Experiments in
Solar Cell and Hydrogen Fuel Cell
Technologies
For NI™ ELVIS I and II/+
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Solar Cell and Hydrogen Fuel Cell Technologies
For NI™ ELVIS I and II/+
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1 - An introduction to the NI ELVIS II test equipment
Experiment 1 – An introduction to the NI ELVIS II/+ test equipment

Preliminary discussion
The digital multimeter and oscilloscope are probably the two most used pieces of test equipment in the electronics industry. The bulk of measurements needed to test and/or repair electronics systems can be performed with just these two devices.

At the same time, there would be very few electronics laboratories or workshops that don’t also have a DC Power Supply and Function Generator. As well as generating DC test voltages, the power supply can be used to power the equipment under test. The function generator is used to provide a variety of AC test signals.

Importantly, NI ELVIS II has these four essential pieces of laboratory equipment in one unit (and others). However, instead of each having its own digital readout or display (like the equipment pictured), NI ELVIS II sends the information via USB to a personal computer where the measurements are displayed on one screen.

On the computer, the NI ELVIS II devices are called "virtual instruments". However, don't let the term mislead you. The digital multimeter and scope are real measuring devices, not software simulations. Similarly, the DC power supply and function generator output real voltages.

As well as the instruments mentioned above, the NI ELVIS II has available eight analogue inputs and two analog outputs which can be controlled and written to by our LabVIEW program and the input readings processed and displayed on screen. This allows for the creation of many more custom "virtual instruments" which may be required in a particular experimental setup.

The experiments in this manual make use of only four of the available analogue inputs as well as several digital outputs which, in conjunction with the HELEX board, are able to implement voltmeters, ammeters and programmable loads for use throughout this manual.

Rather than providing several independent instruments as the NI ELVIS does for other EMONA plug-in accessory boards (such as EMONA DATEx Telecoms-Trainer and the EMONA FOTEx Fiber optics trainer), these instruments are all merged into one full-screen virtual instrument for the HELEX board known as the HELEX Main soft front panel (SFP).
When an NI ELVIS unit is connected to a PC it will automatically run the Instrument Launcher panel as shown below:

![NI ELVIS Instrument Launcher](image)

**Figure 1: NI ELVIS Instrument Launcher**

This panel gives the user access to each individual instrument. However these are not used by the HELEEx and this “Instrument Launcher” panel can be closed.

When using NI ELVIS with the EMONA HELEEx board to conduct solar energy and hydrogen fuel cell experiments the user will run the HELEEx Main SFP VI shown below:

![HELEEx Main SFP](image)

**Figure 2: HELEEx Main SFP**
As the figure above shows, there are four customised meters which graphical and numeric output as well as control panel for the electronic load, and a number of customised data input/output display panels (selected by tabs) for the numerous experiments in this manual.

These instruments are taking their signals directly from the HELEx board via the EMONA ETT-040 Universal Base Board, into the ELVISmx circuitry, and after processing by LabVIEW are displayed on screen as required.

The combination of the LabVIEW programmability of the NI ELVIS unit as well as the numerous analog and digital inputs and outputs available make it convenient to create customised instrumentation for use in real world hands-on experimentation. The EMONA HELEx board is a good example of this integration of available hardware and the software control.

The experiment
For this experiment you'll connect your NI ELVIS unit to your PC, view the Instrument Launcher and run the HELEx Main SFP.

It should take you about 5 minutes to complete this experiment.

Equipment

- PC with LabVIEW 8.5 (or higher)
- NI ELVIS 1, 2 or 2+ and USB cable to suit
- EMONA HELEx experimental add-in module and Universal Base board
Procedure

Part A - Setting up the NI ELVIS/HELex apparatus

1. Turn off the NI ELVIS unit and its Prototyping Board switch.
2. Plug the HELex board into the base board, then the base board into the NI ELVIS unit. Lock it into place with the knurled knob on the HELex board.
3. Connect the NI ELVIS to the PC using the USB cable.
4. Turn on the PC (if not on already) and wait for it to fully boot up (so that it’s ready to connect to external USB devices).
5. Turn on the NI ELVIS unit but not the Prototyping Board switch yet. You should observe the USB light turn on (top right corner of ELVIS unit). The PC may make a sound to indicate that the ELVIS unit has been detected if the speakers are activated.
6. Confirm that the instrument launcher panel has activated and close it as it will not be used in this experiments.
7. Turn on the NI ELVIS Prototyping Board switch to power the HELex board. Check that all three power LEDs are on. If not call the instructor for assistance.
8. Launch the HELex Main VI.
9. If you’re asked to select a device number, enter the number that corresponds with the NI ELVIS that you’re using and restart the HELex VI if necessary.
10. Set the HELex module’s PC CONTROL/MANUAL mode switch to the MANUAL position.
11. You’re now ready to work with the NI ELVIS/HELex bundle.

Note: To stop the HELex VI when you’ve finished the experiment, it’s preferable to use the STOP button on the HELex SFP itself rather than the LabVIEW window STOP button at the top of the window. This will allow the program to conduct an orderly shutdown and close the various DAQmx channels it has opened.

Ask the instructor to check your work before continuing.
2 - An introduction to the HELEX experimental add-in module
Experiment 2 – An introduction to the EMONA HELE\textsuperscript{x} experimental add-in module

Preliminary discussion

The experiments possible with the EMONA HELE\textsuperscript{x} board bring together the worlds of the electromagnetic, electrical and chemical. We are able to explore, in a hands-on manner, the actions of photons, electrons and molecules upon each other. We are reminded of the interconnectedness of these complementary systems and of the universal principles of conservation of energy. Through measurements, calculations and observations we are able to consolidate our understanding of these processes.

The HELE\textsuperscript{x} board customizes the instrumentation available on the NI ELVIS to create seven experiment-specific instruments which can be used with the additional solar cell-electrolyzer-fuel cell equipment provided.

As well the ability to programmatically control, measure and automate our measurements using LabVIEW bring us closer to real-world practices of system control and monitoring. Although the principles of being studied date back several centuries their application in real world devices is continually being explored and implemented. The instrumentation used has changed substantially however the rigorous nature of the scientific process remains the same and is a skill which is best learned in a hands-on manner.

An important skill for the engineer and scientist is the ability to take rigorous and precise measurements, often repetitively, in order to study the phenomena at hand. The EMONA HELE\textsuperscript{x} Solar -Hydrogen Fuel Cell Experimenter (ETT-411) provides an abundance of opportunities to learn and practice experimental methodology in various fields including electrical and chemical energy.
The experiment
For this experiment you will familiarize yourself with the various instruments available on the HELEx board and how they are used. The use of the additional lux meter, solar cell, electrolyzer and fuel cell apparatus will be covered as the need arises in further experiments in this manual.

It should take you about 15 minutes to complete this experiment.

Pre-requisites:
You should have completed the introductory chapter 1 so that you’re familiar with the equipment setup and capabilities.

Equipment

- PC with LabVIEW 8.5 (or higher)
- NI ELVIS 1, 2 or 2+ and USB cable to suit
- EMONA HELEx experimental add-in module and Universal Base board
- Assorted patch leads
Procedure

Part A - Setting up the NI ELVIS/HELex apparatus

1. Turn off the NI ELVIS unit and its Prototyping Board switch.
2. Plug the HELex board into the base board, then the base board into the NI ELVIS unit. Lock it into place with the knurled knob on the HELex board.
3. Connect the NI ELVIS to the PC using the USB cable.
4. Turn on the PC (if not on already) and wait for it to fully boot up (so that it's ready to connect to external USB devices).
5. Turn on the NI ELVIS unit but not the Prototyping Board switch yet. You should observe the USB light turn on (top right corner of ELVIS unit). The PC may make a sound to indicate that the ELVIS unit has been detected if the speakers are activated.
6. Turn on the NI ELVIS Prototyping Board switch to power the HELex board. Check that all three power LEDs are on. If not call the instructor for assistance.
7. Launch the HELex Main VI.
8. If you're asked to select a device number, enter the number that corresponds with the NI ELVIS that you're using and restart the HELex VI if necessary.
9. Set the HELex module's PC CONTROL/MANUAL mode switch to the MANUAL position.
10. You're now ready to work with the NI ELVIS/HELex bundle.

Note: To stop the HELex VI when you've finished the experiment, it's preferable to use the STOP button on the HELex SFP itself rather than the LabVIEW window STOP button at the top of the window. This will allow the program to conduct an orderly shutdown and close the various DAQmx channels it has opened.
Safe operating guidelines to be followed at all times

Intended use:
This equipment is only to be used as directed in this Lab manual and User Manual and for experiments under the supervision of teaching staff.

All users must carefully read the User Manual to become familiar with the operation of this equipment before using this equipment and keep this information available with the equipment at all times.

This equipment may not be used with any other components other than what is supplied with the EMONA HELEX kit and is provided for teaching and demonstration purposes only.

This equipment may only be operated in accordance with local statutory regulations.

DOs – SAFE PRACTICES:
Always read and precisely follow the operating instructions. Ask your instructor if unsure at any time. The instructor is responsible for maintaining correct supervision at all times.
Always wear safety glasses when near the equipment in operation.
Always place the equipment safely at correct distances and with sufficient clear, flat and stable room around it.
Always work in well ventilated spaces with adequate clearance above and around the equipment.
Always fill or empty the electrolyser away from other equipment and over a sink.
Always work in a typical indoor environment of between 10 – 35°C.

DON'Ts – WARNINGS:
Never have any sources of ignition near the equipment.
Never touch the lamp or solar cell when in operation or immediately after until confirming that it has cooled down sufficiently.
Never apply external components or equipment to the HELEX kit such as external power supplies or other apparatus or any signals other than those provided on the HELEX board itself.
Never allow hydrogen or oxygen to accumulate in quantities of more than 20 ml.
Never leave the equipment operating unattended.
Never use any liquid other than steam-distilled water with the electrolyser unit.
Never place the operating lamp closer than 30 cm from any surface.

DANGERS:
Hydrogen and oxygen are highly flammable and explosive gases. There is danger of explosion.

The lamp and solar cell will heat up to high temperatures and there is danger of skin burns if touched.

