

REIES – Lesson 4d: Chemical Energy

Exercise Sheet

Complete the exercises below to practise the concepts from Lesson 4d. Show all working for calculation questions.

Section A – Knowledge Questions

Exercise 1



Knowledge

The lesson introduces electrolysis and the electrolyser as a way to convert electrical energy into chemical energy.

- Explain in your own words what electrolysis is and what the role of the membrane is in an electrolyser. Why is separation of the anode and cathode compartments important?
- The lesson shows the overall water dissociation reaction: $2 \text{H}_2\text{O} \rightleftharpoons 2 \text{H}_2 + \text{O}_2$. Identify which gas is produced at the anode and which at the cathode. Why would it be dangerous to allow these two gases to mix?
- Three scientists are mentioned in connection with the early history of electrolysis. Name at least two of them and describe one industrial process (other than water electrolysis) that is based on electrolysis.

Exercise 2



Knowledge

The lesson covers four types of electrolyzers that are commercially relevant: Alkaline (ALK/AEL), Anion Exchange Membrane (AEM), Proton Exchange Membrane (PEM), and Solid Oxide (SOEC/HT).

- Complete the comparison table below using information from the lesson.

Property	Alkaline (ALK)	AEM	PEM	SOEC / HT
Ion transported across membrane				
Electrolyte type				
Operating temperature (°C)				
Electrode material (cathode)				

Key advantage (one)				
Key disadvantage (one)				

- What is meant by the 'balance of plant' in an electrolyser system? Give three examples of balance-of-plant components mentioned in the lesson.
- The lesson says that electricity cost is by far the largest operating expenditure (Opex) for an electrolyser. Why does this make PEM electrolyzers particularly attractive for integration with intermittent renewable energy sources such as wind and solar?

Exercise 3



Knowledge

The lesson discusses fuel cells as the reverse process of electrolysis, and batteries as a second form of chemical energy storage.

- Explain the key difference between a fuel cell and a combustion engine, even though both convert chemical energy into useful work. What unique advantage does a hydrogen fuel cell have in terms of emissions?
- What is a reversible solid oxide cell (rSOC)? What does it enable that a conventional electrolyser or fuel cell cannot do individually?
- Compare batteries and hydrogen storage as forms of chemical energy storage. Give one advantage and one disadvantage of each in the context of integrating renewable energy into the grid. Which is better suited for seasonal (long-duration) storage, and why?

Exercise 4



Knowledge

The lesson discusses home batteries and neighbourhood batteries as tools for managing electricity in decentralised energy systems.

- What is 'peak shaving' and how can a home battery contribute to it? Who benefits from peak shaving: the individual household, the grid operator, or both?
- The lesson identifies several factors that make the payback time of a home battery difficult to predict. List at least four of these factors.
- Explain the concept of a neighbourhood battery and how it differs from a home battery. The lesson mentions that '100 % coincidence of energy uses is quite rare'. What does this mean, and how does it make a neighbourhood battery more effective than individual home batteries?

Section B – Calculation Questions

Exercise 5

Calculation

Water electrolysis – minimum voltage and energy requirement. The lesson shows that the minimum voltage required to split water is 1.229 V (the theoretical minimum at standard conditions).

- An industrial alkaline electrolyser operates at a cell voltage of 1.8 V due to overpotentials and ohmic losses. What is the voltage efficiency of this cell compared to the theoretical minimum of 1.229 V? Use: $\eta_V = V_{\text{theoretical}} / V_{\text{actual}}$.
- The electrolyser operates at a current of 5 000 A per cell and has 100 cells in its stack. Calculate the total electrical power consumed by the stack in kW. Use: $P = V \times I \times N_{\text{cells}}$.
- Producing 1 kg of hydrogen by electrolysis requires approximately 55 kWh of electricity in a real system. If the electrolyser from part (b) runs for 24 hours, how many kg of hydrogen can it produce? What is the equivalent energy content of this hydrogen, given that the higher heating value (HHV) of hydrogen is 39.4 kWh/kg?

