When you switch the bulb on what happens to the speed of the motor generator pair?

So what?

There are losses at each stage in the energy conversion.

The losses in commercial systems will be lower than in this system.

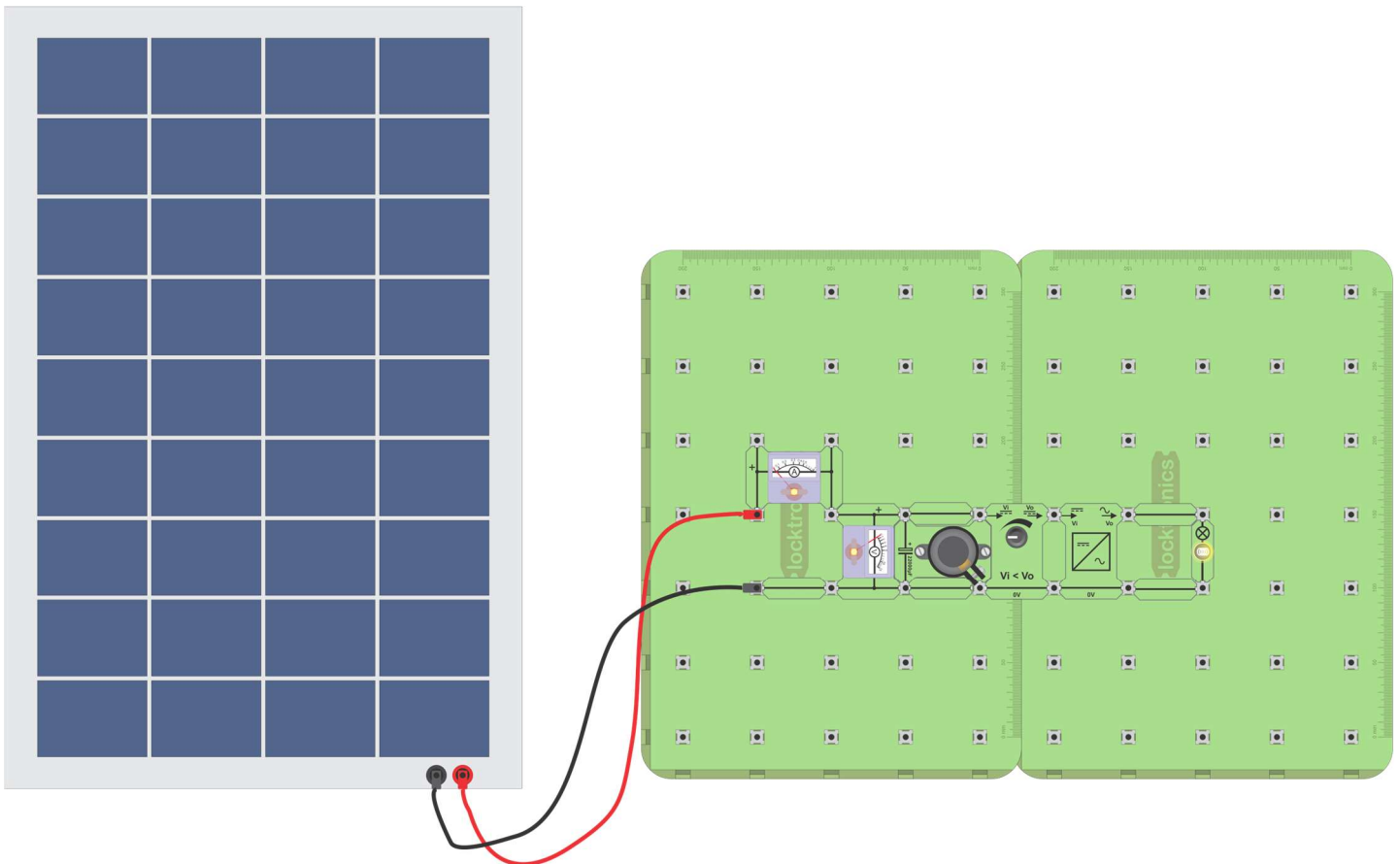
Putting an electrical load on the system puts a mechanical load on the motor generator pair which slows it down. A significant problem for wind farms is that in high winds the rotating speed of the windmills needs to be slowed down by having a load on the electrical system at all times - even when energy is not needed. Dumping this excess electricity is a significant problem for wind energy generating companies.

Worksheet 15

Using solar power to provide AC

The output from solar panels is DC. It varies depending on the brightness of the sun, the angle of the incident rays on the surface of the panels, and the time of day. The DC energy is first passed to a DC to DC converter and then to a DC to AC inverter before the energy can be distributed in the home or through the electricity grid.

The photograph shows a solar farm with power management units.

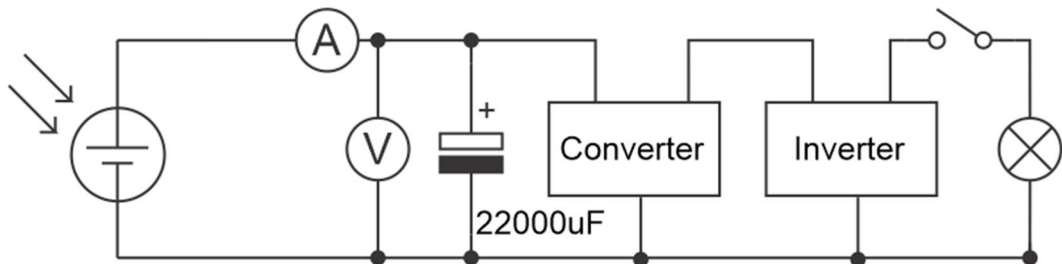


Over to you:

- Build the layout shown above. The solar panel will produce around **12V at 0.5 Amps** (6 watts) when in reasonably bright light. You will need to place the panel outdoors to achieve this level of power - indoor lights will not produce enough electricity.
- You will get around **12V** across the large capacitor.
- Adjust the potentiometer on the upconverter until current starts to flow. This should be when the DC output from the upconverter is around 12V.

Worksheet 15

Using solar power to provide AC



So what?

The diagram above shows you the schematic of your system

To create AC the voltage needs to first be regulated to a set voltage, then inverted to AC.

Over to you:

Calculate the efficiency of the system at each stage:

- Power into and out of the voltage converter DC V_{in} DC I_{in} DC V_{out} DC I_{out}
- Power into and out of the inverter. DC V_{in} DC I_{in} AC V_{out} AC I_{out}

Research what typical efficiencies you would find in commercial units.

So what?