The lamp will cause surfaces to overheat and burn if placed closer than 30 cm whilst operating.

Avoid spilling the distilled water on any of the HELEX kit, especially the board itself and the NI ELVIS unit and power supply block, to avoid electrical hazards.

Avoid using the equipment if it shows any signs of damage or malfunction. Contact EMONA immediately for repair or replacement after referring to the User Manual for confirmation of correct specifications. There are no user-repairable parts in this kit.
Part B - The voltage meters VM1 & VM2 and the voltage source VS
Two voltage meters are supplied on the HELEX board. They are labeled VM1 and VM2 and are shown in the figures below. These voltmeters use two of the sampled analog voltage inputs available on the NI ELVIS unit. They have differential inputs and can be connected in reverse direction without damage (though the REVERSED lamp lights up to indicate the error). Part B introduces you to these meters and the voltage source labeled VS.

Figure 1: cutout of VM1,CM1,VM2,CM2 on the HELEX board

Figure 2: detail of VM1,CM1,VM2,CM2 on the HELEX SFP
11. Connect VM1 as shown in the figure below.

12. Switch the adjustable voltage source (VS) to ON.

13. Vary the adjustable voltage source and confirm that the voltage meter displays the signal as well as the changing value of the voltage.

![Figure 3: VS connected to VM1 correctly](image)

14. Modify your connections to match the figure below.

![Figure 4: VS connected to VM1 reversed and incorrectly](image)

15. Confirm that a negative value is displayed although the moving meter display stops at zero. Confirm also that the REVERSED lamp is lit.

16. Repeat these steps for VM2 - It should perform in an identical way.

Ask the instructor to check your work before continuing.
Part C - The current meters CM1 & CM2 and the constant current source CS

Two current meters are supplied on the HELEEx board. They are labeled CM1 and CM2. These ammeters use two of the sampled analog voltage inputs available on the NI ELVIS unit. They have differential inputs and can be connected in reverse direction without damage (though the REVERSED lamp lights up to indicate the error). Part C introduces you to these meters and the constant current source labeled CS.

17. Connect CM1 as shown in the figure below.

![Figure 5: CS connected to CM1 correctly](image)

18. Switch the constant current source (CS) to ON.

19. Confirm that the current meter CM1 displays a constant signal of approximately 200 mA.

20. Modify your connections to match the figure below.

![Figure 6: CS connected to CM1 reversed and incorrectly](image)

21. Confirm that a negative value is displayed although the moving meter display stops at zero. Confirm also that the REVERSED lamp is lit.

22. Repeat these steps for CM2 - It should perform in an identical way.
Notice that in the top right-hand corner of the HELEx soft front panel (SFP) there are some display option switches. The following notes explain their function.

**Smooth switch:** Selecting this option performs a three-point moving average on all four data signals displayed (that is, on VM1, VM2, CM1 and CM2). This is useful for determining an average value for any rapidly changing unstable signals.

**Scale switch:** Selecting this option changes the scale of the moving signal displays only, halving the maximum range and thus doubling the viewing resolution. This is useful for viewing low-level signals more easily.

![Figure 7: close up of switches on SFP](image)

Ask the instructor to check your work before continuing.
Part D - The programmable load PGL
The HELEX board provides a variable resistance or load that is both manually adjustable via the board or controllable via LabVIEW from the HELEX SFP in a variety of ways.

Figure 8: programmable load on HELEX board

Figure 9: detail of programmable load control on SFP

23. Set the programmable load mode select switch to MANUAL.

24. Vary the load switch through the 10 possible positions.

Note: As you perform this step, familiarize yourself with the LED load display (to the right of the switch) and how it relates to the load setting. This display serves to give immediate intuitive visual feedback regarding the current level of the load.

There are a number of ways of thinking about the word "load". In this manual it's used in the following way. As the resistance decreases towards zero ohms (or SHORT CIRCUIT) the load is increasing. Conversely, as the resistance increases toward infinite ohms (or OPEN CIRCUIT) the load decreasing. Why is a lower resistance a greater load? Because more current flows into the load and so more energy is consumed by the load.
The LED display on the HELEX board is arranged to show the changing resistance of the load in a proportional manner. That is, for resistances of 1, 2, 4 Ohms etc, the LEDs are close together. When the resistance changes between 32, 64 and 128 Ohms, the LEDs are spaced further apart.

The programmable load on the HELEX board has one end permanently connected to ground (0 volts) so you don’t need to make that connection yourself. As such, a terminal for this connection isn’t provided.

25. Set the programmable load mode select switch to PC CONTROL.

26. On the HELEX SFP in the programmable load control area, select the radio button option KNOB.

27. Use the mouse’s cursor to vary the on-screen control knob and notice that its value changes between 0 and 255.

28. Confirm that as you vary the control knob on screen the LED display on the HELEX board also varies accordingly.

Note: Refer to the HELEX User Manual for details of the relationship between specific LEDs and control knob index values.

Other programmable load radio button options will be discussed in later experiments as the need arises.

Ask the instructor to check your work before continuing.
Part D - Other external HELEEx kit equipment

Other equipment supplied with the HELEEx includes: two solar cells, electrolyzer, dismantlable PEM fuel cell, intact PEM fuel cell and lux meter. This equipment will be introduced to you as they’re required in later experiments to avoid repeating steps and processes unnecessary in this chapter.

Throughout this manual this equipment will be represented by the following diagrams

**Figure 10: Solar cell**

**Figure 11: Electrolyzer**
Figure 12: Dismantlable Fuel cell

Figure 13: PEM Fuel cell
Figure 14: Lux meter

Ask the instructor to check your work before finishing.
7 - Multiple solar cell configurations and performance
Experiment 7 - Multiple solar cell configurations and performance

Preliminary discussion

The typical photovoltaic panel you will see being used is an array of many individual solar cells connected together in achieve a useful amount of total power output. This power is often converted by inverter units into AC power for general use, used directly from the panels and stored and accumulated for future use in batteries or other storage mediums.

A single silicon solar cell creates a maximum voltage of about 600mV. To achieve the commonly used voltage of 12V DC, 36 of these cells are connected in series. In this experiment we investigate how we may accumulate solar cells into arrays in order to supply larger and variable loads. It makes sense to use many solar cells in arrays to create larger sources of electrical power. A group of solar cells is a scalable source in that we have the option of connecting numbers of them in either parallel, series or a combination of both.

When we connect DC electrical sources in series and in correct orientation we create the addition of voltages with a common current.

Connecting them in parallel creates the addition of currents at a common voltage. We have the option of increasing the capacity of the array to supply higher voltages or higher currents. If we connect solar cells in series, and then connect these series groups in parallel, then we can scale both the voltage AND current capacity of the system. By using two solar cells we will investigate the performance of the pair in both series and parallel and gain familiarity with these important concepts.

In order to maximize the accumulated performance of the arrays it is important that each individual cell has identical characteristics. Any cells which do not are labeled as "mismatched" cells. Mismatched cells will cause the output of the entire array to be limited to the capacity of that "bad" cell.
The experiment
For this experiment you will connect two solar cells in series and parallel configurations and take various performance measurements for these configurations.

It should take you about 40 minutes to complete this experiment.

Pre-requisites:
You should have completed the introductory chapters 1, 2 & 5 so that you’re familiar with the equipment setup and capabilities.

Equipment
- PC with LabVIEW 8.5 (or higher)
- NI ELVIS 1, 2 or 2+ and USB cable to suit
- EMONA HELEEx experimental add-in module and Universal Base board
- Assorted patch leads
- Solar cell × 2
Procedure

Part A – Setting up the NI ELVIS/HELEX apparatus

1. Turn off the NI ELVIS unit and its Prototyping Board switch.

2. Plug the HELEX board into the base board, then the base board into the NI ELVIS unit. Lock it into place with the knurled knob on the HELEX board.

Note: This may already have been done for you.

3. Connect the NI ELVIS to the PC using the USB cable.

4. Turn on the PC (if not on already) and wait for it to fully boot up (so that it’s ready to connect to external USB devices).

5. Turn on the NI ELVIS unit but not the Prototyping Board switch yet. You should observe the USB light turn on (top right corner of ELVIS unit). The PC may make a sound to indicate that the ELVIS unit has been detected if the speakers are activated.

6. Turn on the NI ELVIS Prototyping Board switch to power the HELEX board. Check that all three power LEDs are on. If not call the instructor for assistance.

7. Launch the HELEX Main VI.

8. If you’re asked to select a device number, enter the number that corresponds with the NI ELVIS that you’re using and restart the HELEX VI if necessary.

9. Set the HELEX module’s PC CONTROL/MANUAL mode switch to the MANUAL position.

10. You’re now ready to work with the NI ELVIS/HELEX bundle.

Note: To stop the HELEX VI when you’ve finished the experiment, it’s preferable to use the STOP button on the HELEX SFP itself rather than the LabVIEW window STOP button at the top of the window. This will allow the program to conduct an orderly shutdown and close the various DAQmx channels it has opened.

Ask the instructor to check your work before continuing.
Safe operating guidelines to be followed at all times

Intended use:
This equipment is only to be used as directed in this Lab manual and User Manual and for experiments under the supervision of teaching staff.

All users must carefully read the User Manual to become familiar with the operation of this equipment before using this equipment and keep this information available with the equipment at all times.

This equipment may not be used with any other components other than what is supplied with the EMONA HELEX kit and is provided for teaching and demonstration purposes only.

This equipment may only be operated in accordance with local statutory regulations.

DOs – SAFE PRACTICES:
Always read and precisely follow the operating instructions. Ask your instructor if unsure at any time. The instructor is responsible for maintaining correct supervision at all times.
Always wear safety glasses when near the equipment in operation.
Always place the equipment safely at correct distances and with sufficient clear, flat and stable room around it.
Always work in well ventilated spaces with adequate clearance above and around the equipment.
Always fill or empty the electrolyser away from other equipment and over a sink.
Always work in a typical indoor environment of between 10 - 35 C

DONTs - WARNINGS:
Never have any sources of ignition near the equipment.
Never touch the lamp or solar cell when in operation or immediately after until confirming that it has cooled down sufficiently.
Never apply external components or equipment to the HELEX kit such as external power supplies or other apparatus or any signals other than those provided on the HELEX board itself.
Never allow hydrogen or oxygen to accumulate in quantities of more than 20 ml.
Never leave the equipment operating unattended.
Never use any liquid other than steam-distilled water with the electrolyser unit.
Never place the operating lamp closer than 30 cm from any surface.