Exercise 6

Calculation

Round-trip efficiency of hydrogen energy storage. Hydrogen is produced by a PEM electrolyser with an efficiency of 70 % (electricity-to-hydrogen), stored, and then converted back to electricity by a PEM fuel cell with an efficiency of 60 % (hydrogen-to-electricity).

- Calculate the round-trip efficiency (electricity $\rightarrow$ hydrogen $\rightarrow$ electricity). Use: $\eta_{\text{RT}} = \eta_{\text{electrolyser}} \times \eta_{\text{fuel cell}}$.
- A wind farm produces 1 000 kWh of surplus electricity on a windy day. This energy is stored as hydrogen and later converted back to electricity via the fuel cell. How many kWh of electricity are recovered? How many kWh are lost in the round trip?
- Compare this round-trip efficiency to a lithium-ion battery, which typically achieves 90–95 % round-trip efficiency. For what reason might hydrogen storage still be preferred despite lower efficiency? Give a practical example from the lesson.

Exercise 7

Calculation

Hydrogen storage – pressure and energy density. Hydrogen at ambient conditions has a very low volumetric energy density. Compressing it increases the amount stored per volume.

- At standard conditions (1 bar, 20 °C), 1 kg of hydrogen gas occupies approximately 11.1 m³. If hydrogen is compressed to 700 bar (a typical car tank pressure), what volume does 1 kg of hydrogen occupy? Assume ideal gas behaviour: $V \propto 1/P$. (V and P are inversely proportional to each other)
- A hydrogen car tank holds 5 kg of hydrogen at 700 bar. Using the HHV of hydrogen (39.4 kWh/kg), calculate the total energy stored in the tank in kWh. Compare this to a 75 kWh lithium-ion battery pack of a comparable electric car. Which stores more energy per kg? (Assume the hydrogen tank system weighs 90 kg and the battery pack weighs 450 kg.)
- Liquid hydrogen has a density of about 71 kg/m³. What volume (in litres) would be needed to store 5 kg of liquid hydrogen? Why is liquid hydrogen storage energy-intensive, according to the lesson?

Exercise 8

Calculation

Battery energy density and EV range. A lithium-ion battery pack for an electric vehicle has a total capacity of 75 kWh and a mass of 450 kg.

- Calculate the gravimetric energy density of this battery pack in Wh/kg. Using the lesson's chart, how does this compare to a lead-acid battery (approximately 40 Wh/kg) and to the projected solid-state battery (approximately 400–500 Wh/kg)?
- The electric vehicle consumes 18 kWh per 100 km. Calculate the maximum range of the vehicle on a full charge. If only 80 % of the battery capacity is usable (to preserve battery life), what is the practical range?
- The battery degrades to 80 % of its original capacity after 1 500 full charge–discharge cycles. If the car is charged once per day, after how many years does it reach 80 % capacity? What is the practical range at that point (using the 80 % usable capacity rule)?

Exercise 9

Calculation

Home battery – sizing and payback time. A household with solar PV panels generates 4 500 kWh of electricity per year and consumes 3 500 kWh per year. The excess (1 000 kWh/year) is currently exported to the grid for a feed-in tariff of €0.05/kWh. The household buys electricity from the grid at €0.30/kWh.

- Calculate the annual revenue from exporting excess solar electricity to the grid at the current feed-in tariff of €0.05/kWh.
- The household installs a 5 kWh home battery (round-trip efficiency 90 %) and can now use 900 kWh of the previously exported solar energy for self-consumption (assuming 10 % losses in the battery). Calculate the annual saving from avoiding grid

purchases of 900 kWh at €0.30/kWh. Compare this to the lost feed-in income (900 kWh × €0.05/kWh).

- The home battery costs €3 500. Using the net annual saving from part (b), calculate the simple payback time in years. The lesson notes that payback time is uncertain – list two additional factors not captured by this simple calculation that could shorten or lengthen the actual payback time.

Exercise 10

Calculation

Neighbourhood battery – peak shaving. A neighbourhood of 50 households each has a peak electricity demand of 3.5 kW. However, statistical analysis shows that at any given moment only 60 % of households are simultaneously at peak demand.

