

REIES – Lesson 4c: Electricity Delivery

Answer Key

You have worked through the exercises — well done! Use this document to check your answers and deepen your understanding. The core skill in this lesson is being able to apply Ohm's Law and the power formula, understand voltage levels across the grid, and trace how electricity is generated and converted.

Section A – Knowledge Questions

Answer – Exercise 1



Knowledge

Term	Definition	SI Unit	Water analogy
Electric current (I)	The rate of flow of electric charge through a conductor.	Ampere (A)	Flow rate of water (litres/second)
Voltage (V)	The difference in electric potential between two points; the 'pressure' driving charges.	Volt (V)	Water pressure (height difference)
Resistance (R)	The tendency of a material to oppose the flow of electric current.	Ohm (Ω)	Narrowness of the pipe
Electric power (P)	The rate at which electrical energy is transferred or converted.	Watt (W)	Rate of water doing work (e.g. turning a mill)

Derived power expressions:

- $P = I^2 \times R$ (substitute $V = I \times R$ into $P = V \times I$)
- $P = V^2 / R$ (substitute $I = V / R$ into $P = V \times I$)

These are extremely useful: $P = I^2 \times R$ shows that cable losses grow with the square of current – the key reason high-voltage (low-current) transmission is used.

Answer – Exercise 2



Knowledge

Conductors from the lesson: copper, silver, aluminium, gold. Insulators: PVC, glass, air, ceramic.

Atomic explanation: in conductors, the outermost shell electrons (valence electrons) are loosely bound to their nucleus and can detach and move freely through the lattice of atoms. In insulators, the valence electrons are tightly bound and there is a large energy gap

between the valence band and the conduction band – electrons cannot move freely without a very large energy input.

Copper has 29 protons and 29 electrons. Its outermost shell contains just one valence electron which is very loosely held. This single electron can detach easily from its atom and travel through the copper lattice, making copper an excellent conductor with low resistivity.

In a household wire: the copper core carries the current (low resistance path); the PVC or plastic insulation prevents the current from leaking out, from shorting to adjacent wires, and from causing electric shock to users. PVC is one of the most common insulating jacket materials.

Answer – Exercise 3



Knowledge

DC vs AC: in direct current the electrons flow steadily in one direction (e.g. from the negative to positive terminal of a battery through the circuit). In alternating current the direction of electron flow reverses periodically – in Europe at 50 Hz, meaning 50 complete cycles per second. DC applications: batteries, electric vehicles, solar panel output, laptop power supplies. AC applications: household mains grid (230 V / 50 Hz in Europe), industrial motors.

Transformer and AC: a transformer consists of two coils wound on a shared iron core. When AC flows through the primary coil it creates a continuously changing magnetic field in the core. By Faraday's law of electromagnetic induction, this changing flux induces a voltage in the secondary coil. With DC, the magnetic field would be constant – a constant field induces no voltage in the secondary – so no energy is transferred.

DC-to-DC converter: changes the voltage level of a DC signal by rapidly switching the current on and off (using transistors) and using inductors and capacitors to smooth the output. Example: a smartphone contains a DC-DC buck converter that steps the 3.7 V battery voltage down to 1.8 V for the processor. A transformer cannot be used because transformers require AC.

Solar inverter: a solar PV panel outputs DC (typically 30–60 V per panel). To connect to the household AC grid (230 V AC) a DC-to-AC inverter is required. It converts the DC output of the panels into AC at the correct voltage and frequency to synchronise with the grid.

Answer – Exercise 4



Knowledge

DC vs AC generator: both spin a coil in a magnetic field. The DC generator uses a split-ring commutator that reverses the electrical connections every half turn, ensuring the output current always flows in the same direction (though it pulsates). The AC generator (alternator) uses continuous slip rings, allowing the current to reverse naturally with each half rotation, producing a sinusoidal waveform. The AC design is simpler, more robust, and dominant in large-scale power generation.

Photovoltaic effect: when photons of light hit a semiconductor (typically silicon), they transfer energy to electrons, freeing them from their atom. Inside the solar cell, the p-n junction creates an internal electric field: the n-type layer has extra electrons and the p-type has

'holes' (electron absences). This field sweeps the freed electrons in one direction, creating a net current. The output is DC.

Technology	Advantages	Disadvantages
Electrical generator (wind/steam turbine)	High power output (MW to GW scale); established technology; works 24/7 with fuel or wind; AC output compatible with grid.	Requires moving parts (maintenance); needs a primary energy source (wind, steam, water); turbines have significant capital cost and land use.
PV solar panel	No moving parts (low maintenance); silent; modular and scalable; no direct emissions; fuel is free (sunlight).	Intermittent (no output at night, low output on cloudy days); requires storage or backup; lower efficiency (~20%); manufacturing has environmental impact.