Solar power has fewer problems than wind power. It is cheaper to install and maintain in term of cost per kilowatt hour generated.

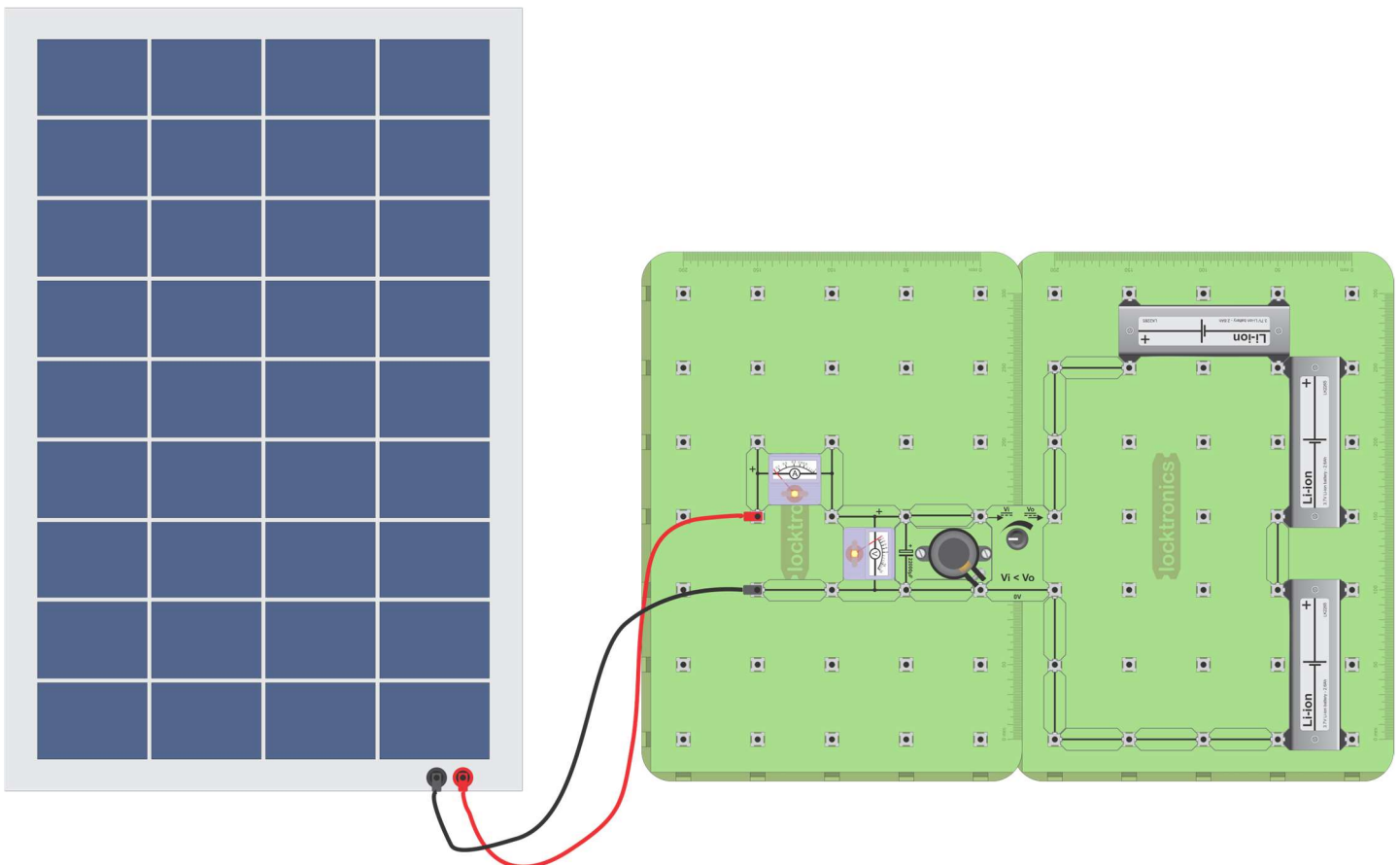
But it does not generate much electricity at night.

Worksheet 16

Using solar power to charge batteries

Solar and wind power have one significant problem: the output varies so much in any one day and from day to day. We can get round that by storing energy in batteries. This means that we need to use an inverter to convert the voltage from the solar panel to a suitable voltage for the battery pack.

The photograph shows one of Tesla's power banks in Australia.



Over to you:

- Build the layout shown above. The solar panel will produce around **12V at 0.5 Amps** (6 watts) when in reasonably bright light. You will need to place the panel outdoors to achieve this level of power - indoor lights will not produce enough electricity.
- You will get around **12V** across the large capacitor.
- Adjust the potentiometer on the upconverter until current starts to flow. This should be when the DC output from the upconverter is around 11V.

Student Handout

Worksheet 1 - Testing Sealed Lead-Acid batteries

Effect of load on output voltage:

Switches closed	None	1st only	1st and 2nd	1st, 2nd and 3rd
Battery voltage				
Total current	0			

Effect of discharge time on output voltage:

Time in mins	0	5	10	15
Battery voltage				
Battery current				

Worksheet 2 - Charging SLA batteries

Time in mins	0	5	10	15
Battery voltage	N/A			
Battery current				
Battery voltage open-circuit				

Worksheet 3 - Testing Li-ion batteries

Effect of load on output voltage:

Switches closed	None	1st only	1st and 2nd	1st, 2nd and 3rd
Battery voltage				
Total current	0			

Worksheet 4 - Charging Li-ion batteries

Time in mins	0	5	10	15
Battery voltage	N/A			
Battery current				
Battery voltage open-circuit				

For two Li-ion batteries in series:

Initial charging current = A

Voltage across battery 1 =V

Voltage across battery 2 =V

Worksheet 5 - Building larger batteries

Two 6V SLA batteries in series:

Voltage (V)	Current (A)	Power delivered (W)

Six Li-ion cells in a 2,3 battery:

Voltage (V)	Current (A)	Power delivered (W)

Challenge 1: six Li-ion cells in a 3,2 battery:

Voltage (V)	Current (A)	Power delivered (W)

Cell voltage	A	3.7	V
Individual cell current rating	B		Ah
Cells in parallel	C		
Groups of cells in series	D		
Combined power rating	$A \times B \times C \times D$		Wh

Challenge 2: six Li-ion cells in a 6,1 battery:

Voltage (V)	Current	Power delivered

Cell voltage	A	3.7	V
Individual cell current rating	B		Ah
Cells in parallel	C		
Groups of cells in series	D		
Combined power rating	$A \times B \times C \times D$		Wh

Challenge 3: Tesla model S battery

For one brick:

Cell voltage	A		V
Individual cell current rating	B		Ah
Cells in parallel	C		
Cells in series	D		
Combined power rating	$A \times B \times C \times D$		Wh

For 16 bricks the total power rating is 16 times this number or 66.5kWh.