- Calculate the actual simultaneous peak demand of the neighbourhood (in kW). Compare this to the theoretical maximum if all households peaked at the same time. What is the ‘diversity gain’ in kW?
- The local grid connection is rated at 100 kW. The neighbourhood installs a 50 kWh battery to handle the remaining peaks. On a summer afternoon, the neighbourhood’s net demand (after solar PV) peaks at 120 kW for 30 minutes. How much energy (in kWh) must the battery supply during this 30-minute period? Is the 50 kWh battery sufficient?
- The battery is charged from excess solar PV during the day (at 0 kW grid import cost) and discharged during the evening peak. If the grid charges a peak demand tariff of €50/kW/month for the highest 15-minute demand recorded, calculate the monthly saving from keeping the peak below 100 kW (i.e. cutting the 120 kW peak to 100 kW using the battery). Assume the battery is used this way every day of the month.

Section C – Internet Exploration Questions

Exercise 11

Internet Exploration

Explore the current state of green hydrogen and electrolyzers using the IEA electrolyzers page (<https://www.iea.org/energy-system/low-emission-fuels/electrolyzers>) and the IEA Global Hydrogen Review (<https://www.iea.org/reports/global-hydrogen-review-2023>).

- Find the current global installed electrolyser capacity (in GW). How has this changed in the last three years? Which regions or countries are leading in electrolyser deployment?
- Find the current cost of producing green hydrogen (in € or \$ per kg of H₂). The lesson mentions that electricity cost is the dominant operating cost. If electricity costs €0.04/kWh and producing 1 kg of H₂ requires 55 kWh, calculate the electricity cost

contribution per kg of H₂. How does this compare to the total green hydrogen cost you found?

- Find one specific large-scale green hydrogen project that is under construction or recently completed anywhere in the world. Describe the project: where is it, what is its electrolyser capacity (MW or GW), what type of electrolyser is used (if stated), and what will the hydrogen be used for? Write 3–5 sentences connecting this to what you learned in the lesson.

Exercise 12



Internet Exploration

Explore home battery systems and energy storage markets using one or more of the following: the Clean Energy Reviews home battery guide

(<https://www.cleanenergyreviews.info/blog/home-solar-battery-cost-guide>), the

BloombergNEF energy storage tracker, or the IEA energy storage page

(<https://www.iea.org/energy-system/electricity/grid-scale-storage>).

- Find the current price range for home battery systems (in € or \$ per kWh of storage capacity). How does this compare to the chart shown in the lesson (which was from August 2021)? Has the price gone up or down, and by approximately how much?
- Find one real-world example of a neighbourhood or community battery project in Europe or Australia (both regions have active programmes). Describe the project: its location, capacity (kWh or MWh), the technology used, and its stated purpose (peak shaving, solar integration, grid support, etc.).
- The lesson mentions the ‘chicken-and-egg’ problem for hydrogen cars: few refuelling stations lead to few cars, and vice versa. Find a similar chicken-and-egg dynamic that previously existed for electric vehicle charging infrastructure, and describe how it was resolved. Write 3–5 sentences.

Section D – Home Experiments

Exercise 13



Home Experiment – Electrolysis of Water (Safe Version)

In this experiment you will perform a safe, small-scale version of water electrolysis using a 9 V battery and common kitchen materials. You will observe hydrogen and oxygen gas being produced at the electrodes, connecting directly to the water dissociation slide in the lesson.

Safety note: the amounts of gas produced are tiny and completely safe. Do NOT scale this up to mains voltage. Do NOT allow the gases to accumulate in an enclosed container – always work in a well-ventilated space or outdoors.

Materials needed (total cost < €2 if you don't already have them):

- 1 × 9 V battery (PP3 type, standard from any supermarket)
- 2 × pencils sharpened at both ends (graphite electrodes)
- A glass or transparent plastic cup
- Salt (NaCl) or baking soda (NaHCO₃) – a teaspoon is enough
- Tap water
- 2 short lengths of wire with crocodile clips (or improvise with aluminium foil strips)
- Optionally: red and blue litmus paper (from a pharmacy or hobby shop, < €2)

Procedure:

- Fill the cup with tap water and dissolve a teaspoon of salt or baking soda (this increases conductivity – pure water conducts very poorly).
- Insert two pencils into the water about 3–4 cm apart, leaning against opposite sides of the cup so that the graphite tips are submerged.
- Connect the positive terminal of the 9 V battery to one pencil (this will be your anode) and the negative terminal to the other (cathode). Use wires with crocodile clips.
- Observe for 1–2 minutes. You should see small bubbles forming on both pencils.
- Optional – test the gases: hold a piece of damp red litmus paper near the anode. If it turns blue, chlorine or oxygen is being produced. Hold damp blue litmus paper near the cathode – if it turns red, the solution is becoming acidic near the hydrogen electrode.
- Try increasing the salt concentration – what happens to the bubble rate?