DANGERS:
Hydrogen and oxygen are highly flammable and explosive gases. There is danger of explosion.

The lamp and solar cell will heat up to high temperatures and there is danger of skin burns if touched.

The lamp will cause surfaces to overheat and burn if placed closer than 30 cm whilst operating.

Avoid spilling the distilled water on any of the HELEX kit, especially the board itself and the NI ELVIS unit and power supply block, to avoid electrical hazards.

Avoid using the equipment if it shows any signs of damage or malfunction. Contact EMONA immediately for repair or replacement after referring to the User Manual for confirmation of correct specifications. There are no user-repairable parts in this kit.
Part B - Solar cells connected in series
Part B lets you investigate the performance of solar cells connected in series.

11. Set up the equipment as shown in the figure below.

![Figure 1: Lamp onto loaded solar cell, with measuring instruments](image)

12. Manually set the load to OPEN Ohms.

13. Adjust the lamp to a distance of 40 cm from the solar cell and an incident angle of 0 degrees.

14. Turn on the lamp and leave it on throughout this part of the experiment.

15. Record the solar cell's output current (measured on CM1) and output voltage (measured on VM1) in the table below. You may wish to use the SMOOTH feature in top right hand corner of the HELEx SFP to average the readings.

<table>
<thead>
<tr>
<th>Connection</th>
<th>Load (ohm)</th>
<th>Current CM1 (mA)</th>
<th>Voltage VM1 (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar cell 1</td>
<td>OPEN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar cell 2</td>
<td>OPEN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Series</td>
<td>OPEN</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

16. Change the set-up as shown in the figure below to add the second solar cell in series.

**Note 1:** Keep the light intensity and load the same.

**Note 2:** Take care not to vary the light’s position as slight changes will nullify the measured values.
17. Record the set-up's output current and output voltage in the table above.

18. Confirm that the current and voltages for the series connection are as you would expect theoretically.

Note: If not, repeat this section of the experiment. Remember to adjust the lamps direction for a maximum reading at the beginning of measurements.

Question 1
Quantify any differences between your measurements and the theoretical expectation. Explain how these differences may have occurred.
Part C - Parallel connection
Part C lets you investigate the performance of solar cells connected in parallel.

19. Set up the equipment as shown in the figure below.

![Diagram of solar cells and measuring instruments](image)

Figure 1: Lamp onto loaded solar cell, with measuring instruments

20. Manually set the load to 1 Ohm.

21. Adjust the lamp to a distance of 40 cm from the solar cell and an incident angle of 0 degrees.

22. Turn on the lamp and leave it on throughout this part of the experiment.

23. Record the solar cell’s output current and output voltage in the table below.

<table>
<thead>
<tr>
<th>Connection</th>
<th>Load (ohm)</th>
<th>Current CM1 (mA)</th>
<th>Voltage VM1 (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar cell 1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar cell 2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ask the instructor to check your work before continuing.
24. Change the set-up as shown in the figure below to add the second solar cell in parallel.

**Note 1:** Keep the light intensity and load the same.

**Note 2:** Take care not to vary the light's position as slight changes will nullify the measured values.

![Solar Cells Diagram](image)

*Figure 3: Lamp onto loaded solar cells in parallel, with measuring instruments*

25. Record the set-up's output current and output voltage in the table above.

26. Confirm that the current and voltages for the series connection are as you would expect theoretically.

**Note:** If not, repeat this section of the experiment.

**Question 2**
Why is a 1 Ohm load used to test the parallel connection and an OPEN circuit load used to test the series connection?

To obtain maximum or near maximum readings in both cases

**Question 3**
Quantify any differences between your measurements and the theoretical expectation. Explain how these differences may have occurred.
Part D – Series & parallel connection load curves
Part D gets you to repeat the tests you conducted in Parts B & C for different values of load to develop load curves for the two connections.

27. Continue with the parallel experiment already set up from Part C.

28. Record the set-up's output current and output voltage in the table below with the manual load (ML1) set to the values listed.

<table>
<thead>
<tr>
<th>Load (ohm)</th>
<th>Current CM1 (mA)</th>
<th>Voltage VM1 (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPEN circuit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHORT circuit</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ask the instructor to check your work before continuing.
29. Reconnect the solar cells in series.

30. Record the set-up's output current and output voltage in the table below with the manual load (PGL) set to the values listed.

Table: I-V readings versus load for series connection

<table>
<thead>
<tr>
<th>Load (ohm)</th>
<th>Current CM1 (mA)</th>
<th>Voltage VM1 (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPEN circuit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
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<tr>
<td>8</td>
<td></td>
<td></td>
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<tr>
<td>4</td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td></td>
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<tr>
<td>SHORT circuit</td>
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</tbody>
</table>

31. Select HELEx SFP tab "Lab 7".

32. Enter the values into the onscreen tables and view the I-V diagrams as well as the calculated power curve.

33. Take a screen shot for your records of all the curves together.

Note: Use the built-in LabVIEW function “export simplified image” to capture the graph. Right click on the graph to select this option.
Question 4
Describe the shape of the curves.

MPP occurs for different load values between series and parallel configurations.

Question 5
For what load values is the maximum power output for both series and parallel configurations? Can you explain why this is so?

Series: approx 32 ohm; this is at the "knee" of the series IV curve
Parallel: approx 4 ohm: in parallel the combined cells have more current drive capability.

Question 6
How can power be supplied to a varying load so that the system is always operating as close to the maximum-power point as possible? What equipment would you need?

Have a MPP tracker, dc-dc converter, to present the optimum load to the solar source and the optimum supply impedance to the load.

Part E - Automated performance monitoring using LabVIEW
Part D of this experiment had you manually construct the I-V-P curves with several readings across the load range. If this process was automated, you could concentrate on varying other parameters whilst observing the performance of the system. This part of the experiment gets you to do that using the programmable load (PGL). This device continuously and rapidly sweeps across the load range while measurements of voltage and current from VM1 and CM1 are taken and plotted by the LabVIEW program.

34. It is preferable if the manual readings are still being displayed in the HELEX SFP.
35. Set up either the series or parallel connections as in previous parts of this experiment.
36. Select the "Expt 7" tab on the HELEX SFP and ensure that the HELEX SFP is running.
37. Select the "TAB" mode on the programmable load PGL panel. This will adjust the programmable load according to values specific to the EXPT 7 TAB. These can be edited if preferred.
38. Set the HELEX module's PC CONTROL/MANUAL mode switch to the PC CONTROL position.
The PGL will vary automatically, at a rate dependent on the "loop delay" value, and the I, V & calculated P values will be displayed 10 points at a time.

39. Compare the automated data points with the static manual points. They should be similar. Vary the light position and study the effect this has on the performance curves.

40. For more detail, switch the PGL mode to FAST and "loop delay" to 10 ms, which will cycle the load through ALL load resistance values from minimum to maximum.

**Question 7**
Has the MPP changed, now that you have more detailed readings? Compare the plots just made with the plots you produced manually. Are they the same? Explain any differences.

MPP may be higher as we capture the peak with the extra resolution.

Ask the instructor to check your work before continuing.
LabVIEW programming task
Using the EXPT 7 TAB code as a starting point, vary the code so that ALL readings accumulated and displayed with infinite persistence. This will give a total overview of the systems performance. Vary the light conditions to see changes more clearly. This data can also be plotted in 3D with the 3rd axis being incident light level. (Use the lux meter to measure this).

Ask the instructor to check your work before finishing.
9 - Electrolyzer performance and the decomposition voltage
Experiment 9 - Electrolyzer performance and the decomposition voltage

Preliminary discussion

What is the value of the voltage at which a current starts to flow in the electrolyser? The initial application of a small voltage does not cause an electrolysis current leading to the release of hydrogen and oxygen. Nothing appears to happen at 1 volt.

The gases that may form at this voltage are initially absorbed on the surface of the electrodes; an electrochemical cell develops. This cell has a certain voltage known as the polarization voltage, which causes a current. This internal current acts in the opposite direction to the electrolysis current. More gases are absorbed if the external voltage is increased. At a certain voltage, the gas pressure at the electrodes reaches the level of the external air pressure, and gas bubbles begin to rise at the electrodes.

A further increase in the external voltage leads to continuous gas production and a steep rise in the electrolysis current strength. The minimum voltage at which the splitting of water begins is called the decomposition voltage. For our electrolyzer, this voltage is equal to the cell voltage of the $\text{H}_2//\text{H}_2\text{O}//\text{O}_2$ electrochemical cell under standard conditions. This value is 1.23 volts.

However, the electrolyzer does not appear to begin operating at this voltage. The difference between the theoretical decomposition voltage and the actual decomposition voltage determined experimentally is termed 'overpotential' or 'overvoltage'.

The overpotential is a function of the electrode material, the texture of the electrode surfaces, the type and concentration of the electrolyte, the current density and the temperature. Overpotentials are small in the case of electrode reactions that lead to the depositing of metals; however, they are particularly large when gases are released.

In practical applications the aim is to keep overpotential to a minimum. It is important in this context to use very good, active electrode and electrolyte materials. The electrolyzer has no liquid electrolyte. The function of the electrolyte is taken over by a special proton conducting membrane called a proton exchange membrane (PEM). This membrane has roughly the acidity of 1 mol.dm$^{-3}$ sulphuric acid. Only precious metals can be used as an electrode in acidic environments.

The oxygen side of the PEM electrolyzer membrane is coated with a special ruthenium - iridium alloy, the hydrogen side with platinum. Very small amounts of both catalysts are applied directly to the membrane in the form of tiny particles. The current is conducted onto the outside using high-grade stainless steel electrodes.