Worksheet 6 - Li-ion battery faults

No load output voltage: _____

Output voltage when connected to motor: _____

Output voltage with corrosion at point A _____

Output voltage with corrosion at point A - with load _____

Voltage across the corrosion component _____

Battery 1 (V)	Battery 2 (V)	Battery 3 (V)	Battery 4 (V)	Battery 5 (V)	Battery 6 (V)
(V)					

Student Handout



Worksheet 7 - SLA battery faults

Part 1 - COMmon connected to node 4:

Switch	Voltage across battery (between nodes 1 and 4)
Open	
Closed	

Part 2 - COMmon connected to node 3:

Switch	Voltage across battery (between nodes 1 and 3)
Open	
Closed	

Question 1: Why are both readings the same when the switch is open?

.....

.....

Question 2: In part 1, why does the reading change when the switch is closed?

.....

.....

Part 3 - Effect of corrosion on load voltage:

Switch	Voltage across battery (between nodes 1 and 3)
Open	
Closed	

Question 3: What is the effect of corrosion in the cables and connectors on the brightness of the bulb?

.....

Challenge:

Results of the investigation:

.....

.....

.....

.....

.....

Describe how you would check whether there is corrosion on the battery.

.....

.....

.....

.....

.....

Student Handout



Worksheet 8 - Battery management

Battery 1 (V)	Battery 2 (V)	Battery 3 (V)	Battery 4 (V)	Battery 5 (V)	Battery 6 (V)
(V)					

Battery	Initial voltage (V)	Charge current (A)	Bypass current (A)
1		0.7	
2		0.7	

BMS system

	Pair 1	Pair 2	Pair 3
Voltage V			
Current I			

Worksheet 9 - Voltage converters

Pot position	Fully anti-clockwise	Half way	Fully clockwise
Input current			
Input voltage			
Input power			
Output current			
Output voltage			
Output power			
Efficiency			

	Reading
Input current	
Input voltage	
Input power	
Output current	
Output voltage	
Output power	
Efficiency	

Student Handout



Worksheet 10 - Voltage inverters

Input voltage DCV	Input current DCA	Input power W	Output voltage ACV (rms)	Output current AV A (rms)	Output power W

Frequency:

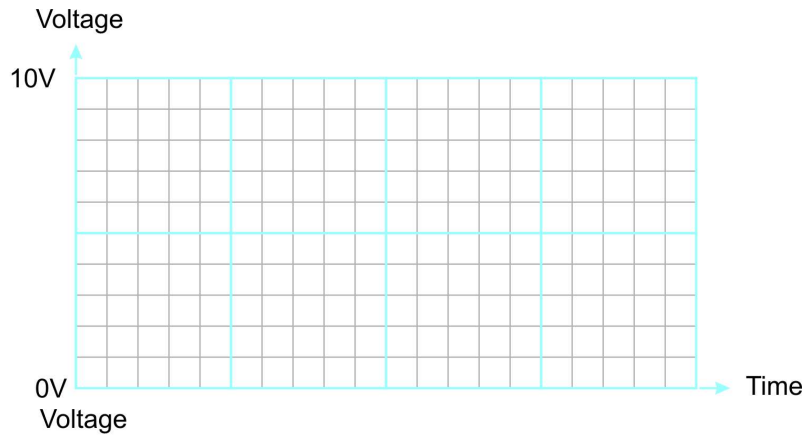
Worksheet 11 - solar panels:

	Luminous flux (lux)	Voltage (V)	Current (I)	Power (W)
On the bench				
Facing the window				
Outside				
Outside at 90 degrees to sun's rays				

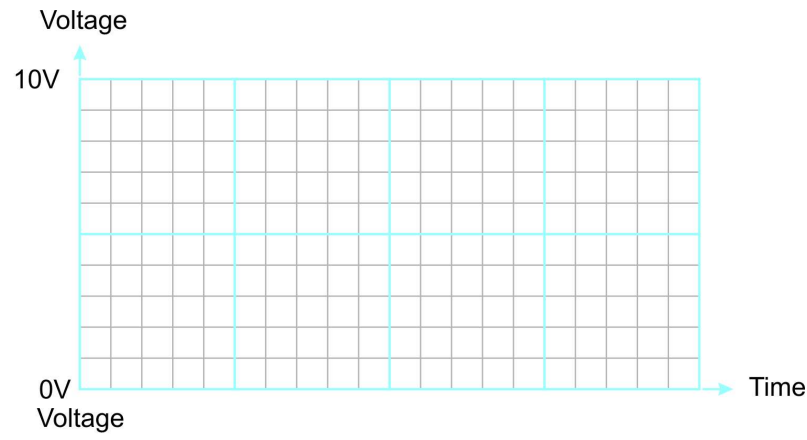
Student Handout

Worksheet 12 - Three-phase generators

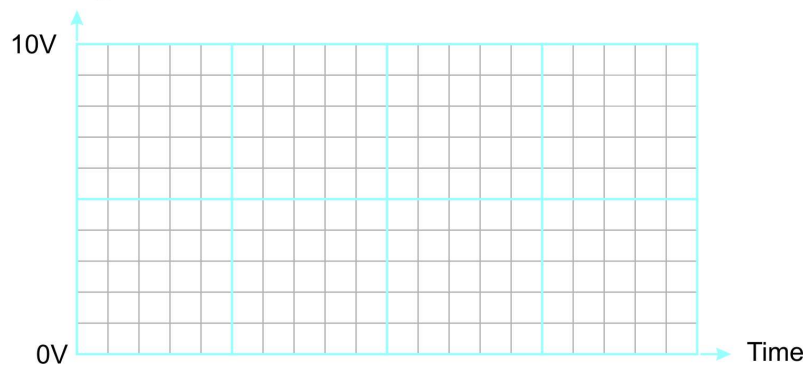
Phase 1:



Phase 2:



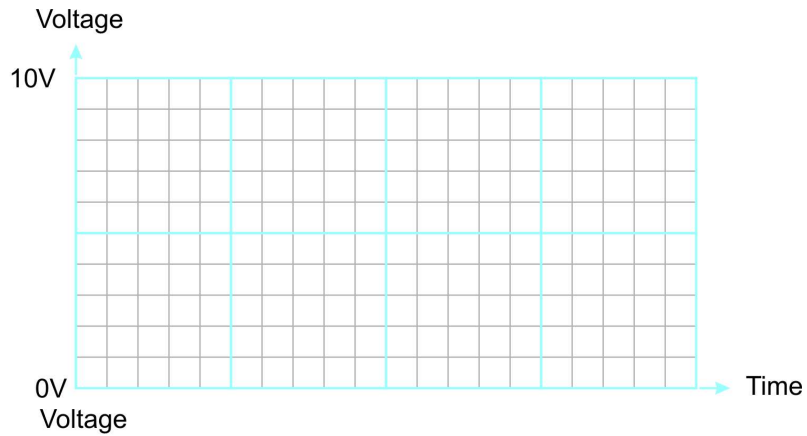
Phase 3:



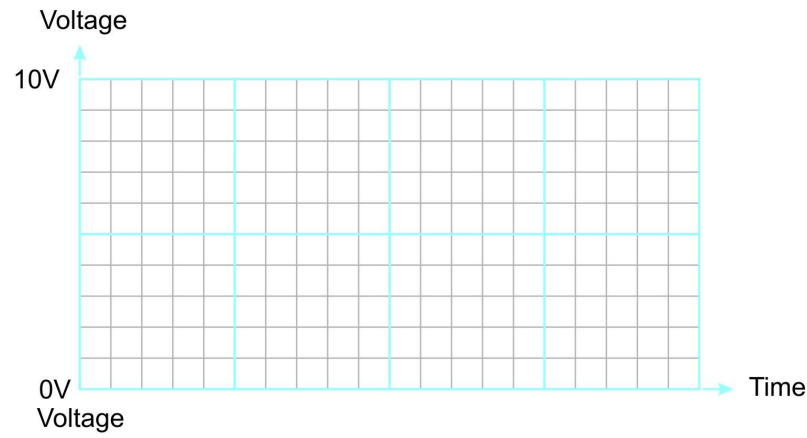
Student Handout

Worksheet 13 - three phase rectifiers

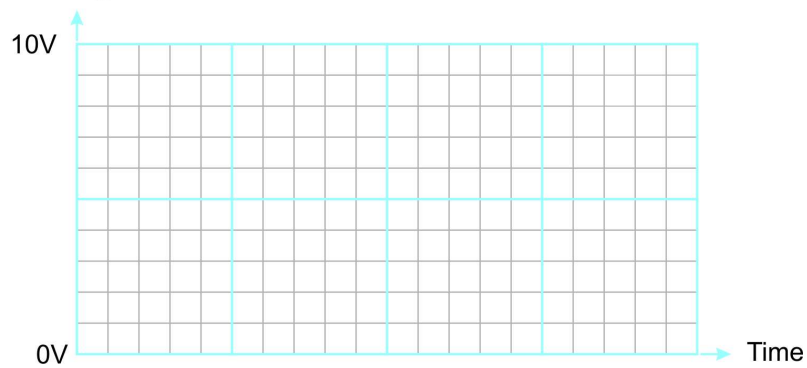
Phase 1:



Phase 2:



Phase 3:



Student Handout



Worksheet 14 - Using wind power to provide AC:

Power in to the motor _____

Power into voltage converter _____

Power into the inverter _____

Power into the load _____

Worksheet 15 - Using solar power to provide AC:

Power from the solar panel _____

Power out of the inverter _____

Worksheet 16 - Using solar power to charge batteries

No written tasks.

Notes for the Instructor

Please make sure that you read the section on Battery care in the Reference section to make sure your batteries are well kept.

About this course

Introduction

This module allows students to develop an understanding of electrical systems in modern domestic wind and solar panel installations. The course is essentially a practical one. Using Locktronics equipment, students set up and test circuits that simulate the behaviour of these high-voltage electrical systems.

Measurements use multimeters, clamp meters and oscilloscopes, following guidelines set out in each worksheet. The significance of the results is examined.

Aims

The course gives students an overview of modern domestic wind and solar panels systems.

Prior Knowledge

It is recommended that students have completed our Electrical installation and HVAC principles 2 or 3 courses, or have equivalent knowledge and experience of building and testing simple circuits, including the use of multimeters and clamp meters to measure voltage and current, and oscilloscopes to analyse AC signals.

Using this course:

There are two main parts to the workbook: the worksheets and the Student Handout. We envisage that you print (and bind) one copy of the worksheets, to stay with each set of Locktronics equipment. You will need print a copy of the Student Handout for each student.

The worksheets are written in a student-centred way. The plan is that you give each pair of students a set of equipment, the bound workbook and a Student Handout each. You then allow them to work through the topics in the workbook, offering help and assistance where needed. Students record their measurements in the Student Handout.

This approach encourages self-study, with students working at a rate that suits their ability. It is for the instructor to monitor that their understanding is keeping pace with progress through the worksheets. The Student Handout is one element of this monitoring. The instructor can assess progress by looking at the quality of their entries. This can form the basis for the feedback given to the students.

Time:

It will take from ten to fifteen hours to complete the module.

Bill Of Materials

To deliver this course you will need the following components in a Locktronics kit:

1	HP2001	DC / Brushless motor
1	HP2666	Adjustable DC power supply
4	HP4039	Tray lid
1	HP4561	Lux light meter
3	HP5540	Deep tray
1	HP5540	Shallow tray
1	HP6827	Solar panel
3	HP7750	Daughter tray foam cutout
3	HP8600	Crash foam
3	HP9564	62mm daughter tray
1	LAS9556	SLA cut out foam
1	LK2121	2200uF 25V capacitor.
6	LK2265	3.7V Lithium-ion battery
1	LK2346	12V incandescent MES bulb
1	LK2389	Voltmeter, 0V to 30V
1	LK3374	6V Sealed Lead Acid battery
1	LK3982	Voltmeter, 0V to 15V
3	LK4025	10 ohm resistor
3	LK5202	1Kohm resistor
2	LK5214	Potentiometer, 10K ohm (DIN)
6	LK5243	Diode, power, 1A, 50V
28	LK5250	Connecting Link
2	LK5291	Lampholder, MES
2	LK5603	Red 4mm to 4mm lead, 1m
2	LK5604	Black 4mm to 4mm lead, 1m
2	LK5607	Blue 4mm to 4mm lead, 1m
2	LK5609	Yellow 4mm to 4mm lead, 1m
1	LK5894	Battery Management System
1	LK6152	Corrosion component
3	LK6209	Switch, on/off, metal strip
2	LK6705	Power transistor
1	LK6716	Downconverter
1	LK6841	12V LED bulb white
1	LK8000	Schottky diode
1	LK8275	Power supply carrier with battery symbol
1	LK8397	Ammeter 0A to 1A
3	LK8900	7 x 5 metric baseboard with 4mm pillars
1	LK8910	Inverter
1	LK9593	Upconverter