Section B – Calculation Questions

Answer – Exercise 5

Calculation

Ohm's Law – toaster

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Current:  I = V / R = 230 V / 23 Ω = 10 A
Power:    P = V × I = 230 V × 10 A = 2 300 W = 2.3 kW
(or: P = I2 × R = 102 × 23 = 2 300 W ✓)
Energy in 5 min (= 300 s):
E = P × t = 2 300 W × 300 s = 690 000 J = 690 kJ
In Wh: 690 000 / 3 600 = 191.7 Wh ≈ 0.19 kWh
Fraction of daily use: 0.19 kWh / 10 kWh = 1.9 % per 5-min use
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The toaster consumes about 2 % of a household's daily electricity in a single 5-minute use – a significant share for such a short operation. Most of the energy converts to heat via resistance (I^2R), which is exactly the intended purpose. This is also why heating appliances (toasters, kettles, showers) are among the largest electricity consumers in a home.

Answer – Exercise 6

Calculation

Power transmission losses

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Generated power: P = V × I = 10 000 V × 1 000 A = 10 000 000 W = 10 MW
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Cable loss at 10 kV / 1 000 A:

$$P_{\text{loss}} = I^2 \times R = 1\,000^2 \times 5 = 5\,000\,000 \text{ W} = 5 \text{ MW}$$

$$\text{Loss percentage} = 5 \text{ MW} / 10 \text{ MW} = 50 \% \quad (\text{half the power wasted!})$$

After step-up transformer to 380 kV:

$$\text{New current: } I_{\text{new}} = P / V_{\text{new}} = 10\,000\,000 / 380\,000 \approx 26.3 \text{ A}$$

$$\text{New cable loss: } P_{\text{loss}} = 26.3^2 \times 5 \approx 3\,460 \text{ W} \approx 0.0035 \text{ MW}$$

$$\text{Loss percentage} = 0.0035 / 10 = 0.035 \%$$

Reduction factor: $5\,000\,000 / 3\,460 \approx 1\,445\times$ reduction

(approximately $(380/10)^2 = 38^2 = 1\,444$ – confirms I^2R logic)

This exercise powerfully illustrates why high-voltage transmission is essential. At the original 10 kV, 50 % of generated power would be wasted as heat in the cables – economically and energetically catastrophic. Stepping up to 380 kV reduces losses by a factor of ~1 444, making the grid efficient enough to function. This is the reason national grids use 220–400 kV for long-distance transmission.

Answer – Exercise 7



Calculation

Distribution transformer

$$\text{Turns ratio: } N_p / N_s = V_p / V_s = 10\,000 / 230 \approx 43.5$$

$$\text{Secondary turns: } N_s = 2\,000 / 43.5 \approx 46 \text{ turns}$$

Primary current (100 % efficiency):

$$V_p \times I_p = V_s \times I_s$$

$$10\,000 \times I_p = 230 \times 20 = 4\,600 \text{ VA}$$

$$I_p = 4\,600 / 10\,000 = 0.46 \text{ A}$$

$$\text{Power check: } P = 230 \text{ V} \times 20 \text{ A} = 4\,600 \text{ W} = 4.6 \text{ kW} \checkmark$$

Losses at 98 % efficiency:

$$P_{\text{in}} = 5\,000\,000 \text{ W}$$

$$P_{\text{out}} = 5\,000\,000 \times 0.98 = 4\,900\,000 \text{ W}$$

$$P_{\text{lost}} = 100\,000 \text{ W} = 100 \text{ kW}$$

100 kW of losses in a single distribution transformer handling 5 MW is 2 % – relatively small, but at grid scale (thousands of transformers nationwide) these losses accumulate to significant amounts. Transformer losses appear mainly as heat in the copper windings (I^2R , called copper losses) and in the iron core (eddy currents and hysteresis, called iron or core losses). Modern transformers are carefully designed to minimise both.

Answer – Exercise 8

Calculation

PV rooftop system

Total panel area: $12 \text{ panels} \times 1.7 \text{ m}^2 = 20.4 \text{ m}^2$
Peak power: $P = 700 \text{ W/m}^2 \times 0.20 \times 20.4 \text{ m}^2 = 2\,856 \text{ W} \approx 2.86 \text{ kW}$

Annual energy: $E = P_{\text{peak}} \times \text{peak sun hours}$
 $E = 2.856 \text{ kW} \times 1\,050 \text{ h} = 2\,999 \text{ kWh} \approx 3\,000 \text{ kWh/year}$

Self-sufficiency:
Coverage = $3\,000 / 3\,500 = 85.7 \%$
For 100 % self-sufficiency:
Panels needed = $3\,500 / (3\,000/12) = 3\,500 / 250 = 14 \text{ panels}$
(each panel generates $\approx 250 \text{ kWh/year}$)

A 12-panel system covers about 86 % of the household's needs – a very good result. In practice, the grid acts as a virtual battery: excess solar in summer is exported, and shortfalls in winter are imported. Full self-sufficiency from solar alone in the Netherlands is challenging in winter months, which is why battery storage or demand flexibility is increasingly important.