Observations to record:

Observation	Anode (+)	Cathode (–)
Bubble rate (fast/slow/none)		
Relative volume of bubbles		
Litmus test result (if done)		
What gas is produced here?		

Reflection questions:

- Which electrode produces more bubbles? The overall reaction $2 \text{H}_2\text{O} \rightarrow 2 \text{H}_2 + \text{O}_2$ produces hydrogen and oxygen in a 2:1 molar ratio. Does this match what you observe?
- What energy conversion is taking place? Draw the full conversion chain: starting form → intermediate → output.
- In a real industrial electrolyser, a membrane separates the two electrodes. Why is this not necessary in your simple experiment (the gases are still safely produced), and why would a membrane be critical in a large-scale system?
- You added salt to the water to increase conductivity. Recall from the lesson: what does the electrolyte do in an electrolyser? Name the electrolyte used in an alkaline electrolyser and explain why it is chosen.

Exercise 14



Home Experiment – Measure Battery Discharge and Estimate Capacity

In this experiment you will measure how a battery discharges over time under a constant load, connecting to the lesson content on batteries and energy storage. You will also estimate the battery's capacity in mAh and Wh.

Materials needed:

- 1 × AA or AAA battery (alkaline, new – cost < €1)
- 1 × small torch bulb or LED with a suitable resistor (e.g. 100 Ω resistor to limit current – from a hobby shop, < €1, or reuse from a kit)
- A digital multimeter (for voltage measurement – see lesson 4c experiment; cost €5–10 or borrow one)
- A stopwatch or phone timer
- Pen, paper, or a spreadsheet to log data

Procedure:

- Connect the battery to the bulb (or LED + resistor) to create a simple discharge circuit. Measure and record the open-circuit voltage of the battery before connecting the load (V_0).
- Once connected, measure the terminal voltage across the battery every 5 minutes. Record the time and voltage in the table below. Continue until the voltage drops below 1.0 V (the battery is effectively discharged).
- Also measure the current (mA) once at the beginning and once near the end. If you don't have an ammeter, estimate the current using Ohm's Law: $I = V / R_{\text{total}}$ (use the bulb's rated resistance or estimate it from the power rating).

Data table:

Time (min)	Voltage (V)	Notes
0 (open circuit)		Before connecting load
0 (under load)		
5		
10		
15		
20		
25		
30		
...		Continue until < 1.0 V

Analysis and reflection questions:

- Plot your voltage vs. time graph. Describe the shape of the curve: is the voltage drop linear, or does it drop slowly at first and then rapidly? What does this tell you about how an alkaline battery stores and releases energy?
- Estimate the average current drawn during the test (use your two measurements). Calculate the approximate capacity of the battery: $\text{Capacity (mAh)} = \text{average current (mA)} \times \text{total discharge time (hours)}$. Compare your result to the rated capacity printed on the battery (typically 1 800–2 850 mAh for AA alkaline). Why might your measured value differ?
- Calculate the energy stored in the battery: $E = \text{average voltage (V)} \times \text{capacity (Ah)} \times 1\,000 = \text{energy in Wh}$. A typical AA battery is rated at about 1.5 V and 2 500 mAh. What is its theoretical energy content in Wh? How does your result compare?
- The lesson distinguishes between disposable and rechargeable batteries. An alkaline AA battery can deliver its energy once and is then discarded. A lithium-ion cell of similar size can be recharged about 500 times. If both hold the same energy per charge, calculate the total lifetime energy throughput (in Wh) of each. What does this tell you about the environmental case for rechargeable batteries?