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Learning Objectives

On successful completion of this course the student will be able to:

- state that batteries convert energy between chemical and electrical forms;
- recall that a battery can be thought of as containing an internal resistor in series with the battery;
- state that the internal resistance of a lead-acid cell increases as the cell discharges;
- explain the significance of battery energy capacity and recall that it is measured in units called amp.hours (A.h);
- compare SLA and Li-ion cells in terms of their output voltage and internal resistance;
- hence appreciate the need to avoid short-circuiting a Li-ion battery;
- describe the meaning of 'state of charge (SOC)' and explain its significance;
- use a battery voltage/SOC curve to predict the state of charge of a battery;
- explain why the SOC of a Li-ion battery cannot be predicted from its output voltage;
- given data on voltage and current, calculate the power delivered by a battery;
- given the battery type and its energy capacity, C, estimate a suitable charging current for 'normal' and 'fast' charging;
- given the energy capacity of each cell and its rated voltage, calculate the energy, in watt.hours, deliverable in a given time;
- describe the effect of combining a number of cells or batteries to make a larger battery;
- interpret the meaning of the term '2,3' battery;
- describe the effects of corrosion on the electrical devices in a vehicle;
- describe how to use a multimeter to check for the presence of corrosion;
- explain why it may be necessary to select individual cells for a battery pack;
- describe the function of a DC-to-DC step-up converter, giving examples of its use in vehicles;
- describe the function of a DC-to-DC step-down converter, giving examples of its use in vehicles;
- recall that DC motor speed increases as the applied voltage increases;
- explain what is meant by 'duty cycle' and convert it to mark:space ratio;
- sketch a voltage / time graph to illustrate the meaning of 'three-phase supply';
- draw a circuit diagram for a three-phase rectifier, using six diodes;
- Understand that wind turbines need to have a load when they produce electricity
- Understand that wind turbines are three phase
- Understand the operation of an AC inverter
- Understand efficiency calculations in modern power systems
- Understand that the output of solar panels varies with type of light and light intensity
- Understand the circuitry and system blocks in modern power systems

Preliminary issue

Health and Safety:
Students must be made aware of the potential hazards should SLA or Li-ion cells be connected incorrectly.
(All batteries include a thermal cut-out triggered by excess currents.)

Some groups may need initial guidance / revision on using an oscilloscope, including an explanation of the significance of the various settings and help with interpreting and taking measurements from the oscilloscope trace. In some investigations, it will be necessary to use the 'x10' setting on the probes to reduce the voltage sensitivity. Students may need guidance on how to use this and interpret the results.

Similarly, some will need an overview of the uses of multimeters and current-clamp meters.

General checks

- Is the correct type of plug-top power supply (AC or DC) being used?
- Is it on the correct voltage setting?
- Are cells connected with the correct polarities in multiple-cell configurations?
- Is the layout correct (including connections to potentiometer carriers)?
- Are all components, including the power supply carrier, connected with the correct polarity?

Multimeter and current clamp-meter checks:

- Is the meter connected to the circuit correctly?
If not, the '-' sign will appear in the wrong place.
- Are the leads connected to the correct sockets on the multimeter?
- Is the meter set on the correct range?
- Some voltage readings are negative.
The meter leads are the wrong way round.
- The current clamp meter keeps flipping out the connecting link.
It may be easier to remove the connecting link and replace it with a 'flying lead' to make the current measurement. It may also be an advantage to use the 'Hold' button to retain the reading.

Oscilloscope checks:

- Is the oscilloscope connected to the circuit properly?
- Are the oscilloscope settings correct?
If not, the correct trace will not be created. (Try the 'Auto' trigger mode / 'AC' coupling)

Worksheet	Notes
<p>1 Testing Sealed Lead-Acid bat- teries</p>	<p>Specific problem:</p> <ul style="list-style-type: none"> Resistors may heat up. Do not leave switched on. Unexpected meter readings - see Multimeter and current clamp-meter checks on previous page. <p>Points for discussion:</p> <ul style="list-style-type: none"> Distinction between cells and batteries. Significance of internal resistance of a cell. Significance of 'State of Charge' (SOC). Meaning and significance of energy capacity, C, of a battery. Amp.hour (A.h) as a unit of energy capacity.
<p>2 Charging Sealed Lead-Acid bat- teries</p>	<p>Specific problem:</p> <ul style="list-style-type: none"> In the event of difficulty using the current clamp meter, swap the connecting link for a wire. Unexpected meter readings - see Multimeter and current clamp-meter checks and General Checks on previous page. check polarity of SLA and plug-top power supply. <p>Points for discussion:</p> <ul style="list-style-type: none"> Link between energy capacity, charging current and charging time. Significance of 'Output voltage / SOC' graph for SLA batteries.
<p>3 Testing Li-ion cells</p>	<p>Points for discussion:</p> <ul style="list-style-type: none"> Comparison of Li-ion and SLA cells.
<p>4 Charging Li-ion cells</p>	<p>Points for discussion:</p> <ul style="list-style-type: none"> Significance of 'Output voltage / SOC' graph for Li-ion cells (c.f. SLA batteries).
<p>5 Building larger batteries</p>	<p>Points for discussion:</p> <ul style="list-style-type: none"> Calculating power delivered by a battery. Benefits of combining cells in series and in parallel. Health and safety when handling Li-ion batteries. Nomenclature such as '2,3' battery. Calculating amp.hour rating, current capability and power capability of a battery.

Worksheet	Notes
6 Li-ion battery faults	Points for discussion: <ul style="list-style-type: none">• Corrosion - causes and effects.• Issues when charging cells in parallel.
7 SLA battery faults	Points for discussion: <ul style="list-style-type: none">• How to detect corrosion problems.
8 Battery management	Points for discussion: <ul style="list-style-type: none">• The need for battery management.• The operation of the circuit on p.21.• Battery charging with complex batteries
9 Voltage converters	Points for discussion: <ul style="list-style-type: none">• Roles for voltage converters in modern power systems• Significance of, and how to calculate, energy efficiency.
10 Voltage inverters	Points for discussion: <ul style="list-style-type: none">• Roles for voltage inverters in modern power systems• Significance of, and how to calculate, energy efficiency.
11 Solar panels	Points for discussion: <ul style="list-style-type: none">• Types of light and how they convert into energy• Angle of incidence• Calculating efficiency in systems

Worksheet	Notes
12 Wind turbines	Points for discussion: <ul style="list-style-type: none">• Reasons for using three phase• Angle between waveforms
13 Three phase rectifiers	Points for discussion: <ul style="list-style-type: none">• Need for AC to DC conversion• Role of a capacitor
14 Using wind power to provide AC	Points for discussion: <ul style="list-style-type: none">• Reason we need AC inverters• Reasons why AC is used in electricity distribution• Efficiency drops at each stage
15 Using solar power to provide AC	Points for discussion: <ul style="list-style-type: none">• Combined solar power and wind power systems and the circuits they will use.