In electrolysis, the catalytic activity of the electrodes is normally the decisive factor in minimizing operational voltage and thus increasing efficiency.
The experiment
For this experiment you'll measure the decomposition voltage for the electrolyser.

It should take you about 30 minutes to complete this experiment.

Pre-requisites:
You should have completed the introductory chapters 1, 2, 5 & 8 so that you’re familiar with the equipment setup and capabilities. Part C of the experiment refers to previous Expt 5, and requires the solar cell data from that experiment.

Equipment

- PC with LabVIEW 8.5 (or higher)
- NI ELVIS 1, 2 or 2+ and USB cable to suit
- EMONA HELE\text{\textregistered}x experimental add-in module and Universal Base board
- Assorted patch leads
- Electrolyzer
- Distilled water \textbf{IMPORTANT}: you must use steam distilled water ONLY
Procedure

Part A – Setting up the NI ELVIS/HELex apparatus

1. Turn off the NI ELVIS unit and its Prototyping Board switch.

2. Plug the HELex board into the base board, then the base board into the NI ELVIS unit. Lock it into place with the knurled knob on the HELex board.

Note: This may already have been done for you.

3. Connect the NI ELVIS to the PC using the USB cable.

4. Turn on the PC (if not on already) and wait for it to fully boot up (so that it’s ready to connect to external USB devices).

5. Turn on the NI ELVIS unit but not the Prototyping Board switch yet. You should observe the USB light turn on (top right corner of ELVIS unit). The PC may make a sound to indicate that the ELVIS unit has been detected if the speakers are activated.

6. Turn on the NI ELVIS Prototyping Board switch to power the HELex board. Check that all three power LEDs are on. If not call the instructor for assistance.

7. Launch the HELex Main VI.

8. If you’re asked to select a device number, enter the number that corresponds with the NI ELVIS that you’re using and restart the HELex VI if necessary.

9. Set the HELex module’s PC CONTROL/MANUAL mode switch to the MANUAL position.

10. You’re now ready to work with the NI ELVIS/HELex bundle.

Note: To stop the HELex VI when you’ve finished the experiment, it’s preferable to use the STOP button on the HELex SFP itself rather than the LabVIEW window STOP button at the top of the window. This will allow the program to conduct an orderly shutdown and close the various DAQmx channels it has opened.

Ask the instructor to check your work before continuing.
Safe operating guidelines to be followed at all times

**Intended use:**
This equipment is only to be used as directed in this Lab manual and User Manual and for experiments under the supervision of teaching staff.

All users must carefully read the User Manual to become familiar with the operation of this equipment before using this equipment and keep this information available with the equipment at all times.

This equipment may not be used with any other components other than what is supplied with the EMONA HELEX kit and is provided for teaching and demonstration purposes only.

This equipment may only be operated in accordance with local statutory regulations.

**DOs – SAFE PRACTICES:**
Always read and precisely follow the operating instructions. Ask your instructor if unsure at any time. The instructor is responsible for maintaining correct supervision at all times.
Always wear safety glasses when near the equipment in operation.
Always place the equipment safely at correct distances and with sufficient clear, flat and stable room around it.
Always work in well ventilated spaces with adequate clearance above and around the equipment.
Always fill or empty the electrolyser away from other equipment and over a sink.
Always work in a typical indoor environment of between 10 - 35°C

**DONTs - WARNINGS:**
Never have any sources of ignition near the equipment.
Never touch the lamp or solar cell when in operation or immediately after until confirming that it has cooled down sufficiently.
Never apply external components or equipment to the HELEX kit such as external power supplies or other apparatus or any signals other than those provided on the HELEX board itself.
Never allow hydrogen or oxygen to accumulate in quantities of more than 20 ml.
Never leave the equipment operating unattended.
Never use any liquid other than steam-distilled water with the electrolyser unit.
Never place the operating lamp closer than 30 cm from any surface.

**DANGERS:**
Hydrogen and oxygen are highly flammable and explosive gases. There is danger of explosion.

The lamp and solar cell will heat up to high temperatures and there is danger of skin burns if touched.

The lamp will cause surfaces to overheat and burn if placed closer than 30 cm whilst operating.

Avoid spilling the distilled water on any of the HELEX kit, especially the board itself and the NI ELVIS unit and power supply block, to avoid electrical hazards.

Avoid using the equipment if it shows any signs of damage or malfunction. Contact EMONA immediately for repair or replacement after referring to the User Manual for confirmation of correct specifications. There are no user-repairable parts in this kit.
Part B - Investigating electrolyzer performance
Part B of the experiment gets you to quantitatively and qualitatively investigate the performance of the electrolyzer.

11. Connect the experimental equipment as shown in the figure below and set the VOLTAGE SOURCE to OFF.

12. Unplug both tubes from the electrolyzer - You'll not be storing the gases.

![Figure 1: Adjustable voltage source driving the electrolyzer, with measuring instruments](image)

13. Set the manual voltage setting on VS to minimum (fully clockwise).

14. Turn the VOLTAGE SOURCE switch to ON. It should read about 1.2 V on VM1 on the HELEx SFP.

Question 1
Did you notice an initial surge of current into the electrolyzer? What type of electronic component does this remind you of?

The capacitor.

Ask the instructor to check your work before continuing.
15. Record the electrolyzer's voltage and current in the top row of the table on the next page.

**Note 1:** These are being measured on VM1 and CM1.

**Note 2:** Allow time for the values to stabilize after the initial current surge. About 20 seconds should be enough.

16. Make a qualitative comment about the volume of gas discharge in the third column of the same row in the table.

---

17. Increase VS by 0.05 V for each reading.

18. Record the electrolyzer’s voltage, current and gas discharge in the next row of the table.

**Note:** Allow at least 20 seconds for the measurements to stabilize before recording them.

19. Repeat these two steps until the electrolyzer's voltage is about 1.5V.

20. Turn VS control fully counter clockwise and then switch to OFF.

---

Ask the instructor to check your work before continuing.
Table 1: voltage at electrolyzer; current into electrolyzer; gas activity comment

<table>
<thead>
<tr>
<th>Voltage at EZ</th>
<th>Current into EZ</th>
<th>Gas activity comment</th>
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Ask the instructor to check your work before continuing.
21. Select the "Expt 9" tab on the HELEX SFP.

22. Enter these values into the on-screen tables to observe the plotted relationship between these parameters.

**Question 2**
Describe the performance of the electrolyzer based on your measurements in the table. Indicate whether it has a voltage at which it becomes active.

*It becomes active and draws significant current only above about 1.4 V*

**Question 3**
What is this activation voltage called?

*The decomposition voltage + overpotential*

**Question 4**
How does this compare with your theoretical expectations?

*It matches expectations of a minimum decomposition voltage + overpotential*

**Question 5**
How would the current change if the VS voltage was increased further?

*It would increase exponentially, until the electrolyser was destroyed.*

Ask the instructor to check your work before continuing.
Part C - Matching electrolyzer load to the solar cell source

In this part of the experiment we will compare the electrolyser load curves with the load curves of the solar cell source. An optimum situation would be that the MPP of the solar cell corresponds closely with the power consumption of the electrolyser load. As discussed previously in Experiment 5, the optimum condition is for the solar cell to operate at its MPP.

It is important to understand the benefit of matching the source with the load. Keep in mind that the electrolyzer operates at points along its own load curve, and nowhere else. So the point of intersection of both the electrolyzer curve and the solar cell curves will be the operating point for the combination.

These operating curves are like “train tracks” in that they specifically define where the unit will and won’t operate.

23. Refer to the data in table 1 of experiment 5 of this manual which was a pre-requisite for this section of the experiment.

24. Enter the I & V values into the on-screen tables of TAB “Expt 9” and compare the electrolyser curves with the solar cell curve. HINT: You may wish to estimate an I-V point which extends the tail of the electrolyser curve to above 300 mA, to make your display easier to view. If so you can enter this new value into the data table. Or else you can simply imagine the extension of the tail.

Question 6
Where is the electrolyser curve relative to the MPP of the solar cell?

To the left of the MPP

Question 7
Describe where the MPP of the solar cell should be for optimum matching between the solar cell source and the electrolyser load.

Optimum would be if the EZ curve ran very closely to the solar cell’s MPP
Question 8
Describe what happens if the electrolyser curve is to the right of the solar cells MPP.

The operating point between the electrolyser and solar cell would fluctuate dramatically.

Question 9
What needs to be done to optimise the power transfer between the solar cell and the electrolyser load?

The load must be made to match the MPP operating point of the source.

Ask the instructor to check your work before finishing.
13 - System efficiency and fuel cell characteristic curves
Experiment 13 - System efficiency and fuel cell characteristic curves

Preliminary discussion

The fuel cells we are using use polymer electrolyte membrane technology (PEMFC) or sometimes known as proton exchange membrane technology as the electrolyte. This electrolyte facilitates electrochemical conversion of energy inside the PEM fuel cell which is practically the reversal of water electrolysis.

A single fuel cells maximum theoretical output voltage depends on the thermodynamics data of the reaction between hydrogen and oxygen to water. Under standard conditions this value is equal to 1.23 V. Notice that this is the same theoretical value as for the decomposition of water in the electrolysis.

\[ \frac{dG}{zF} = 1.23 \text{ V} \]

This theoretical voltage is not achievable due to various losses known as "overvoltage" which occur during operation.

![Figure 1: PEM fuel cell characteristic curve](image-url)
The size of the overvoltage is the decisive factor which determines a fuel cell's efficiency. It is made up of three contending factors:

1) **penetration overvoltage** -- influence of the catalyst
at low currents and voltages close to the thermodynamics voltage, the shape of the characteristic curve is determined by the catalytic processes taking place at the electrodes. This is shown in the characteristic curve by an exponential increase in current relative to the overvoltage. The decisive determinant of the level of current is the speed of the catalytic conversion of the gases hydrogen and oxygen ie the speed with which the electrons passed through the border between the Pt catalyst and the electrolyte. The overvoltage involved in this factor is termed "penetration overvoltage".

2) **internal resistance** -- influence of the fuel cell's structure
every fuel cell has a total internal resistance which manifests as an internal voltage drop at high currents. This voltage drop is proportional to current and this section of the characteristic curve is therefore linear. Keeping the resistance as small as possible is critical to reduce excessive power losses inside the fuel cell.

