Environmental Science Units 3 & 4

Chapter 12 — Energy sources, conversions and efficiency

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Contents

Theory

The definition is about rate, not about quantity. A **non-renewable energy source** is one whose stock is replenished so slowly, relative to the rate at which humans consume it, that for any practical purpose it is being drawn down and not replaced. The study design names five of them: *“non-renewable energy sources: oil, coal, natural gas, coal seam gas and nuclear”*. Notice what the definition does **not** say. It says nothing about how much is left, nothing about how polluting the source is, and nothing about whether the source is a fuel that burns. Each of those three gets substituted for the definition, and the third is the substitution the examiners have reported: treating nuclear as a fossil fuel cost 42% of the 2025 cohort every mark on the question that asked for it.

The comparison that matters is a ratio of two rates:

	Rate of formation	Rate of human use	Verdict
Coal, oil, natural gas, coal seam gas	Millions of years for a single deposit	A deposit’s worth in years to decades	**Non-renewable**
Uranium ore	Formed with the crust; concentrated by geological processes over hundreds of millions of years	Mined and consumed within decades	**Non-renewable**
Sunlight, wind, flowing water, tides	Arriving continuously	Cannot be used faster than it arrives	Renewable — see 12B
Biomass	Years to decades	Can be harvested faster or slower than it regrows	Renewable **only if** harvest ≤ regrowth — see 12B

The Area of Study asks students to weigh consequences over *“short (seconds to years), medium (multiple years to hundreds of years) and long (thousands to millions of years) time scales”*. The five sources in this subtopic all have the same signature against that scale: the **useful life** of the resource is short or medium, and the **replacement time** is long. That mismatch is the whole reason the classification exists.

Where this subtopic sits. This subtopic owns the five sources themselves — what each is, how it formed, where Australia has it, how it is extracted, what it is worth per kilogram, and how each is regulated. The siblings own what is done with them.

Question	Where it is taught
Renewable sources: biomass, biofuels, solar, hydro-electric, wind, tidal, geothermal	12B
What burning fossil fuel does to the carbon cycle	12C
How fast fossil fuel use has changed, and peak oil	12D
Efficiency calculations for single and multi-step energy conversions	12E
The first and second laws of thermodynamics as constraints on energy choice	12F
Sustainability principles across accessing, extracting, processing, transporting and using energy	12G
Rehabilitating a mine or well site after extraction	13A
Base load and peak load, and which sources can meet them	13B
Options for a sustainable energy future	13C
Global warming potential of methane and carbon	9D

Question	Where it is taught
dioxide	

Efficiency figures and emissions intensities appear below as **properties of each source**, because a comparison of sources is impossible without them. The *method* for calculating conversion efficiency is 12E's, and the thermodynamic reason losses are unavoidable is 12F's.

The three axes students collapse into one. Keep these separate and most of the traps disappear.

Axis	Question it answers	Coal	Oil	Natural gas	Coal seam gas	Nuclear
Origin	What did it form from?	Fossil — land plants	Fossil — marine plankton	Fossil — marine organic matter	Fossil — land plants, gas held in coal	**Mineral ore — no biological origin**
Renewability	Replenished as fast as used?	No	No	No	No	**No**
Carbon at generation	CO_2 released when the energy is released?	Very high	High	Moderate	Moderate	**None**

So nuclear shares the second row with the fossil fuels and shares neither of the others. "Non-renewable" and "fossil fuel" are not synonyms, and neither is a synonym for "high-emitting".

Coal. Coal is a combustible sedimentary rock formed from the compressed remains of land plants. Plant material accumulating in waterlogged, oxygen-poor swamps decays only partly, forming **peat**; burial under later sediment then applies heat and pressure, driving off water and volatile matter and concentrating the carbon. This progression is called **coalification**, and how far a coal has travelled along it is its **rank**:

peat → **brown coal** (lignite) → sub-bituminous → **black coal** (bituminous) → anthracite

with carbon content and energy content rising, and moisture and volatile content falling, at every step.

	Brown coal (lignite)	Black coal (bituminous)
Rank	Low	High
Moisture as mined	About 48–70% — typically near 60% in the Latrobe Valley	About 5–10%
Energy content as mined	About 6–10 MJ kg^{-1}	About 24–30 MJ kg^{-1}
Age of the main Australian deposits	Eocene to Miocene, roughly 15–50 million years	Permian, roughly 250–300 million years
Where in Australia	**Latrobe Valley, Victoria** — one of the world's largest deposits, seams over 100 m thick and close to the surface	Sydney and Gunnedah Basins (NSW); Bowen, Surat and Galilee Basins (Qld)
Mining method	Open cut	Open cut and underground longwall
Traded internationally?	No — too wet and too low in energy per tonne to be worth shipping	Yes — Australia is the world's largest exporter of metallurgical coal and a leading exporter of thermal coal
Typical station thermal efficiency	About 22–27%	About 33–35% subcritical, up to about 42% supercritical

	Brown coal (lignite)	Black coal (bituminous)
Typical emissions intensity	About 1.2–1.4 t CO_2-e MWh^{-1}	About 0.8–1.0 t CO_2-e MWh^{-1}

Two consequences follow from that table and both are examinable. First, brown coal must be burnt where it is dug, because its energy per tonne is too low to justify transport — which is why Victoria's generators sit at the mine mouth in the Latrobe Valley while black coal is railed to ports and shipped to Asia. Second, brown coal's emissions intensity is high for **two independent reasons**, and a complete answer gives both: its carbon is less concentrated, so more mass must be burnt per unit of energy; and a large share of the heat released goes into evaporating the coal's own water, which is then lost up the stack, lowering the station's thermal efficiency. Neither reason alone explains the size of the gap.

Coal is converted to electricity by pulverising it, burning it in a boiler, using the heat to raise high-pressure steam, expanding the steam through a turbine and turning a generator. Coal also has a non-electrical use with no easy substitute: **metallurgical (coking) coal** is the reducing agent in conventional blast-furnace steelmaking, a chemical role rather than an energy one.

Oil. Crude oil, or petroleum, is a liquid mixture of hydrocarbons formed from marine plankton and algae that settled into oxygen-poor sea-floor muds. Burial converted the organic matter to **kerogen** in a **source rock**; further heating in the **oil window**, roughly 60–120 °C at 2–4 km depth, cracked the kerogen into liquid hydrocarbons. Being less dense than water, the oil then **migrated** upwards through porous, permeable **reservoir rock** until it was stopped by an impermeable **cap rock** in a geological **trap**. All three elements — source, reservoir and seal — must coincide, which is why oil is found in particular basins and not everywhere.

Crude oil is not used as it comes. **Fractional distillation** in a refinery separates it by boiling point into LPG, petrol, kerosene and jet fuel, diesel, fuel oils, bitumen and petrochemical feedstock. Australia's own production comes from the Gippsland Basin under Bass Strait, the Carnarvon Basin off Western Australia and the Cooper–Eromanga Basin, and it is in long-term decline. Refining capacity has contracted further still: after the closure of the Altona and Kwinana refineries in 2021, **two refineries remain in Australia** — Viva Energy's at Geelong and Ampol's at Lytton in Brisbane — so most refined liquid fuel is now imported.

Oil has two properties no other source matches. Its **energy density** is exceptional in the form that matters for vehicles — about 34 MJ L^{-1} for petrol and about 38.6 MJ L^{-1} for diesel, in a liquid that is easy to store and pour at ordinary temperatures. And a substantial fraction of a barrel becomes something other than fuel: lubricants, bitumen, solvents, and the feedstock for plastics, synthetic fibres and pharmaceuticals. Those two facts are why transport is the hardest sector to shift and why an argument exists for reserving oil for uses that have no substitute — a point that becomes an intergenerational equity argument at 12G.

Natural gas. Natural gas is a gaseous mixture that is mostly **methane** (CH_4, typically 70–95%), with smaller amounts of ethane, propane, carbon dioxide, nitrogen and sometimes hydrogen sulfide. It forms in the same source rocks as oil but at higher temperatures — the **gas window**, above roughly 120 °C — where hydrocarbon molecules are cracked further; some shallow gas is instead **biogenic**, generated by microorganisms. **Conventional** gas has migrated out of the source rock and collected in a porous reservoir beneath a seal, often as a "gas cap" above oil, and it flows to a well under its own pressure.

Raw gas is processed to remove water, carbon dioxide and sulfur compounds and to strip out condensate and LPG, then either piped to users or chilled to about **−162 °C** to become **liquefied natural gas (LNG)**, which occupies about 1/600 of its gaseous volume — liquefaction itself consumes of the order of a tenth of the gas's energy. Australia's conventional resources are in the Carnarvon and Browse Basins (WA), the Bonaparte Basin (NT), the Cooper Basin (SA/Qld) and, closest to Victorian students, the **Gippsland and Otway Basins**, with the Longford plants processing Bass Strait gas for the eastern market. Australia is one of the world's largest LNG exporters.

Gas is burnt in an **open-cycle gas turbine** (about 30–35% efficient, fast-starting), a **combined-cycle gas turbine** that reuses the exhaust heat to raise steam (about 50–60% efficient), or directly for industrial process heat, space heating and cooking. It is also a chemical feedstock — ammonia, and from it fertiliser and explosives. Its emissions intensity in a combined-cycle plant, roughly 0.4–0.5 t CO_2-e MWh^{-1}, is about half black coal's and about a third of brown coal's, which is the basis for calling gas a lower-emission fossil fuel. That advantage is real but conditional: methane leaked unburnt as **fugitive emissions** from wells, processing and pipelines is a far stronger greenhouse gas per kilogram than carbon dioxide over both 20- and 100-year horizons (9D), so a small percentage leakage rate erodes a large part of the combustion advantage.

Coal seam gas. Coal seam gas (CSG), also called coal bed methane, is methane generated during coalification that never escaped the coal. Understanding it turns on one fact: the gas is not sitting in pore space, it is **adsorbed** onto the enormous internal surface area of the coal, held there by the pressure of the water that saturates the seam's natural fracture network, or **cleats**.

That single difference drives everything else about it.

	Conventional natural gas	Coal seam gas
Where the gas is	Free in the pore space of a reservoir rock, under a seal	**Adsorbed onto the coal itself**, in a water-saturated seam
What holds it	The cap rock	**Water pressure** in the seam
How it is released	Drill into the reservoir; gas flows out under its own pressure	**Dewatering** — pump the water out to drop the pressure below the desorption pressure, so gas comes off the coal and flows
Depth	Often 2–4 km	Usually 300–1000 m
Wells needed	Few, high-yield	**Many, low-yield** — hundreds across a gasfield
Stimulation	Sometimes	**Hydraulic fracturing** where the coal's permeability is too low: water, sand and chemical additives injected at high pressure to open fractures
Water produced	Small	**Very large volumes of co-produced water**, usually saline and often sodic, requiring treatment and brine disposal

The environmental risk profile therefore differs from conventional gas in kind, not just in degree. Dewatering lowers the pressure in the coal seam aquifer, and where that aquifer is connected to overlying or underlying aquifers used for stock, irrigation or town water, drawdown can propagate — the reason the lag and the poorly-mapped connections make this a textbook trigger for the precautionary principle (12G). The co-produced water is a waste stream in its own right. The well density spreads infrastructure across productive farmland, creating land-access and coexistence disputes with existing users. And fugitive methane escapes from a larger number of wellheads and gathering lines.

Australia's CSG industry is in the **Surat and Bowen Basins of Queensland**, where it supplies most of that state's gas and feeds the LNG trains at Curtis Island near Gladstone; the Narrabri project in the Gunnedah Basin of New South Wales was approved in 2020. **In Victoria, coal seam gas is prohibited.** The specific provisions matter and are worth learning by name:

Instrument	What it does
Mineral Resources (Sustainable Development) Act 1990 (Vic), s 8AC	Prohibits **coal seam gas exploration and mining** in Victoria
Petroleum Act 1998 (Vic), s 16A	Prohibits **hydraulic fracturing** in Victoria
Constitution Amendment (Fracking Ban) Act 2021 (Vic)	**Entrenches** both bans in the *Constitution Act 1975* (Vic): a Bill to remove or amend them needs a special majority of **three-fifths of both Houses**
Petroleum Act 1998 (Vic), as amended in 2020	Ended the moratorium on **onshore conventional** gas exploration and production from **1 July 2021** — conventional gas is permitted, CSG and fracking are not
Environment Protection and Biodiversity Conservation	Makes a significant impact on a water resource from

Instrument	What it does
Act 1999 (Cth) — the **"water trigger"**	**coal seam gas or large coal mining development** a matter of national environmental significance requiring Commonwealth assessment; **expanded on 15 December 2023** to cover all unconventional gas development, including shale and tight gas. The Independent Expert Scientific Committee established under the Act advises on such proposals
Offshore Petroleum and Greenhouse Gas Storage Act 2006 (Cth)	Governs petroleum activity in Commonwealth waters beyond three nautical miles — the regime that applies to Bass Strait, administered by NOPSEMA

Nuclear. Nuclear energy is not released by burning anything. **Uranium** is a metallic element mined as an ore; natural uranium is 99.27% uranium-238 and only **0.72% uranium-235**, and it is the U-235 that is **fissile**. For most reactors the uranium is **enriched** to about 3–5% U-235 and fabricated into ceramic uranium dioxide pellets sealed in metal fuel rods.

The energy comes from **nuclear fission**. A U-235 nucleus absorbs a slow neutron, becomes unstable and splits into two lighter nuclei plus two or three further neutrons, releasing about 200 MeV — overwhelmingly as kinetic energy of the fragments, which becomes thermal energy in the fuel and coolant. Those released neutrons can cause further fissions, giving a **chain reaction** that is held steady by control rods that absorb neutrons and a moderator that slows them. From that point the plant is conventional: heat raises steam, steam drives a turbine, the turbine drives a generator, at a thermal efficiency of about 33–37%.

The **energy density** is the property that sets nuclear apart from everything else in this subtopic. Complete fission of 1 kg of U-235 releases of the order of 8×10^7 MJ, roughly **three million times** the energy from burning 1 kg of black coal. The same arithmetic runs both ways: fuel quantities and transport are trivially small, and the waste — a few tonnes per reactor per year — is correspondingly concentrated and intensely radioactive, needing isolation for time scales of 10^5 years.

Australia's position is distinctive and is regularly examined.

Fact	Detail
Resources	Australia holds roughly a third of the world's known low-cost recoverable uranium
Operating mines	Olympic Dam, Four Mile and Honeymoon, all in **South Australia**. Ranger in the Northern Territory ceased processing in 2021 and is in rehabilitation
Where it goes	All production is **exported**, under bilateral safeguards agreements restricting it to peaceful use; Australia is a party to the Treaty on the Non-Proliferation of Nuclear Weapons
Reactors in Australia	**One** — the OPAL **research** reactor at Lucas Heights, operated by ANSTO, which makes medical and industrial isotopes and generates **no electricity**
Nuclear electricity	**Prohibited.** *Environment Protection and Biodiversity Conservation Act 1999* (Cth) **s 140A** forbids the Minister approving a nuclear power plant, enrichment plant, fuel fabrication plant or reprocessing facility; the *Australian Radiation Protection and Nuclear Safety Act 1998* (Cth) **s 10** forbids the regulator licensing the same facilities
Victoria	*Nuclear Activities (Prohibitions) Act 1983* (Vic) prohibits uranium exploration and mining and the construction of a nuclear reactor in Victoria

Fact	Detail
Waste	The *National Radioactive Waste Management Act 2012* (Cth) provides for a facility, but the Napandee site near Kimba was set aside by the Federal Court in July 2023 and not pursued, so Australia still has **no permanent disposal facility**; waste remains in interim storage

Nuclear's balance sheet as a *source* is therefore unusual: no carbon dioxide from the reaction itself, a very high capacity factor, a small land footprint per unit of energy and a fuel supply Australia already owns — set against very high capital cost and long construction times, large cooling water requirements, long-lived waste with no Australian disposal route, a low-probability but high-consequence accident risk, and a linkage to weapons proliferation that no other energy source carries.

How much of it Australia actually uses. Two figures, kept apart.

Fuel	Share of Australian electricity generation, calendar year 2025
Coal (black and brown)	42.7%
Gas	16.2%
Oil	1.7%
All non-renewable sources	**60.6%**
Renewable sources (solar, wind, hydro, bioenergy)	the balance, about 39%

Source: Department of Climate Change, Energy, the Environment and Water, Australian Energy Statistics, Table O — electricity generation by fuel type, calendar year 2025. Retrieved July 2026. Shares are rounded independently, so the published renewables figure of 39.5% and the non-renewable total above sum to slightly over 100%; quote the published figures, note the rounding, and do not silently adjust either. Check for a later release before reuse.

The second figure is the one that catches students out. Fossil fuels supply close to **90% of Australia's total primary energy consumption**, because electricity is only part of the energy system: transport fuel, industrial process heat, mining and agriculture are largely unelectrified. Quoting the electricity share as though it described the whole energy system is an error of scope, not of arithmetic (the same distinction is drawn at 8D). Nuclear contributes nothing to either figure, for the legal reasons set out above — while Australia simultaneously supplies other countries' reactors.

Comparing the five, on the criteria the Outcome asks for. Unit 4 Outcome 2 requires students to *"compare the advantages and disadvantages of using a range of energy sources"*. A comparison needs the same criteria applied to each source, not a list of facts per source.

	Coal	Oil	Natural gas	Coal seam gas	Nuclear
Energy content	6–10 MJ kg^{-1} brown; 24–30 MJ kg^{-1} black	About 42–45 MJ kg^{-1}; 34–39 MJ L^{-1} as fuels	About 39 MJ m^{-3}; about 54 MJ kg^{-1}	Same as natural gas — it is methane	About 8×10^7 MJ kg^{-1} of U-235 fissioned
CO_2 at generation	Highest	High	Moderate	Moderate	**None**
Main Australian occurrence	Latrobe Valley (brown); NSW and Qld basins (black)	Gippsland, Carnarvon, Cooper Basins	Carnarvon, Browse, Gippsland, Otway Basins	Surat and Bowen Basins, Qld	Olympic Dam, Four Mile, Honeymoon, SA
Extraction impact	Very large open cuts or longwall subsidence	Offshore infrastructure; spill risk	Wells and processing plant	**Many wells; dewatering; saline co-produced water**	Ore body, tailings, radioactive waste rock
Chief advantage	Cheap,	Unmatched	Lowest-emission	Domestic	Enormous

	Coal	Oil	Natural gas	Coal seam gas	Nuclear
	abundant, energy-dense per hectare of plant	liquid energy density; non-fuel products	fossil fuel; fast-starting turbines	resource close to eastern markets	energy density; no operating CO_2
Chief disadvantage	Highest emissions; largest land disturbance	Finite, largely imported, hardest to substitute	Fugitive methane erodes its emissions advantage	Groundwater and land-use conflict	Cost, waste, proliferation; unlawful in Australia
Australian legal status	Permitted, licensed and declining	Permitted; refining capacity nearly gone	Permitted, including onshore conventional in Victoria since 1 July 2021	**Prohibited in Victoria**	**Prohibited nationally**

Where students lose marks.

- **Calling nuclear a fossil fuel.** It is a mined mineral, has no biological origin, and releases energy by fission rather than combustion. It is non-renewable for a completely different reason: uranium ore is a finite deposit.
- **Defining "non-renewable" as "it will run out" or "there is only a limited amount".** The test is the rate of replenishment against the rate of use. Say so.
- **Equating non-renewable with dirty, and renewable with clean.** Nuclear is non-renewable and emits no carbon dioxide at generation; biomass is renewable and does emit carbon dioxide when burnt.
- **Confusing coal seam gas with conventional natural gas.** They are the same molecule obtained in different ways. The distinguishing facts are *adsorbed onto coal*, *held by water pressure*, and *released by dewatering*.
- **Confusing coal seam gas with fracking.** Fracking is a stimulation technique used in some CSG wells and in shale and tight gas; it is not what CSG *is*. Victoria bans both, under two separate sections of two separate Acts.
- **Saying brown coal is worse "because it is dirtier".** Give the two mechanisms: less carbon per tonne, so more mass burnt; and heat consumed evaporating about 60% moisture, so lower thermal efficiency.
- **Giving Australia's electricity mix when asked about its energy use**, or the reverse.
- **Writing that Australia has no nuclear industry.** It mines and exports uranium and operates a research reactor at Lucas Heights; what it does not have is nuclear electricity, and that is prohibited by name in two Commonwealth Acts.
- **Naming no instrument.** "It's illegal" earns less than "s 140A of the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) prohibits approval of a nuclear power plant".
- **Dropping units.** Energy content is MJ kg^{-1}, MJ L^{-1} or MJ m^{-3} and they are not interchangeable; emissions intensity is t CO_2-e MWh^{-1}.

Worked examples

Example 1 — scaffolded

Ulverbrook Energy Pty Ltd operates a brown coal power station at the mine mouth in the Latrobe Valley and is comparing fuels. Take the energy content of as-mined Latrobe Valley brown coal as 8.0 MJ kg^{-1} and of export grade black coal as 25 MJ kg^{-1}.

a. Calculate the mass of each coal needed to supply 1.00 TJ of chemical energy. (2 marks)

b. Express the two masses as a ratio in the form *n* : 1. (1 mark)

c. Explain, in terms of the composition of brown coal, why its energy content per kilogram is so much lower. (2 marks)

d. State one consequence of your answer to **b** for where a brown coal power station can be built. (1 mark)

Step 1 — get the units consistent. 1.00 TJ = 1.00×10^6 MJ. Mass = energy ÷ energy content.

Step 2 — answer a. Brown coal: $1.00 \times 10^6 \div 8.0 = 1.25 \times 10^5$ kg = **125 t**. Black coal: $1.00 \times 10^6 \div 25 = 4.0 \times 10^4$ kg = **40 t**.

Step 3 — answer b. 125 ÷ 40 = **3.1 : 1**. Just over three times the mass of brown coal is needed for the same chemical energy.

Step 4 — answer c. Brown coal is a low-rank coal. Around 60% of its mass as mined is **water**, which contributes no chemical energy at all and absorbs latent heat when it is evaporated in the boiler; and coalification has proceeded less far, so the remaining solid is less concentrated in carbon and retains more volatile matter.

Step 5 — answer d. Because more than three tonnes must be moved for every tonne-equivalent of black coal, and most of the extra mass is water, the fuel is not worth transporting far. Brown coal stations are therefore built adjacent to the open cut — at the **mine mouth** — whereas black coal is economic to rail to port and ship overseas.

Example 2 — scaffolded

The table gives the fuel shares of Australian electricity generation for calendar year 2025.

Fuel	Share
Coal	42.7%
Gas	16.2%
Oil	1.7%
Renewables	39.5%

a. Calculate the share supplied by non-renewable sources. (1 mark)

b. Calculate the ratio of coal-fired to gas-fired generation, to two significant figures. (1 mark)

c. A student writes: *"Renewables are nearly 40% of generation, so Australia now gets nearly 40% of its energy from renewable sources."* Identify and correct the error. (2 marks)

d. Nuclear does not appear in the table. Give two reasons, and state one way Australia is nevertheless part of the world nuclear industry. (3 marks)

Step 1 — answer a. 42.7 + 16.2 + 1.7 = **60.6%**.

Step 2 — answer b. 42.7 ÷ 16.2 = **2.6 : 1**.

Step 3 — answer c. The error is one of **scope**, not arithmetic: the figure describes **electricity generation**, and electricity is only part of the energy system. Transport fuel, industrial process heat, mining and agriculture are largely unelectrified, so fossil fuels still supply close to **90% of Australia's total primary energy consumption**. The corrected statement is that renewables supply about 40% of Australia's *electricity*, not of its energy.

Step 4 — answer d. Two reasons: nuclear electricity is prohibited — s 140A of the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) bars the Minister from approving a nuclear power plant, and s 10 of the *Australian Radiation Protection and Nuclear Safety Act 1998* (Cth) bars the regulator from licensing one — and Australia has no reactor capable of generating electricity and no permanent radioactive waste disposal facility. Australia is nevertheless a major participant: it holds roughly a third of the world's known low-cost uranium resources, mines uranium at Olympic Dam, Four Mile and Honeymoon in South Australia, and exports all of it under safeguards agreements. (It also runs the OPAL research reactor at Lucas Heights, which makes medical isotopes but no electricity.)

Example 3 — unscaffolded

Uranium is classified as a non-renewable energy source. Explain why this classification is correct even though uranium is not a fossil fuel, and explain why the classification tells you nothing about nuclear power's greenhouse gas emissions. (6 marks)

Solution. The classification rests on a comparison of rates, not on the origin of the material. Uranium occurs as an ore body concentrated by geological processes over hundreds of millions of years; mining and fissioning it consumes the deposit over decades. Because the rate of replenishment is effectively zero on any human time scale while the rate of use is high, uranium satisfies the definition of a non-renewable energy source in exactly the same way coal and oil do.