Caution: if you mistreat Li-ion batteries they can catch fire. Do not use any other charger than the one supplied with this kit and make sure you use the correct voltage.

Do not discharge the batteries below 3.2V

We have taken considerable precautions against any mishap here: the batteries are all encased in stainless steel casings to protect the students and the equipment. However students using batteries should be supervised at all times, and batteries should not be left on charge for more than 2 hours.

Reference



Li-Ion Battery

Long Term Storage Voltage: 3.85V

Short Term Storage Voltage: 3.7V – 4.0V

Absolute Max Voltage: 4.2V

Absolute Min Voltage: 3.0V

Recommendations

At the end of each session we highly recommend checking the voltage of each battery. Batteries with a voltage of 3V and below should be topped up to around 3.8V or they risk becoming permanently damaged and will need replacing. Batteries with a voltage higher than 4V should be discharged to around 4V or they risk losing both capacity and current capability. Checking the voltage of the batteries after each session also allows students to be held accountable for any misuse or abuse.

The battery voltage is very important when storing the battery for any mid to long period of time. The storage voltage should be around 3.85V and should be checked and topped up at least once every 6 months to prevent the battery becoming damaged. The batteries should be stored in a cool and dry environment for maximum life expectancy.

Lead Acid Battery

Long Term Storage Voltage: > 6.4V

Short Term Storage Voltage: > 6.0V

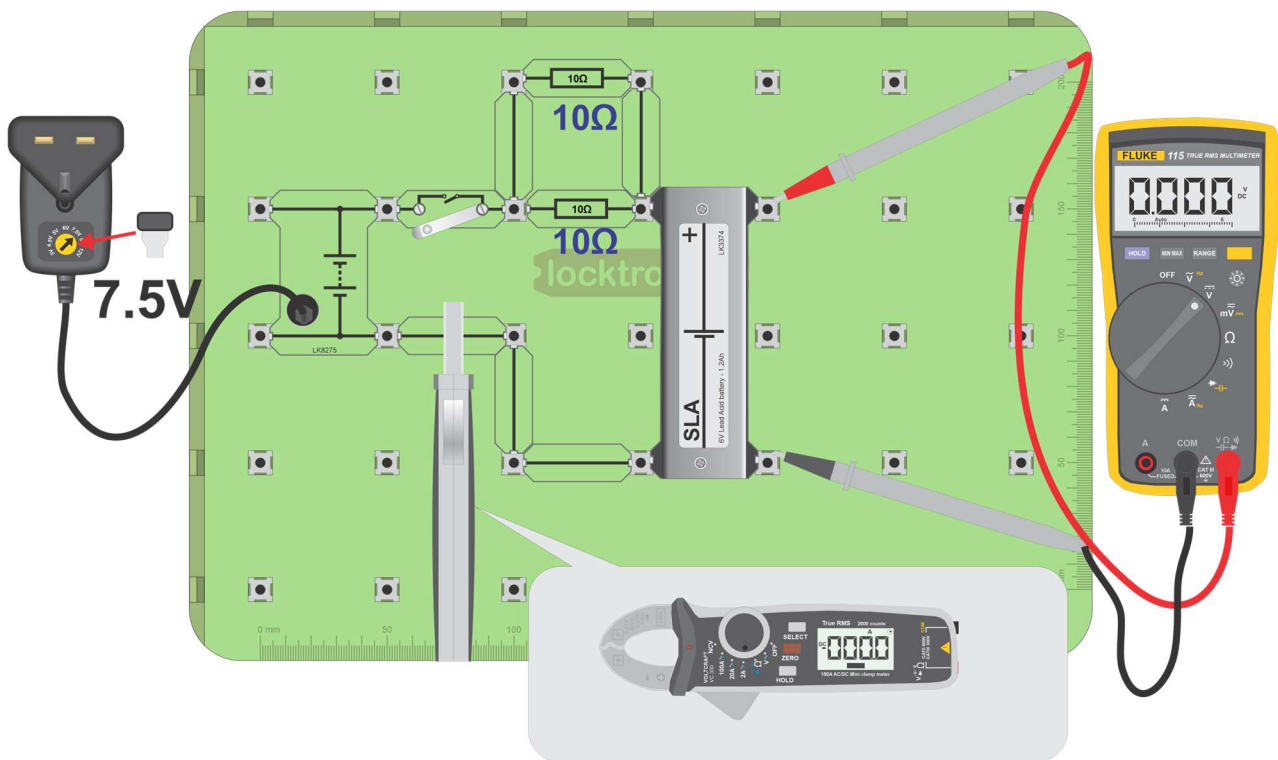
Absolute Max Voltage: 6.7V

Absolute Min Voltage: 5.3V

Recommendations

At the end of each session we highly recommend checking the voltage of each battery. Batteries with a voltage of less than 6.2V should be topped up to around 6.4V or higher or they risk losing capacity and current capability. Checking the voltage of the batteries after each session also allows students to be held accountable for any misuse or abuse.

The battery voltage is very important when storing the battery for any mid to long period of time. The storage voltage should be around 6.4V and should be checked and topped up at least once every 6 months to prevent the battery becoming damaged. The batteries should be stored in a cool and dry environment for maximum life expectancy.