3) **diffusion overvoltage** -- influence of the transport of material
at the highest currents of operation the ability to import gases through the porous electrodes structure becomes decisive. Diffusion overvoltage occurs when the gases at the catalyst used up more quickly than they can diffuse to the catalyst. This results in a sudden dip in the characteristic curve of the fuel cell and the fuel cell's voltage declines very quickly as the electrode is "starved" of gas.

The aim of all fuel cell development is to minimise these three elements by (1) better catalysts, (2) highly conductive materials, and (3) optimised electrode structures and gas ducts.

The shape of the characteristic curve for the fuel cell is a clear and precise expression of these issues in action.
The experiment
For this experiment you’ll measure the characteristic curve for the fuel cell. As well you will determine the fuel cells efficiency. You will also explore the automating of this process using the LabVIEW controlled programmable load. We will focus on the power output from the fuel cell and consider the need to optimize the operating point of the system with respect to the loads to be supplied. We will assume an adequate store of available $H_2/O_2$ and conduct measurements with the available supplies.

It should take you about 40 minutes to complete this experiment.

Pre-requisites:
You should have completed the introductory chapters 1, 2, 8, 9, 10, 11 & 12 so that you’re familiar with the equipment setup and capabilities.

Equipment
- PC with LabVIEW 8.5 (or higher)
- NI ELVIS 1, 2 or 2+ and USB cable to suit
- EMONA HELEX experimental add-in module and Universal Base board
- Assorted patch leads
- Electrolyzer
- Distilled water
- Dismantlable PEM fuel cell
Procedure

Part A - Setting up the NI ELVIS/HEEx apparatus

1. Turn off the NI ELVIS unit and its Prototyping Board switch.

2. Plug the HEEx board into the base board, then the base board into the NI ELVIS unit. Lock it into place with the knurled knob on the HEEx board.

Note: This may already have been done for you.

3. Connect the NI ELVIS to the PC using the USB cable.

4. Turn on the PC (if not on already) and wait for it to fully boot up (so that it’s ready to connect to external USB devices).

5. Turn on the NI ELVIS unit but not the Prototyping Board switch yet. You should observe the USB light turn on (top right corner of ELVIS unit). The PC may make a sound to indicate that the ELVIS unit has been detected if the speakers are activated.

6. Turn on the NI ELVIS Prototyping Board switch to power the HEEx board. Check that all three power LEDs are on. If not call the instructor for assistance.

7. Launch the HEEx Main VI.

8. If you’re asked to select a device number, enter the number that corresponds with the NI ELVIS that you’re using and restart the HEEx VI if necessary.

9. Set the HEEx module’s PC CONTROL/MANUAL mode switch to the MANUAL position.

10. You’re now ready to work with the NI ELVIS/HEEx bundle.

Note: To stop the HEEx VI when you’ve finished the experiment, it’s preferable to use the STOP button on the HEEx SFP itself rather than the LabVIEW window STOP button at the top of the window. This will allow the program to conduct an orderly shutdown and close the various DAQmx channels it has opened.

Ask the instructor to check your work before continuing.
Safe operating guidelines to be followed at all times

Intended use:
This equipment is only to be used as directed in this Lab manual and User Manual and for experiments under the supervision of teaching staff.

All users must carefully read the User Manual to become familiar with the operation of this equipment before using this equipment and keep this information available with the equipment at all times.

This equipment may not be used with any other components other than what is supplied with the EMONA HELEX kit and is provided for teaching and demonstration purposes only.

This equipment may only be operated in accordance with local statutory regulations.

DOs – SAFE PRACTICES:
Always read and precisely follow the operating instructions. Ask your instructor if unsure at any time. The instructor is responsible for maintaining correct supervision at all times.
Always wear safety glasses when near the equipment in operation.
Always place the equipment safely at correct distances and with sufficient clear, flat and stable room around it.
Always work in well ventilated spaces with adequate clearance above and around the equipment.
Always fill or empty the electrolyser away from other equipment and over a sink.
Always work in a typical indoor environment of between 10 – 35 ℃

DONTs – WARNINGS:
Never have any sources of ignition near the equipment.
Never touch the lamp or solar cell when in operation or immediately after until confirming that it has cooled down sufficiently.
Never apply external components or equipment to the HELEX kit such as external power supplies or other apparatus or any signals other than those provided on the HELEX board itself.
Never allow hydrogen or oxygen to accumulate in quantities of more than 20 ml.
Never leave the equipment operating unattended.
Never use any liquid other than steam-distilled water with the electrolyser unit.
Never place the operating lamp closer than 30 cm from any surface.

DANGERS:
Hydrogen and oxygen are highly flammable and explosive gases. There is danger of explosion.

The lamp and solar cell will heat up to high temperatures and there is danger of skin burns if touched.

The lamp will cause surfaces to overheat and burn if placed closer than 30 cm whilst operating.

Avoid spilling the distilled water on any of the HELEX kit, especially the board itself and the NI ELVIS unit and power supply block, to avoid electrical hazards.

Avoid using the equipment if it shows any signs of damage or malfunction. Contact EMONA immediately for repair or replacement after referring to the User Manual for confirmation of correct specifications. There are no user-repairable parts in this kit.
Part B - Preparation
Part B of the experiment gets you to purge the system of air and build a storage of H₂ and O₂.

Purge the tubes:

11. Connect the experimental equipment as shown in the figure below.

![Diagram of experimental setup](image)

**Figure 2:** Current driven electrolyzer connected to the loaded fuel cell, with measuring instruments.

12. Set the load manually to OPEN CIRCUIT.

13. Fill both sides of the electrolyzer with distilled water up to the 0 ml mark.

14. Turn on the current flow to the electrolyzer at the CURRENT SOURCE ON switch.

**Note:** You should see a constant release of gases in the electrolyzer.

15. Continue to release gases at this rate for 3 minutes. Ensure that the tubes are both unplugged.

**Note 1:** Use the TIMER on the HELEEx SFP for this purpose.

**Note 2:** This activity purges the electrolyzer and fuel cell’s connecting tubes of air by displacing it with O₂ and H₂ respectively.

16. Set the load manually to 32 Ohm and confirm that current and voltage are being generated.

**Note:** You should obtain readings other than 0 mA and 0V on CM2 and VM2.

17. Record the current and voltage readings in the table below.
Table 1: load (Ohms); current (mA); voltage (V)

<table>
<thead>
<tr>
<th>Load (Ohms)</th>
<th>Current (mA)</th>
<th>Voltage (V)</th>
</tr>
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<tbody>
<tr>
<td>32</td>
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</table>

18. Set the load back to OPEN CIRCUIT.
19. After 3 more minutes, turn the current to OFF to temporarily stop the electrolysis.
20. Insert the stoppers into the ends of the fuel cell outlet tubes at points A & B.

Ask the instructor to check your work before continuing.

Build up storage:

21. Turn the current source back ON.

Note 1: Check to make sure that gas is again being released in the electrolyzer.

Note 2: These gases are now being stored in the storage compartments of the electrolyzer. You’ll be able to see this over time.

22. Keep the electrolyzer running until 10 ml of H₂ is created.

Note: Don’t let the electrolyzer create more than 10 ml of H₂.

23. Turn the current source to OFF when exactly 10 ml of H₂ is created.

24. Note the level of H₂ & O₂ in the table.

Table 2: starting levels of H₂ & O₂ (ml)

<table>
<thead>
<tr>
<th>H₂ (ml)</th>
<th>O₂ (ml)</th>
</tr>
</thead>
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</table>
Part C - Manually measuring the fuel cell characteristic curve

Part C gets you to consume all of the stored H₂ and O₂ while taking voltage and current measurements for different loads in order to build up load curves for the fuel cell.

Important note: You're limited in this activity by the time it takes to consume the stored gases. So read all of the instructions in Part C before attempting them to ensure that you know what you're going to be doing and have all the equipment needed. For a guide about how long you have to perform these steps, see Part E of Experiment 12.

You will need to move quickly from measurement to measurement, so as to complete before your gas supply runs out. If it does, then replenish your storage and then continue.

25. Set the fuel cell's load to OPEN CIRCUIT.

26. Reset and restart the TIMER.

27. Give the set-up about 20 seconds to settle down then note the time, voltage and current. Record these in the table on the next page.

28. Set the fuel cell's load to the next value in the table.

29. Repeat Steps 27 and 28 until you have taken the measurement for 0.25 ohm.

Note: The setting below 0.25 ohm on the HELEX is SHORT CIRCUIT but don't use this setting as it will consume gas unnecessarily.

30. Once you have taken all the measurements return the load setting to 1 ohm to allow all the fuel to be consumed.

Note: Notice that air is now being drawn into the storage chambers. It is interesting to note how the air is drawn into the storage chambers via the submerged inlet pipe.
### Table 3: load (Ohms); time (s); voltage (V); current (mA)

<table>
<thead>
<tr>
<th>load (Ohms)</th>
<th>time (s)</th>
<th>voltage (V)</th>
<th>current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPEN CIRCUIT</td>
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<td>32</td>
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Ask the instructor to check your work before continuing.
**Question 1**
What is drawing air into the storage chambers?

The fuel cell is drawing it in as it consumes the hydrogen remaining in the tubes.

---

**Question 2**
What happens to the output voltage and current into the load as air enters the system replacing the oxygen and hydrogen?

The output power starts to reduce.

---

31. Select the "Expt 13" tab in the HELEX SFP.
32. Enter the readings you have just taken into the on-screen table.
33. Study the measured load curves and the calculated power curve.

**Question 3**
For what value of load does the fuel cell achieve the maximum output power?

Between 0.25 and 1 ohm

---

Ask the instructor to check your work before continuing.
Question 4
What aspect of the fuel cell is responsible for this?

Max power occurs for a load which matches the fuel cell's internal output impedance.

Question 5
What implications does this have on an electrical system being supplied by a fuel cell?

The design should aim to load the fuel cell with the optimum value for maximum power transfer.