Answer – Exercise 9

Calculation

Wind turbine to grid

Wind power intercepted: $2\,000 \text{ kW} = 2 \text{ MW}$

After generator (96 % efficiency):
 $P_{\text{gen}} = 2\,000 \times 0.96 = 1\,920 \text{ kW}$

After step-up transformer 690 V $\rightarrow$ 33 kV (99 % efficiency):
 $P_{\text{grid1}} = 1\,920 \times 0.99 = 1\,900.8 \text{ kW} \approx 1\,901 \text{ kW}$
% of wind: $1\,901 / 2\,000 = 95.05 \%$

After second transformer 33 kV $\rightarrow$ 150 kV (99 % efficiency):
 $P_{\text{grid2}} = 1\,900.8 \times 0.99 \approx 1\,882 \text{ kW}$
% of wind: $1\,882 / 2\,000 = 94.1 \%$

Total losses: $2\,000 - 1\,882 = 118 \text{ kW}$ (5.9 % of wind power)

Even with two transformers each at 99 % efficiency, and a generator at 96 %, the chain delivers 94 % of the wind energy to the regional grid. At 2 MW, 118 kW of losses might seem

small, but for a large offshore wind farm of 500 MW capacity, equivalent losses would be about 30 MW – enough to power thousands of homes. This motivates careful engineering of every component in the chain.

Section C – Internet Exploration

Answer – Exercise 10

Internet Exploration

Reference: <https://ourworldindata.org/solar-energy> | <https://www.iea.org/energy-system/renewables/solar-pv>

Global installed capacity (2024/2025): global solar PV capacity has surpassed 2 000 GW (2 TW) as of 2024/2025, compared to roughly 600 GW ten years earlier – more than a threefold increase in a decade. China leads with over 700 GW installed, followed by the European Union and the United States. China alone accounted for more than 60 % of new installations in recent years.

Price reduction: from approximately \$100/W in 1976 to \$0.26/W in 2024, the cost fell by $(100 - 0.26)/100 \times 100 = 99.74$ %. This exponential cost decline follows Swanson's Law (the solar equivalent of Moore's Law): for every doubling of cumulative solar PV production, the price falls by approximately 20–25 %.

Grid challenge example: rapid solar PV growth causes the 'duck curve' phenomenon – a large mid-day surplus of solar power followed by a steep evening ramp-up in demand when solar output drops. This requires either large-scale battery storage, flexible demand (e.g. EV charging), or grid interconnections with other regions. The lesson's future power grid diagram showing local storage and generation units directly addresses this challenge: decentralised batteries and smart inverters can absorb solar surpluses and smooth the duck curve.

Go deeper: <https://ourworldindata.org/solar-energy> | https://en.wikipedia.org/wiki/Swanson%27s_law

Answer – Exercise 11

Internet Exploration

Reference: https://en.wikipedia.org/wiki/High-voltage_direct_current | <https://new.siemens.com/global/en/products/energy/high-voltage/hvdc.html>

HVDC vs HVAC: High Voltage Direct Current uses DC at very high voltages (typically ± 320 kV to ± 800 kV) for long-distance or subsea transmission. Key advantages over HVAC: (1) HVDC cables have no reactive power losses (AC cables have significant capacitive losses, especially in long subsea cables); (2) HVDC can connect grids that operate at different

frequencies or that are not synchronised; (3) for cables longer than approximately 50–80 km under water, HVDC is more efficient than HVAC.

Real-world example: the NordLink cable between Norway and Germany (operational 2021) is 623 km long, with a capacity of 1.4 GW, connecting Norwegian hydropower to the German grid. Another example is the Viking Link between the UK and Denmark (1 400 km, 1.4 GW, operational 2024). The EGL1 project shown in the lesson slide connects Scotland and England.

Why AC-to-DC conversion has become viable: historically, HVDC required mercury arc valves that were expensive, large, and unreliable. The development of power semiconductor devices – thyristors in the 1970s and insulated-gate bipolar transistors (IGBTs) in the 1990s–2000s – made converter stations far smaller, more efficient, and more controllable. Voltage Source Converters (VSC) using IGBTs can now be built modularly at lower cost. As more offshore wind capacity is built far from shore, HVDC becomes the default transmission technology, driving further cost reductions through scale.