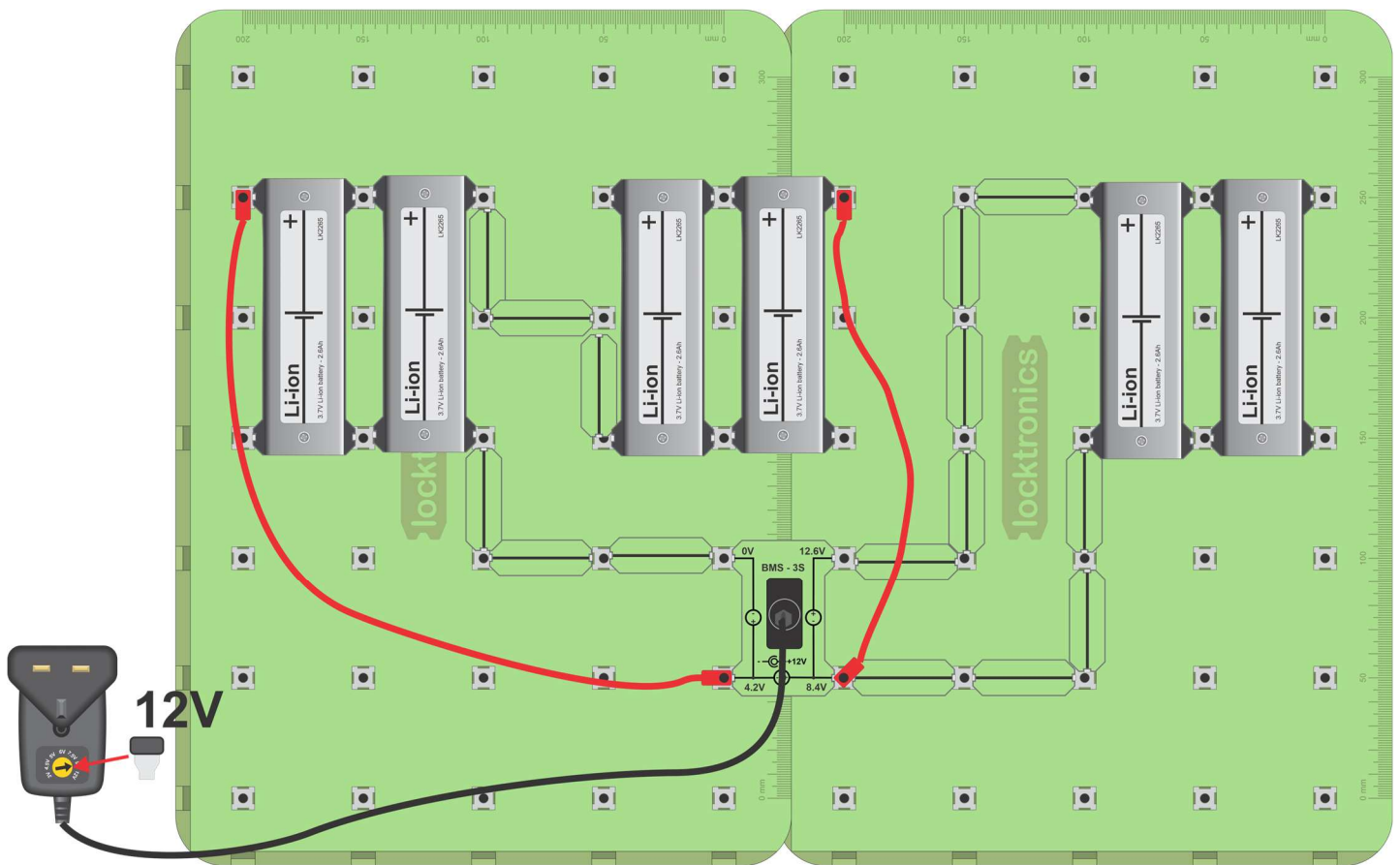
Information:

- The charge time and current your battery needs depends on the State of Charge (**SOC**) of the battery. However, you are unlikely to know the battery **SOC** when you open the kit.
- The battery we are using is RS Pro part number 727-0388. For this Sealed Lead Acid (**SLA**) battery, a recommended method is to charge it at a constant current of $(0.1 \times C)$ for up to twenty-four hours, where **C** is the battery energy capacity. For this battery, **C** is 1.2A.h, which implies a constant current of 0.12A.
- The kit does not include a constant-current generator circuit. The circuit shown above is a near equivalent. The plug-top power supply outputs 7.5V. The resistors drop between 1V and 1.5V so that the current varies between 0.15A and 0.3A as the battery charges up.

Method:

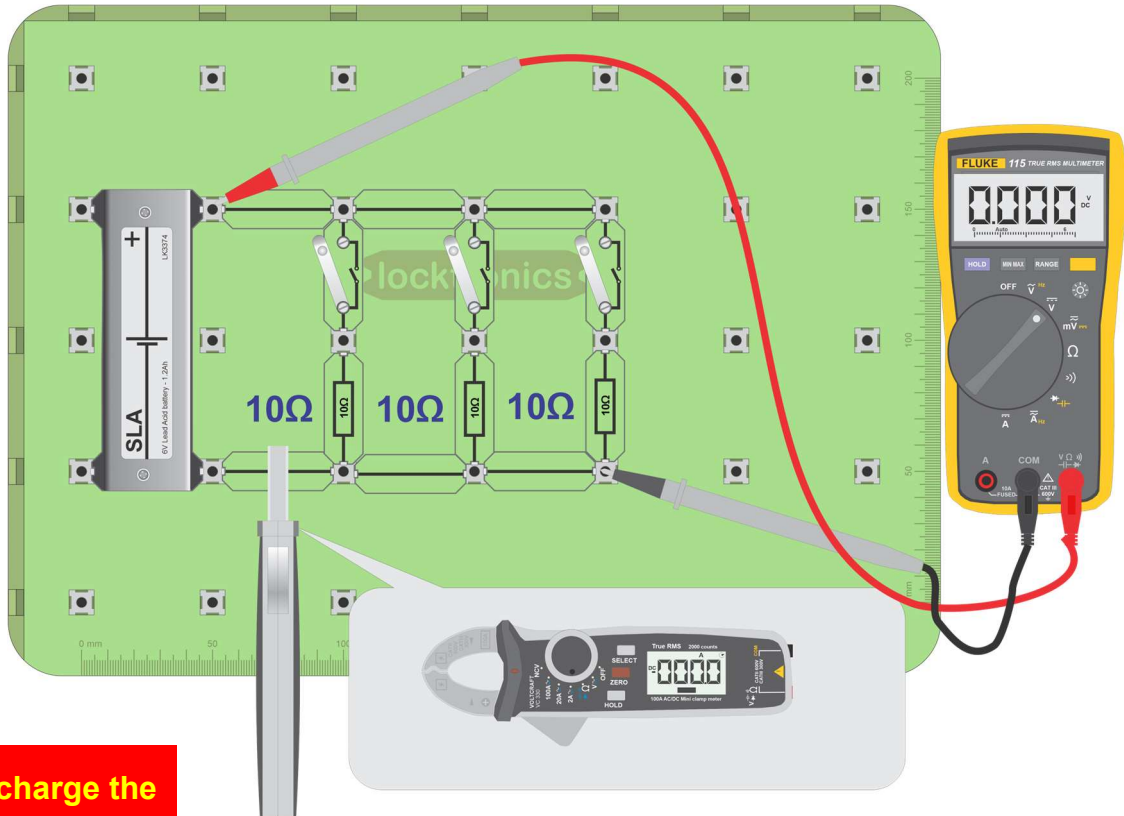
- Construct the circuit shown above.
- Measure the charge current with your clamp meter, positioned as shown.
- Charge the battery in this way for two hours. Assuming that the battery has a reasonably high **SOC**, then that will probably be enough. As the battery charges the battery voltage rises and the charge current falls. When the charge current falls to below 0.05A then replace the diode with a link and carry on charging for a further hour.