Question 6
Was the rate of gas consumption constant? What seems to affect this?

No. The power delivered to the load.

Question 7
What would happen if you restricted the gas flow into the device?

The output power would drop.

Ask the instructor to check your work before continuing.
Part D - Automated performance monitoring using LabVIEW

Part C of this experiment had you manually construct the load curves with several readings across the load range. If this process was automated, you could concentrate on varying other parameters whilst observing the performance of the system. This part of the experiment gets you to do that using the programmable load (PGL). This device continuously and rapidly sweeps across the load range while measurements of voltage and current from VM2 and CM2 are taken and plotted by the LabVIEW program.

34. Set the HELEX module's PC CONTROL/MANUAL mode switch to the PC CONTROL position.

35. Select the "Expt 13" tab on the HELEX SFP.

36. Repeat steps 11 to 24 from Part B to build up a store of H₂ & O₂ in the storage chambers.

37. Once the set-up is ready, select TAB for the PGL mode.

38. RUN the PGL on the HELEX SFP.

Note: This will continuously vary the load presented to the fuel cell according to the array of values defined in the EXPT 13 TAB code. As this is runs, you will see displayed the V-I-P curves plotted in real time.

Question 8
Compare the plots just made with the plots you produced manually. Are they the same? Explain any differences.

They should be the same because none of the other parameters have been changed.

We can now vary system parameters affecting the fuel cell to view changes in the output performance as they are being graphed.

39. Repeat steps 11 to 24 from Part B to build up a store of H₂ & O₂ in the storage chambers. This time, pinch the hydrogen supply tube close to the fuel cell to reduce the amount of H₂ getting to the fuel cell.

Question 9
What affect does this have on the performance?

Peak power point drops after the fuel cell has consumed the remaining gas within its casing.
40. Pinch the oxygen supply tube close to the fuel cell to reduce the amount of $O_2$ getting to the fuel cell.

**Question 10**
What affect does this have on the performance?

_Same as Q9_

41. Pinch both the Hydrogen & Oxygen supply tubes to reduce the amount of $H_2$ and $O_2$ getting to the fuel cell.

**Question 11**
What affect does this have on the performance?

_Same as Q9_

42. Disconnect the oxygen supply line to the fuel cell at point C to introduce air instead of pure oxygen. Air has approx. 30% oxygen. Do this while viewing the automated characteristic curves in real time.

**Question 12**
What affect does this have on the fuel cell performance?

_Slight reduction in power output after a minute or so_

---

Ask the instructor to check your work before continuing.
Part E - System efficiency under load
In this experiment we use data from previous experiments to calculate efficiencies throughout the system.

**Question 13**
Calculate how much potential energy is contained in the stored H$_2$ and O$_2$?

From EXPT 10, 10 ml of hydrogen contains 119 J of energy

**Question 14**
From your previous measurements what is the maximum instantaneous output power of the fuel cell?

Approx 600 mW

**Question 15**
For how long can the fuel cell maintain its max output power using the stored gas in the chambers?

How long can it run before all gas consumed...approx 70 sec

**Question 16**
What is the efficiency of the fuel cell’s output relative to the potential energy of the gases?

\[
\text{Elec energy output (P x t)} / \text{chemical energy of the gas (119J)}
\]

Should do better than 40 %

**Question 17**
How much energy is input to the electrolyzer from the constant current source on the HELEEx board?

\[
\text{Energy in = P x t = V.I.t}
\]
Figure 3: system efficiency diagram

The system efficiency diagram allows us to see the compounding effects of progressive losses throughout each point in the system.

Power source: for simplicity let us normalise this to an initial value of 100 units. This source of power to the electrolyser may be either (a) the power output by a solar cell using renewable solar energy or (b) the power output by a current source such as that on the HELEX board.

Electrolyser: the electrolyser loss is the difference between the input energy and the chemical energy contained in the produced hydrogen and oxygen gases.

$H_2/O_2$ energy: this loss is the difference between the maximum possible energy contained in the gases and the available energy that can be actually utilised.

Fuel cell: the fuel cell loss is the difference between the actual usable energy input to the fuel cell as gases compared to the actual energy output by the fuel cell into the load.

Load: depending on the level of the load the efficiency of the fuel cell will vary. We will aim to take measurements at the optimum load level for the fuel cell.

**Question 18**
From the calculation of power into the electrolyzer, and the maximum instantaneous output power of the fuel cell, calculate the maximum efficiency of the electrolyzer-fuel cell system.
Using Figure 2, an efficiency diagram, fill in each efficiency for the components of the system.

$1 \times .92 \times .95 \times .35 = 31\%$

**Question 19**
What implications does this have?

Most losses occur in the fuel cell, however this is twice as good as an internal combustion engine.
**Question 20**
Which parts of this model do not matter or will be replaced in a real world application?

*Power source from renewable can be considered as “free” energy.*

**Question 21**
What are the advantages and disadvantages of using systems of this nature?

*Establishment costs need to be factored, as well as life span.*

*Fuel cells are very low maintenance due to no moving parts.*

**Question 22**
What are the various costs at each point in the chain?
eg: environmental, production, maintenance, other? Discuss.

*Energy is needed to store and recover stored hydrogen, leakage, manufacturing energy costs.*
LabVIEW programming task
Create a program to plot the load power curve in real time, and calculate the area under the curve, hence the total energy consumed by the load for 10 ml of hydrogen. This will create a more accurate figure for energy.

Ask the instructor to check your work before finishing.
17 - Stacking multiple fuel cells - parallel and series
Experiment 17 - Stacking multiple fuel cells - parallel and series

Preliminary discussion
The hydrogen fuel cell produces an output voltage by electrochemically combining hydrogen and oxygen gases. As you have seen in previous experiments the output voltage of a single fuel cell is limited to approximately 1 V. In the same way that solar cells and conventional batteries can be connected in series to achieve higher output voltages, multiple fuel cells can also be connected in series to produce a high output voltage.

To achieve a higher output current than is possible with a single fuel cell, multiple fuel cells can be connected in parallel. This ability to combine multiple fuel cells is usually achieved in what is known as a "stacked" fuel cell where multiple identical fuel cells are very closely packed together.

The ability to produce efficient stacked fuel cells makes it possible to use fuel cells in a variety of different applications. Unlike conventional batteries supplies where the reactants are eventually used up and the batteries are disposed of or recharged, a fuel cell stack will continue to provide energy so long as hydrogen and oxygen are supplied to it.

Some typical applications of stacked fuel cells are:

Hydrogen powered electric vehicles: being able to switch multiple fuel cells into different configurations improves the flexibility and adaptability of multiple fuel cells in electric vehicles.

Space travel: the modern fuel cell was developed for use in space travel when in the 1960’s a source of electrical energy which did not require combustion was required.

Portable devices and appliances: smaller electronic devices such as laptops can also be powered using fuel cells by having small refillable hydrogen canisters in place of where our current batteries are now.
The experiment
In this experiment you will model a simple stacked fuel cell using two elements. You'll measure the characteristic curve for two fuel cells connected in parallel and also in series. You will investigate how increase voltages can be achieved or increased current output capability can be achieved, using multiple fuel cells. You'll see how the operating point of stacked fuel cells is determined by the electric load being driven. As well, you’ll investigate the issues involved in combining different fuel cells in parallel.

This experiment requires 4 complete sets of measurements. Each set of measurements should only take less than five minutes, though building up adequate supplies of hydrogen and oxygen and purging the tubes may take a little time. The familiarity of the students with using apparatus in previous experiments will make a big difference in the time taken to complete this experiment.

Throughout this experiment, you will need to purge and ensure that the tubes are well charged with gasses to achieve good performance from the cell. As there is more tube length it will take longer to purge and prime the fuel cells. Be aware that any weak performance from a fuel cell is most likely causes by not having been adequately purged and charged with gasses.

It should take you about 60 minutes to complete this experiment.

Pre-requisites:
You should have completed the introductory chapters 1,2,11,12,13 so that you’re familiar with the equipment setup and capabilities.

Equipment

- PC with LabVIEW 8.5 (or higher)
- NI ELVIS 1, 2 or 2+ and USB cable to suit
- EMONA HELEx experimental add-in module and Universal Base board
- Assorted patch leads
- Electrolyzer
- Distilled water
- PEM fuel cell
- Dismantable PEM fuel cell
- 2 x 40cm tubes, 4 x 20cm tubes, 2 stoppers
Procedure

Part A - Setting up the NI ELVIS/HELeX apparatus

1. Turn off the NI ELVIS unit and its Prototyping Board switch.

2. Plug the HELeX board into the base board, then the base board into the NI ELVIS unit. Lock it into place with the knurled knob on the HELeX board.

Note: This may already have been done for you.

3. Connect the NI ELVIS to the PC using the USB cable.

4. Turn on the PC (if not on already) and wait for it to fully boot up (so that it's ready to connect to external USB devices).

5. Turn on the NI ELVIS unit but not the Prototyping Board switch yet. You should observe the USB light turn on (top right corner of ELVIS unit). The PC may make a sound to indicate that the ELVIS unit has been detected if the speakers are activated.

6. Turn on the NI ELVIS Prototyping Board switch to power the HELeX board. Check that all three power LEDs are on. If not call the instructor for assistance.

7. Launch the HELeX Main VI.

8. If you're asked to select a device number, enter the number that corresponds with the NI ELVIS that you're using and restart the HELeX VI if necessary.

9. Set the HELeX module's PC CONTROL/MANUAL mode switch to the MANUAL position.

10. You're now ready to work with the NI ELVIS/HELeX bundle.

Note: To stop the HELeX VI when you've finished the experiment, it's preferable to use the STOP button on the HELeX SFP itself rather than the LabVIEW window STOP button at the top of the window. This will allow the program to conduct an orderly shutdown and close the various DAQmx channels it has opened.

Ask the instructor to check your work before continuing.
Safe operating guidelines to be followed at all times

Intended use:
This equipment is only to be used as directed in this Lab manual and User Manual and for experiments under the supervision of teaching staff.

All users must carefully read the User Manual to become familiar with the operation of this equipment before using this equipment and keep this information available with the equipment at all times.