What uranium does not share with coal and oil is their **origin** and their **mechanism**. Coal formed from land plants and oil from marine plankton, both altered by heat and pressure over millions of years; that biological ancestry is what the term *fossil fuel* names. Uranium is a metallic element that has been part of Earth's crust since the planet formed, with no biological involvement at all. Nor is it burnt. Fossil fuels release energy by **combustion** — a chemical reaction between the fuel's carbon and hydrogen and atmospheric oxygen, whose products necessarily include carbon dioxide. Uranium releases energy by **nuclear fission**: a U-235 nucleus absorbs a neutron, splits into lighter nuclei and two or three further neutrons, and releases about 200 MeV, mostly as kinetic energy of the fragments. No carbon is involved and no oxygen is consumed.

That is why the two ideas must be kept apart. "Non-renewable" is a statement about the resource's rate of replenishment; the emissions of a source depend on its **chemistry**. Because fission is not a combustion reaction, a nuclear power station emits no carbon dioxide at the point of generation, and the emissions associated with nuclear electricity arise from mining, enrichment, construction and decommissioning rather than from the energy-releasing reaction itself. The converse also holds and makes the point sharply: biomass is a **renewable** source that does release carbon dioxide when burnt. So classification by renewability and classification by emissions are independent axes, and neither one can be read off the other.

Example 4 — unscaffolded

Braxholme Gas Pty Ltd is seeking finance for a 340-well coal seam gas field in the Surat Basin, Queensland, which would also produce about 4.2 GL of co-produced water a year at about 4200 mg L^{-1} total dissolved solids. Its prospectus states:

> "Coal seam gas is a clean, renewable transition fuel — the coal seams keep generating it. Because the gas comes out of coal rather than a petroleum reservoir, no water approvals are required. On the strength of the Surat project we will replicate the model in Victoria's Latrobe Valley, where the brown coal seams are thicker and shallower."

Evaluate the four claims. (8 marks)

Solution. One claim is partly defensible, and the other three are wrong — one scientifically and two legally.

"Renewable" is wrong. The methane in a coal seam was generated during **coalification**, the same burial, heating and compression process that converted peat to coal over tens to hundreds of millions of years. Whatever residual microbial generation occurs is negligible against a production rate that draws the seam down over the field's 20–30 year life. Since replenishment is many orders of magnitude slower than extraction, coal seam gas is **non-renewable** by definition — the fact that the source rock remains in the ground is irrelevant, because it is the gas that is being consumed.

"Clean" is only half right, and the half that is right is a comparison. Burning methane does release less carbon dioxide per unit of energy than burning coal: a combined-cycle gas plant emits roughly 0.4–0.5 t CO_2-e MWh^{-1} against about 0.8–1.0 for black coal and 1.2–1.4 for brown coal. That is a genuine advantage and it is the legitimate core of the "transition fuel" argument. But it is not *clean* in absolute terms — it is a fossil fuel and its combustion adds carbon dioxide to the atmosphere — and the advantage is conditional on **fugitive emissions**. Methane leaked unburnt from 340 wellheads, gathering lines and processing is a far more potent greenhouse gas per kilogram than carbon dioxide over both 20- and 100-year horizons, so a leakage rate of a few per cent erodes much of the combustion benefit.

"No water approvals are required" is the reverse of the law. Coal seam gas is precisely the activity the Commonwealth **water trigger** was created for: under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth), a coal seam gas or large coal mining development likely to have a significant impact on a water resource is a matter of national environmental significance and must be referred for assessment, with advice from the Independent Expert Scientific Committee established under that Act. The trigger was expanded on 15 December 2023 to all unconventional gas development. Nor is the concern theoretical here: extraction requires **dewatering** the seam — pumping water out to drop the pressure below the desorption pressure so methane comes off the coal — and 4.2 GL a year of water at 4200 mg L^{-1} is both a drawdown of a coal seam aquifer that may be connected to aquifers used for stock, irrigation or town water, and a saline waste stream needing treatment and brine disposal in its own right. State approvals under Queensland law apply as well.

The Victorian limb is unlawful, not merely difficult. Coal seam gas exploration and mining are prohibited in Victoria by s 8AC of the *Mineral Resources (Sustainable Development) Act 1990* (Vic), and hydraulic fracturing by s 16A of the *Petroleum Act 1998* (Vic). Both bans are **entrenched** by the *Constitution Amendment (Fracking Ban) Act 2021* (Vic), so removing them would require a special majority of three-fifths of both Houses of the Victorian Parliament. What Victoria has permitted, since 1 July 2021, is **onshore conventional** gas exploration and production — a different resource obtained a different way, and not what this proposal describes.

On balance, the prospectus should be read as one sound comparative claim about combustion emissions wrapped in a misclassification of the resource, a misstatement of Commonwealth approval requirements and a proposal that Victorian law prohibits outright.

Practice questions

Scaffolded

Q1. Define the term *non-renewable energy source*. (1 mark)

Q2. Name the five non-renewable energy sources listed in the study design. (2 marks)

Q3. Nuclear energy is frequently and wrongly classified as a fossil fuel. Explain why it is not a fossil fuel, and state what does make it non-renewable. (2 marks)

Q4. Complete the table. (4 marks)

Source	Material it formed from	Approximate time scale of formation
Brown coal		
Crude oil		
Conventional natural gas		
Uranium ore		

Q5. Distinguish between brown coal and black coal, referring to rank, moisture content and energy content. (3 marks)

Q6. Explain where the methane is held in a coal seam and how it is released at a coal seam gas well. (3 marks)

Q7. Explain two reasons a brown coal power station emits more carbon dioxide per megawatt hour of electricity than a black coal power station. (2 marks)

Q8. Describe how a nuclear reactor releases energy, and state one consequence of nuclear fuel's very high energy density. (4 marks)

Q9. The table gives approximate energy contents.

Fuel	Energy content
Latrobe Valley brown coal	8.0 MJ kg^{-1}
Black coal	25 MJ kg^{-1}
Diesel	38.6 MJ L^{-1}
Natural gas	39 MJ m^{-3}

a. Calculate the mass of black coal and the volume of diesel that each supply 500 GJ. (2 marks)

b. State which of the four fuels is best suited to powering long-distance road freight, and justify your choice using the table. (2 marks)

Q10. In calendar year 2025 the published fuel shares of Australian electricity generation were coal 42.7%, gas 16.2%, oil 1.7% and renewables 39.5%. Non-renewable sources therefore supplied 60.6%.

a. Calculate the percentage of Australia's non-renewable generation that was supplied by coal. (1 mark)

b. Add the four published shares. State the total, and explain why it is not exactly 100% and what you should do about that when quoting the figures. (2 marks)

c. Fossil fuels supply close to 90% of Australia's total primary energy consumption, well above the 60.6% figure above. Explain why the two percentages differ. (1 mark)

Q11. Australia mines and exports uranium but generates no nuclear electricity.

a. Name one Commonwealth Act that prohibits a nuclear power plant in Australia and state what it prohibits. (2 marks)

b. Explain why mining and exporting uranium is not inconsistent with that prohibition. (2 marks)

c. Name the Victorian Act that prohibits uranium mining and the construction of a nuclear reactor in Victoria. (1 mark)

Unscaffolded

Q12. Explain why "non-renewable" is a statement about the rate at which a source is replenished rather than about the quantity remaining. (3 marks)

Q13. Compare conventional natural gas and coal seam gas as sources of methane, referring to where the gas is held, how it is extracted, and the principal additional environmental consequence of coal seam gas extraction. (4 marks)

Q14. Australia exports coal, natural gas and uranium in large volumes, yet imports most of its refined liquid fuel. Explain how both statements can be true. (4 marks)

Q15. The table gives typical emissions intensities for three fossil-fuelled generators.

Station type	Emissions intensity (t CO_2-e MWh^{-1})
Brown coal	1.3
Black coal	0.9
Combined-cycle gas	0.45

a. Calculate the mass of CO_2-e each station emits in generating 1000 MWh. (2 marks)

b. Calculate the percentage reduction in emissions when brown coal generation is replaced by combined-cycle gas. Show your working. (2 marks)

c. Explain why this substitution reduces emissions but does not eliminate them. (2 marks)

Q16. Explain why oil is the hardest of the five non-renewable sources to replace, referring to both its energy density and its non-energy uses. (4 marks)

Q17. *"Non-renewable means dirty and renewable means clean."* Evaluate this statement, using nuclear power and at least one other source as evidence. (5 marks)

Q18. Ravensedge Petroleum Pty Ltd produces oil and gas from ageing Gippsland Basin fields in Bass Strait. Facing declining output, it proposes to develop coal seam gas from the thick, shallow brown coal seams of the Latrobe Valley. Its investor briefing states that coal seam gas is "the same resource as our Bass Strait gas, just held in a different rock", that the project is "effectively renewable because the coal keeps making gas", and that as an established offshore operator the company is "regulated by NOPSEMA and needs no further approvals".

Evaluate the briefing, identifying what is correct and what is not. (8 marks)

Q19. *"The five non-renewable energy sources named in the study design have so much in common that they can be treated as a single group."*

Discuss this statement. Refer to origin, extraction, energy content, greenhouse gas emissions and Australian regulation. (10 marks)

Answers

Q1. A source whose stock is replenished so slowly relative to the rate at which humans use it that it is effectively being depleted and not replaced. (1)

Q2. Oil; coal; natural gas; coal seam gas; nuclear (2 — 1 mark for three or four correct, 2 marks for all five).

Q3. It is not a fossil fuel because uranium is a mined metallic ore with no biological origin and its energy is released by nuclear fission, not by combustion (1). It is non-renewable because uranium ore is a finite deposit concentrated over geological time and consumed within decades (1).

Q4. Brown coal — land plants accumulating as peat in waterlogged swamps; roughly 15–50 million years for the main Australian deposits (1). Crude oil — marine plankton and algae in oxygen-poor sea-floor muds; tens to hundreds of millions of years (1). Conventional natural gas — the same marine organic matter, cracked at higher temperatures, or shallow microbial (biogenic) action; tens to hundreds of millions of years (1). Uranium ore — no biological origin; a crustal element concentrated by geological processes over hundreds of millions of years (1).

Q5. Brown coal is low rank and black coal high rank on the coalification sequence (1). Brown coal contains about 48–70% moisture as mined, typically near 60% in the Latrobe Valley, against about 5–10% for black coal (1). Brown coal supplies about 6–10 MJ kg^{-1} against about 24–30 MJ kg^{-1} for black coal (1).

Q6. The methane is **adsorbed** onto the very large internal surface area of the coal itself, not held free in pore space (1), and is retained there by the pressure of water saturating the seam's natural fractures or cleats (1). The well is **dewatered** — water is pumped out to lower the pressure below the desorption pressure — so the gas comes off the coal surfaces and flows to the well (1).

Q7. Brown coal contains less carbon per tonne, so a greater mass must be burnt for the same energy (1); and a large part of the heat released is consumed evaporating the coal's own moisture and is lost up the stack, so the station's thermal efficiency is lower, at about 22–27% against 33–42% (1).

Q8. A uranium-235 nucleus absorbs a slow neutron and becomes unstable (1), splitting into two lighter nuclei plus two or three further neutrons and releasing about 200 MeV, mostly as kinetic energy of the fragments, which becomes thermal energy (1); the released neutrons cause further fissions, giving a controlled chain reaction whose heat raises steam to drive a turbine and generator (1). Consequence of the high energy density — any one of: fuel quantities and transport are very small; or the waste is correspondingly concentrated and intensely radioactive, requiring isolation for of the order of 10^5 years (1).

Q9. a. 500 GJ = 5.00×10^5 MJ. Black coal: $5.00 \times 10^5 \div 25 = 2.0 \times 10^4$ kg = 20 t (1). Diesel: $5.00 \times 10^5 \div 38.6 = 1.30 \times 10^4$ L (1). **b.** Diesel (1), because it has by far the highest energy content per unit **volume** of a fuel that is liquid at ordinary temperatures, so a vehicle can carry the energy for a long journey in a small, easily refilled tank — coal cannot be used in a vehicle engine and gas at 39 MJ m^{-3} would need an impractically large or high-pressure tank (1).

Q10. a. 42.7 ÷ 60.6 × 100 = 70.5%, so coal supplies about 70% of Australia's non-renewable generation (1). **b.** 42.7 + 16.2 + 1.7 + 39.5 = 100.1% (1). The four shares are published rounded independently, so their rounding errors do not cancel and the set need not total exactly 100; quote the published figures and note the rounding rather than silently adjusting one of them (1). **c.** The 60.6% figure describes **electricity generation** only, and electricity is only part of the energy system — transport fuel, industrial process heat, mining and agriculture are largely unelectrified and are supplied directly by fossil fuels (1).

Q11. a. Either: the *Environment Protection and Biodiversity Conservation Act 1999* (Cth), s 140A, which prohibits the Minister approving an action involving a nuclear power plant, enrichment plant, fuel fabrication plant or reprocessing facility; or the *Australian Radiation Protection and Nuclear Safety Act 1998* (Cth), s 10, which prohibits the regulator licensing those facilities (2 — 1 for the Act, 1 for what it prohibits). **b.** The prohibitions apply to constructing and operating nuclear **facilities** in Australia, not to mining or selling the ore (1); uranium is mined in South Australia and exported for use in other countries' reactors under bilateral safeguards agreements restricting it to peaceful purposes (1). **c.** The *Nuclear Activities (Prohibitions) Act 1983* (Vic) (1).

Q12. See fully-worked solutions. Key points: the classification compares two rates, replenishment against use (1); a source with a vast remaining stock is still non-renewable if it is not being replaced on a human time scale, and a small stock that is continuously replenished is renewable (1); biomass shows the converse, being renewable only while harvest does not exceed regrowth (1).

Q13. Conventional gas sits free in the pore space of a reservoir rock beneath a sealing cap rock; coal seam gas is adsorbed onto the coal itself (1). Conventional gas flows to the well under its own reservoir pressure; coal seam gas requires dewatering to drop the seam pressure below the desorption pressure, and often hydraulic fracturing where permeability is low (1). Coal seam gas needs many low-yield wells rather than a few high-yield ones (1). The principal additional consequence is very large volumes of saline, often sodic co-produced water, together with drawdown of the coal seam aquifer and possible propagation to connected aquifers used for stock, irrigation or town supply (1).

Q14. See fully-worked solutions. Key points: Australia's endowment is concentrated in coal, gas and uranium, which it has far in excess of domestic need (1); its crude oil resources are comparatively small and declining (1); refining capacity has contracted to two refineries, Geelong and Lytton, after the 2021 closures (1); so most refined liquid fuel is imported, and export strength in one energy commodity says nothing about self-sufficiency in another (1).

Q15. a. Brown coal 1.3 × 1000 = 1300 t CO_2-e; black coal 0.9 × 1000 = 900 t CO_2-e; combined-cycle gas 0.45 × 1000 = 450 t CO_2-e (2 — 1 for method, 1 for all three values with units). **b.** (1.3 − 0.45) ÷ 1.3 × 100 = 0.85 ÷ 1.3 × 100 = 65% reduction (2 — 1 for working on the correct base, 1 for the value and direction). **c.** Gas is still a fossil fuel, so its combustion still adds carbon dioxide to the atmosphere (1); and methane leaked unburnt as fugitive emissions from wells, processing and pipelines is a much more potent greenhouse gas per kilogram than carbon dioxide, so part of the calculated saving is offset (1).

Q16. See fully-worked solutions. Key points: liquid fuels refined from oil carry about 34–39 MJ L^{-1} in a form that is liquid, pourable and storable at ordinary temperatures, which no other source matches for vehicles (1); transport, aviation and shipping are therefore the hardest sectors to electrify (1); a substantial share of each barrel becomes non-fuel product — lubricants, bitumen, solvents, plastics, synthetic fibres, pharmaceutical feedstock (1); those uses have no ready substitute, so oil demand does not disappear even if all combustion uses are replaced (1).

Q17. See fully-worked solutions. (5)

Q18. See fully-worked solutions. (8)

Q19. See fully-worked solutions. (10)

Fully-worked solutions

Q1. The mark is for the **comparison of rates**. "It will run out" and "there is only a limited amount" both describe a stock, not a rate, and neither distinguishes coal from biomass — which is also finite at any instant but renewable because it regrows. Say *replenished far more slowly than it is consumed, so it is effectively depleted and not replaced*.

Q2. The list is worth memorising exactly, because coal seam gas is listed **separately** from natural gas even though the molecule is the same. Answers that give four sources and merge the two gases lose a mark for a reason worth understanding: the study design separates them because their extraction, well density, water impacts and legal status differ, not because the gas differs.

Q3. Two distinct ideas, one mark each, and they must not be run together. *Not a fossil fuel:* uranium is a metallic element mined as ore, has no biological origin, and releases energy by fission rather than combustion. *Still non-renewable:* the ore body was concentrated over hundreds of millions of years and is consumed within decades, so the rate test is failed just as it is for coal. This is the trap that cost 42% of candidates every mark in 2025, and it is nearly always caused by treating "non-renewable" as a synonym for "fossil fuel".

Q4. Each row needs a *material* and a *time scale*, and the fourth row is the discriminator. Brown coal: land plants, via peat, over roughly 15–50 million years for the Latrobe Valley deposits. Crude oil: marine plankton and algae buried in anoxic muds, converted to kerogen and then cracked in the oil window, over tens to hundreds of millions of years. Conventional natural gas: the same marine organic matter taken to higher temperatures in the gas window, or shallow microbial generation. Uranium ore: **no biological material at all** — a crustal element concentrated by geological processes over hundreds of millions of years. Writing "ancient organisms" in the uranium row is the commonest error and gives away the whole distinction.

Q5. All three criteria in the stem must be answered, with figures. Rank is the position on the coalification sequence peat → brown coal → sub-bituminous → black coal → anthracite. Moisture is about 48–70% as mined for brown coal against 5–10% for black. Energy content is about 6–10 against 24–30 MJ kg^{-1}. If room allows, add the consequence that makes the comparison matter: brown coal is not worth transporting, so it is burnt at the mine mouth, whereas black coal is exported.

Q6. Three marks, three ideas: **adsorbed onto the coal**, **held by water pressure**, **released by dewatering**. The word *adsorbed* is doing real work — the gas is stuck to the surface of the coal, not sitting in pore space, and the coal's internal surface area is what allows it to hold so much. Answers that describe a gas reservoir with a cap rock have described conventional gas instead. Fracturing may be added as a stimulation used where permeability is too low, but it should not be presented as how coal seam gas is obtained.

Q7. The examiner is looking for **two mechanisms**, not one mechanism twice. Mechanism one is composition: less carbon per tonne, so a greater mass must be burnt per unit of energy released. Mechanism two is efficiency: about 60% of the fuel's mass is water, and evaporating it consumes heat that leaves as vapour up the stack, so a brown coal station converts only about 22–27% of the fuel's chemical energy to electricity against 33–42% for black coal. "Brown coal is dirtier" states the conclusion, not a reason.

Q8. Marks are in the sequence, and it must be a nuclear sequence, not a chemical one. Neutron absorbed by a U-235 nucleus → nucleus becomes unstable and splits into two lighter nuclei plus two or three neutrons → about 200 MeV released, mostly as kinetic energy of the fragments, which appears as thermal energy → the released neutrons sustain a controlled chain reaction, and the heat raises steam for a turbine and generator. Nothing is burnt and no oxygen is consumed. The fourth mark is the consequence of energy density, and either direction earns it: fuel volumes are tiny, or the waste is correspondingly concentrated and needs isolating for of the order of 10^5 years.

Q9. a. Convert first: 500 GJ = 5.00×10^5 MJ. Then mass or volume = energy ÷ energy content, giving 20 t of black coal and 1.30×10^4 L of diesel. Both answers need units, and the units come from the table — one is per kilogram, the other per litre, and mixing them is the standard slip. **b.** Diesel, and the justification must use the *volumetric* figure: 38.6 MJ L^{-1} is far higher than natural gas at 39 MJ m^{-3} (a cubic metre is 1000 litres, so gas carries about 0.039 MJ L^{-1} at atmospheric pressure), and coal is a solid that cannot fuel a vehicle engine. This is the concrete reason oil dominates transport, and it returns at Q16.

Q10. a. The base of the percentage is the **non-renewable total**, not the whole 100%: 42.7 ÷ 60.6 × 100 = 70.5%. Coal is therefore about seven-tenths of everything non-renewable Australia burns for electricity — and note that this is coal *in total*; the brown coal that Victoria burns is roughly a tenth of national generation, with black coal supplying the rest. Dividing by 100 instead of 60.6 simply returns 42.7%, which answers a different question. **b.** 42.7 + 16.2 + 1.7 + 39.5 = 100.1%. Each share is published rounded independently to one decimal place, so the rounding errors do not cancel and a rounded set need not sum to exactly 100. The right response is to report the figures as published and say why they exceed 100, not to shave 0.1 off one of them: an adjusted figure is no longer the published figure and cannot be cited as one. **c.** The scope distinction. 60.6% is **electricity** generation, and electricity is a fraction of total energy use; across the whole energy system, including transport fuel, industrial heat, mining and agriculture, fossil fuels supply close to 90% of primary energy consumption. Being able to say which figure answers which question is worth more than either figure on its own.

Q11. a. Name the Act *and* what it does. Section 140A of the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) prohibits the Minister from approving an action involving a nuclear power plant, an enrichment plant, a fuel fabrication plant or a reprocessing facility. Section 10 of the *Australian Radiation Protection and Nuclear Safety Act 1998* (Cth) prohibits the regulator from licensing the same facilities. Either is sufficient; naming both is stronger. "It is banned" without an instrument earns little. **b.** The prohibition attaches to **facilities in Australia**, not to the ore: uranium is mined at Olympic Dam, Four Mile and Honeymoon in South Australia and exported under bilateral safeguards agreements restricting it to peaceful use. **c.** The *Nuclear Activities (Prohibitions) Act 1983* (Vic), which bars uranium exploration and mining and the construction of a reactor in Victoria — worth remembering because it means the Victorian answer differs from the South Australian one.

Q12. Build the answer around a ratio. The classification compares the **rate of replenishment** with the **rate of use**: if replenishment is negligible on a human time scale while use is rapid, the source is non-renewable however much of it remains. Two illustrations settle it. Australia's brown coal resource is enormous and would last centuries at current rates, yet it is unambiguously non-renewable, because nothing is replacing it. Conversely, the flow of sunlight arriving at any moment is finite and quite small, yet solar energy is renewable, because the flow is continuously renewed and cannot be depleted by use. Biomass makes the rate test explicit: it is renewable only while harvest does not exceed regrowth, and becomes effectively non-renewable if it does. A source can therefore be abundant and non-renewable, or scarce and renewable, which is exactly why quantity is the wrong test.

Q13. Answer on the three axes the stem names, and keep the identity of the molecule clear — both are methane, so the differences are geological and technical, not chemical. *Where the gas is held:* conventional gas sits free in the pore space of a porous, permeable reservoir rock, trapped beneath an impermeable cap rock, typically 2–4 km down; coal seam gas is adsorbed onto the internal surfaces of a coal seam, usually 300–1000 m down, held there by the water pressure in the seam's cleats. *How it is extracted:* conventional gas flows to the well under its own reservoir pressure, from relatively few high-yield wells; coal seam gas requires dewatering to drop the pressure below the desorption pressure so the gas comes off the coal, from many low-yield wells, sometimes with hydraulic fracturing where permeability is low. *Additional consequence:* the water. Very large volumes of saline and often sodic co-produced water must be treated and its brine disposed of, and the pressure drawdown in the coal seam aquifer can propagate to connected aquifers relied on for stock, irrigation or town water — a lag-plus-uncertainty combination that engages the precautionary principle at 12G. A fourth point available if room allows: well density spreads infrastructure across farmland, producing land-access conflict that conventional gas rarely creates.

Q14. The two statements are about different commodities, and the answer must say so explicitly rather than treat "energy" as one substance. Australia's geological endowment is heavily weighted to **coal, gas and uranium**: it is the world's largest exporter of metallurgical coal, a leading thermal coal and LNG exporter, and holder of roughly a third of known low-cost uranium resources — all far beyond domestic need. Its **crude oil** position is the opposite: resources in the Gippsland, Carnarvon and Cooper Basins are modest and in long-term decline. The refining limb compounds it. Australia had eight refineries two decades ago and, after the Altona and Kwinana closures in 2021, has two — Geelong and Lytton — so even domestically produced crude is largely exported while refined product is imported. The conclusion worth stating is the general one: **self-sufficiency is commodity-specific**, and a large export surplus in one form of energy implies nothing about security of supply in another, because the forms are not interchangeable at the point of use.

Q15. a. Emissions = intensity × energy, so 1300 t, 900 t and 450 t of CO_2-e respectively. Units are part of the answer. **b.** Percentage change is taken on the **starting** value, the brown coal case: (1.3 − 0.45) ÷ 1.3 × 100 = 65%. Dividing by 0.45 instead gives 189%, which answers a different question. State the direction — a reduction. **c.** Two ideas. Gas is a fossil fuel, so 450 t CO_2-e per 1000 MWh is still being emitted; and the figure is a combustion figure, while fugitive methane leaking unburnt from wells, processing and pipelines is a far stronger greenhouse gas per kilogram than carbon dioxide, so the real saving is smaller than the calculation implies. A 65% cut is a large and genuine improvement, and it is not a solution — a distinction that recurs at 13C.