Caution: if you mistreat Li-ion batteries they can catch fire. Do not use any other charger than the one supplied with this kit and make sure you use the correct voltage and the shottky diode.



Information:

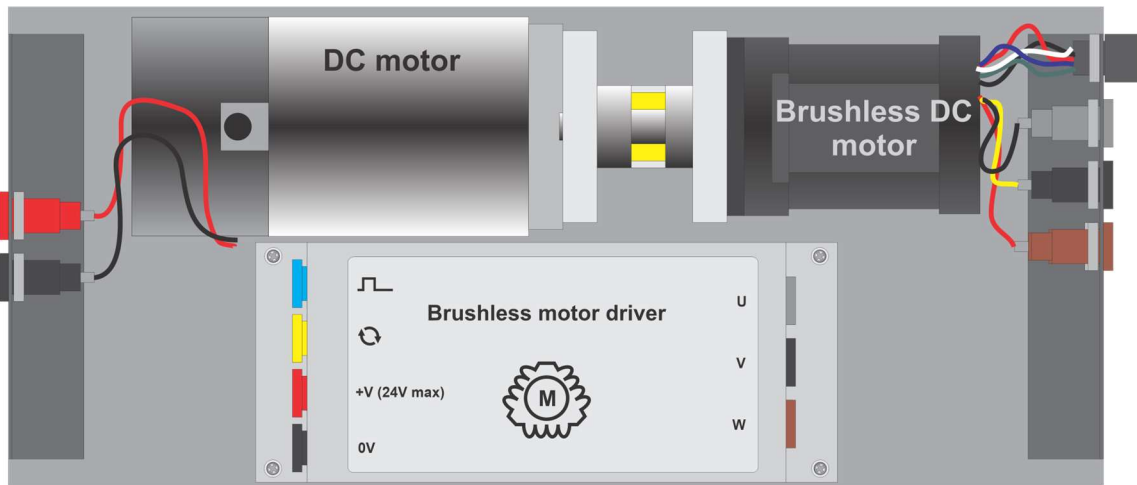
- Before each lesson you will need to make sure that there is enough energy in your batteries. That's hard to measure. Most of the time you will not need to charge the batteries as they will not fully discharge much over a single lesson.
- To charge the batteries use the BMS supplied with the kit and set up the circuit above. You can get students to do this for you at the end of a lesson.
- The BMS will cut out when one set of batteries reaches 4.2V. That will not ensure that all batteries are charged to the maximum, but it will be more than good enough for your students.



Do not discharge the batteries below 3.2V

Over to you:

- Discharge your Li-ion cells slightly if you feel that they are overcharged.
- To discharge a Li-ion cell or a SLA battery, you can use the same circuit used to test them, using up to three 10 ohm resistors in parallel.
For the SLA, this should give a discharge current of around 1.5A.
For the Li-ion, this should give a current of around 1A.
- 10% discharge:
 - for the SLA will take around 10 minutes;
 - for the Li-ion battery will take around 15 minutes.
- 50% discharge:
 - for the SLA will take around 40 minutes;
 - for the Li-ion battery will take around 50 minutes.



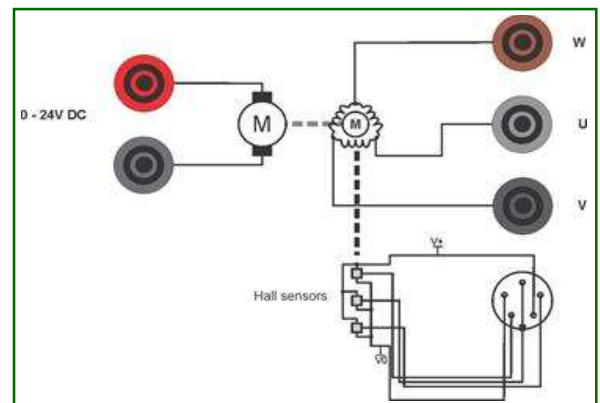
The HP2001 DC motor/brushless motor pair consists of two parts: the motors themselves, coupled together, and a brushless DC motor driver.

The coupled DC motor / brushless motor pair can be driven in two ways:

- the DC motor drives the brushless DC motor;
- the brushless DC motor drives the DC motor.

The DC motor supply voltage can be up to 24V.

With the Brushless DC motor unloaded the approximate speeds are:



Volt-age	RPM
2.4	0
4.8	180
7.2	390
9.6	600
12.0	800
14.4	1000
16.8	1210
19.2	1410
21.6	1680
24.0	2010

When driving the DC motor with the brushless DC motor at 2000 rpm, the DC motor acts as a generator and generates 25VDC.

The polarity of the voltage generated on the terminals will depend on the direction of rotation. When driven clockwise with respect to the face of the motor the red terminal will be positive.

When driven at full speed (speed input 5V) and unloaded, the DC motor speed of rotation is approximately 2000rpm.

The following table shows the relationship (approximate) between speed and generated voltage for the brushless DC motor for varying speed input voltages when a 24V DC power supply is used and no load:

Speed rpm	Output V(DC)
1199	14
1795	21.5
2292	27
2565	29
2522	28
2631	30
3099	35

Brushless DC motor driver

The brushless DC motor driver board is housed in a rugged stainless steel casing. It should be supplied from a 24V power supply. This is included with HP2001.

The HP2001 has two additional inputs: a direction input and a speed input.

- The direction input should be 0V or +5V.
- The speed input should vary from 0V to 5V.

Brushless motor as a three phase generator

When driven by the DC motor the brushless DC motor will generate three phase electricity. Unloaded, the brushless DC motor will generate $6V_{RMS}$ between two phases at 2000 rpm.

Version control



- 12 08 21** First prototype
- 18 01 22** First release
- 03 03 22** Added BMS. To do: BOM update to others
- 05 12 23** small changes to value of a capacitor on some diagrams