This equipment may not be used with any other components other than what is supplied with the EMONA HELEx kit and is provided for teaching and demonstration purposes only.

This equipment may only be operated in accordance with local statutory regulations.

DOs – SAFE PRACTICES:
Always read and precisely follow the operating instructions. Ask your instructor if unsure at any time. The instructor is responsible for maintaining correct supervision at all times.
Always wear safety glasses when near the equipment in operation.
Always place the equipment safely at correct distances and with sufficient clear, flat and stable room around it.
Always work in well ventilated spaces with adequate clearance above and around the equipment.
Always fill or empty the electrolyser away from other equipment and over a sink.
Always work in a typical indoor environment of between 10 – 35 C

DONTs - WARNINGS:
Never have any sources of ignition near the equipment.
Never touch the lamp or solar cell when in operation or immediately after until confirming that it has cooled down sufficiently.
Never apply external components or equipment to the HELEx kit such as external power supplies or other apparatus or any signals other than those provided on the HELEx board itself.
Never allow hydrogen or oxygen to accumulate in quantities of more than 20 ml.
Never leave the equipment operating unattended.
Never use any liquid other than steam-distilled water with the electrolyser unit.
Never place the operating lamp closer than 30 cm from any surface.

DANGERS:
Hydrogen and oxygen are highly flammable and explosive gases. There is danger of explosion.

The lamp and solar cell will heat up to high temperatures and there is danger of skin burns if touched.

The lamp will cause surfaces to overheat and burn if placed closer than 30 cm whilst operating.

Avoid spilling the distilled water on any of the HELEx kit, especially the board itself and the NI ELVIS unit and power supply block, to avoid electrical hazards.

Avoid using the equipment if it shows any signs of damage or malfunction. Contact EMONA immediately for repair or replacement after referring to the User Manual for confirmation of correct specifications. There are no user-repairable parts in this kit.
Part B - Preparation
Part B of the experiment gets you to purge the system of air and build a storage of $H_2$ and $O_2$.

Purge the tubes:

11. Connect the experimental equipment as shown in the figure below.

Figure 1 shows both fuel cells being supplied with hydrogen and oxygen from the electrolyser. The load is only connected to one of the fuel cells in order to take individual fuel cell characteristic curve measurements later in this experiment. The other fuel cell is unloaded ie has an open circuit load, and will consume very little hydrogen or oxygen.

![Figure 1: Current driven electrolyzer, with multiple fuel cells and measuring instruments. Only one fuel cell is loaded.](image)

12. Set the load manually to OPEN CIRCUIT.

13. Fill both sides of the electrolyzer with distilled water up to the 0 ml mark.

14. Turn on the current flow to the electrolyzer at the CURRENT SOURCE ON switch.

Note: You should see a constant release of gases in the electrolyzer.

15. Continue to release gases at this rate for 10 minutes. This is longer than usual as we have a second fuel cell and connecting tubes to be purged. The tube ends should both be unplugged.

Note 1: Use the TIMER on the HELEX SFP for this purpose.

Note 2: This activity purges the electrolyzer and fuel cell's connecting tubes of air by displacing it with $O_2$ and $H_2$ respectively.
16. Set the load manually to 32 Ohm and confirm that current and voltage are being generated.

**Note:** You should obtain readings other than 0 mA and 0V on CM2 and VM2.

17. Record the current and voltage readings in the table below as confirmation.

<table>
<thead>
<tr>
<th>Load (Ohms)</th>
<th>Current (mA)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td></td>
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</table>

18. Set the load back to OPEN CIRCUIT.

19. After 5 more minutes, turn the current to OFF to temporarily stop the electrolysis.

20. Insert the stoppers into the ends of the fuel cell outlet tubes at points A & B.

Build up storage:

21. Turn the current source back ON.

**Note 1:** Check to make sure that gas is again being released in the electrolyzer.

**Note 2:** These gases are now being stored in the storage compartments of the electrolyzer. You’ll be able to see this over time.

22. Keep the electrolyzer running until 10 ml of H₂ is created.

**Note:** Don’t let the electrolyzer create more than 10 ml of H₂.

23. Turn the current source to OFF when exactly 10 ml of H₂ is created.

Ask the instructor to check your work before continuing.
24. Note the level of $\text{H}_2$ & $\text{O}_2$ in the table as confirmation.

**Table 2: starting levels of H$_2$ & O$_2$ (ml)**

<table>
<thead>
<tr>
<th>H$_2$ (ml)</th>
<th>O$_2$ (ml)</th>
</tr>
</thead>
<tbody>
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</table>

25. Set the fuel cell's load to OPEN CIRCUIT.

26. Reset and restart the TIMER.

27. Give the set-up about 5 seconds to settle down then note the time, voltage and current. Record these in the table on the next page.

28. Set the fuel cell's load to the next value in the table.

29. Repeat Steps 27 and 28 until you have taken the measurement for 0.25 Ohm.

**Note:** The setting below 0.25 Ohm on the HEEX is SHORT CIRCUIT but don't use this setting! See the next step.

30. Set the fuel cell's load to OPEN CIRCUIT so as to not consume any more gases.

**Part C - Manually measuring the individual fuel cells' characteristic curve**  
In Part C you will consume all of the stored $\text{H}_2$ and $\text{O}_2$ while taking voltage and current measurements for different loads in order to build up the characteristic load curves for each individual fuel cell.

**Important note:** You're limited in this activity by the time it takes to consume the stored gases. So read all of the instructions in Part C before attempting them to ensure that you know what you're going to be doing and have all the equipment needed.

31. Ask the instructor to check your work before continuing.
### Table 3: FIRST FUEL CELL ONLY: load (Ohms); voltage (V); current (mA); power (mW)

<table>
<thead>
<tr>
<th>load (Ohms)</th>
<th>voltage (V)</th>
<th>current (mA)</th>
<th>power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPEN CIRCUIT</td>
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<td></td>
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<td>32</td>
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<tr>
<td>0.25</td>
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</tbody>
</table>

31. Calculate and tabulate the power for each load setting in the table above. Note the MPP.

You have completed the measurements for one of the fuel cells, you’ll now repeat the above process for the second fuel cell to take its individual measurements.

32. Connect the experimental equipment as shown in the figure below.

Figure 2 shows both fuel cells being supplied with hydrogen and oxygen from the electrolyser. The load is only connected to the second of the fuel cells in order to its individual fuel cell characteristic curve measurements. The other fuel cell is unloaded ie has an open circuit load, and will consume very little hydrogen or oxygen.
Figure 2: Current driven electrolyzer, with multiple fuel cells and measuring instruments. Only one fuel cell is loaded.

Build up storage again:

33. Turn the current source back ON.

Note 1: Check to make sure that gas is again being released in the electrolyzer.

Note 2: These gases are now being stored in the storage compartments of the electrolyzer. You’ll be able to see this.

34. Keep the electrolyzer running until 10 ml of H$_2$ is created.

Note: Don’t let the electrolyzer create more than 10 ml of H$_2$.

35. Turn the current source to OFF when exactly 10 ml of H$_2$ is created.

36. Note the level of H$_2$ & O$_2$ in the table as confirmation.

Table 4: starting levels of H$_2$ & O$_2$ (ml)

<table>
<thead>
<tr>
<th>H$_2$ (ml)</th>
<th>O$_2$ (ml)</th>
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</thead>
<tbody>
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</tbody>
</table>

Important note: You’re limited in this activity by the time it takes to consume the stored gases. So read all of the instructions before attempting them to ensure that you know what you’re going to be doing and have all the equipment needed. Take down the reading quickly then immediately move onto the next load value.

37. Set the fuel cell’s load to OPEN CIRCUIT.

38. Reset and restart the TIMER.
39. Give the set-up about 15 seconds to settle down then note the time, voltage and current. Record these in the table on the next page.

40. Set the second fuel cell’s load to the next value in the table.

41. Repeat Steps 27 and 28 until you have taken the measurement for 0.25 Ohm.

**Note:** The setting below 0.25 Ohm on the HELEX is **SHORT CIRCUIT** but **don't use this setting!** See the next step.

42. Set the fuel cell’s load to OPEN CIRCUIT so as to not consume any more gases.

43. Calculate and tabulate the power for each load setting in the table. Note the MPP.

Table 5: SECOND FUEL CELL ONLY: load (Ohms); voltage (V); current (mA); power (mW)

<table>
<thead>
<tr>
<th>load (Ohms)</th>
<th>voltage (V)</th>
<th>current (mA)</th>
<th>power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPEN CIRCUIT</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>32</td>
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<tr>
<td>0.25</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

**Question 1**
How do the readings for each individual fuel cell compare?

They are about the same..but not exactly
Part D - Fuel cells in series measurements

You have completed the measurements for each individual fuel cell. You’ll now repeat the above process for both fuel cells connected in series.

44. Connect the experimental equipment as shown in the figure below.

Figure 3 shows both fuel cells being supplied with hydrogen and oxygen from the electrolyser. The electrical outputs of the fuel cells are connected in series and the load is connected across the series combination of the outputs.

![Figure 3: Current driven electrolyzer, with multiple fuel cells connected in series and measuring instruments. Both fuel cells are now loaded in series.](image)

Build up storage again:

45. Turn the current source back ON.

**Note 1:** Check to make sure that gas is again being released in the electrolyzer.

**Note 2:** These gases are now being stored in the storage compartments of the electrolyzer. You’ll be able to see this.

46. Keep the electrolyzer running until 10 ml of H₂ is created.

**Note:** Don’t let the electrolyzer create more than 10 ml of H₂.

47. Turn the current source to OFF when exactly 10 ml of H₂ is created.

---

17-12 © Emona Instruments Experiment 17 - Stacking multiple fuel cells-parallel and series
48. Note the level of \( H_2 \) & \( O_2 \) in the table as confirmation.

Table 6: starting levels of \( H_2 \) & \( O_2 \) (ml)

<table>
<thead>
<tr>
<th>H2 (ml)</th>
<th>O2 (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

**Important note:** You're limited in this activity by the time it takes to consume the stored gases. So read all of the instructions before attempting them to ensure that you know what you're going to be doing and have all the equipment needed.