Q16. Four marks, and the question names both limbs, so both must appear. *Energy density:* refined liquid fuels carry about 34 MJ L^{-1} (petrol) to 38.6 MJ L^{-1} (diesel) in a substance that is liquid, pourable and storable at ordinary temperature and pressure. Nothing else in this subtopic comes close in that form — natural gas must be compressed or chilled to −162 °C, coal is a solid, and nuclear fuel cannot be miniaturised into a vehicle. That is why road freight, shipping and aviation are the hardest sectors to shift. *Non-energy uses:* a substantial share of every barrel becomes lubricants, bitumen, solvents, petrochemical feedstock for plastics and synthetic fibres, and precursors for pharmaceuticals. These are chemical uses, not energy uses, so they cannot be electrified at all. The conclusion is that oil demand would not fall to zero even if every combustion use were replaced — which is the basis for the intergenerational equity argument that a finite liquid hydrocarbon resource should be reserved for uses with no substitute (12G).

Q17. *Model response (5 marks).* The statement conflates two independent classifications and is false in both directions.

Renewability is a statement about the **rate at which a source is replenished** relative to the rate at which it is used. Emissions are a consequence of a source's **chemistry** — specifically, whether releasing its energy oxidises carbon. Because the two questions are answered by different properties, neither answer can be read off the other.

Nuclear power falsifies the first half. Uranium is unambiguously non-renewable: it is a finite ore body concentrated over hundreds of millions of years and consumed within decades. But fission is not combustion. A U-235 nucleus splits when it absorbs a neutron, releasing about 200 MeV with no carbon and no oxygen involved, so a nuclear station emits **no carbon dioxide at the point of generation**. Its serious disadvantages are real — long-lived radioactive waste with no Australian disposal facility, very high capital cost, a low-probability high-consequence accident risk and a proliferation linkage — but they are not greenhouse gas emissions.

Biomass falsifies the second half. It is classified as renewable, because plant material regrows on a time scale of years to decades, yet burning it releases carbon dioxide immediately, along with particulates and other air pollutants. Its climate case rests on regrowth reabsorbing the carbon, which holds only if harvest does not exceed regrowth; harvested faster than it regrows, biomass is both effectively non-renewable *and* emitting.

A defensible reformulation is that the four fossil fuels in this subtopic are both non-renewable and carbon-emitting, so for them the statement's two ideas happen to coincide — and it is that coincidence, over four of the five sources, that makes the false generalisation so tempting. The safe practice is to state the axis being used: renewable or non-renewable by rate of replenishment; high- or low-emitting by what the energy-releasing reaction produces.

Q18. *Model response (8 marks).* One of the three claims is partly right, one is wrong scientifically, and one is wrong legally.

"The same resource, just held in a different rock" — half right, and the half that is wrong matters. The molecule is the same: coal seam gas is methane, as is the bulk of Bass Strait natural gas. But the study design lists them separately because everything about obtaining them differs. Conventional Gippsland gas has migrated out of its source rock and collected free in the pore space of a permeable reservoir beneath an impermeable cap rock, kilometres below the sea floor, and flows to a small number of high-yield wells under its own pressure. Coal seam gas is **adsorbed onto the internal surfaces of the coal seam itself**, held there by the pressure of water in the seam's cleats at depths of only a few hundred metres, and it can only be released by **dewatering** — pumping the water out until the pressure falls below the desorption pressure — from a large number of low-yield wells, with hydraulic fracturing where the coal is not permeable enough. Treating an offshore conventional field and an onshore coal seam gas field as the same operation misstates the technique, the well count, the footprint and the water balance.

"Effectively renewable because the coal keeps making gas" — wrong. The methane in the seam was generated during coalification, over the tens of millions of years that converted Latrobe Valley peat to brown coal. Any continuing generation is negligible against a field producing over a 20–30 year life, so replenishment is many orders of magnitude slower than extraction and the resource is **non-renewable** on the definition. The presence of the coal after the gas is removed is beside the point: the gas is what is being consumed, and the coal is itself non-renewable.

"Regulated by NOPSEMA and needs no further approvals" — wrong, and wrong twice. NOPSEMA administers the *Offshore Petroleum and Greenhouse Gas Storage Act 2006* (Cth) in **Commonwealth waters** beyond three nautical miles, which is why it regulates the company's existing Bass Strait operations. It has no role in an **onshore Victorian** project. Onshore, two things are fatal to the proposal. Coal seam gas exploration and mining are prohibited in Victoria by **s 8AC of the *Mineral Resources (Sustainable Development) Act 1990* (Vic)**, and hydraulic fracturing by **s 16A of the *Petroleum Act 1998* (Vic)**; both bans are entrenched by the *Constitution Amendment (Fracking Ban) Act 2021* (Vic), so removing them would require a special majority of three-fifths of both Houses of the Victorian Parliament, not a change of policy. And at Commonwealth level, had the project been proposed in a jurisdiction that permits coal seam gas, the **water trigger** under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) would make a significant impact on a water resource a matter of national environmental significance requiring referral and assessment, with advice from the Independent Expert Scientific Committee — a trigger created for coal seam gas and large coal mining and expanded on 15 December 2023 to all unconventional gas.

What the company could lawfully pursue. Victoria ended its moratorium on **onshore conventional** gas exploration and production on 1 July 2021, so a conventional onshore target — in the Otway Basin, for instance — is legally available and is much closer to the company's existing expertise than coal seam gas is. Declining Bass Strait output is a genuine commercial problem and gas does have a real, if conditional, emissions advantage over coal. The briefing's failure is not its commercial premise but its handling of the science and the law: it misdescribes how coal seam gas is held and produced, misclassifies a geologically-formed resource as renewable, and asserts a regulatory position that Victorian statute contradicts outright.

Q19. *Model response (10 marks).* The statement is defensible on exactly one criterion and fails on every other, so the honest answer is that the group is real but shallow — useful for classification, useless for decision-making.

Where the grouping holds. All five share the single property the classification is built on: their rate of replenishment is negligible compared with the rate at which they are used. Coal formed from land plants over tens to hundreds of millions of years; oil and conventional gas from marine plankton over comparable spans; coal seam gas during the coalification of those same coals; uranium ore was concentrated by geological processes over hundreds of millions of years. Every one is consumed within decades of being found. Because of that, all five raise the same structural questions — depletion, the intergenerational distribution of a finite stock, and the disturbance that extraction causes to the site — and those are genuinely common ground.

Origin splits the group four to one. Coal, oil, natural gas and coal seam gas are **fossil fuels**: they formed from once-living organisms, and their energy is released by **combustion**, a chemical reaction with oxygen whose products necessarily include carbon dioxide. Uranium has no biological origin whatsoever and releases energy by **nuclear fission** — a U-235 nucleus absorbing a neutron and splitting into lighter nuclei plus two or three neutrons, releasing about 200 MeV. Treating the five as one group is what produces the best-known misclassification in this Area of Study: calling nuclear a fossil fuel.

Extraction differs so much that the sources have almost nothing in common operationally. Brown coal is dug from vast shallow open cuts, black coal from open cuts and underground longwalls; oil and conventional gas come from a small number of deep, high-yield wells, offshore in Bass Strait under Commonwealth jurisdiction; coal seam gas requires hundreds of shallow, low-yield wells across farmland plus dewatering of the seam and the management of very large volumes of saline co-produced water; uranium comes from conventional mining at Olympic Dam and in-situ leaching at Four Mile and Honeymoon, with radioactive waste rock and tailings. The environmental risk each creates differs in kind — subsidence and landform loss, marine spill risk, aquifer drawdown and land-use conflict, radiological containment — so no single management response covers them.

Energy content spans seven orders of magnitude. Latrobe Valley brown coal delivers about 8 MJ kg^{-1}; black coal about 25; liquid fuels 34–39 MJ L^{-1}; natural gas about 39 MJ m^{-3}; and complete fission of uranium-235 about 8×10^7 MJ kg^{-1}, some three million times a kilogram of black coal. This is not a detail. It determines whether the fuel can be transported at all — brown coal cannot economically leave the Latrobe Valley, so stations sit at the mine mouth, while black coal is shipped to Asia; it determines that only liquid fuels are practical for road freight, shipping and aviation; and it determines that nuclear fuel and waste volumes are tiny while the waste itself is intensely concentrated.

Greenhouse gas emissions do not follow from the classification at all. Per megawatt hour, brown coal emits roughly 1.2–1.4 t CO_2-e, black coal 0.8–1.0, combined-cycle gas 0.4–0.5, and nuclear **none at the point of generation**, because fission is not a combustion reaction. Within the fossil group the spread is threefold, driven both by carbon content and by thermal efficiency — brown coal converts only about 22–27% of its fuel energy to electricity, partly because so much heat goes into evaporating its roughly 60% moisture, against 33–42% for black coal and 50–60% for combined-cycle gas. And gas's advantage is conditional on fugitive methane, which is much more potent per kilogram than carbon dioxide. A single "non-renewable" label conceals all of this.

Australian regulation treats them as five different things. Coal and conventional gas are lawfully produced, the latter including onshore conventional gas in Victoria since 1 July 2021. Offshore petroleum in Bass Strait sits under the *Offshore Petroleum and Greenhouse Gas Storage Act 2006* (Cth), administered by NOPSEMA. Coal seam gas is **prohibited in Victoria** by s 8AC of the *Mineral Resources (Sustainable Development) Act 1990* (Vic), with hydraulic fracturing prohibited by s 16A of the *Petroleum Act 1998* (Vic), both entrenched by the *Constitution Amendment (Fracking Ban) Act 2021* (Vic) — while it is a major industry in Queensland, subject to the Commonwealth water trigger under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth). Nuclear electricity is prohibited nationally by s 140A of that same Act and s 10 of the *Australian Radiation Protection and Nuclear Safety Act 1998* (Cth), and uranium mining is additionally prohibited in Victoria by the *Nuclear Activities (Prohibitions) Act 1983* (Vic) — even as Australia mines uranium in South Australia and exports all of it. Five sources, five distinct legal regimes, varying by state as well as by source.

Conclusion. "Non-renewable" is a sound and necessary classification, because it identifies the one property these five sources genuinely share and the depletion and equity questions that follow from it. But it is a single-axis label, and the Outcome asks students to *compare advantages and disadvantages* and *evaluate suitability* — work that requires the axes the label suppresses: origin and reaction, extraction method and impact, energy content per kilogram or litre, emissions per megawatt hour, and legal availability. On those criteria brown coal and nuclear power, both non-renewable, are about as different as two energy sources can be. The group should be used to classify, and never to conclude.

Chapter 12 Energy sources, conversions and efficiency — 12B Renewable energy sources

Theory

Every source in this subtopic is a way of intercepting an energy flow that is already happening. The Sun is already heating the atmosphere unevenly; the Moon is already dragging the ocean across the seabed; heat is already leaking out of Earth's interior. A **renewable energy source** takes a share of one of those flows and converts it into a form we can use, and the flow continues whether we tap it or not. That is the whole of the difference between this subtopic and **12A**: a non-renewable source is a *store* being drawn down, and a renewable source is a *flow* being tapped. The study design names seven — **"biomass, biofuels, solar, hydro-electric, wind, tidal and geothermal"** — and every one of them has to be understood as a conversion pathway with a resource behind it, not as a label on a list.

Where this subtopic sits. Chapter 12's other subtopics deal with the rest of the energy picture: **12A** with the non-renewable sources, **12C** with what fossil fuel combustion does to the carbon cycle, **12D** with rates of fossil fuel use and peak oil, **12E** with efficiency calculations for single and multi-step conversions, **12F** with the two laws of thermodynamics as they bear on energy choices, and **12G** with the six sustainability principles applied across the energy supply chain. Chapter 13 then takes it further: **13A** rehabilitation of extraction sites, **13B** base and peak load, **13C** options for a sustainable energy future, **13D** the tensions in deciding between them. This subtopic's job is narrower and prior to all of those — for each of the seven named sources, what is the resource, how is it converted, how much is available and how reliably, and what does using it cost the environment. Where a calculation here needs an efficiency figure, it is given to you as a single number; building the conversion chain step by step is **12E**'s work, not this subtopic's.

What makes a source renewable — and the three drivers behind all seven

A source is **renewable** if the natural processes that replenish it operate at a rate **comparable to or faster than** the rate at which it is used, on a human timescale. **12A** establishes that this rate test, not the size of the deposit, is what sorts sources into the two classes, and hands the renewable side to this subtopic. Two consequences of the test bear directly on the seven sources below, and both are examinable.

First, renewability is a statement about **rates**, not about the material. Wood from a plantation harvested on a 25-year rotation is renewable; the same wood taken from a forest that is cleared and not replaced is not. Nothing about the timber changed — the harvest rate relative to the regrowth rate did.

Second, renewability is decided at the point of use, not at the planetary scale. Geothermal heat is inexhaustible for all practical purposes globally, but a particular reservoir can be cooled to uselessness in twenty years if heat is withdrawn faster than rock conducts it back. **Renewable does not mean infinite, and it does not mean it cannot be mismanaged.**

Behind the seven named sources there are only **three ultimate drivers**, and organising them this way makes the whole dot point tractable.

Ultimate driver	Sources it powers	The chain from driver to source
Solar radiation	solar, wind, hydro-electric, biomass, biofuels	Sunlight is used directly (solar); or it heats the atmosphere unevenly, creating pressure gradients and therefore wind; or it evaporates water that falls as rain at altitude, giving hydro its gravitational potential energy; or it is captured by photosynthesis into chemical bonds, giving biomass and the biofuels made from it
Gravitational interaction and Earth's rotation	tidal	The Moon's (and to a lesser extent the Sun's) gravitational pull raises

Ultimate driver	Sources it powers	The chain from driver to source
		tidal bulges; Earth rotates beneath them, so water moves. The energy is ultimately drawn from Earth's rotation, which is why the day lengthens by about 2 milliseconds per century
Earth's internal heat	geothermal	Heat left from the planet's formation, plus continuing radioactive decay of uranium-238, thorium-232 and potassium-40 in the crust and mantle, conducts and convects towards the surface

Five of the seven are therefore solar energy in disguise. Only **tidal** and **geothermal** run on something else — a point worth holding onto, because it is why those two behave so differently from the rest when the weather changes.

Renewable, low-emission and sustainable are three different claims. They are routinely collapsed into one, and marks are lost for it. *Renewable* is about the replenishment rate of the resource. *Low-emission* is about greenhouse gases released across the whole life cycle, which for every renewable source is greater than zero. *Sustainable* is a broader judgement about biodiversity, equity and intergenerational effects — the six principles at **12G**. A biomass station burning unreplaced native forest is arguably none of the three; a run-of-river hydro scheme is renewable and low-emission while still fragmenting a river. Say which claim you are making.

Solar: the direct route

The resource. Radiation arrives at the top of the atmosphere at about **1361 W m^{-2}** — the solar constant. Absorption and scattering reduce this to roughly **1000 W m^{-2}** on a surface facing the Sun at midday under clear skies, which is the figure solar panels are rated against. Australia receives more solar radiation per square metre than any other continent, about **58 million PJ per year** according to Geoscience Australia — some four orders of magnitude more than the country's total annual energy consumption. The constraint on solar has never been the resource.

Conversion pathway 1 — photovoltaic (PV). A **photovoltaic cell** is a semiconductor, almost always silicon, built as a **p–n junction**. A photon carrying more energy than the semiconductor's band gap lifts an electron out of a bond, and the electric field built into the junction sweeps the freed electron one way and the resulting positive hole the other. The separated charges drive a **direct current** through an external circuit, which an **inverter** converts to the alternating current the grid uses. There is no combustion, no working fluid and no moving part in the cell itself — light goes in and current comes out. Commercial modules convert about **20–23 per cent** of incident radiation; the theoretical ceiling for a single-junction silicon cell, the Shockley–Queisser limit, is around 33 per cent. Output is rated at 1000 W m^{-2} and 25 °C, and falls as the cell heats — typically by about **−0.35 per cent for each degree Celsius** above 25 °C, which is why a very hot still day can yield less than a bright mild one.

Conversion pathway 2 — solar thermal. Here sunlight is used as *heat*. **Concentrated solar power (CSP)** uses parabolic troughs or a field of mirrors focusing on a central tower to raise a fluid to several hundred degrees, boil water and drive a conventional steam turbine. Its distinguishing feature is that heat is cheap to store: molten salt tanks let a CSP plant keep generating for hours after sunset, making it **dispatchable** in a way that PV alone is not. At the low-temperature end, domestic **solar hot water** — flat-plate or evacuated-tube collectors — displaces gas or electricity directly, without ever making electricity at all.

In Australia. Rooftop PV is the standout. Around **four million** small-scale systems are installed, on roughly one in three free-standing houses — the highest per-capita uptake in the world — alongside utility-scale farms such as Kiamal near Ouyen in Victoria's Mallee, at about 200 MW. The characteristic limitation is unavoidable: output is **zero every night**, falls in winter, and drops sharply under cloud.

Wind and hydro-electric: solar energy, one step removed

Wind — the resource. The Sun heats the equator more than the poles and land more than sea. The resulting temperature differences create pressure gradients, and air flows down them. Roughly one to two per cent of incoming solar energy ends up as atmospheric kinetic energy, which is still an enormous flow.

Wind — the conversion. Air passing over the aerofoil section of a blade generates **lift**, which turns the rotor; the rotor drives a generator, through a gearbox or by direct drive. The power available in the wind passing through the swept area is

$$P = \tfrac{1}{2}\rho A v^3$$

where ρ is air density (about **1.225 kg m^{-3}** at sea level), A is the swept area (πr^2 for a rotor of radius r) and v is wind speed in m s^{-1}.

The **cubic dependence on wind speed** is the single most important fact about wind energy. Doubling the wind speed multiplies the available power by **eight**. A site with a mean wind speed of 8 m s^{-1} carries nearly twice the resource of one at 6.5 m s^{-1}, which is why developers spend a year measuring a site before committing to it, and why hub heights have climbed to 100–150 m — wind speed increases with height above the ground.

No turbine can capture all of that power. If it did, the air behind the rotor would be stationary and could not get out of the way of the air behind it. The maximum extractable fraction, the **Betz limit**, is **16/27 ≈ 59.3 per cent**; real turbines reach about 75–80 per cent of Betz across their working range. A turbine's **power curve** has a **cut-in** speed around 3–4 m s^{-1}, reaches its **rated** output around 12–15 m s^{-1}, holds that output flat as the wind rises further by pitching the blades, and shuts down at a **cut-out** speed near 25 m s^{-1} to protect itself.

Offshore wind is the same physics in a steadier, stronger and less turbulent flow. Capacity factors reach 45–55 per cent overseas against 35–40 per cent for onshore wind in Australia, and turbines are far larger — 14–15 MW machines are in service internationally. No offshore turbine yet generates in Australian waters, so the 45–55 per cent is a figure to be *expected*, not one measured here. Australia's first projects are proposed for the Gippsland declared area, established under the *Offshore Electricity Infrastructure Act 2021* (Cth), which licenses generation in Commonwealth waters beyond three nautical miles.

Hydro-electric — the resource. Solar energy evaporates water; it falls as precipitation, some of it on high ground. Water held at altitude has **gravitational potential energy**, and hydro-electricity converts it as the water descends. The power available is

$$P = \rho g Q h$$

with ρ the density of water (1000 kg m^{-3}), g = 9.8 m s^{-2}, Q the flow rate in m^3 s^{-1} and h the **head** — the vertical drop in metres. Multiply by the turbine-and-generator efficiency, typically 0.85–0.92, which is the highest of any generating technology.

Three configurations, which behave completely differently.

- **Run-of-river.** Little or no storage; the scheme generates whatever the river is delivering at the time. Low environmental footprint, but output follows the hydrograph and is not controllable.
- **Storage (reservoir) hydro.** A dam impounds water, and generation is turned on and off at will. Response time is seconds to minutes — the fastest of any large generator — which makes storage hydro the most valuable **dispatchable** renewable source Australia has.
- **Pumped hydro.** Water is pumped uphill using surplus electricity and released later. This is a **store, not a source**: it is a net *consumer* of energy, returning about 75–80 per cent of what it takes in. Snowy 2.0, at 2200 MW and around 350 000 MWh of stored energy, is a storage project, and calling it a renewable energy source is a category error.

In Australia. The Snowy Mountains Scheme totals about 4100 MW across eight power stations, and Hydro Tasmania operates roughly 2.6 GW across about 30 stations. Victoria's contribution — the Kiewa scheme and Dartmouth among them — is comparatively small. Australian hydro is **energy-limited rather than power-limited**: the installed capacity is available, but how much it can generate in a year depends on inflows, so capacity factors sit near 20–30 per cent and fall in drought.

Biomass and biofuels: solar energy stored in chemical bonds

These are the two the study design lists separately, and the distinction is worth stating plainly before anything else. **Biomass** is *organic matter used as a fuel* — solid or wet feedstock, burnt or digested, mostly to make heat and electricity. **Biofuels** are *liquid or gaseous fuels manufactured from biomass* — processed products, mostly for transport. Biomass is the raw material; biofuel is the refined product.

Biomass — feedstocks and conversion. Feedstocks include forestry and sawmill residues, agricultural residues such as sugarcane **bagasse**, straw and husks, purpose-grown energy crops, the organic fraction of municipal waste, and manure and sewage sludge. Three conversion routes matter:

- **Direct combustion** — burn the material, raise steam, drive a turbine. Simple, and the dominant route worldwide.
- **Gasification** — heat the feedstock with restricted oxygen to produce a combustible **syngas** of carbon monoxide and hydrogen, which burns more cleanly and can drive a gas engine.
- **Anaerobic digestion** — methanogenic bacteria break down wet organic matter without oxygen, producing **biogas** that is roughly 55–65 per cent methane. Landfill gas capture is the same chemistry happening in an unmanaged reactor.

Biomass has two genuine advantages that no weather-dependent source can match: the fuel is **storable**, and the plant is **dispatchable**, so capacity factors of 60–85 per cent are normal. Its characteristic weakness is **low energy density** — wood runs about 8–19 MJ kg^{-1} depending on moisture content, against 24–30 MJ kg^{-1} for black coal — so the fuel is bulky, and haulage distance, not technology, usually sets the maximum viable size of a plant.

The carbon accounting, stated carefully. Biomass is counted as renewable because its carbon was taken from the atmosphere recently, within the fast carbon cycle of **9E**, rather than from a store with a residence time of 10^8 years. That is a real and important difference, and what fossil combustion does by contrast is **12C**'s dot point. But three qualifications stop "carbon neutral" from being an automatic conclusion:

1. **Timing.** The CO_2 is released now; the regrowth that reabsorbs it takes years for a crop, decades for a plantation and a century or more for a forest. The gap between them is the **carbon payback period**, and during it the atmosphere carries the extra carbon.
2. **Replacement.** Neutrality assumes the harvested vegetation is actually replaced. If it is not, the emission is permanent and the fuel was not renewable in the first place.
3. **Life cycle.** Harvesting, chipping, drying and trucking the feedstock consume energy, usually diesel. The IPCC's Fifth Assessment gives a median life-cycle figure for dedicated biomass electricity of about **230 g CO_2-e kWh^{-1}** — an order of magnitude above wind, and not zero.

Biofuels — the three families.

- **Ethanol** is made by fermenting sugars (sugarcane, sweet sorghum) or starches (wheat, maize) with yeast, then distilling. It carries about **23.4 MJ L^{-1}** against petrol's **34.2 MJ L^{-1}**, so a litre of ethanol does roughly **68 per cent** of the work of a litre of petrol. Both figures are the energy content factors published together in Australia's *National Greenhouse Accounts*, which matters: energy contents may only be divided into each other when they are quoted on the **same basis**, and pairing one fuel's *net* (lower) heating value with another's *gross* (higher) value is the standard way this ratio comes out wrong by several points. It is blended into petrol as **E10**; the Commonwealth fuel quality standards made under the *Fuel Quality Standards Act 2000* (Cth) cap ethanol in general-supply petrol at 10 per cent by volume. New South Wales mandates minimum ethanol and biodiesel volumes under the *Biofuels Act 2007* (NSW); **Victoria has no equivalent mandate**, so Victorian uptake is driven by price alone.
- **Biodiesel** is made by **transesterification** — reacting vegetable oils, tallow or used cooking oil with methanol and a catalyst to yield fatty acid methyl esters plus glycerol. At about **34.6 MJ L^{-1}** against fossil diesel's **38.6 MJ L^{-1}** — again both *National Greenhouse Accounts* factors — it reaches roughly 90 per cent of diesel's energy per litre, far closer than ethanol comes to petrol. **Renewable diesel** and **sustainable aviation fuel (SAF)** are made by **hydrotreating** instead, which yields paraffinic hydrocarbons rather than esters. Renewable diesel is a genuine **drop-in** fuel and can replace fossil diesel outright. SAF cannot: hydrotreated SAF contains **no aromatics**, and jet fuel needs roughly 8–25 per cent aromatics to swell the elastomer seals in

existing aircraft and fuelling systems, so SAF is certified only up to a **50 per cent blend** with conventional jet fuel. That ceiling is the single best-known constraint on decarbonising aviation with liquid fuel.