Go deeper: https://en.wikipedia.org/wiki/High-voltage_direct_current | <https://www.entsoe.eu>

Section D – Home Experiments

Answer – Exercise 12

Home Experiment – Resistance and Ohm's Law

Expected observations:

Resistance measurements (typical values):

Material	Typical resistance	Conductor / Insulator
Pencil lead (graphite)	20–200 Ω (depends on length and thickness)	Poor conductor (semiconductor-like)
Aluminium foil	< 1 Ω for a short strip	Good conductor
Rubber eraser	Megaohms (> 1 M Ω , off-scale on most meters)	Insulator
Torch bulb (e.g. 9 V, 1 W)	$\approx 81 \Omega$ ($R = V^2/P = 81 \Omega$)	Conductor (resistive)

Bulb power: if the battery reads 8.5 V (batteries slightly below rated voltage under load) and the bulb draws 90 mA: $P = V \times I = 8.5 \times 0.09 = 0.77 \text{ W}$. This should be close to the rated wattage.

Without multimeter – brightness ranking: aluminium foil (brightest, lowest resistance) > pencil lead (dim, moderate resistance) > rubber eraser (bulb does not light – too high resistance).

Connection to lesson: the pencil lead is graphite – a form of carbon with delocalised electrons – so it conducts but with significant resistance. The aluminium foil has a metallic lattice of free electrons and conducts well. The rubber has no free electrons and is a classic

insulator. These results confirm Ohm's Law: at the same voltage, a higher resistance means less current and a dimmer bulb.

Go deeper: <https://www.khanacademy.org/science/physics/circuits-topic/circuits-resistance/a/what-is-resistance> | <https://phet.colorado.edu/en/simulations/ohms-law>

Answer – Exercise 13



Home Experiment – Lemon Battery

Expected observations and explanations:

A single lemon cell typically produces 0.7–0.9 V open-circuit. This is enough to be measured by a multimeter but usually too low to light an LED (which needs at least 1.8–2.2 V). With two or three lemons in series, the LED should glow faintly.

Chemical reactions: at the zinc electrode, zinc atoms lose electrons and dissolve into the lemon juice as Zn^{2+} ions (oxidation: $\text{Zn} \rightarrow \text{Zn}^{2+} + 2\text{e}^-$). The electrons flow through the external circuit to the copper electrode, where hydrogen ions from the citric acid in the lemon gain electrons and form hydrogen gas (reduction: $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$). The copper does not dissolve – it acts as an inert positive terminal.

DC identification: the LED only lights in one orientation (one leg positive, one negative) – this is direct evidence of DC. An AC source would cause the LED to flash at 50 Hz (appearing to glow continuously) or would light it in both orientations.

Energy conversion chain: Chemical energy (in the zinc and the acid) → Electrical energy (current through the wire) → Light energy (in the LED) + some Heat.

Series vs parallel: connecting cells in series adds their voltages (e.g. $3 \times 0.8 \text{ V} = 2.4 \text{ V}$). Connecting in parallel keeps the voltage the same but increases the current capacity and life of the battery. For lighting an LED, series connection (higher voltage) is needed.

High internal resistance: the lemon juice is a weak electrolyte – ions move slowly through it, creating high internal resistance. From Ohm's Law: $V_{\text{terminal}} = V_{\text{open}} - I \times R_{\text{internal}}$. When a high current is drawn (as a hairdryer would require), the terminal voltage drops to near zero. The lemon battery can only supply micro- to milliamperes. A hairdryer at 230 V needs about 4–5 A – completely beyond reach.

Go deeper: https://www.sciencebuddies.org/science-fair-projects/project-ideas/Elec_p011 | <https://www.khanacademy.org/science/physics/circuits-topic>

References & Resources for Further Study

- IEA – Solar PV: <https://www.iea.org/energy-system/renewables/solar-pv>
- Our World in Data – Solar Energy: <https://ourworldindata.org/solar-energy>
- Wikipedia – HVDC: https://en.wikipedia.org/wiki/High-voltage_direct_current
- Khan Academy – Circuits and Ohm's Law: <https://www.khanacademy.org/science/physics/circuits-topic>

- PhET Simulations – Ohm's Law: <https://phet.colorado.edu/en/simulations/ohms-law>
- Swanson's Law (solar cost curve): https://en.wikipedia.org/wiki/Swanson%27s_law
- The Engineering Mindset – How Electricity Works:
<https://www.youtube.com/watch?v=mc979OhitAg>
- The Engineering Mindset – How Transformers Work:
<https://www.youtube.com/watch?v=UchitHGF4n8>
- Science Buddies – Lemon Battery: https://www.sciencebuddies.org/science-fair-projects/project-ideas/Elec_p011
- Ouwehand et al. (2012) Toegepaste Energietechniek, Sdu, Den Haag.
- Ouwehand et al. (2017) Duurzame energietechniek, Boom, Amsterdam.