49. Set the fuel cell's load to OPEN CIRCUIT.

50. Reset and restart the TIMER.

51. Give the set-up about 5 seconds to settle down then note the time, voltage and current. Record these in the table on the next page.

52. Set the combined in-series fuel cells' load to the next value in the table.

53. Repeat Steps 27 and 28 until you have taken the measurement for 0.25 Ohm.

**Note:** The setting below 0.25 Ohm on the HELEX is SHORT CIRCUIT but don't use this setting! See the next step.

54. Set the fuel cell's load to OPEN CIRCUIT so as to not consume any more gases.

55. Calculate and tabulate the power for each load setting in the table above. Note the MPP.
Table 7: SERIES CONNECTION: load (Ohms); time (s); voltage (V); current (mA); power (mW)

<table>
<thead>
<tr>
<th>load (Ohms)</th>
<th>voltage (V)</th>
<th>current (mA)</th>
<th>power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPEN CIRCUIT</td>
<td></td>
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<tr>
<td>32</td>
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<td>0.5</td>
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<td>0.25</td>
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</table>

56. Take a look at your measurements and compare them with those for either of the individual fuel cell measurements above. Confirm that the output voltage is greater for the series connection as you would expect. This quick check confirms that your experimental procedure is working correctly.

You should always check that the measurements you are getting are what you would expect in order to confirm that your experimental procedure is working correctly. This is good experimental procedure.

**Question 2**
How do the voltage readings for the series connection compare with either of the readings for the individual fuel cells?

They are about double.
Part E – Fuel cells in parallel measurements

You have completed the measurements for the series connection of the fuel cells. You’ll now repeat the above process for both fuel cells connected in parallel.

Figure 4: Current driven electrolyzer, with multiple fuel cells connected DIRECTLY in parallel and measuring instruments. DO NOT CONNECT THE FUEL CELLS LIKE THIS. CONTINUE READING.

Think back to your notes on “Experiment 7 -- Multiple solar cell configurations and performance”, where you connected to solar cells in parallel. In that experiment you used to identical solar cells. By identical we mean that they’re output voltage was identical and the internal output impedance was also very similar. They had identical construction.

In the previous sections of this experiment you have taken measurements for each of the two fuel cells individually. In the table below note the OPEN circuit voltage of each of the fuel cells.

<table>
<thead>
<tr>
<th>Dismantlable fuel cell (V)</th>
<th>PEM fuel cell (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</table>

Notice that the OPEN circuit voltage for each fuel cell is different. If you were to connect these fuel cells directly in parallel, current would flow from the fuel cell output with the
higher output voltage value into the fuel cell with the lower output voltage. This current flow into a fuel cell is something that we must avoid and which in fact will damage the fuel cell.

The two fuels cells supplied, a dismantlable fuel cell and an intact fuel cell, do in fact have differing internal resistances and output voltages. They cannot be connected directly in parallel.

In a stacked fuel cell, many identical fuel cell membranes are used together, and the fact that they are identical avoids this problem.

In order to complete this experiment so as to be able to explore the principal of additive currents for fuel cells in parallel there is an additional piece of apparatus which must be used. Diodes must be placed into the output path of each of the supplied fuel cells in order to stop current flowing into the fuel cell. On the HELEX board are provided two diodes for this very purpose. Refer to the user manual for more specific information about these diodes.

When current flows through a diode in the conducting direction there will be a voltage drop across the diode. This is an unavoidable loss of power from the fuel cells and will bias our voltage readings by a small amount if measurements are taken at the load, after the diodes. By using the diodes, and taking our measurements before the diodes however, we will still be able to explore the principal of parallel fuel cells.

57. Connect the experimental equipment as shown in the figure below.

Figure 4 shows both fuel cells being supplied with hydrogen and oxygen from the electrolyser. The electrical outputs of the fuel cells are connected in parallel through diodes and the load is connected to the junction of the diodes. The load will receive the summed currents, \( CM1 + CM2 \).
CM1 is measuring the current out of fuel cell 1. CM2 is measuring the current out of fuel cell 2. VM1 is measuring the voltage directly at the output of the fuel cell, and VM2 is measuring the voltage directly at the output of fuel cell 2.

\[ VM_{average} = \frac{VM1 + VM2}{2} \]

As these output voltages differ, we will use the average voltage to estimate the output voltage for our modeled stack of fuel cell.

Build up storage again:

58. Turn the current source back ON.

**Note 1:** Check to make sure that gas is again being released in the electrolyzer.

**Note 2:** These gases are now being stored in the storage compartments of the electrolyzer. You’ll be able to see this.

59. Keep the electrolyzer running until 10 ml of H₂ is created.

**Note:** Don’t let the electrolyzer create more than 10 ml of H₂.

60. Turn the current source to OFF when exactly 10 ml of H₂ is created.

61. Note the level of H₂ & O₂ in the table as confirmation.

**Table 8: starting levels of H₂ & O₂ (ml)**

<table>
<thead>
<tr>
<th>H₂ (ml)</th>
<th>O₂ (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Important note:** You’re limited in this activity by the time it takes to consume the stored gases. So read all of the instructions before attempting them to ensure that you know what you’re going to be doing and have all the equipment needed.

62. Set the fuel cell's load to OPEN CIRCUIT.

63. Reset and restart the TIMER.

64. Give the set-up about 5 seconds to settle down then note the CM1, CM2, VM1 and VM2 readings. Record these in the table on the next page.

65. Set the load to the next value in the table.

66. Repeat Steps 64 and 65 until you have taken the measurement for 0.25 Ohm.
Note: The setting below 0.25 Ohm on the HELEX is SHORT CIRCUIT but don’t use this setting! See the next step.

67. Set the fuel cell’s load to OPEN CIRCUIT so as to not consume any more gases.

<table>
<thead>
<tr>
<th>load (Ohms)</th>
<th>VM1 (V)</th>
<th>CM1 (mA)</th>
<th>VM2 (V)</th>
<th>CM2 (mA)</th>
<th>(VM1+VM2)/2 (V)</th>
<th>CM1 + CM2 (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPEN CIRCUIT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>32</td>
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<td>16</td>
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<td>8</td>
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<td>4</td>
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<td>2</td>
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<tr>
<td>1</td>
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<tr>
<td>0.5</td>
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</tr>
<tr>
<td>0.25</td>
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</tr>
</tbody>
</table>

68. Take a look at your measurements and compare them with those for either of the individual fuel cell measurements above. Confirm that the total current is greater for the parallel connection as you would expect. This quick check confirms that your experimental procedure is working correctly.

You should always check that the measurements you are getting are what you would expect in order to confirm that your experimental procedure is working correctly. This is good experimental procedure.

69. Add the CM1 and CM2 current values together and enter into the "CM1 + CM2" column. This is the total current from both fuel cells, in effect, the current from our higher power “stacked cell”.
Notice how the current from each fuel cell is different.

**Question 3**
Can you explain why the currents from each fuel cell are different to each other?

Each fuel cell has a different characteristic curve as they are not identical.

**Question 4**
How do the total current readings for the parallel connection compare with either of the readings for the individual fuel cells?

They are about double.

70. Calculate the average voltage for both the fuel cells, and enter into the appropriate column. This will be your voltage estimate for the modeled "stacked fuel cell".

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Part F – Plotting the measurements using LabVIEW

71. Select the "Expt 17" tab in the HELEX SFP.

72. Enter the readings you have just taken from the tables in Parts B, C, D into the on-screen table.

73. For part E, make the following changes. For "parallel current" enter the total current value.

74. For "parallel voltage" enter the average value calculated above.

75. Study the measured load curves.

---
76. Take a screenshot or printout of these results for your report.

**Note:** Use the built-in LabVIEW function "export simplified image" to capture the graph. Right click on the graph to select this option.

**Question 5**
How do the individual fuel cell curves compare to each other?

They are similar

**Question 6**
For current level of 400 mA, what is the voltage output for the series connection and the individual fuel cells? Draw an imaginary vertical line at 400 mA to help with this measurement.

Series should be the sum of the average individual values.

**Question 7**
For voltage level of 0.7 V, what is the current output for the parallel connection and the individual fuel cells? Draw an imaginary horizontal line at 0.7 V to help with this measurement.

Parallel should be the sum of the average individual values.
Part G – Revisiting Ohm’s law

You currently have onscreen four characteristic curve plots which have all used a purely resistive load. These measurements should be in accordance with Ohm’s law, which states:

\[ V = I \times r \]

For a resistive load the voltage shall be proportional to the current and so a plot of the voltage versus the current should be a straight line with slope equal to the value of the load, \( r \).
In this case the points on each of the four curves for a particular load value should all be on a straight line passing through the origin of the plot.

77. Using a printout of the plot generated above, draw a line through the four points associated with the load value 4 ohms.

78. Draw in a line through all points associated with the load value 1 ohm.

**Question 8**
Do these points each sheet on a straight line which passes through the origin?

Yes

**Question 9**
For the series connection readings taken at 4 ohms, what is the value of the voltage divided by the current at that load setting?

Should be close to 4

**Question 10**
Explain why any differences may have occurred if you’re readings are not as expected?

Various reasons, depending on the students experimental procedure.

Question aims to get students reviewing their process.
LabVIEW programming task - Ohm’s law in action

Using a copy of the LabVIEW program provided, modify the graph output for TAB “Expt 17” to plot the four values for each of the 10 load settings as an individual plot line emanating from the origin. In this way you can use LabVIEW to see if the data for each load setting does indeed lie on a straight line as stated by Ohms law. If it doesn't then review your measurements and procedures as Ohms law is unlikely to be at fault.

LabVIEW programming task - Automated tabulation

Using the supplied program as a starting point, edit the program to add a button which when pressed automatically enters the VM1, CM1, VM2, CM2 readings directly into your onscreen table. This will reduce the time needed to tabulate the readings, whilst still maintaining manual control over the process.
Emona HELEX™ Lab Manual for NI™ ELVIS I & II/+  
Experiments in Solar Cell and Hydrogen Fuel Cell Technologies  
For NI™ ELVIS I and II.  
Author: Carlo Manfredini

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