- **Biogas and biomethane** — the anaerobic digestion product above, scrubbed of CO_2 and hydrogen sulfide until it can be injected into a gas network.

Biofuels are conventionally sorted into **first generation** (from food crops — which raises the **food-versus-fuel** problem and **indirect land-use change**, where displaced food production clears land somewhere else), **second generation** (from lignocellulosic residues, which avoids the food conflict but is chemically much harder), and **third generation** (from algae, still not commercial at scale). Their real niche is the part of the transport task that is hardest to electrify — aviation, shipping and heavy haulage.

Tidal and geothermal: the two sources the Sun does not drive

Tidal — the resource. The Moon's gravitational gradient across Earth raises two tidal bulges, and Earth rotates beneath them, so most coastlines see two high and two low tides in each **lunar day of about 24 hours 50 minutes** — which puts successive high tides about **12 hours 25 minutes** apart. (The lunar day exceeds the solar day because the Moon has moved along its orbit by the time a point on Earth comes back under it, which is also why the tide runs about 50 minutes later each day.) The Sun adds a smaller effect that reinforces the Moon's at new and full moon (**spring** tides) and opposes it at the quarters (**neap** tides), on a cycle of about 14.8 days. The defining advantage of tidal energy follows directly from this: it is **completely predictable, years in advance**, because it depends on orbital mechanics rather than weather. It is still **variable** — output rises and falls with the tide and drops to nothing at slack water — but variability that can be forecast exactly is a far smaller problem than variability that cannot.

Tidal — two conversion families.

- **Tidal range** schemes build a **barrage** or lagoon across an estuary, hold water behind sluice gates through the tide, and release it through low-head turbines. The energy stored behind the barrage goes as $\mathbf{h^2}$, so a doubling of tidal range quadruples the yield, and a range above about 5 m is generally needed. La Rance in France has run at 240 MW since 1966; Sihwa Lake in South Korea, at 254 MW, is the largest.
- **Tidal stream** schemes put turbines in fast currents and take their **kinetic** energy, using the same $P = \frac{1}{2}\rho A v^3$ relationship as wind. The difference is density: seawater at about **1025 kg m^{-3}** is some 830 times denser than air, so a much smaller, slower rotor delivers comparable power. MeyGen in Scotland's Pentland Firth is the leading array.

In Australia the resource is excellent and the installed capacity is essentially nil. King Sound near Derby, in Western Australia's Kimberley, has a spring range approaching 11 m, among the largest anywhere; Banks Strait in Tasmania and Clarence Strait in the Northern Territory carry strong streams. What has stopped development is distance from load centres, capital cost, and a marine environment that corrodes and fouls everything placed in it.

Geothermal — the resource. Heat flows outward from Earth's interior, sourced from the planet's original heat of accretion and from the continuing decay of long-lived radioisotopes. The average **geothermal gradient** is about 25–30 °C per kilometre of depth, and considerably steeper above granites rich in radiogenic elements.

Geothermal — three settings and three conversions. Where naturally circulating hot water or steam reaches shallow depths, at plate boundaries, **hydrothermal** systems can be tapped straight away — this is Iceland, New Zealand and Indonesia. Australia sits in the middle of a plate and has almost none. Instead it has **hot sedimentary aquifers**, warm water in deep basins, and **hot dry rock**, which requires an **enhanced geothermal system (EGS)**: drill 3–5 km into hot granite, fracture it hydraulically, circulate water through the fractures and produce steam at the surface. Conversion is by dry steam or **flash steam** at high temperatures, or by a **binary (Organic Rankine) cycle** at 100–150 °C, where the geothermal fluid heats a secondary working fluid with a lower boiling point.

In Australia, the story is one of a large resource and almost no electricity. The Habanero project at Innamincka in the Cooper Basin demonstrated an EGS with a 1 MW pilot in 2013 but was wound up in 2016 on cost. The country's **longest-running** geothermal power station was an 80 kW binary unit at Birdsville in Queensland, which generated from 1992 to 2017; the handful of others — Habanero among them — were pilots that ran briefly and closed, so at no point has Australia had a commercial geothermal fleet. **Direct use**, where the heat is used as heat and never becomes electricity, has gone further, though not without setbacks of its own: from **1983 until 2006** Portland, in south-west Victoria, heated its aquatic centre and other council buildings with roughly 58 °C water from the **Dilwyn aquifer**, until the difficulty of disposing of the cooled water closed the scheme. What remains in service across Victoria today is the low-temperature end — **ground-source heat pumps**, which exploit the near-constant 15–20 °C of shallow ground for building heating and cooling. Exploration for and extraction of deep geothermal resources in Victoria are licensed under the ***Geothermal Energy Resources Act 2005* (Vic)**; a shallow, low-temperature scheme such as Portland's falls outside that Act and is regulated as groundwater under the *Water Act 1989* (Vic) instead.

Geothermal's great strength is **availability**: independent of weather, day or season, it delivers the highest capacity factors of any renewable source — 70–90 per cent at the hydrothermal fields of Iceland, New Zealand and Indonesia, which is where that figure comes from, since no Australian plant has ever generated at a scale that could produce one. Its subtlety is the one flagged earlier — a reservoir from which heat is drawn faster than rock conducts it back will cool over decades. Geothermal is renewable at the scale of the planet and **depletable at the scale of the well**, and managing the extraction rate is what keeps it in the renewable column.

The five pathways on one page

Figure 12B.1 puts the conversion pathways side by side. Read the grey line under each schematic before the drawing above it: the marks in this dot point are carried by naming the **form of energy** correctly at each step, and the commonest error in the whole subtopic is calling biomass *thermal* rather than **chemical** at the point of conversion, or tidal *gravitational potential* when the scheme is a stream turbine taking **kinetic** energy.

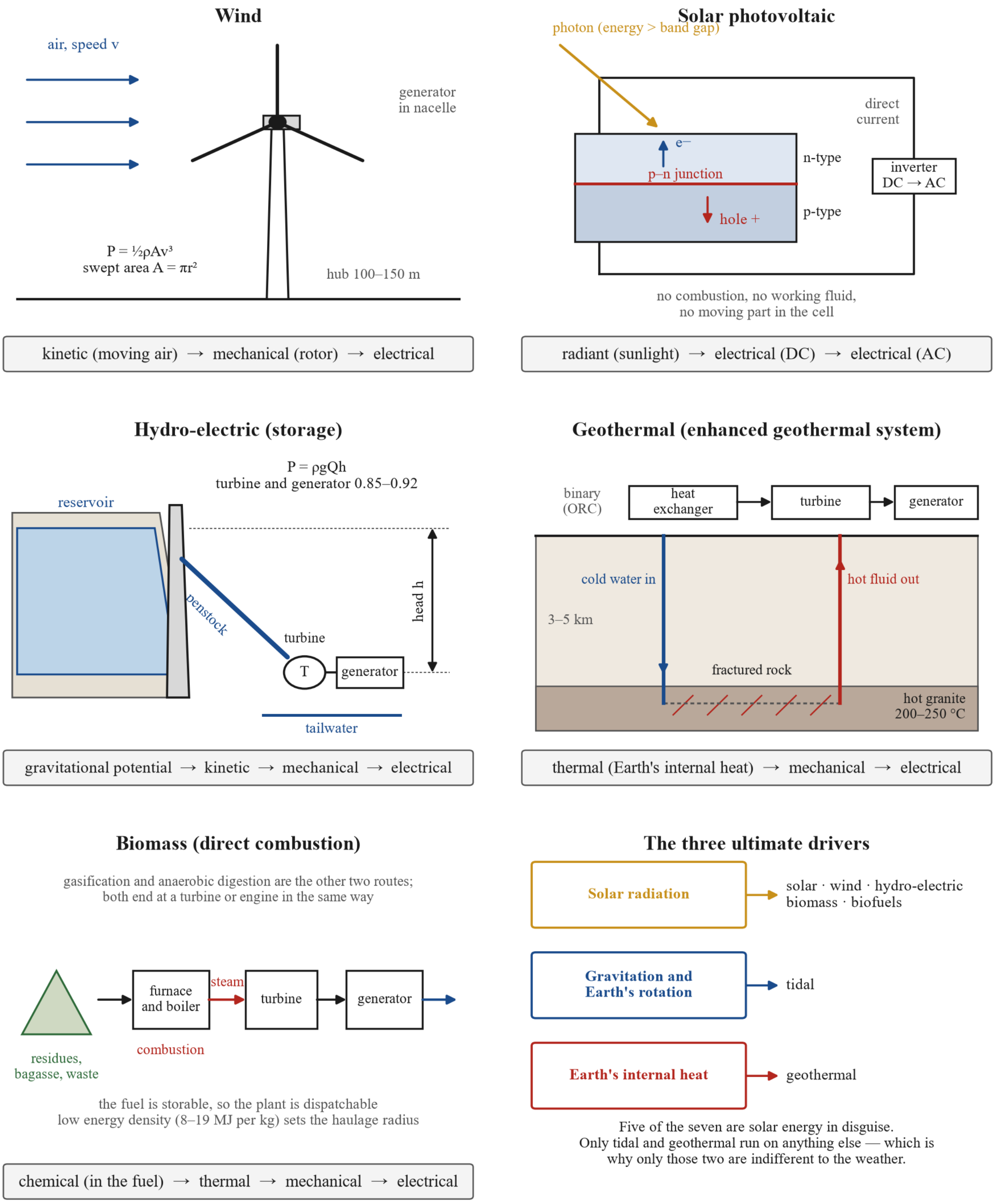


Figure 12B.1 Generation schematics for the five renewable pathways that make electricity from a resource, each with its energy chain named in full, and the three ultimate drivers that sit behind all seven study-design sources.

Comparing sources: availability, reliability and the vocabulary that carries the marks

Comparisons collapse when two different quantities are confused, exactly as stores and fluxes are confused in **9E**.

Nameplate (installed) capacity is the maximum power a plant can produce, in MW. **Generation** is the energy actually produced over a period, in MWh. A 100 MW wind farm and a 100 MW gas turbine have the same nameplate and will not produce the same energy in a year. The measure that connects them is the **capacity factor**:

capacity factor = energy actually generated ÷ (nameplate capacity × hours in the period)

Source	Typical capacity factor	Availability character
Geothermal	70–90% *(international; no Australian plant)*	Constant; independent of weather
Biomass / biogas	60–85%	Dispatchable; fuel is storable

Source	Typical capacity factor	Availability character
Offshore wind	45–55% *(international; Australian projects proposed only)*	Variable, weather-dependent, partly forecastable
Onshore wind	35–40%	Variable, weather-dependent, partly forecastable
Tidal	25–40% *(international; no Australian plant)*	Variable but **exactly predictable**
Utility solar PV (tracking)	25–30%	Variable; zero at night, seasonal, cloud-affected
Hydro (Australian)	20–30%	Dispatchable but energy-limited by inflows
Rooftop solar PV	13–16%	Variable; fixed tilt, often shaded or poorly oriented

Read the three italicised rows carefully. Australia has **no operating geothermal, offshore wind or tidal generation**, so those figures are what plants overseas achieve or what models predict, not what an Australian fleet has measured. A capacity factor is an observation about existing plant; quoting an international one as though it described an Australian option is exactly the move **Worked example 4** is written to take apart.

A capacity factor is a measure of **availability**, not of conversion — it describes how fully the installed capacity was used across the year, and it is set mainly by the resource rather than by the machine. Two identical turbines on different sites have different capacity factors. Efficiency, and the reasons quoting one figure as the other is an error, belong to **12E**.

Three further terms do the comparative work:

- **Variable** — output is set by a resource we do not control (solar, wind, tidal).
- **Dispatchable** — output can be raised or lowered on command (biomass, storage hydro, geothermal, CSP with thermal storage).
- **Firming** — pairing a variable source with storage, a dispatchable plant or demand management so the combination can be relied on. **Curtailment** is the opposite problem: generation deliberately spilled because supply exceeds what the network can take.

How these characteristics are matched against a day's actual demand is **13B**'s dot point, and how a system is built from them is **13C**'s. What belongs here is the property of the *source*.

Impacts: every source has them, and they are not interchangeable

Source	Life-cycle emissions (median, g CO_2-e kWh^{-1})	Principal environmental impacts
Onshore wind	11	Bird and bat collision; noise and visual amenity; composite blades are difficult to recycle; turbine footprint under 2% of site, so grazing and cropping continue between them
Offshore wind	12	Seabed disturbance and pile-driving noise during construction; collision risk for seabirds; interaction with fisheries
Tidal (ocean)	17	Barrages alter the tidal prism and drain or drown intertidal mudflats used by migratory shorebirds; sediment trapping; stream turbines pose collision and noise risk to marine mammals

Source	Life-cycle emissions (median, g CO_2-e kWh^{-1})	Principal environmental impacts
Hydro-electric	24	Barrier to fish passage; altered flow and thermal regime, including cold-water pollution from deep releases; sediment trapping; inundation of habitat and cultural sites; methane from decomposition in warm reservoirs
Concentrated solar	27	Large land area; water for mirror washing and cooling; avian mortality at tower receivers
Geothermal	38	Induced seismicity from EGS fracturing; dissolved CO_2 and hydrogen sulfide in the produced fluid; brine disposal and scaling; subsidence
Utility solar PV	48	Land occupation of the whole site; module end-of-life waste; silver, silicon and glass demand; energy payback of roughly one to two years
Biomass (dedicated)	230	Particulate and NO_x air emissions; harvest pressure on forests; feedstock haulage; competition for land and water
Comparators: **gas combined cycle**	490	*Non-renewable — treated at* **12A**
Comparators: **coal**	820	*Non-renewable — treated at* **12A**

Medians from the IPCC Fifth Assessment Report, Working Group III, Annex III. Ranges around each median are wide — biomass in particular spans roughly 130 to 420 depending on feedstock and haulage. Accurate as at July 2026.

Two conclusions follow. First, **no renewable source is emissions-free**, because manufacturing, construction, maintenance and decommissioning all consume energy; what the low figures show is that those emissions are one to two orders of magnitude below fossil generation. Second, the **impacts are of different kinds** and cannot be traded off on a single scale — a wind farm's problem is birds and amenity, a hydro scheme's is river ecology, a biomass plant's is air quality and land. Choosing between them is a values judgement as much as a scientific one, which is why **12G** and **13D** exist.

The Australian and Victorian picture

12A gives the non-renewable side of this table — coal 42.7 per cent, gas 16.2 per cent and oil 1.7 per cent, for a non-renewable total of 60.6 per cent. The renewable balance, about **39.5 per cent**, breaks down as follows.

Renewable source	Share of Australian electricity generation, calendar year 2025
Rooftop (small-scale) solar	12.3%
Large-scale solar	7.4%
Wind	14.0%
Hydro	4.7%
Bioenergy	1.1%
All renewable sources	**39.5%**

Source: Department of Climate Change, Energy, the Environment and Water, Australian Energy Statistics, *Table O — electricity generation by fuel type, calendar year 2025. Retrieved July 2026. Shares are rounded independently, so* *components may not sum exactly to the published total; quote the published figures and note the rounding rather than adjusting either. Renewables were near 35 per cent as recently as 2023, so check for a later release before reuse. Globally, renewables supplied roughly 30 per cent of electricity in 2024, with hydro the largest single contributor at about 14 per cent, wind about 8 per cent and solar about 7 per cent.*

Two features of that table are worth naming. **Solar is now the largest renewable contributor**, and most of it is on roofs rather than in solar farms — an unusual structure internationally, and a direct consequence of the small-scale certificate scheme described below. And **hydro, the oldest renewable source in the country, has been overtaken by both solar and wind** — wind now generates about **three times** what hydro does — not because hydro declined in capacity but because it is limited by the number of suitable rivers and by inflows in any given year, while the other two are limited only by how many turbines and modules get installed.

The instruments that shape this, named accurately, are:

- The ***Renewable Energy (Electricity) Act 2000* (Cth)**, which creates the **Large-scale Renewable Energy Target** and the **Small-scale Renewable Energy Scheme**, administered by the **Clean Energy Regulator**. Accredited large generators create **large-scale generation certificates (LGCs)**, one per megawatt hour; small rooftop installations create **small-scale technology certificates (STCs)**, which is the mechanism behind the discount on a household solar quote.
- Amendments to the regulations under that Act **excluded native forest biomass from renewable eligibility from December 2022**, so electricity generated from that feedstock cannot create LGCs.
- Victoria's renewable electricity targets are legislated in the ***Renewable Energy (Jobs and Investment) Act 2017* (Vic)** — 65 per cent by 2030 and 95 per cent by 2035 — with separate legislated offshore wind targets of at least 2 GW by 2032, 4 GW by 2035 and 9 GW by 2040.
- Wind energy facilities in Victoria are permitted under the ***Planning and Environment Act 1987*** (Vic) and Clause 52.32 of the planning scheme, which prevents a permit being granted for a turbine within **1 km of an existing dwelling** without the owner's written consent.
- Thermal waste-to-energy in Victoria is capped statewide at **2.5 million tonnes of waste per financial year**. The cap scheme is created by the ***Circular Economy (Waste Reduction and Recycling) Act 2021* (Vic)**, but the limit itself is set by the *Circular Economy (Waste Reduction and Recycling) (Waste to Energy Scheme) Regulations 2023* (Vic) and administered through cap licences issued by Recycling Victoria — so the number is in the regulations and can be moved without amending the Act, as it has been twice since 2024.
- Projects with a significant impact on nationally listed species or communities are assessed as controlled actions under the ***Environment Protection and Biodiversity Conservation Act 1999*** (Cth) — the pathway by which wind farm proposals are examined for their effect on listed birds.

Accurate as at July 2026.

Worked examples

The organisations named below are fictional; the processes, quantities, schemes and legislation are real.

Example 1 — scaffolded

For each of the following sources, state the ultimate driver of the energy, name the form of energy that is converted at the point of generation, and classify the source as variable or dispatchable: (i) onshore wind; (ii) tidal stream; (iii) biomass combustion; (iv) storage hydro-electric. *(4 marks)*

Working	Comment
(i) **Wind** — driver: **solar radiation**, through uneven heating of the atmosphere. Converted: **kinetic energy** of moving air, via lift on the blades. **Variable.**	Wind is solar energy one step removed; its variability is weather-driven and only partly forecastable.
(ii) **Tidal stream** — driver: **gravitational interaction of the Moon and Sun with the ocean, plus Earth's rotation**. Converted: **kinetic energy** of moving water.	Not solar. Predictability is the property that distinguishes it from wind, and it is worth a mark on its own.

Working	Comment
Variable, but exactly predictable.	
(iii) **Biomass** — driver: **solar radiation**, captured by photosynthesis. Converted: **chemical energy** in the fuel, released as heat by combustion. **Dispatchable.**	The fuel is storable, so the operator chooses when to generate — the key contrast with (i) and (ii).
(iv) **Storage hydro** — driver: **solar radiation**, through evaporation and precipitation at altitude. Converted: **gravitational potential energy** of impounded water. **Dispatchable.**	Dispatchable but energy-limited: the reservoir sets how much can be generated in total, not just how fast.

Example 2 — scaffolded

A wind turbine has a rotor diameter of 150 m and a rated output of 6.0 MW. Take air density as 1.225 kg m^{-3}.

(a) Calculate the swept area. (b) Calculate the power in the wind passing through that area at a wind speed of 9.0 m s^{-1}. (c) Calculate the maximum power the turbine could extract at that wind speed. (d) The wind speed later rises to 18.0 m s^{-1}. Explain what happens to the power in the wind and to the turbine's output. *(5 marks)*

Working	Comment
(a) $r = 150 \div 2 = 75$ m. $A = \pi r^2 = \pi \times 75^2 = \pi \times 5625 =$ **17 700 m²** (3 s.f.).	Diameter is given, the formula needs radius. Halving it first is the step most often skipped.
(b) $P = ½\rho A v^3 = 0.5 \times 1.225 \times 17\,671 \times 9.0^3 = 0.5 \times 1.225 \times 17\,671 \times 729 = 7.89 \times 10^6$ W = **7.89 MW**.	Cube the speed, do not multiply by 3. Keep the unrounded area in the calculation and round at the end.
(c) Betz limit = 16/27 = 0.593. Maximum extractable = 7.89 × 0.593 = **4.68 MW**.	No turbine can take all the kinetic energy — the air must retain enough speed to leave the rotor.
(d) Doubling v multiplies P by 2^3 = **8**, so the power in the wind rises to about **63 MW**. The turbine's output does **not** rise: it is already at or above its rated 6.0 MW, so the blades pitch to spill the excess and output is held flat at **6.0 MW**.	The v^3 law describes the *resource*, not the machine. Turbines are deliberately rated well below peak wind power because the strongest winds are rare.

Example 3 — unscaffolded

Merrindeen Bioenergy Pty Ltd advertises that electricity from its wood-fired station is "carbon neutral, because the carbon released was absorbed from the atmosphere by the trees in the first place." Evaluate this claim. *(4 marks)*

The claim rests on something true and then stops too early. It is correct that the carbon in wood was fixed from the atmosphere within the **fast carbon cycle** — years to a century — rather than drawn from a fossil store with a residence time of the order of 10^8 years, and that difference is exactly why biomass is classed as renewable while coal is not. But "carbon neutral" is a conclusion about a *net balance over time*, and three conditions have to hold before it can be drawn.

Timing. The CO_2 enters the atmosphere the moment the wood burns, while the regrowth that reabsorbs it takes decades for a plantation and a century or more for a forest. Across that **carbon payback period** the atmosphere carries the additional carbon and it exerts its full warming effect. **Replacement.** Neutrality assumes the harvested vegetation is genuinely replaced. If the area is cleared and converted, or harvested faster than it regrows, the emission is permanent and the fuel was never renewable. **Life cycle.** Felling, chipping, drying and trucking the feedstock consume diesel, and the IPCC's median life-cycle figure for dedicated biomass electricity is about 230 g CO_2-e kWh^{-1} — low against coal at 820, but roughly twenty times onshore wind at 11.

Takeaway: biomass carbon neutrality is a claim that has to be **earned by the management of the resource**, not a property of the fuel. The right question is never "is this biomass?" but "is it being replaced, how fast, and what was burnt getting it here?"

Example 4 — unscaffolded

A commentator writes that "geothermal is plainly the best renewable source, because it runs at an 85 per cent capacity factor while solar manages barely 28 per cent." Calculate the annual generation per megawatt installed for each, and evaluate the conclusion for a Victorian setting. *(5 marks)*

Per megawatt of nameplate capacity, over a 365-day year of 8760 hours:

Geothermal: 1 MW × 8760 h × 0.85 = **7450 MWh**. Solar: 1 MW × 8760 h × 0.28 = **2450 MWh**.

The geothermal plant delivers about **three times** the energy per megawatt installed, and the commentator's figures are right. The reasoning is still wrong, for two reasons.

A capacity factor describes a plant that exists, not a resource that does. Australia sits in the middle of a tectonic plate, so it has almost no shallow hydrothermal resource of the kind that gives Iceland or New Zealand their high-capacity-factor plants. Reaching usable temperatures here means drilling 3–5 km into hot granite and creating an **enhanced geothermal system** — which is exactly what the Habanero project in the Cooper Basin attempted before being wound up in 2016 on cost. Australia's longest-running geothermal power station was an 80 kW unit at Birdsville, which closed in 2017, and there is no operating Australian geothermal generation at all — so the 85 per cent is an *international* capacity factor, borrowed from plants in Iceland and New Zealand and attached here to a plant that does not exist. An 85 per cent capacity factor on a plant that cannot economically be built in Victoria delivers nothing. Solar, by contrast, is installed here in quantity: the commentator's 28 per cent is a **utility-scale tracking** figure, and Victoria's rooftop fleet runs lower again at **13–16 per cent** — but between them they already supply a substantial share of the state's electricity.

Availability is not the only axis of comparison. Geothermal is renewable at the planetary scale but **depletable at the well**: draw heat faster than the surrounding rock conducts it back and the reservoir cools within decades, taking that capacity factor down with it. Solar's resource cannot be depleted by use at all.

Takeaway: a capacity factor compares how fully installed plants are used; it says nothing about whether the resource exists where you need it, what it costs to reach, or whether it can be depleted. "Best" needs the resource, the site and the impacts, not one number.

Practice questions

Scaffolded

Q1. (a) Define a renewable energy source. (b) State the three ultimate drivers of the seven renewable sources named in the study design. (c) State which of the seven are **not** ultimately driven by solar radiation. *(3 marks)*

Q2. For each of solar photovoltaic, geothermal, tidal range and biofuels: (a) name the form of energy that is converted at the point of use; (b) classify the source as variable or dispatchable; (c) state one factor that limits where it can be sited. *(4 marks)*

Q3. A wind turbine has a rotor diameter of 130 m. Take air density as 1.225 kg m^{-3}. (a) Calculate the swept area. (b) Calculate the power in the wind at a wind speed of 10.0 m s^{-1}. (c) Calculate the maximum power that could be extracted, given the Betz limit of 16/27. (d) Explain why the turbine's actual output at this wind speed will be lower still. *(5 marks)*

Q4. Nardowie Wind Farm has 38 turbines of 6.0 MW each and generated 745 000 MWh last year. (a) Calculate the nameplate capacity of the farm. (b) Calculate the maximum energy the farm could have generated in a 365-day year. (c) Calculate the capacity factor. (d) With reference to the turbine's power curve, state two reasons why the capacity factor is well below 100 per cent. *(5 marks)*

Q5. A run-of-river hydro-electric scheme operates with a head of 90 m and a flow rate of 25 m^3 s^{-1}. Take the density of water as 1000 kg m^{-3} and g as 9.8 m s^{-2}. (a) Calculate the power available in the falling water. (b) Calculate the electrical output, given a combined turbine-and-generator efficiency of 0.90. (c) Calculate the annual generation in MWh if the scheme achieves a capacity factor of 0.30. (d) State one assumption made in part (c). *(6 marks)*

Q6. Dunmarrow Ethanol Pty Ltd processes 45 000 tonnes of wheat a year, yielding 380 L of ethanol per tonne. Take the energy content of ethanol as 23.4 MJ L^{-1} and of petrol as 34.2 MJ L^{-1}. (a) Calculate the annual ethanol production, in litres. (b) Calculate the total energy content of that ethanol, in MJ. (c) Calculate the volume of petrol that would deliver the same energy. (d) Express the answer to (c) as a percentage of the answer to (a), and state what this shows. (e) State one limitation of using wheat as a biofuel feedstock. *(6 marks)*

Unscaffolded

Q7. State what is meant by **firming** a variable renewable source. *(1 mark)*

Q8. Distinguish between biomass and biofuels, giving one example of each. *(2 marks)*

Q9. Explain why tidal energy is described as variable but predictable, and state why that combination is useful. *(2 marks)*

Q10. A site's mean wind speed is measured at 6.0 m s^{-1} at 50 m above ground and 8.0 m s^{-1} at 120 m. Explain, with reference to the relationship between wind speed and power, why this difference matters so much to a wind farm developer. *(3 marks)*

Q11. Explain why geothermal energy is classified as renewable even though a particular geothermal reservoir can be exhausted. *(3 marks)*

Q12. *(Stimulus.)* Callowyn Solar Pty Ltd makes the following statement in its promotional material.

> **Stimulus.** "Our solar farm is completely emissions-free and runs on a fuel that will never run out, so it has no environmental impact at all."

Identify two scientific problems with this statement and explain each. *(4 marks)*

Q13. *(Stimulus.)* The table gives monthly generation, in GWh, from a 100 MW solar farm and a 100 MW wind farm in the same region of southern Victoria.

Stimulus.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Solar	30	26	24	18	13	11	12	16	21	26	28	31
Wind	24	21	23	26	30	32	34	33	32	30	27	25

Describe the seasonal pattern of each source and use the data to explain why the two together are valued more highly than twice as much of either alone. *(4 marks)*

Q14. *Renewable*, *low-emission* and *sustainable* are three different claims about an energy source. Distinguish between the three, then use one named renewable source to show that satisfying one of them does not settle the others. *(4 marks)*

Q15. Explain why a hydro-electric scheme with a large storage reservoir is described as dispatchable while a run-of-river scheme largely is not, and describe two ecological consequences that follow from building the storage. *(5 marks)*

Q16. Kestermayne Renewables Pty Ltd states that a proposed site has "an excellent wind resource". Describe the measurements and evidence you would gather to test that claim. *(5 marks)*

Q17. Compare solar photovoltaic and onshore wind as renewable energy sources, referring to the resource and conversion process, availability and variability, capacity factor, land requirements and principal environmental impacts. *(6 marks)*

Q18. *(Stimulus.)* Merrindeen Bioenergy Pty Ltd has proposed a 15 MW biomass power station for a Victorian regional centre.

> **Stimulus.** "The station will run at an 85 per cent capacity factor on wood residues trucked from within 150 km, including plantation thinnings and sawmill offcuts. Because the trees regrow, the electricity is carbon neutral and produces no net emissions. We expect to create large-scale generation certificates for every

> megawatt hour. Our fuel supply agreement permits up to 40 per cent of feedstock to be sourced from native forest harvesting operations if plantation residue is unavailable."

Evaluate this proposal as a renewable energy source. *(8 marks)*

Q19. Wandrella Shire Council has funding for one renewable generation project to supply its own depots, offices and leisure centre. It is considering three options: solar photovoltaic arrays on council rooftops and one ground-mounted array; a share in Nardowie Wind Farm, 40 km away; and a small run-of-river hydro-electric scheme on a regulated river within the shire. For each option, explain the resource and the conversion, describe its availability and reliability, and identify its principal environmental impact. Recommend one option with justification, and state one limitation of your recommendation. *(10 marks)*

Answers

Q1. (a) A source replenished by natural processes at a rate comparable to or faster than the rate at which it is used, on a human timescale. (b) Solar radiation; gravitational interaction with the Moon and Sun combined with Earth's rotation; Earth's internal heat. (c) Tidal and geothermal.

Q2. Solar PV — radiant (light) energy; variable; needs high solar radiation and unshaded area. Geothermal — thermal energy; dispatchable; needs a high geothermal gradient or a hot aquifer at drillable depth. Tidal range — gravitational potential energy of impounded water; variable but predictable; needs an estuary with a tidal range above about 5 m. Biofuels — chemical energy; the processed fuel is storable, so dispatchable; needs feedstock land, water and a processing plant.

Q3. (a) $A = \pi \times 65^2 =$ **13 300 m²** (3 s.f.). (b) $P = 0.5 \times 1.225 \times 13\,273 \times 1000 =$ **8.13 MW**. (c) $8.13 \times 16/27 =$ **4.82 MW**. (d) Real turbines reach only about 75–80 per cent of the Betz limit, and there are further losses in the gearbox, generator and transformer.

Q4. (a) $38 \times 6.0 =$ **228 MW**. (b) $228 \times 8760 =$ **1 997 280 MWh**. (c) $745\,000 \div 1\,997\,280 =$ **37.3 per cent**. (d) Any two of: the wind is below the cut-in speed of about 3–4 m s^{-1} for part of the year, so the turbines produce nothing; the wind is between cut-in and rated speed for much of the year, so they produce less than 6.0 MW each; the wind occasionally exceeds the cut-out speed of about 25 m s^{-1} and they shut down; turbines are offline for maintenance or fault.

Q5. (a) $P = 1000 \times 9.8 \times 25 \times 90 =$ **22.05 MW**. (b) $22.05 \times 0.90 =$ **19.8 MW**. (c) $19.845 \times 8760 \times 0.30 =$ **52 000 MWh** (2 s.f.). (d) Any one of: head and flow remain constant year-round; efficiency is constant at all flows; no outages for maintenance; the capacity factor of 0.30 is representative of an average rainfall year.

Q6. (a) $45\,000 \times 380 =$ **1.71×10^7 L** (17.1 ML). (b) $1.71 \times 10^7 \times 23.4 =$ **4.00×10^8 MJ**. (c) $4.0014 \times 10^8 \div 34.2 =$ **1.17×10^7 L** (11.7 ML). (d) $11.7 \div 17.1 \times 100 =$ **68 per cent** — a litre of ethanol carries only about 68 per cent of the energy of a litre of petrol, so a larger volume must be carried and burnt for the same work. (e) Any one of: food-versus-fuel competition; indirect land-use change; energy consumed growing, harvesting and distilling the feedstock; water and fertiliser demand.

Q7. Pairing the variable source with storage, a dispatchable plant or demand management so that the combination can be relied on to deliver at a nominated time.

Q8. Biomass is organic matter used directly as a fuel, burnt or digested — for example sugarcane bagasse burnt at a mill. Biofuels are liquid or gaseous fuels manufactured from biomass, mostly for transport — for example ethanol fermented from wheat starch.

Q9. Variable because output rises and falls with the tidal cycle and falls to nothing at slack water; predictable because the tides follow orbital mechanics and can be calculated years ahead. Useful because variation that can be forecast exactly can be planned around, unlike weather-driven variation.

Q10. Power in the wind goes as v^3. $(8.0 \div 6.0)^3 = 2.37$, so the higher measurement carries about 2.4 times the power of the lower one for the same rotor. This is why hub heights have risen to 100–150 m and why small differences in mean wind speed decide whether a site is viable.

Q11. Renewable because Earth's internal heat is continuously supplied by primordial heat and radioactive decay, on a timescale of billions of years. Depletable locally because heat can be withdrawn from one reservoir faster than rock conducts it back, cooling that reservoir within decades. Renewability is judged by the rate of use against the rate of replenishment, and that comparison is made at the well, not at the planet.

Q12. (i) It is not emissions-free: manufacturing modules, mounting, inverters and construction all release greenhouse gases, giving utility solar a life-cycle figure near 48 g CO_2-e kWh^{-1}. Only *operating* emissions are near zero. (ii) "No environmental impact" is false: the array occupies land for decades, modules must be disposed of or recycled at end of life, and manufacture consumes silver, silicon and glass. (Also creditable: the sunlight will not run out but the panels degrade and are replaced after roughly 25–30 years.)

Q13. Solar peaks in summer (31 GWh in December) and troughs in winter (11 GWh in June), a ratio of about 2.8. Wind does the reverse, peaking in winter (34 GWh in July) and troughing in summer (21 GWh in February), a ratio of about 1.6. Added together the monthly totals range only from 43 to 56 GWh, a ratio of about 1.3 — much flatter than either alone, because each source is strongest when the other is weakest.

Q14. *Renewable* is about the resource: its replenishment rate compared with the rate of use. *Low-emission* is about greenhouse gases across the whole life cycle, which for every renewable source is above zero. *Sustainable* is a broader judgement covering biodiversity, ecological integrity and equity between and within generations. Worked example: storage hydro is renewable (rainfall replenishes the inflow) and low-emission (about 24 g CO_2-e kWh^{-1}), yet the dam blocks fish passage, floods habitat and cultural sites and alters the flow and thermal regime, so its sustainability is contested. (Also creditable: biomass from unreplaced native forest, which is arguably none of the three.)

Q15. Storage hydro holds water behind a dam and can release it on command in seconds to minutes, so output is controllable; run-of-river has little or no storage and generates whatever the river is delivering, so output follows the hydrograph. Two ecological consequences of the storage: the dam blocks fish passage and fragments the river; and the flow and thermal regimes are altered, including cold-water pollution when water is released from deep in the reservoir. (Also creditable: sediment trapping; inundation of habitat and cultural sites; methane from decomposition in the reservoir.)

Q16. Erect a met mast or lidar at hub height, not at ground level; log wind speed and direction at short intervals for at least 12 months to capture the full seasonal cycle; build a wind rose and a speed-frequency (Weibull) distribution rather than relying on a mean; measure turbulence intensity and wind shear; correlate the record against a long-term nearby reference station to place the measurement year in context; then apply a candidate turbine's power curve to the distribution to predict generation and capacity factor.

Q17. Both convert solar energy, PV directly from radiation via a p–n junction and wind indirectly from the kinetic energy of air. Both are variable: solar predictably diurnal and seasonal, wind weather-driven and less forecastable. Capacity factors around 25–30 per cent for utility solar and 35–40 per cent for onshore wind. Solar occupies the whole site; a wind farm's turbines occupy under 2 per cent of theirs, allowing grazing to continue. Solar's impacts are land occupation and module waste; wind's are bird and bat collision, noise, visual amenity and blade disposal. See the fully-worked solution.

Q18. Strengths: a genuinely dispatchable, storable-fuel source; a realistic capacity factor; residues used rather than purpose-felled timber. Weaknesses: "no net emissions" ignores carbon payback and a life-cycle figure near 230 g CO_2-e kWh^{-1}, including 150 km of diesel haulage; native forest biomass has been excluded from renewable eligibility since December 2022, so the 40 per cent limb would create no certificates; Victoria ended native timber harvesting in state forests from 1 January 2024, so that feedstock is not available anyway; biomass's low energy density makes the haulage radius a hard constraint; particulate emissions near a regional centre. See the fully-worked solution.

Q19. Solar PV: radiant energy converted by p–n junction; variable, zero at night, capacity factor 13–16 per cent on rooftops; impact is land occupation and end-of-life module waste. Wind share: kinetic energy of air via lift; variable and weather-driven, capacity factor 35–40 per cent; impact is bird and bat collision, noise and amenity. Run-of-river hydro: gravitational potential energy of falling water; output follows river flow, so barely dispatchable and drought-exposed; impact is fish passage and altered flow regime. Recommendation with justification and one stated limitation required. See the fully-worked solution.

Fully-worked solutions

Q1. (a) A **renewable energy source** is one whose **natural replenishment rate is comparable to or faster than the rate at which it is used**, on a human timescale. (b) **Solar radiation**; **gravitational interaction of the Moon and Sun with the ocean, together with Earth's rotation**; and **Earth's internal heat**, from primordial heat and radioactive decay. (c) **Tidal** and **geothermal**. *Marker's note:* the definition must be about a **rate comparison**. "A source that does not run out" is not the definition and does not survive the geothermal case in Q11.

Q2. Solar PV — radiant (light) energy; **variable**; needs high incident radiation and an unshaded, correctly oriented area. **Geothermal — thermal energy**; **dispatchable**; needs a steep geothermal gradient or a hot aquifer within drillable depth, which in Australia rules out most of the continent. **Tidal range — gravitational potential energy** of water impounded behind the barrage; **variable but exactly predictable**; needs an estuary with a tidal range above roughly 5 m. **Biofuels — chemical energy** in the fuel; **dispatchable**, because the processed fuel is storable; needs feedstock land, water and a fermentation or transesterification plant. *Common error:* calling tidal "dispatchable" because it is predictable. Predictability and controllability are different properties — you cannot ask for a tide.

Q3. (a) r = 65 m; A = π × 65² = π × 4225 = **13 300 m²** (3 s.f.). (b) P = ½ρAv³ = 0.5 × 1.225 × 13 273 × 10.0³ = 0.5 × 1.225 × 13 273 × 1000 = **8.13 × 10⁶ W = 8.13 MW**. (c) Betz limit = 16/27 = 0.593; maximum extractable = 8.13 × 0.593 = **4.82 MW**. (d) The Betz limit is an **ideal** ceiling on the fraction of kinetic energy a rotor can take from the airstream. Real blades reach only about **75–80 per cent** of it, because of blade drag, tip losses and the finite number of blades, and further energy is lost in the **gearbox, generator and transformer** before electricity reaches the network. *Marker's note:* the commonest errors are using diameter in place of radius, which multiplies the area by four, and multiplying the speed by three instead of cubing it.

Q4. (a) Nameplate capacity = 38 × 6.0 = **228 MW**. (b) Maximum possible generation = 228 MW × 8760 h = **1 997 280 MWh**. (c) Capacity factor = 745 000 ÷ 1 997 280 = 0.373 = **37.3 per cent** — a typical figure for a well-sited Australian onshore wind farm. (d) Any two, referred to the **power curve**: for part of the year the wind is **below the cut-in speed** of roughly 3–4 m s⁻¹ and the turbines generate **nothing at all**; for much of the year the wind sits **between cut-in and rated speed**, roughly 12–15 m s⁻¹, so each turbine produces **less than its rated 6.0 MW**; occasionally the wind **exceeds the cut-out speed** near 25 m s⁻¹ and the turbines shut down to protect themselves; and turbines are **offline for maintenance or fault** for some hours each year. *Marker's note:* the reason a wind farm's capacity factor is 37 per cent rather than 100 is the **wind speed distribution**, not any shortcoming of the machines — a site is windy enough to reach rated output only a small fraction of the time. The related distinction between capacity factor and conversion efficiency is **12E**'s.

Q5. (a) P = ρgQh = 1000 × 9.8 × 25 × 90 = **2.205 × 10⁷ W = 22.05 MW**. (b) Electrical output = 22.05 × 0.90 = **19.8 MW**. (c) Annual generation = 19.845 MW × 8760 h × 0.30 = **52 000 MWh** (2 s.f.). (d) Any one, clearly stated: that **head and flow stay constant** all year, which for a run-of-river scheme they emphatically do not; that **efficiency is 0.90 at every flow rate**, whereas turbines lose efficiency well away from their design flow; that there are **no outages** for maintenance or fault; or that a capacity factor of **0.30 represents an average rainfall year**, so a drought year would deliver considerably less. *Marker's note:* the units in ρgQh work out to watts directly (kg m⁻³ × m s⁻² × m³ s⁻¹ × m = kg m² s⁻³ = W); converting to MW before multiplying by hours avoids the common factor-of-10⁶ slip in (c).

Q6. (a) 45 000 t × 380 L t⁻¹ = **17 100 000 L = 1.71 × 10⁷ L**. (b) 1.71 × 10⁷ L × 23.4 MJ L⁻¹ = **4.00 × 10⁸ MJ** (400 140 000 MJ, or about 400 TJ). (c) 4.0014 × 10⁸ MJ ÷ 34.2 MJ L⁻¹ = **1.17 × 10⁷ L = 11.7 ML**. (d) 11.7 ÷ 17.1 × 100 = **68 per cent**. It shows that **ethanol carries only about 68 per cent of the energy of petrol per litre**, so 17.1 ML of ethanol displaces only about 11.7 ML of petrol. A vehicle running on a high ethanol blend burns more litres to travel the same distance — the reason E10 is priced below standard petrol. (e) Any one: **food-versus-fuel competition**, since 45 000 t of wheat is food diverted to fuel; **indirect land-use change**, where displaced food production clears land elsewhere; the **energy consumed** growing, harvesting, transporting and distilling the feedstock, which must be subtracted from the yield; or the **water and fertiliser** demand of the crop. *Marker's note:* the marks in (d) are for the interpretation, not the percentage. A bare "68%" answers half the question. Note also that both figures given in the stem are *National Greenhouse Accounts* energy content factors, so they are quoted on the **same basis** and may be divided into each other; mixing a *net* (lower) heating value for one fuel with a *gross* (higher) value for the other is the standard way this ratio comes out wrong.

Q7. Firming is pairing a variable source with **storage, a dispatchable plant or demand management**, so that the combination can be relied on to deliver at a nominated time even though the variable source on its own cannot. *Marker's note:* one mark, so the answer must name the *pairing*. "Making renewables reliable" restates the word rather than defining it.

Q8. Biomass is **organic matter used directly as a fuel** — burnt, gasified or digested — such as **sugarcane bagasse** burnt in a mill boiler, forestry residue, or the organic fraction of municipal waste. **Biofuels** are **liquid or gaseous fuels manufactured from biomass**, chiefly for transport, such as **ethanol** fermented from wheat starch or **biodiesel** made by transesterifying used cooking oil. Biomass is the raw material; a biofuel is a processed product made from it. *Marker's note:* two marks, so both need a definition **and** an example.

Q9. It is **variable** because output tracks the tidal cycle: it rises and falls twice in each **lunar day of about 24 hours 50 minutes** — successive high tides about 12 hours 25 minutes apart — and falls to nothing at slack water, and it is stronger at **spring** than at **neap** tides. It is **predictable** because tides are governed by the orbital positions of the Moon and Sun, so the output can be calculated exactly years ahead. That combination is useful because a network operator can **schedule around** variation known in advance, whereas weather-driven variation must be covered by holding reserve capacity in case a forecast is wrong.

Q10. The power available in the wind goes as the **cube of wind speed**, $P = \frac{1}{2}\rho A v^3$. Raising the measurement height from 50 m to 120 m raises the mean speed from 6.0 to 8.0 m s^{-1}, and $(8.0 \div 6.0)^3 = 1.33^3 =$ **2.37**, so the same rotor at the greater height intercepts about **2.4 times the power**. A one-third increase in wind speed therefore more than doubles the resource. This is why hub heights have risen to 100–150 m despite the cost of taller towers, and why a site that appears only marginally windier than another can be the difference between a viable project and an unviable one. *Marker's note:* the mark for "matters so much" requires the **cubic** relationship to be used numerically, not merely named.

Q11. Geothermal energy is **renewable at the planetary scale**: Earth's internal heat is continuously supplied by the **primordial heat of formation** and by the **ongoing radioactive decay** of uranium-238, thorium-232 and potassium-40 in the crust and mantle, and that supply will persist for billions of years. A **particular reservoir**, however, is a local body of hot rock and fluid. If heat is extracted faster than conduction from the surrounding rock replaces it, the reservoir **cools within decades** and the wells become uneconomic. There is no contradiction because renewability is defined by comparing the **rate of use with the rate of replenishment**, and that comparison must be made at the scale at which the resource is actually being drawn — the well, not the planet. Managing the extraction rate, or re-injecting spent fluid, is what keeps a field in the renewable column. *Common error:* treating "renewable" and "inexhaustible" as synonyms. Every source in this subtopic can be mismanaged.

Q12. First, "completely emissions-free" is wrong. Only the *operating* phase is near zero. Mining and refining silicon, manufacturing modules, producing mounting steel and inverters, transporting components, constructing the site and eventually decommissioning it all release greenhouse gases, giving utility-scale solar a life-cycle median around **48 g CO_2-e kWh^{-1}** — very low against coal at about 820, but not zero. The honest claim is "very low emissions", not "no emissions". **Second, "no environmental impact at all" does not follow from a renewable fuel.** The resource being inexhaustible says nothing about the plant: a utility solar farm **occupies its whole site** for decades, changing land use and habitat; modules reach end of life after roughly **25–30 years** and become a waste stream that is only partly recyclable; and manufacture consumes **silver, silicon and glass**, with their own extraction impacts. *Marker's note:* four marks means two problems **with an explanation of each**. Naming a life-cycle figure without saying what it is a life cycle *of* earns one.

Q13. *"Use the data" means the figures must appear.*

Solar peaks in **summer** and troughs in **winter**: 31 GWh in December and 30 in January against 11 GWh in June and 12 in July, a ratio of about **2.8 to 1**, tracking day length and solar elevation. **Wind** does very nearly the reverse, peaking in **winter** at 34 GWh in July and 33 in August and troughing in **summer** at 21 GWh in February, a ratio of about **1.6 to 1**, tracking the winter passage of frontal systems across southern Victoria.

Adding the two columns month by month gives 54, 47, 47, 44, 43, 43, 46, 49, 53, 56, 55 and 56 GWh — a range of only **43 to 56 GWh**, a ratio of about **1.3 to 1**. The combination is far flatter across the year than either source alone, because **each is strongest in the season the other is weakest**. Two solar farms would double the summer peak and the winter trough alike, leaving the seasonal shortfall untouched; one of each fills it. *Marker's note:* the marks are in the **arithmetic of the combination** — adding the columns and quoting the narrower range — not in asserting that the sources "complement each other".

Q14. The three words are routinely used as though they meant the same thing, and they do not. Each is a claim about a different object, tested against different evidence.

Renewable is a claim about the **resource**, and it is a **rate comparison**: the natural processes that replenish the source operate at a rate comparable to or faster than the rate at which it is used, on a human timescale. It says nothing about emissions and nothing about the plant.

Low-emission is a claim about **greenhouse gases across the whole life cycle** — manufacture, construction, operation, maintenance and decommissioning — expressed in g CO_2-e kWh^{-1}. For every renewable source this figure is **greater than zero**, and the spread across them is wide: onshore wind at about **11** against dedicated biomass at about **230**.

Sustainable is the broadest claim and the only one that is partly a **values judgement**. It takes in conservation of biodiversity and ecological integrity, efficiency of resource use, and equity between and within generations — the six principles at **12G**. A source can be renewable and low-emission and still fail it.

The worked case — storage hydro. It is **renewable**: rainfall and evaporation replenish the inflow continuously. It is **low-emission**: about **24 g CO_2-e kWh^{-1}** over its life cycle, among the lowest of any generating technology. Yet the dam is a **barrier to fish passage**, it inundates terrestrial habitat and cultural sites, and it alters the flow and thermal regime downstream, including cold-water pollution from deep releases. Two claims are satisfied and the third is genuinely contested — which is the whole point.

Marker's note: four marks — one for each of the three claims stated as a claim about something specific, and one for an example that separates them. An answer that defines the three and then names a source satisfying all three has not shown the distinction doing any work. The reverse case is equally creditable: biomass burnt from unreplaced native forest is arguably **none** of the three.

Q15. Why the storage scheme is dispatchable. A dam **decouples generation from river flow**. Water accumulates in the reservoir whenever inflows allow, and the operator opens the gates when electricity is wanted, so output is **controllable on command** and responds within **seconds to minutes** — faster than any thermal plant. A **run-of-river** scheme has little or no impoundment, so it can only generate what the river is delivering at that moment; its output follows the **hydrograph** and rises and falls with rainfall and season regardless of what is wanted. Note that even storage hydro is **energy-limited**: the reservoir sets a ceiling on total generation, so it is dispatchable in timing but not unlimited in quantity.

Two ecological consequences of the storage. *First,* the dam is a **barrier to fish passage** and fragments the river, cutting migratory species off from spawning habitat upstream and isolating populations — fishways mitigate this only partially and only for some species. *Second,* the **flow and thermal regimes are altered**: natural seasonal flow variation is flattened and replaced by releases timed to demand, and water drawn from deep in a thermally stratified reservoir is **several degrees colder** than the natural river, a **cold-water pollution** effect that can suppress spawning cues in native fish for tens of kilometres downstream. (Also creditable: sediment trapped behind the wall starves downstream reaches and the river mouth; inundation destroys terrestrial habitat and cultural sites; decomposing vegetation in warm reservoirs releases methane.)

Marker's note: the question asks for consequences **of building the storage**, so an impact that a run-of-river scheme shares equally does not earn the mark.

Q16. The claim is about a **resource**, so the evidence must be a **measured wind distribution**, not an impression.

Measure at the right place. Erect a **met mast at hub height** — 100 m or more — or use a **lidar/sodar** unit. Ground-level or 10 m readings are not transferable upward without assumption, because wind speed increases with height.

Measure for long enough. Log **speed and direction** at short intervals (typically 10-minute averages) for **at least 12 months**, so the full seasonal cycle is captured. Southern Victorian wind peaks in winter and troughs in summer, so a three-month campaign can mislead by a wide margin.

Analyse the distribution, not the mean. Because power goes as v^3, a mean speed conceals the answer. Build a **speed –frequency (Weibull) distribution** and a **wind rose** showing how much energy arrives from each direction, and measure **turbulence intensity** and **wind shear**, which affect both yield and turbine fatigue loading.

Place the year in context. Correlate the on-site record against a **long-term reference station** nearby with decades of data, so a measurement year that happened to be unusually windy or still can be corrected to a long-term mean.

Convert to the quantity that matters. Apply a **candidate turbine's power curve** to the measured distribution to predict **annual energy yield and capacity factor**, and compare that against the 35–40 per cent that a good Australian onshore site achieves. That number, not the adjective, is what "excellent" has to mean.

Marker's note: an answer that measures only a **mean wind speed** has not tested the claim, because the cubic relationship means two sites with identical means and different distributions yield very differently.

Q17. *"Compare" means the same points addressed for both, not two separate descriptions.*

Resource and conversion. Both are ultimately **solar**. Solar PV uses radiation **directly**: photons above the band gap free electrons across a **p–n junction** in silicon, producing direct current that an inverter converts for the grid. Wind uses solar energy **one step removed**: uneven heating creates pressure gradients, air flows, and **lift** on aerofoil blades turns a rotor driving a generator. PV has no moving parts and no working fluid; wind is a mechanical machine with a gearbox or direct drive.

Availability and variability. Both are **variable**, but differently. Solar is **predictably variable**: zero every night, lower in winter, with cloud the only genuinely uncertain element, so its daily shape is known even if its magnitude is not. Wind is **weather-driven** and can be still or at cut-out for days, making it less forecastable at a given hour but available at any hour, including overnight.

Capacity factor. Utility solar with tracking reaches about **25–30 per cent** in Australia, rooftop solar only **13–16 per cent**; onshore wind reaches **35–40 per cent**. Wind therefore delivers more energy per megawatt installed, which is why the two are usually built together rather than chosen between.

Land requirements. A solar farm occupies **effectively its whole site**, excluding most other uses, though sheep grazing between rows is possible. A wind farm's turbines, access tracks and pads occupy **under 2 per cent** of the site area, so cropping and grazing continue between them — but the turbines are visible for many kilometres, so the *amenity* footprint far exceeds the physical one.

Principal environmental impacts. Solar's are **land occupation**, **module end-of-life waste**, and materials demand, at about **48 g CO_2-e kWh^{-1}** over its life cycle. Wind's are **bird and bat collision**, **noise and visual amenity**, and difficult-to-recycle composite **blades**, at about **11 g CO_2-e kWh^{-1}** — the lowest of any generating technology.

Marker's note: six marks reward the **parallel structure** — the same five headings answered for both technologies. Two separate paragraphs, one per source, with no point-by-point contrast, is a description rather than a comparison and caps out well below full marks.

Q18. *Model response (8 marks).*

The proposal describes a real renewable pathway with two genuine strengths, but its central claims do not survive examination on four counts.

First, "no net emissions" overstates the science. Biomass carbon is fast-cycle carbon, so it is correctly classed as renewable, and that is a real advantage over coal. But the CO_2 is released at combustion while regrowth takes decades — the **carbon payback period** — and the proposal's own logistics add to the debt: felling, chipping and trucking residues **150 km** by diesel is a substantial life-cycle load. The IPCC median for dedicated biomass electricity is about **230 g CO_2-e kWh^{-1}**, roughly twenty times onshore wind. "Lower emissions than coal" is defensible; "no net emissions" is not.

Second, the certificate claim fails for a defined part of the feedstock. Under the *Renewable Energy (Electricity) Act 2000* (Cth) and its regulations, **native forest biomass has been excluded from renewable eligibility since December 2022**. Electricity generated from the 40 per cent native forest limb would therefore create **no large-scale generation certificates**, and the proposal's expectation of certificates "for every megawatt hour" is wrong as drafted.

Third, the fallback feedstock is not available in Victoria in any case. Victoria ended **native timber harvesting in state forests from 1 January 2024**, so a supply agreement that relies on native forest harvesting operations as a contingency rests on an industry that no longer operates at scale in this state. The proposal has written in a fallback that cannot be exercised — which means the real question is whether plantation and sawmill residue alone can sustain 15 MW at 85 per cent, and the proposal does not demonstrate that it can.

Fourth, the haulage radius is a hard physical constraint, not a commercial detail. Wood carries only about **8–19 MJ kg^{-1}** against 24–30 for black coal, and wet residue is at the bottom of that range. Low energy density means large tonnages, and the economics and emissions of trucking degrade quickly with distance. A 150 km radius is at the outer edge of what biomass plants sustain, and it will be tested hardest in exactly the years when residue supply is short.

What the proposal gets right. The capacity factor of **85 per cent** is realistic and is biomass's genuine advantage: the fuel is **storable** and the plant is **dispatchable**, so it can generate when wind and solar cannot — a characteristic no weather-dependent renewable offers. Using residues rather than purpose-felled timber is also the defensible end of the biomass spectrum.

Judgement. The station is a legitimate renewable source if — and only if — it runs on genuinely residual plantation and sawmill material that is replaced by continued planting, and if its emissions are described as *low* rather than *absent*. It should be assessed on a plantation-only feedstock, with the native forest clause removed as both ineligible and unavailable, and with a documented residue supply sufficient for 15 MW inside a haulage radius that the proponent can defend. Air quality near a regional centre would also need assessment, since particulate emissions are biomass's most immediate local impact. *Marker's note:* an evaluation must reach a **judgement** and must engage with the stimulus's own internal problem — a fallback feedstock that is simultaneously ineligible for certificates and no longer harvested in Victoria.

Q19. *Model response (10 marks).*

Option 1 — solar photovoltaic on council rooftops and one ground-mounted array. The resource is **direct solar radiation**, which in Victoria delivers roughly 1000 W m^{-2} at midday under clear skies. Conversion is by **photovoltaic effect**: photons free electrons across a p–n junction in silicon, producing direct current that inverters convert to alternating current. **Availability** is predictably poor at exactly the times a depot's lights are on — output is **zero every night**, falls by more than half in winter, and drops sharply under cloud — and rooftop capacity factors are only **13–16 per cent** because roof pitch and orientation are fixed by the building rather than chosen. Its great practical strength is that it is generated **behind the meter**, displacing electricity at the retail price rather than the wholesale price. The **principal environmental impact** is **end-of-life module waste** after 25–30 years; the rooftop portion occupies no new land at all, which is what separates it from a utility array.

Option 2 — a share in Nardowie Wind Farm, 40 km away. The resource is the **kinetic energy of moving air**, itself solar in origin. Conversion is by **lift** on aerofoil blades turning a rotor and generator, with power in the wind following **$P = \frac{1}{2}\rho A v^3$**. **Availability** is the best of the three in energy terms — a capacity factor of **35–40 per cent** — and crucially the farm generates **at any hour including overnight and in winter**, when the council's demand is highest and solar contributes least. It is **variable and weather-driven**, so it cannot be relied on at a nominated hour. The **principal environmental impacts** are **bird and bat collision** and **noise and visual amenity** for neighbours; the turbines themselves occupy under 2 per cent of the site, so farming continues around them. Being 40 km away, the arrangement is a contractual share rather than a physical supply, so the council buys the generation profile without controlling the asset.

Option 3 — a small run-of-river hydro-electric scheme. The resource is the **gravitational potential energy** of water at altitude, following **$P = \rho g Q h$**, and the conversion — turbine to generator — is the **most efficient of the three at 85–92 per cent**. **Availability** is the weakest feature: with little or no storage the scheme generates whatever the river delivers, so output follows the **hydrograph**, falls away in summer and collapses in drought, and is **barely dispatchable**. On a **regulated** river it is worse than that, because flow is set by the storage manager's release schedule and by environmental flow obligations under the *Water Act 1989* (Vic), not by the council. The **principal environmental impact** is on the river itself — **obstruction of fish passage** at the intake and weir, and **altered flow** through the bypassed reach — even without a large reservoir.

Recommendation. I would recommend **Option 1, the solar photovoltaic installation**, for a council buying energy for its own facilities. It is the only option that generates **behind the meter**, so each kilowatt hour displaces electricity at the retail rate rather than the wholesale rate, and the rooftop component adds **no new land occupation and no new ecological impact** — a decisive advantage for a body whose sites are already built. Its low capacity factor is a real weakness, but capacity factor measures how fully an asset is used, not how much value it delivers, and a council's daytime load in depots, offices and a leisure centre is a **good match to a solar generation profile**. The wind share would deliver more energy per dollar of nameplate capacity and a better winter profile, and it would be the stronger choice if the objective were maximum total generation; it is weaker here because a contractual share gives the council no physical asset and no behind-the-meter benefit. The hydro scheme is the weakest of the three: its output is set by a regulated river the council does not control, and it carries the most direct ecological impact.

Limitation. The recommendation assumes the council's demand **coincides with daytime generation** closely enough that most output is self-consumed rather than exported at a low feed-in rate. A leisure centre with evening peaks, or depots drawing overnight, could shift a large share of generation into export, which would substantially weaken the economic case that the recommendation rests on. Testing it requires **interval meter data** for each site — half-hourly consumption over a full year — matched against a modelled generation profile. Without that, the assumption is plausible for offices but unverified for the leisure centre, which is likely to be the largest single load.

Marker's note: ten marks require **all three options** treated on **all three criteria** — resource and conversion, availability and reliability, principal impact — plus a **justified** recommendation and a **specific** limitation. Naming a limitation such as "costs may change" is not specific; the strongest answers identify the assumption their own recommendation depends on and say what evidence would test it.

Chapter 12 Energy sources, conversions and efficiency — 12C Fossil fuel combustion and the carbon cycle

Theory

A coal-fired generator does not create carbon dioxide out of nothing. It takes carbon that has been out of circulation for tens of millions of years and puts it back into circulation in a fraction of a second. That single sentence is the whole of this dot point — **"the consequences of fossil fuel combustion for the carbon cycle"** — and everything below is either the chemistry that makes it happen, the arithmetic that quantifies it, or the consequences that follow from it.

Where this subtopic sits. Chapter 12's other subtopics deal with the *sources* and the *engineering*: **12A** with the non-renewable sources themselves, **12B** with the renewable ones, **12D** with how fast we are using fossil fuels and the concept of peak oil, **12E** with efficiency calculations, **12F** with the two laws of thermodynamics, and **12G** with sustainability principles across the supply chain. This subtopic deals with what the **combustion reaction** does to the carbon cycle. It assumes the cycle itself — stores, fluxes, residence times, the short- and long-term sequestration bands, the ocean pumps — from **9E**, which owns that dot point, and it hands the *concentration record over time* to **9F**, *warming potential* to **9D**, and *what to do about it* to **11B** and **13C**. Read 9E first: this subtopic is the perturbation, and 9E is the system being perturbed.

What is actually being burnt

A **fossil fuel** is buried organic carbon — plant and plankton tissue that escaped decomposition, was buried under sediment, and was compressed and heated over tens to hundreds of millions of years into coal, oil or natural gas. In carbon-cycle terms it is not a fuel at all but a **store**: the deepest, slowest and most complete terrestrial carbon store there is, the end point of the sequestration pathways set out in 9E.

Combustion is the rapid oxidation of that carbon, releasing energy. **Complete combustion** — oxidation in an ample supply of oxygen — converts every carbon atom to carbon dioxide and every hydrogen atom to water:

$C + O_2 \rightarrow CO_2$ (the carbon fraction of coal)

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ (methane, the main constituent of natural gas)

$2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O$ (octane, representing petrol)

Two things about those equations matter more than the equations themselves. First, they are the **reverse of photosynthesis** — the same transformation 9E sets out for respiration and decomposition. Combustion is not chemically novel; what is novel is *which store it draws on*. Second, the mass of CO_2 produced is always **greater than the mass of fuel burnt**, because most of the product's mass is oxygen taken from the atmosphere. Burning one tonne of carbon yields 44 ÷ 12 = **3.67 tonnes** of CO_2. Students who assume a tonne of coal makes a tonne of CO_2 are out by a factor of nearly four.

Incomplete combustion occurs where oxygen is limited, and produces **carbon monoxide (CO)** and **soot** (elemental carbon, or **black carbon**) alongside CO_2:

$2CH_4 + 3O_2 \rightarrow 2CO + 4H_2O$

$CH_4 + O_2 \rightarrow C + 2H_2O$

Incomplete combustion is a serious air-quality and health problem, and black carbon deposited on snow and ice alters albedo (**9B**). But for the *carbon cycle* it changes almost nothing in the long run: atmospheric carbon monoxide is oxidised to CO_2 within a few months, and soot is deposited within days to weeks and is then largely oxidised too. The carbon arrives in the atmosphere by a slower route and with extra harms attached, but essentially all of it arrives. **Efficiency of combustion changes how much energy you get per unit of carbon, not whether the carbon is released.**

The one consequence everything else follows from

Every flux in the fast carbon cycle runs in **both directions**. Photosynthesis takes roughly 120 Gt C a year out of the atmosphere and respiration and decomposition put roughly 118 back; the ocean absorbs about 80 and outgasses about 78. Those pairs are large and nearly cancelling, and they have been for millennia.

Fossil fuel combustion is different in kind. It is a **one-way flux from the slow cycle into the fast cycle**, of the order of **10 Gt C per year**, with no return limb operating on a comparable timescale. The processes that put carbon *into* fossil stores — burial of organic carbon in sediment, then compression and heating — run at a small fraction of a gigatonne of carbon a year in total, and only a tiny part of that ever becomes coal, oil or gas. Combustion therefore runs the slow cycle's accumulation step **backwards, tens of thousands of times faster than it ran forwards**.

This is why the single most common error on this dot point fails. *"Photosynthesis removes 120 Gt C a year and we only add 10, so the biosphere absorbs our emissions easily."* The 120 is already matched by 118 coming back. What determines the change in the atmosphere is not the size of the gross fluxes but the **net imbalance**, and the combustion flux is pure imbalance. A large two-way flux that nearly cancels cannot absorb a small one-way flux; it can only cycle it.

Set out as a ledger, the transfer looks like this:

	Before combustion	After combustion
Where the carbon is	Coal, oil or gas in sedimentary rock	Atmosphere, then cycling among atmosphere, vegetation and surface ocean
Which cycle it belongs to	Slow (geological)	Fast (biological and physical)
Residence time of that store	10^7–10^8 years	~4 years for a molecule; centuries to millennia for the addition (9E)
Chemical form	Reduced organic carbon and hydrocarbons	Oxidised: CO_2, plus HCO_3^- in seawater
Rate of the transfer	~10 Gt C yr^{-1} out	Return to a comparable store: $\ll$1 Gt C yr^{-1}

The right way to describe this in an answer is that combustion **does not add carbon to the Earth; it moves carbon from a store that was not exchanging into one that is**, and thereby increases the total quantity of carbon in active circulation. That is a permanent change to the cycle on any human timescale.

Carbon intensity: why the same energy costs different amounts of carbon

Not all fossil fuels do the same damage per unit of useful energy, and the reason is chemical. Energy is released both when carbon is oxidised to CO_2 and when hydrogen is oxidised to H_2O — but only the carbon limb produces a greenhouse gas. So the **hydrogen-to-carbon (H:C) ratio** of a fuel sets its carbon cost.

Fuel	Approximate formula	H:C ratio	Typical energy content	Emission factor (g CO_2 MJ^{-1})
Natural gas (mainly methane)	CH_4	4.0	39.3 MJ m^{-3}	~51
Petrol	~C_8H_{18}	2.3	34.2 MJ L^{-1}	~67
Diesel	~$C_{12}H_{23}$	1.9	38.6 MJ L^{-1}	~70
Black coal (bituminous)	~$CH_{0.8}$	0.8	~27 MJ kg^{-1}	~90
Victorian brown coal (lignite, as mined)	~$CH_{0.8}$ plus ~60% water	0.8	~9.8 MJ kg^{-1}	~93

Emission factors are rounded values of the order used in Australian compliance reporting under the National Greenhouse and Energy Reporting (Measurement) Determination 2008, as amended — a single instrument, updated *by amendment determinations rather than remade each year; energy contents are typical, not exact. Use the figures given in a question in preference to these. Accurate as at July 2026.*

Read the table as a ranking with a reason. Methane has four hydrogens per carbon, so a large share of its energy comes from the hydrogen limb and it releases roughly **51 g of CO_2 per megajoule**. Coal is close to pure carbon, so almost all of its energy comes from the carbon limb, at about **90 g CO_2 MJ^{-1}** — about 1.8 times as much CO_2 for the same energy. Victorian **brown coal** is worse again for a second, different reason: as mined it is roughly 60 per cent water, so a large fraction of the energy released is spent evaporating that water rather than generating steam, giving it both the highest emission factor per megajoule and, historically, the lowest conversion efficiency of any generation fuel used in Australia. The Latrobe Valley generators are consequently among the most carbon-intensive electricity sources in the developed world.

From fuel to emissions in four steps. Nearly every calculation in this subtopic is the same sequence, and it is worth learning as a sequence rather than as separate formulas:

1. **Quantity of fuel** × **energy content** = chemical energy released (MJ)
2. **Chemical energy** × **emission factor** = mass of CO_2
3. **Chemical energy** × **efficiency** = useful energy delivered
4. **Mass of CO_2 ÷ useful energy = emission intensity**

Step 3 uses an efficiency figure; how that figure is defined and calculated is **12E**'s dot point, and it is only an input here. Step 4 is where the two combine, and it is the number that actually matters for the carbon cycle: **emission intensity** is the mass of CO_2 released per unit of *useful* energy delivered, usually expressed as kilograms or tonnes of CO_2 per megawatt hour of electricity. An efficient plant burning a dirty fuel and an inefficient plant burning a clean one can land in the same place, which is exactly why intensity, and not fuel choice alone, is the meaningful comparison.

The fugitive limb: carbon that is released without being burnt

Combustion is not the only way the energy supply chain moves fossil carbon into the fast cycle. **Fugitive emissions** are releases of greenhouse gas from extraction, processing, storage and transport rather than from deliberate burning: methane liberated from a coal seam when the seam is mined or depressurised, methane vented or flared at a gas well, and leakage from pipelines, compressors, valves and storage. In Australia fugitives are a reported emissions category in their own right.

Their carbon-cycle consequence is the same in kind but delayed in form. Methane released to the atmosphere is oxidised there, principally by hydroxyl radicals, with a lifetime of about **12 years**, and the net result is:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

So fugitive methane becomes fast-cycle CO_2 regardless — but while it remains methane it absorbs infrared radiation far more strongly than the CO_2 it will become. (How that is quantified as **warming potential** is **9D**'s dot point.) The consequence for this dot point is a warning about arithmetic: an emissions figure calculated only from fuel burnt understates the transfer, because it omits the carbon that reached the atmosphere without passing through a furnace. This matters most for natural gas, whose advantage over coal at the point of combustion can be substantially eroded by leakage upstream of it.

One boundary is worth stating so it is not mistaken for an omission. **Cement manufacture** releases CO_2 by calcination — $CaCO_3 \rightarrow CaO + CO_2$ — which is a transfer out of the *carbonate rock* store rather than out of a fossil fuel, and it belongs to **9F**'s list of altered-concentration drivers. It is a slow-cycle-to-fast-cycle transfer of the same type, but it is not combustion.

Consequences over short, medium and long timescales

Unit 4 Area of Study 2 asks for consequences over **short (seconds to years)**, **medium (multiple years to hundreds of years)** and **long (thousands to millions of years)** timescales. Note that these bands are *not* the same as the short-term and long-term sequestration bands used in 9E, which are drawn at under 100 years and over 1000 years. Use the Area of Study 2 bands here, and say which set you are using.

Short — seconds to years. The oxidation itself is complete in milliseconds. Within about a year the released CO_2 has mixed through the whole atmosphere, which is why a molecule from a Victorian chimney is measurable at a monitoring station in the Southern Ocean. Within the same period the fast fluxes begin taking part of it up: the surface ocean absorbs CO_2 along the partial-pressure gradient the addition itself created, and vegetation takes up slightly more as concentration rises. Atmospheric oxygen falls in step, and the isotopic composition of atmospheric CO_2 shifts.

Medium — years to centuries. This is the band in which the cycle's response, not the emission, dominates. Roughly **45 per cent of each year's emissions remains airborne**, with land and ocean sinks absorbing the rest; the arithmetic of that airborne fraction is worked in 9E. Because absorbed CO_2 reacts with seawater to form bicarbonate and hydrogen ions, the ocean becomes progressively less alkaline — **ocean acidification**, again 9E's chemistry, but here identified as a *direct consequence of combustion*, since fossil CO_2 is where the added carbon comes from. Over this band the sinks also **weaken**: warmer water holds less dissolved CO_2 and is more strongly stratified, and warmer, drier conditions reduce net uptake by vegetation. A weakening sink means a rising airborne fraction, so the same emission produces a larger atmospheric increase later than it does now.

Long — thousands to millions of years. A fraction of the carbon released stays in circulation until the slow cycle removes it. Carbonate burial in marine sediment and chemical weathering of silicate rock together amount to a few tenths of a gigatonne of carbon a year against emissions near 10 — more than an order of magnitude too slow — so roughly a fifth of a pulse of CO_2 persists for many thousands of years. The carbon in coal burnt this decade will not be back in a comparable store while any institution now existing still exists. **This is the consequence that makes the dot point matter: the transfer is fast, one-way and, on human timescales, irreversible.**

How we know combustion is the source

Three independent lines of evidence identify fossil fuel combustion, rather than a natural change in the cycle, as the origin of the added carbon. Together they are the strongest example in this study of **evidence** as distinct from **assertion** (**2G**).

- **Carbon-13 depletion.** Plant tissue is depleted in the heavier stable isotope **^{13}C** relative to the atmosphere, and fossil fuels inherit that signature. As fossil carbon is added, the atmosphere's **δ^{13}C** falls — and it has, from about **−6.5‰** before industrialisation to about **−8.6‰** today. A release from a volcanic or purely inorganic source would not produce this trend.
- **Radiocarbon dilution.** **^{14}C** has a half-life of 5730 years, so fossil carbon, being millions of years old, contains none at all. Adding it **dilutes** the atmosphere's ^{14}C — the **Suess effect** — and the pre-1950 record shows exactly that dilution. (Above-ground nuclear testing in the 1950s and 1960s added ^{14}C and complicates the later record, which is why the early record carries the argument.)
- **Oxygen decline.** Combustion consumes O_2 in a fixed stoichiometric ratio to the CO_2 it produces — one O_2 per CO_2 for carbon, two for methane. Atmospheric oxygen is measurably declining, in close to the ratio combustion predicts. Outgassing from a warming ocean would raise CO_2 **without** consuming oxygen, so this observation distinguishes the two hypotheses directly.

Measuring and reporting the transfer in Australia

Because the flux is invisible, it is estimated rather than observed, and the estimation is regulated. Under the *National Greenhouse and Energy Reporting Act 2007* (Cth), facilities and corporate groups above set thresholds must report their greenhouse gas emissions and energy use annually to the **Clean Energy Regulator**, using methods prescribed in the Measurement Determination made under that Act. Two distinctions from that framework are examinable in practice because they decide what a reported number means:

- **Scope 1** emissions are released directly from sources the reporter owns or controls — the gas burnt in its own furnaces, the diesel in its own trucks, its own fugitives. **Scope 2** emissions are those released elsewhere in generating the electricity the reporter purchases. **Scope 3** covers other indirect emissions across the value chain. NGER requires scope 1 and scope 2; it does not require scope 3. A business can therefore report truthfully and completely while a large share of the fossil carbon its activity causes to be released sits outside the report.
- **CO_2-equivalent (CO_2-e)** converts a mixture of gases to the mass of CO_2 that would have the same warming effect, which is how fugitive methane and combustion CO_2 can be added together. It is a *warming* accounting unit, not a *carbon* one: a tonne of CO_2-e of methane does not contain a tonne of CO_2-e worth of carbon atoms.

Convert to tonnes of carbon (× 12 ÷ 44 for CO_2) before comparing a reported figure with the gigatonne-of-carbon fluxes in 9E.

Above these reporting obligations sit the emissions limits. The **Safeguard Mechanism**, established under the NGER Act and substantially reformed with effect from 1 July 2023, sets declining baselines for facilities emitting more than **100 000 tonnes of CO_2-e** of scope 1 emissions a year, with baselines reducing by 4.9 per cent annually to 2030 and shortfalls met by surrendering Australian Carbon Credit Units or Safeguard Mechanism Credits. Nationally, the *Climate Change Act 2022* (Cth) legislates targets of a 43 per cent reduction below 2005 levels by 2030 and net zero by 2050; in Victoria, the *Climate Action Act 2017* (Vic) — renamed from the *Climate Change Act 2017* by the amending Act that also brought the target forward — sets a state target of net zero emissions by 2045. Victoria's brown coal generation has been contracting against that framework: Hazelwood closed in 2017, Yallourn is scheduled to close by mid-2028 and Loy Yang A by 2035 on their announced dates. *Accurate as at July 2026.*

One caution about all of it. Offsetting an emission with a credit does not undo the transfer this subtopic describes. Fossil carbon has been moved from a store with a residence time of 10^8 years into the fast cycle; a credit that holds an equivalent mass of carbon in vegetation or soil for 25 or 100 years places it in a store with a residence time three to six orders of magnitude shorter. Whether the *warming* is balanced is a separate question, treated in 9E and 11B. For the **carbon cycle**, a short-term store is not equivalent to a long-term one, and no accounting convention makes it so.

Worked examples

The organisations named below are fictional; the processes, quantities, schemes and legislation are real.

Example 1 — scaffolded

For each of the following, state whether carbon is being transferred from the slow cycle into the fast cycle, or moved within the fast cycle, and justify your answer: (i) burning Victorian brown coal in a generator; (ii) burning firewood from a plantation that is replanted after harvest; (iii) burning ethanol fermented from sugarcane; (iv) methane vented from a coal seam during mining. *(4 marks)*

Working	Comment
(i) **Slow → fast.** The carbon has been buried in sedimentary rock for tens of millions of years and has not been exchanging with the atmosphere; combustion returns it to active circulation with no return limb on a human timescale.	This is the dot point's central case.
(ii) **Within the fast cycle.** The carbon was fixed from the atmosphere by photosynthesis within the last few decades and is returned to it; regrowth refixes an equivalent amount.	Only true if the stand is genuinely replanted — if it is cleared, the store is lost, which is **9E**'s point, not a slow-cycle transfer.
(iii) **Within the fast cycle.** The carbon in the ethanol came from atmospheric CO_2 fixed by the cane in the previous season.	The *fossil* fuel used to grow, harvest and distil it is a slow → fast transfer; the ethanol carbon itself is not.
(iv) **Slow → fast.** The methane is fossil carbon liberated from the seam, and it is oxidised to CO_2 in the atmosphere within about 12 years.	A fugitive emission, not combustion — but the same transfer between compartments.

Example 2 — scaffolded

Kalbindra Energy Company operates a brown coal generator that burns 6.2 Mt of coal a year. The coal has an energy content of 9.8 MJ kg^{-1} and an emission factor of 93 g CO_2 MJ^{-1}, and the station converts 27 per cent of the chemical energy released into electricity sent out.

Calculate (a) the chemical energy released each year, (b) the electricity sent out in MWh, (c) the mass of CO_2 released, and (d) the station's emission intensity in t CO_2 MWh^{-1}. *(5 marks)*

Working	Comment
(a) 6.2 Mt = 6.2×10^9 kg. Energy = $6.2 \times 10^9 \times 9.8$ = **6.08×10^{10} MJ** (60 800 TJ).	Convert megatonnes to kilograms before multiplying — the energy content is per kilogram.
(b) Electricity = $0.27 \times 6.08 \times 10^{10} = 1.64 \times 10^{10}$ MJ. 1 MWh = 3600 MJ, so $1.64 \times 10^{10} \div 3600$ = **4.56×10^6 MWh**.	The 3600 conversion is the step most often dropped.
(c) CO_2 = 6.08×10^{10} MJ × 93 g MJ^{-1} = 5.65×10^{12} g = **5.65 Mt CO_2**.	The emission factor applies to the energy released, not to the electricity delivered.
(d) 5.65×10^6 t ÷ 4.56×10^6 MWh = **1.24 t CO_2 MWh^{-1}**.	Typical of Victorian brown coal, and roughly three times a modern gas turbine.

Example 3 — unscaffolded

A submission to a parliamentary inquiry argues: "Terrestrial photosynthesis removes about 120 Gt of carbon from the atmosphere every year. Fossil fuel combustion adds only about 10 Gt. The biosphere therefore has ample capacity to absorb our emissions." Evaluate this argument. *(4 marks)*

The argument compares a **gross** flux with a **net** one, and the comparison is invalid. Photosynthesis does take about 120 Gt C yr^{-1} out of the atmosphere, but respiration and decomposition return about 118 Gt C yr^{-1} to it. The land biosphere is very nearly in balance, so its **net** removal is a small residue — of the order of 2 Gt C yr^{-1} — not 120. The 120 figure measures how fast carbon *circulates*, not how much the biosphere can *accumulate*.

Fossil fuel combustion, by contrast, is a **one-way** flux out of a store that was not exchanging at all. There is no matching return limb: the processes that build fossil stores operate at a small fraction of a gigatonne of carbon a year. So the correct comparison is between the human addition — about 10 Gt C yr^{-1} from combustion, or about 11 Gt C yr^{-1} once land clearing is included — and the ~6 Gt C yr^{-1} that land and ocean sinks between them actually take up, leaving roughly 45 per cent of each year's emission in the atmosphere, which is precisely what the observed concentration rise shows.

The submission's own numbers, read correctly, refute it: if the biosphere had ample absorptive capacity, atmospheric CO_2 would not be rising. *Takeaway:* a large two-way flux cannot absorb a small one-way one. Only the imbalance changes a store, and combustion is entirely imbalance.

Example 4 — unscaffolded

Merrowfen Gas Partners states that its gas "produces 45 per cent less carbon dioxide than coal per unit of energy, and is therefore a low-carbon fuel". Using an emission factor of 51 g CO_2 MJ^{-1} for natural gas and 93 g CO_2 MJ^{-1} for brown coal, assess this statement in terms of the carbon cycle. *(5 marks)*

The arithmetic is defensible. The reduction is (93 − 51) ÷ 93 × 100 = **45 per cent**, so per megajoule of chemical energy released, gas emits 45 per cent less CO_2 than brown coal. The chemical reason is the **H:C ratio**: methane carries four hydrogens per carbon, so more of its energy comes from oxidising hydrogen to water, whereas coal is close to pure carbon and almost all of its energy comes from the carbon limb.

Two things make "therefore a low-carbon fuel" the wrong conclusion. First, **45 per cent less is not low**; it is a different point on the same scale. Burning gas is still a **one-way transfer of fossil carbon from the slow cycle into the fast cycle**, and 51 g CO_2 MJ^{-1} is an addition to active circulation that no fast-cycle process will reverse. A fuel that halves the rate at which an irreversible transfer proceeds does not make the transfer reversible.

Second, the comparison is drawn at the point of combustion only, and so omits **fugitive emissions**. Methane escaping during extraction, processing and pipeline transport reaches the atmosphere without being burnt at all; it is oxidised to CO_2 there over roughly 12 years, and while it remains methane it absorbs infrared radiation far more strongly than the CO_2 it becomes. A sufficient leakage rate erodes much of the 45 per cent advantage, and the statement gives no leakage figure with which to test it.

A defensible version of the claim would read: *lower-emitting than brown coal per unit of energy at the point of combustion, subject to verified fugitive emissions, but still a net transfer of fossil carbon into the fast cycle. Takeaway:*

the comparison a company chooses to draw — which fuels, which stage of the chain — usually decides the answer before any measurement is taken.

Practice questions

Scaffolded

Q1. Define each of the following: (a) complete combustion; (b) a fossil fuel, in carbon-cycle terms; (c) a fugitive emission. *(3 marks)*

Q2. Fossil fuel combustion transfers carbon between two compartments of the carbon cycle. (a) Name the two compartments. (b) Classify each of the following as a transfer from one compartment to the other, or a movement within the fast cycle: burning black coal; burning firewood from a replanted plantation; burning sugarcane ethanol; burning liquefied petroleum gas. (c) State the property of the fossil store that makes the fossil cases different. *(4 marks)*

Q3. Consider the complete combustion of methane and of the carbon in coal. (a) Write the balanced equation for the complete combustion of methane. (b) Calculate the mass of CO_2 produced by burning 1.00 kg of methane. ($M(CH_4)$ = 16.0, $M(CO_2)$ = 44.0) (c) Calculate the mass of CO_2 produced by burning 1.00 t of pure carbon. ($M(C)$ = 12.0) (d) Explain why the mass of CO_2 produced exceeds the mass of fuel burnt. *(5 marks)*

Q4. The table gives emission factors for four fuels.

Fuel	Natural gas	Petrol	Black coal	Victorian brown coal
Emission factor (g CO_2 MJ^{-1})	51	67	90	93

(a) Calculate the mass of CO_2 released in delivering 1.00 GJ of chemical energy from natural gas and from Victorian brown coal.
(b) Calculate how many times more CO_2 brown coal releases than natural gas per unit of energy.
(c) Explain, in terms of chemical composition, why the two fuels differ. *(5 marks)*

Q5. Carralong Power operates a black coal generator in New South Wales that burns 2.8 Mt of coal a year. The coal has an energy content of 27 MJ kg^{-1} and an emission factor of 90 g CO_2 MJ^{-1}, and 36 per cent of the chemical energy released is sent out as electricity. (a) Calculate the chemical energy released each year. (b) Calculate the electricity sent out, in MWh. (c) Calculate the mass of CO_2 released. (d) Calculate the emission intensity in t CO_2 MWh^{-1}. (e) Convert the answer to (c) to a mass of carbon, and express it in Gt C. *(6 marks)*

Q6. Trennowvale Freight Lines burns 2.4 ML of diesel a year. Diesel has an energy content of 38.6 MJ L^{-1} and an emission factor of 69.9 g CO_2 MJ^{-1}. (a) Calculate the chemical energy released. (b) Calculate the mass of CO_2 released, in tonnes. (c) Calculate the mass of CO_2 released per litre of diesel. (d) The company reduces its diesel use to 2.1 ML. Calculate the percentage change in its CO_2 emissions. (e) State one reason why the company's total contribution to the carbon cycle is larger than the figure calculated in (b). *(6 marks)*

Unscaffolded

Q7. State the two products of the complete combustion of a hydrocarbon fuel. *(1 mark)*

Q8. Explain why fossil fuel combustion is described as transferring carbon from the slow carbon cycle into the fast carbon cycle. *(2 marks)*

Q9. Black coal and Victorian brown coal have almost the same H:C ratio, yet brown coal releases considerably more CO_2 per unit of *useful* energy delivered. Explain why. *(2 marks)*

Q10. A student claims that improving the combustion in an engine so that less carbon monoxide and soot are produced "reduces the carbon released to the atmosphere". Explain why this is incorrect. *(3 marks)*

Q11. Explain how the falling $\delta^{13}C$ of atmospheric CO_2 and the measured decline in atmospheric oxygen together identify fossil fuel combustion, rather than outgassing from a warming ocean, as the source of the added carbon. *(3 marks)*

Q12. *(Stimulus.)* Osperton Bakeries Pty Ltd makes the following statement.

> **Stimulus.** "We have replaced our coal-fired ovens with natural gas, cutting our emissions per loaf by 45 per cent. Because the carbon dioxide we now release is absorbed by plants, our baking is part of the natural carbon cycle."

Identify two scientific problems with this statement and explain each. *(4 marks)*

Q13. *(Stimulus.)* The emission intensity of electricity supplied to the Palliston region was recorded as follows.

Stimulus.

Year	2015	2018	2021	2024	2026
Emission intensity (kg CO_2-e kWh^{-1})	1.21	1.08	0.93	0.81	0.74

Describe the pattern shown, calculate the percentage change from 2015 to 2026, and state what the figures do *not* tell you about the region's contribution to the carbon cycle. *(4 marks)*

Q14. Terrestrial photosynthesis moves about 120 Gt C yr^{-1} out of the atmosphere, while fossil fuel combustion moves about 10 Gt C yr^{-1} into it. Explain why the larger flux does not cancel the smaller one. *(4 marks)*

Q15. Osperton Bakeries burns 1.15 million m^3 of natural gas a year in its ovens. Natural gas has an energy content of 39.3 MJ m^{-3} and an emission factor of 51.4 g CO_2 MJ^{-1}. Calculate the mass of CO_2 released each year, and describe the consequence of this release for the carbon cycle over short, medium and long timescales. *(5 marks)*

Q16. Kalbindra Energy Company reports 5.65 Mt of CO_2 to the Clean Energy Regulator for a year of operation. Describe the evidence and measurements you would require in order to test whether that figure is correct. *(5 marks)*

Q17. Compare the consequences for the carbon cycle of burning coal, oil and natural gas, referring to emissions per unit of energy, the chemical reason for the difference, fugitive emissions, and the reversibility of the transfer. *(6 marks)*

Q18. *(Stimulus.)* Halbrenner Metals Pty Ltd operates a Victorian smelter and publishes the following summary.

> **Stimulus.** "Our reported scope 1 emissions are 41 000 t CO_2-e, from gas-fired furnaces, down 18 per cent after we replaced a coal-fired kiln with natural gas. Our reported scope 2 emissions are 620 000 t CO_2-e from purchased grid electricity, and we have retired 620 000 Australian Carbon Credit Units from a 25-year plantation project against them, so our electricity use is carbon neutral. Scope 3 emissions are not reported, as the *National Greenhouse and Energy Reporting Act 2007* (Cth) does not require them."

Evaluate this summary as an account of the company's effect on the carbon cycle. *(8 marks)*

Q19. Palliston Shire Council is preparing a public explanation of how the Shire's energy use affects the carbon cycle. Its annual stationary and transport energy use is 1.9 million m^3 of natural gas (39.3 MJ m^{-3}, 51.4 g CO_2 MJ^{-1}), 12 GWh of purchased electricity at an intensity of 0.74 kg CO_2-e kWh^{-1}, and 480 000 L of diesel (2.70 kg CO_2 L^{-1}). Calculate the Shire's total annual CO_2-e and express it as a mass of carbon, stating the assumption that conversion requires; explain the consequences of this release for the carbon cycle over short, medium and long timescales; explain how scientists know that fossil fuel combustion is the source of the added atmospheric carbon; and identify the one feature of this flux that distinguishes it from every other flux in the cycle. *(10 marks)*

Answers

Q1. (a) Oxidation of a fuel in ample oxygen, converting all carbon to CO_2 and all hydrogen to H_2O. (b) Buried organic carbon — coal, oil or gas — that has been held in a slow-cycle geological store for tens to hundreds of millions of years. (c) A release of greenhouse gas from extraction, processing, storage or transport rather than from deliberate combustion.

Q2. (a) The slow (geological) cycle and the fast (biological and physical) cycle. (b) Black coal — slow to fast; replanted plantation firewood — within the fast cycle; sugarcane ethanol — within the fast cycle; liquefied petroleum gas — slow to fast. (c) Its residence time is of the order of 10^7–10^8 years, so there is no return limb on a human timescale.

Q3. (a) $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$. (b) 44.0 ÷ 16.0 = 2.75, so **2.75 kg CO_2**. (c) 44.0 ÷ 12.0 = 3.67, so **3.67 t CO_2**. (d) Most of the product's mass is oxygen taken from the atmosphere, not from the fuel.

Q4. (a) Gas: 1000 × 51 = 51 000 g = **51 kg CO_2 GJ^{-1}**. Brown coal: 1000 × 93 = **93 kg CO_2 GJ^{-1}**. (b) 93 ÷ 51 = **1.8 times**. (c) Methane has four hydrogen atoms per carbon, so much of its energy comes from oxidising hydrogen to water; coal is close to pure carbon, so nearly all of its energy comes from oxidising carbon to CO_2.

Q5. (a) $2.8 \times 10^9 \times 27$ = **7.56×10^{10} MJ**. (b) $0.36 \times 7.56 \times 10^{10} \div 3600$ = **7.56×10^6 MWh**. (c) $7.56 \times 10^{10} \times 90$ g = **6.80 Mt CO_2**. (d) $6.80 \times 10^6 \div 7.56 \times 10^6$ = **0.900 t CO_2 MWh^{-1}**. (e) 6.80 × 12 ÷ 44 = 1.86 Mt C = **0.0019 Gt C**.

Q6. (a) $2.4 \times 10^6 \times 38.6$ = **9.26×10^7 MJ**. (b) $9.26 \times 10^7 \times 69.9$ g = 6.47×10^9 g = **6.47×10^3 t CO_2**. (c) 6470 t ÷ 2.4×10^6 L = **2.70 kg CO_2 L^{-1}**. (d) (2.1 − 2.4) ÷ 2.4 × 100 = **−12.5 per cent**. (e) Fugitive emissions from extracting, refining and transporting the diesel, and emissions from the electricity and other fuels the company uses, are not counted in that figure.

Q7. Carbon dioxide and water.

Q8. The carbon has been held in coal, oil or gas in sedimentary rock for tens to hundreds of millions of years, isolated from exchange with the atmosphere. Combustion oxidises it to CO_2 and releases it into the atmosphere, where it circulates among atmosphere, vegetation and surface ocean — the fast cycle — with no process returning it to a comparable store on a human timescale.

Q9. As mined, Victorian brown coal is roughly 60 per cent water, so a large share of the heat of combustion is spent evaporating that water rather than raising steam. That gives it both a slightly higher emission factor per megajoule of fuel energy (about 93 against about 90 g CO_2 MJ^{-1}) and a much lower conversion efficiency, so the CO_2 released per megawatt hour actually *sent out* is far higher.

Q10. Better combustion converts carbon monoxide and soot to CO_2 instead, so the same carbon still reaches the atmosphere; atmospheric CO oxidises to CO_2 within months and soot is deposited and largely oxidised within days to weeks. What improves is energy yield per unit of carbon, and air quality — not the quantity of carbon released by burning a given quantity of fuel.

Q11. Fossil carbon is derived from plant tissue and so is depleted in ^{13}C, so adding it lowers atmospheric $\delta^{13}C$ — observed, from about −6.5‰ to about −8.6‰. Combustion also consumes O_2 in a fixed ratio to the CO_2 produced, and atmospheric O_2 is measurably declining. Ocean outgassing would raise CO_2 **without** consuming oxygen, so the oxygen decline rules it out as the main source.

Q12. (i) A 45 per cent reduction per unit of energy is a smaller transfer, not no transfer — burning gas still moves fossil carbon one-way from the slow cycle into the fast cycle. (ii) "Part of the natural carbon cycle" is wrong: fast-cycle uptake by plants is nearly balanced by respiration and decomposition, so it cannot absorb a one-way addition; and the carbon released is fossil carbon that was not in the fast cycle at all. (Also creditable: the comparison omits fugitive methane upstream of the burner.)

Q13. Emission intensity falls throughout, by 0.13 over 2015–18, 0.15 over 2018–21, 0.12 over 2021–24 and 0.07 over 2024–26 — a continuing decline that is decelerating in the most recent interval. Percentage change = (0.74 − 1.21) ÷ 1.21 × 100 = **−38.8 per cent**. The figures give intensity per kilowatt hour only; they say nothing about how many kilowatt hours were used, so total emissions could have risen, and they exclude the Shire's gas and liquid fuel use entirely.

Q14. The 120 Gt C yr^{-1} is a gross flux, matched by about 118 Gt C yr^{-1} returning through respiration and decomposition, so the biosphere's net removal is a small residue. Combustion is a one-way flux with no return limb. Only net imbalances change a store, so a large near-cancelling two-way flux cycles the addition rather than absorbing it. See the fully-worked solution.

Q15. Energy = $1.15 \times 10^6 \times 39.3 = 4.52 \times 10^7$ MJ; $CO_2 = 4.52 \times 10^7 \times 51.4$ g $= 2.32 \times 10^9$ g = **2.32×10^3 t CO_2**. Short: oxidation is immediate and the CO_2 mixes globally within about a year, with surface ocean and vegetation beginning to take part of it up. Medium: roughly 45 per cent remains airborne over years to centuries, the absorbed fraction acidifies the ocean, and the sinks weaken as the climate warms. Long: a fraction persists for thousands of years because carbonate burial and silicate weathering are more than an order of magnitude too slow to remove it.

Q16. Fuel-based mass balance as the primary check — metered coal throughput, with sampled measurements of the coal's carbon content, moisture and energy content, and a stated method from the Measurement Determination; independent verification of the meters; continuous emission monitoring at the stack as a cross-check; documented calibration, sampling frequency and uncertainty; and confirmation that fugitive and scope 2 emissions are reported separately rather than folded in. See the fully-worked solution.

Q17. Per unit of energy: gas about 51, oil about 67–70, coal about 90–93 g CO_2 MJ^{-1}, because the H:C ratio falls from 4 for methane to about 1.9 for diesel to about 0.8 for coal. Fugitives are largest in relative terms for gas and significant for coal seams. All three are one-way slow-to-fast transfers that no fast-cycle process reverses, so the differences are in rate, not in kind. See the fully-worked solution.

Q18. Strengths: reported scope 1 and scope 2 separately and quantified; the coal-to-gas switch is a genuine reduction in CO_2 per unit of energy. Weaknesses: scope 2 is fifteen times scope 1, so the furnace change addresses the smaller share; "carbon neutral" swaps a 10^8-year store for a 25-year one; scope 3 exclusion is lawful but leaves real fossil carbon unreported; fugitive methane upstream of the gas is not addressed. See the fully-worked solution.

Q19. Gas 3.84×10^3 t, electricity 8.88×10^3 t, diesel 1.30×10^3 t, total **1.40×10^4 t CO_2-e**. The × 12 ÷ 44 ratio applies to CO_2, not to CO_2-e, so the conversion is valid only on the stated assumption that the total is essentially all CO_2 — which it is here, the CH_4 and N_2O components of a grid factor being of the order of 1 per cent. On that assumption, about **3.8×10^3 t of carbon**. Consequences across the three bands, the three lines of isotopic and oxygen evidence, and the identification of the flux as one-way are required. See the fully-worked solution.

Fully-worked solutions

Q1. (a) **Complete combustion** is oxidation of a fuel in an **ample supply of oxygen**, so that all carbon is converted to **CO_2** and all hydrogen to **H_2O**. (b) A **fossil fuel** is **buried organic carbon** — plant and plankton tissue that escaped decomposition, was buried and was compressed and heated over **tens to hundreds of millions of years** into coal, oil or gas. In carbon-cycle terms it is a **slow-cycle store**, not a flux. (c) A **fugitive emission** is a release of greenhouse gas from **extraction, processing, storage or transport** rather than from deliberate combustion — for example methane liberated from a coal seam when it is mined. *Marker's note:* (b) must locate the fuel in the cycle; "coal, oil and gas" alone is a list, not a definition.

Q2. (a) The **slow (geological) cycle** and the **fast (biological and physical) cycle**. (b) **Black coal — slow to fast. Replanted plantation firewood — within the fast cycle** (the carbon was fixed from the atmosphere within decades and regrowth refixes it). **Sugarcane ethanol — within the fast cycle** (the carbon came from CO_2 fixed by the cane in the previous season). **Liquefied petroleum gas — slow to fast** (a petroleum product, so fossil carbon). (c) The fossil store's **residence time is of the order of 10^7–10^8 years**, and the processes that refill it run at a small fraction of a gigatonne of carbon a year, so the transfer has **no return limb on a human timescale**. *Common error:* treating biomass combustion as identical to fossil combustion because both produce CO_2. The product is the same; the store it came from is not, and that is the whole distinction.

Q3. (a) **$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$.** (b) One mole of CH_4 (16.0 g) yields one mole of CO_2 (44.0 g), so the mass ratio is 44.0 ÷ 16.0 = 2.75 and 1.00 kg of methane yields **2.75 kg of CO_2**. (c) One mole of C (12.0 g) yields one mole of CO_2 (44.0 g), a ratio of 44.0 ÷ 12.0 = 3.67, so 1.00 t of carbon yields **3.67 t of CO_2**. (d) Because **most of the mass of the product is oxygen drawn from the atmosphere**: in CO_2, 32 of the 44 mass units are oxygen. The fuel supplies only the carbon. *Marker's note:* the 3.67 factor is worth memorising — it converts between tonnes of carbon and tonnes of CO_2, which is the conversion needed whenever an emissions figure has to be compared with the Gt C fluxes of 9E.

Q4. (a) 1.00 GJ = 1000 MJ. **Natural gas:** 1000 × 51 = 51 000 g = **51 kg CO_2**. **Brown coal:** 1000 × 93 = 93 000 g = **93 kg CO_2**. (b) 93 ÷ 51 = **1.8 times as much**. (c) Combustion releases energy from **two** oxidation reactions — carbon to CO_2 and hydrogen to H_2O — but only the carbon limb produces a greenhouse gas. Methane's **H:C ratio is 4.0**, so a large share of its energy comes from the hydrogen limb. Brown coal's is about **0.8**, so almost all of its energy comes from the carbon limb, and it also carries roughly 60 per cent water as mined, part of the energy released being spent evaporating that water. *Marker's note:* the mark in (c) is for the **H:C ratio mechanism**. "Coal is dirtier" is not an explanation.

Q5. (a) 2.8 Mt = 2.8×10^9 kg; energy = $2.8 \times 10^9 \times 27$ = **7.56×10^{10} MJ** (75 600 TJ). (b) $0.36 \times 7.56 \times 10^{10} = 2.72 \times 10^{10}$ MJ; 1 MWh = 3600 MJ, so $2.72 \times 10^{10} \div 3600$ = **7.56×10^6 MWh**. (c) 7.56×10^{10} MJ × 90 g MJ^{-1} = 6.80×10^{12} g = 6.80×10^6 t = **6.80 Mt CO_2**. (d) 6.80×10^6 t ÷ 7.56×10^6 MWh = **0.900 t CO_2 MWh^{-1}**. (e) Carbon = 6.80 × 12 ÷ 44 = 1.86 Mt C = 1.86×10^6 t = **0.0019 Gt C**. *Marker's note:* the emission factor in (c) applies to the **energy released**, not to the electricity sent out. Applying it to the 2.72×10^{10} MJ of electricity gives 2.45 Mt and an intensity of 0.32 t MWh^{-1}, which is roughly the figure for a modern gas turbine and obviously wrong for coal — a useful check that the error has occurred. Compare (d) with Example 2: the same four steps give 0.90 t CO_2 MWh^{-1} for black coal at 36 per cent efficiency against 1.24 t CO_2 MWh^{-1} for Victorian brown coal at 27 per cent, and both the fuel and the efficiency contribute to the gap. Part (e) is the step that connects a facility-scale figure to the global cycle: one large generator moves about 0.0019 Gt C a year, against a global fossil flux near 10 Gt C.

Q6. (a) 2.4 ML = 2.4×10^6 L; energy = $2.4 \times 10^6 \times 38.6$ = **9.26×10^7 MJ** (92 600 GJ). (b) $9.26 \times 10^7 \times 69.9$ g = 6.47×10^9 g = **6.47×10^3 t CO_2**. (c) 6.47×10^3 t ÷ 2.4×10^6 L = 2.70×10^{-3} t L^{-1} = **2.70 kg CO_2 L^{-1}** — the familiar figure for diesel, and a useful sanity check on (b). (d) Emissions are proportional to fuel used, so the percentage change equals the percentage change in fuel: (2.1 − 2.4) ÷ 2.4 × 100 = **−12.5 per cent**. (e) Any one, clearly stated: **fugitive emissions** from extracting, refining and transporting the diesel are not counted; emissions from **purchased electricity** and other fuels are excluded; the figure counts CO_2 only and omits methane and nitrous oxide from the engines. *Marker's note:* in (d) there is no need to recalculate the emissions — recognising the proportionality is the point, and using the proper minus sign matters, since −12.5 per cent and 12.5 per cent are different claims.

Q7. Carbon dioxide and water.

Q8. The carbon in coal, oil and gas has been held in **sedimentary rock for tens to hundreds of millions of years**, chemically reduced and physically isolated from exchange with the atmosphere — a **slow-cycle store** with a residence time of the order of 10^7–10^8 years. Combustion **oxidises it to CO_2 and releases it to the atmosphere in seconds**, where it joins the **fast cycle** and circulates among atmosphere, vegetation and surface ocean. Because the processes that build fossil stores run at a small fraction of a gigatonne of carbon a year, there is **no return flux** on a human timescale.

Q9. The H:C ratio explains the gap between gas and coal, but not the gap between the two coals: both are about **0.8**, so per megajoule of chemical energy *released* they are close — about **90 g CO_2 MJ^{-1}** for black coal against **93** for brown. The difference appears at **step 4** of the four-step sequence, where emissions are divided by *useful* energy rather than by energy released. As mined, Victorian brown coal is roughly **60 per cent water**, and a large share of the heat of combustion is spent evaporating that water instead of raising steam. That depresses conversion efficiency — historically about **27 per cent** in the Latrobe Valley against about **36 per cent** for a modern black coal unit — so the same megajoule of chemical energy delivers considerably less electricity. The result is an emission intensity near **1.24 t CO_2 MWh^{-1}** for Victorian brown coal against about **0.90** for black coal (Example 2 and Q5) — roughly 40 per cent higher, a gap the emission factors alone would not predict. *Marker's note:* the two marks are for the **moisture content** and for its effect on **efficiency, and hence on emissions per unit of useful energy**. Citing the H:C ratio earns nothing here: it is essentially the same for both fuels.

Q10. Improving combustion **converts the carbon monoxide and soot to CO_2 instead**; it does not retain the carbon. The carbon in the fuel leaves the engine as carbon whichever products form, and both intermediates are short-lived: atmospheric **CO is oxidised to CO_2 within a few months**, and **soot is deposited within days to weeks** and is then largely oxidised. What genuinely improves is the **energy obtained per unit of carbon burnt** and **air quality**, since CO and particulates are directly harmful. Better fuel economy may of course lower a vehicle's emissions over a year, but only by reducing **how much fuel is bought and burnt**; it changes nothing about the carbon in the fuel that *is* burnt, which is what the claim asserts. The claim as stated confuses the **form** in which carbon is released with the **quantity** released. *Common error:* treating soot and CO as though they were stores. They are transient forms of fast-cycle carbon.

Q11. δ¹³C. Fossil fuels formed from **plant tissue**, which is depleted in the heavier stable isotope ^{13}C relative to the atmosphere, so fossil CO_2 carries that depleted signature. Adding it lowers the atmosphere's $\delta^{13}C$, and the measured value has fallen from about **−6.5‰** before industrialisation to about **−8.6‰** today. **Oxygen.** Combustion **consumes O_2** in a fixed stoichiometric ratio to the CO_2 it produces, and atmospheric oxygen is measurably declining at close to the rate combustion predicts. **Why this excludes ocean outgassing.** A warming ocean releasing dissolved CO_2 would raise atmospheric CO_2 **without consuming any oxygen**, and the dissolved inorganic carbon it released would not carry a strongly plant-depleted $\delta^{13}C$ signature. The oxygen decline is therefore the decisive observation: it is a fingerprint of **oxidation**, which outgassing is not. *Marker's note:* three marks means both lines of evidence **and** the elimination of the alternative hypothesis. This is the strongest available illustration of evidence discriminating between competing explanations (**2G**).

Q12. First, a 45 per cent reduction is a smaller transfer, not the absence of one. Burning natural gas still moves **fossil carbon one-way from the slow cycle into the fast cycle**, at about 51 g CO_2 MJ^{-1}. Halving the rate at which an irreversible transfer proceeds does not make it reversible, and the emission remains an addition to the carbon in active circulation. **Second, "part of the natural carbon cycle" is false in two ways.** The uptake of CO_2 by plants is a **gross** flux of about 120 Gt C yr^{-1} that is nearly cancelled by respiration and decomposition returning about 118, so the fast cycle is close to balanced and **cannot absorb a one-way addition** — it can only circulate it. And the carbon being released **was not in the fast cycle at all**; it was in a store with a residence time of the order of 10^8 years. Also creditable: the 45 per cent comparison is drawn at the burner and therefore omits **fugitive methane** released upstream during extraction, processing and pipeline transport. *Marker's note:* four marks requires two problems **and** an explanation of each. Asserting that the claim is "greenwashing" without the gross-versus-net argument earns nothing.

Q13. Pattern. Emission intensity **falls throughout the record**, from 1.21 to 0.74 kg CO_2-e kWh^{-1}. The decline is not uniform: 0.13 over 2015–18, 0.15 over 2018–21, 0.12 over 2021–24, then 0.07 over 2024–26 — so the fall is **decelerating in the most recent interval**, although that interval is two years rather than three, which partly accounts for the smaller drop. **Percentage change.** $(0.74 - 1.21) \div 1.21 \times 100 =$ **−38.8 per cent**. **What the data do not tell you.** Intensity is a figure **per kilowatt hour**, so it says nothing about **how many** kilowatt hours the region used: total emissions could have risen even as intensity fell. Intensity is now $0.74 \div 1.21 =$ **0.61** of its 2015 value, so consumption would have to have grown by a factor of $1 \div 0.61 =$ **1.64** — that is, by more than about **64 per cent** — for total emissions to be higher in 2026 than in 2015. (Note that this is *not* 38.8 per cent: offsetting a fall requires the reciprocal, not the same percentage back.) The data also cover **electricity only**, omitting the region's natural gas and liquid fuel combustion, which are direct transfers of fossil carbon in their own right. *Marker's note:* the final mark is for recognising that an **intensity** is a ratio. Concluding that "the region's emissions have fallen by 39 per cent" is the standard error, and it does not follow from these figures.

Q14. *"Explain why" requires the mechanism, not the numbers restated.*

The 120 Gt C yr^{-1} taken up by terrestrial photosynthesis is a **gross flux**. It is very nearly matched by a return flux of about **118 Gt C yr^{-1}** from respiration and decomposition, because almost everything a plant fixes is eventually respired by the plant, by an animal, or by a decomposer. The land biosphere's **net** removal is therefore the small residue between two large numbers — of the order of 2 Gt C yr^{-1} — and not 120.

Fossil fuel combustion has **no return limb at all**. It draws on a store that was not exchanging with the atmosphere, and the processes that would return carbon to a comparable store — burial of organic carbon in sediment and chemical weathering of silicate rock, together a few tenths of a gigatonne of carbon a year — are more than an order of magnitude slower than the release.

Only net imbalances change the size of a store. A large two-way flux that nearly cancels moves carbon around quickly but changes nothing; a small one-way flux changes the total continuously. So the 120 Gt C yr^{-1} **circulates** the added carbon rather than removing it: some of each year's emission is taken up by land and ocean, but about **45 per cent remains in the atmosphere**, which is why the observed concentration is rising. *Marker's note:* four marks reward gross-versus-net, the absence of a return limb, the principle that only imbalances change stores, and the observational consequence. An answer that asserts the fluxes "are not the same thing" without explaining the near-cancellation has given the conclusion without the reasoning.

Q15. Calculation. Energy released = 1.15×10^6 m³ × 39.3 MJ m^{-3} = **4.52×10^7 MJ** (45 200 GJ). CO_2 = 4.52×10^7 MJ × 51.4 g MJ^{-1} = 2.32×10^9 g = **2.32×10^3 t CO_2** — equivalent to 2.02 kg of CO_2 for every cubic metre of gas burnt.

Short (seconds to years). Oxidation is complete in milliseconds, and within about a year the CO_2 has mixed throughout the atmosphere, so it is detectable anywhere on Earth. Over the same period the surface ocean begins absorbing part of it along the partial-pressure gradient the addition itself created, and atmospheric oxygen falls by the stoichiometric amount.

Medium (years to centuries). About **45 per cent stays airborne**; the rest enters land and ocean sinks. The fraction the ocean takes up reacts with seawater to form bicarbonate and hydrogen ions, contributing to **ocean acidification**, and the sinks progressively **weaken** as the water warms and stratifies, so a larger share of later emissions remains in the air.

Long (thousands to millions of years). Removal to a long-term store requires **carbonate burial and silicate weathering**, which together run at a few tenths of a gigatonne of carbon a year against a global fossil flux near 10, so roughly a fifth of the release persists for **many thousands of years**.

Marker's note: the marks are two for the calculation and three for one substantive consequence in each band. Naming the bands without a mechanism in each does not earn them.

Q16. A reported figure of this kind is **calculated, not observed**, so testing it means testing the inputs and the method.

The mass balance is the primary check. Emissions follow from fuel: metered **coal throughput**, and sampled measurements of the coal's **carbon content, moisture content and energy content**, since brown coal varies substantially between seams and with weather. Multiplying quantity by carbon content and by 44 ÷ 12 gives an independent estimate that should reconcile with the reported figure. Given 5.65 Mt of CO_2, the implied carbon is 5.65 × 12 ÷ 44 = 1.54 Mt C, which for 6.2 Mt of coal implies a carbon content near **25 per cent by mass** — a plausible figure for as-mined Victorian brown coal, and one that can be checked against the assay records.

Method, calibration and provenance. Confirm which method under the Measurement Determination made under the *National Greenhouse and Energy Reporting Act 2007* (Cth) was applied, and that it was applied consistently; obtain **meter calibration records**, sampling frequency and sample handling procedures, and a stated **uncertainty** on the result. A figure quoted to three significant figures with no stated uncertainty should be treated with suspicion.

An independent cross-check. Continuous emission monitoring at the stack — flue gas flow rate and CO_2 concentration — gives a measurement that does not depend on the fuel assays, so agreement between the two approaches is far stronger evidence than either alone.

Completeness, not just accuracy. Confirm that **fugitive emissions** and **scope 2** emissions are reported separately rather than omitted or folded in, and that the reporting boundary matches the facility as operated.

Marker's note: the strongest answers propose **two independent estimates** and compare them, rather than listing equipment. An answer that only asks to "check the calculation" has not tested the inputs, which is where the error would be.

Q17. *"Compare" means the same criteria applied to all three, not three descriptions.*

Emissions per unit of energy. Natural gas releases about **51 g CO_2 MJ^{-1}**; oil products about **67 g MJ^{-1}** for petrol and **70** for diesel; coal about **90 g MJ^{-1}** for black coal and **93** for Victorian brown coal. Coal is therefore roughly **1.8 times** as CO_2-intensive as gas for the same energy released, with oil between them.

The chemical reason. Energy comes from oxidising both carbon and hydrogen, but only carbon yields a greenhouse gas, so the ranking follows the **H:C ratio**: 4.0 for methane, about 1.9–2.3 for oil products, about 0.8 for coal. Brown coal is worse than black for an additional reason: as mined it is roughly 60 per cent water, so part of the energy released is spent evaporating that water, which also depresses conversion efficiency and so raises emissions per unit of *useful* energy further still.

Fugitive emissions. These change the ranking's margin. **Gas** is most affected in relative terms, because methane vented or leaked during extraction, processing and pipeline transport reaches the atmosphere unburnt and absorbs infrared radiation strongly before oxidising to CO_2 over about 12 years — so a high leakage rate erodes much of gas's combustion advantage. **Coal** releases seam methane when mined, which is a significant reported category in Australia. **Oil** has fugitives at wells, refineries and in distribution. In every case the consequence is the same in kind: fossil carbon reaching the fast cycle without being burnt.

Reversibility. Here the three are **identical**, and this is the most important point of the comparison. All are one-way transfers from a store with a residence time of the order of **10^7–10^8 years** into the fast cycle, and the return processes — carbonate burial and silicate weathering — are more than an order of magnitude too slow to reverse them. The fuels differ in **how fast the transfer proceeds per unit of energy delivered**, not in **whether it can be undone**.

Marker's note: six marks reward the **parallel structure** across all four criteria, with figures. The mark most often lost is the last one: candidates rank the fuels and stop, without stating that the irreversibility is common to all three.

Q18. *Model response (8 marks).*

The summary is accurate as far as it goes, and misleading in what it concludes. Four points.

First, the reduction is real but addresses the smaller share. Replacing a coal-fired kiln with natural gas cuts CO_2 per unit of energy by roughly 45 per cent, and an 18 per cent fall in scope 1 is a genuine reduction in the rate at which the company transfers fossil carbon into the fast cycle. But scope 1 is **41 000 t CO_2-e against 620 000 t of scope 2** — about **fifteen times larger**. The company's dominant effect on the carbon cycle runs through the electricity it buys. Note where the 18 per cent sits: 41 000 t is the figure **after** the fall, so scope 1 before the change was 41 000 ÷ 0.82 ≈ **50 000 t** and the cut is worth about **9000 t** — roughly **1.4 per cent** of the company's reported total of 661 000 t. (Taking 18 per cent of the 41 000 gives 7400 t and understates the saving; the base of a percentage change is the figure *before* it.) Either way, the furnace is not where the carbon is.

Second, the offset does not restore the cycle. The emissions being offset are fossil carbon taken from a store with a residence time of the order of **10^8 years** and released permanently into the fast cycle. The credits place an equivalent mass of carbon in **plantation biomass on a 25-year permanence period** — a store three to six orders of magnitude shorter-lived, and one exposed to fire, drought, disease and harvest. Whether the *warming* balances is a separate accounting question (9E, 11B); for the **carbon cycle**, swapping a long-term store for a short-term one is not neutrality, and "carbon neutral" overstates what has been achieved.

Third, the scope 3 exclusion is lawful but not scientifically neutral. The NGER Act does require scope 1 and scope 2 and does not require scope 3, so the statement is correct as a matter of compliance. But the carbon released in producing the smelter's inputs and transporting its products enters the atmosphere whether or not anyone reports it. A complete account of the company's effect on the cycle and a complete NGER return are different documents, and the summary presents the second as though it were the first.

Fourth, fugitive methane upstream of the gas is unaddressed. Having switched to gas, the company's scope 1 figure now depends on a fuel whose supply chain leaks methane at extraction, processing and transport. Those emissions sit largely with the supplier, so they will not appear here, yet they partially offset the 45 per cent combustion advantage that justified the switch.

Judgement. The company is reporting honestly against its legal obligations and has made one real reduction, but the summary's framing inverts the significance of its own numbers: it foregrounds a change worth under 2 per cent of the total and describes almost all of the remainder as neutralised by credits that place carbon in a far less durable store. A defensible version would state total scope 1 and 2 emissions, identify **grid electricity as the dominant pathway**, describe the credits as temporary storage rather than neutrality, and disclose scope 3 voluntarily. *Marker's note:* an evaluation must reach a **judgement** and must engage the arithmetic in the stimulus — the 41 000 against 620 000 comparison is the point the response is built to test.

Q19. *Model response (10 marks).*

Calculation. *Natural gas:* 1.9×10^6 m³ × 39.3 MJ m^{-3} = 7.47×10^7 MJ; × 51.4 g MJ^{-1} = 3.84×10^9 g = **3.84×10^3 t CO_2**. *Electricity:* 12 GWh = 1.2×10^7 kWh; × 0.74 kg kWh^{-1} = 8.88×10^6 kg = **8.88×10^3 t CO_2-e**. *Diesel:* 4.8×10^5 L × 2.70 kg L^{-1} = 1.30×10^6 kg = **1.30×10^3 t CO_2**. *Total:* 3840 + 8880 + 1300 = **1.40×10^4 t CO_2-e**.

As carbon — and state the assumption. The **× 12 ÷ 44** ratio is the ratio of carbon to CO_2, and the total above is in **CO_2-e**, which is a *warming* unit rather than a *carbon* one: a tonne of CO_2-e of methane does not contain a tonne of CO_2's worth of carbon. The conversion is therefore legitimate here only because the total is essentially all CO_2 — the gas and diesel figures are CO_2 outright, and the CH_4 and N_2O components of a grid electricity factor are of the order of 1 per cent of it. Stating that assumption, $1.40 \times 10^4 \times 12 \div 44 =$ **3.8×10^3 t C**, or about 0.0000038 Gt C — a figure worth quoting, because it shows a whole Shire contributing well under a millionth of the global fossil flux of about 10 Gt C, and therefore why this is a collective rather than an individual problem.

Short timescale — seconds to years. The oxidation reactions are complete in milliseconds, and within about a year the released CO_2 has mixed through the whole atmosphere, so the Shire's emissions are indistinguishable in the air from anyone else's. Within the same period the fast fluxes begin acting on the addition: the **surface ocean** absorbs CO_2 along the partial-pressure gradient the addition itself created, vegetation takes up marginally more as concentration rises, atmospheric **oxygen falls** by the stoichiometric amount, and the **isotopic composition** of atmospheric CO_2 shifts.

Medium timescale — years to centuries. About **45 per cent of the emission remains airborne**, the land and ocean sinks taking up the rest. The absorbed fraction reacts with seawater to form bicarbonate and hydrogen ions, so the ocean becomes progressively less alkaline — **ocean acidification** is a direct consequence of fossil fuel combustion, since fossil CO_2 is where the added carbon comes from. Over this band the sinks also **weaken**: CO_2 is less soluble in warm water, a warmer surface layer is more stratified so less carbon is mixed downwards, and warmer, drier conditions reduce net uptake by vegetation. A weakening sink means the same emission produces a larger atmospheric increase in future than it does now.

Long timescale — thousands to millions of years. Removing carbon to a long-term store requires the slow cycle: **burial of carbonate and organic carbon** in marine sediment and **chemical weathering** of silicate rock, together a few tenths of a gigatonne of carbon a year against a global fossil flux near 10 Gt C yr^{-1}. Those processes are more than an order of magnitude too slow, so roughly a fifth of the carbon released persists in circulation for **many thousands of years**. Nothing the Shire does later retrieves it.

How we know combustion is the source. Three independent lines of evidence converge. Fossil carbon derives from plant tissue and is **depleted in ^{13}C**, so adding it has driven atmospheric **$\delta^{13}C$** down from about **−6.5‰** to about **−8.6‰**. Fossil carbon is millions of years old and so contains no **^{14}C**, and the pre-1950 record shows the expected **dilution** of atmospheric radiocarbon — the Suess effect. And combustion **consumes oxygen** in a fixed ratio to the CO_2 it produces, with atmospheric O_2 measurably declining at close to the predicted rate. The last of these is decisive against the alternative explanation, because outgassing from a warming ocean would raise CO_2 **without** consuming oxygen.

The distinguishing feature. Every other significant flux in the carbon cycle is **two-way and close to balanced** — photosynthesis against respiration and decomposition, dissolution against outgassing — so it moves carbon rapidly without changing how much is in circulation. Fossil fuel combustion is a **one-way transfer from the slow cycle into the fast cycle, with no return limb operating on a human timescale**. It does not add carbon to the Earth; it increases the quantity of carbon in active circulation, and it does so at a rate tens of thousands of times faster than the geological processes that put that carbon away. That asymmetry — fast, one-way, effectively irreversible — is the consequence from which every other consequence in this subtopic follows.

Marker's note: ten marks require the **three calculations correctly totalled and converted to carbon** — with credit for recognising that × 12 ÷ 44 is a **CO_2** ratio being applied to a **CO_2-e** total, and for stating the assumption that makes that acceptable — a **mechanism in each of the three timescale bands**, at least two of the three lines of evidence with the alternative hypothesis excluded, and the **one-way flux** identified as the distinguishing feature. The commonest way to lose marks here is to describe consequences for the **climate** — warming, sea level, extreme weather — rather than for the **carbon cycle**. Those are the subject of Chapters 09 to 11; this question asks what happens to the carbon.

Chapter 12 Energy sources, conversions and efficiency — 12D Rates of fossil fuel use and peak oil

Theory

Nobody burns a reserve. What a society burns is a **rate** — so many petajoules a year, so many barrels a day, so many tonnes a quarter — and it is the rate, not the size of what is left in the ground, that decides how fast carbon reaches the atmosphere, how exposed an economy is to a price shock, and how much time there is to build something else. The study design asks for two things here: **"changes in the rate of the use of fossil fuels over time"** and **"the concept of peak oil"**. They are the same idea seen from two ends. The first looks backwards at a rate that has already changed and asks why; the second looks forwards at a rate that must eventually stop rising and asks when, and what happens after.

Where this subtopic sits. Chapter 12's other subtopics deal with the sources and the physics: **12A** with what oil, coal, natural gas, coal seam gas and nuclear actually are, **12B** with the renewables, **12C** with what combustion does to the carbon cycle, **12E** with efficiency calculations, **12F** with the thermodynamic limits on any conversion, and **12G** with the sustainability principles that apply across the supply chain. This subtopic deals with **how much is being burnt, how fast that figure is changing, and why**. It is not about the atmospheric consequence — the resulting greenhouse gas concentrations belong to **9F** — and it is not about what should be built instead, which is **13B** and **13C**. Here the question is narrower and prior to all of them: what does the trend line actually do, and what constrains where it can go next?

Measuring a rate of use: the quantities and their units

Three quantities get confused in this topic, and separating them is the whole foundation.

Quantity	What it is	Typical units	Example
Stock — a reserve or resource	An **amount** still in the ground	Gt, barrels, m^3, EJ	World proved oil reserves $\approx 1.7 \times 10^{12}$ barrels
Rate of use — consumption or production	An amount **per unit time**	PJ yr^{-1}, EJ yr^{-1}, Mt yr^{-1}, barrels day^{-1}	World oil use ≈ 100 million barrels day^{-1}
Cumulative use	The rate **added up** over a period	Gt, barrels, EJ	Total oil produced since 1859 $\approx 1.5 \times 10^{12}$ barrels

This is the same store-versus-flux distinction that governs the carbon cycle in **9E**, applied to the resource side of the ledger. A stock divided by a rate gives a time; a rate multiplied by a time gives a cumulative amount; and no arithmetic converts a stock into a rate without a time appearing somewhere.

Energy quantities are compared in **joules** so that fuels with different chemistry can be added. One **petajoule (PJ)** is 10^{15} J and one **exajoule (EJ)** is 10^{18} J, so 1 EJ = 1000 PJ. Australia is conventionally reported in PJ and the world in EJ, which is a convenience of scale, not a difference in kind. Oil is also traded in **barrels** (1 barrel ≈ 159 L ≈ 6.1 GJ) and coal in **tonnes**, and a rate quoted in barrels a day will not sit in the same column as one quoted in petajoules a year until it has been converted.

Four derived measures do most of the analytical work, and all four are calculator-level arithmetic.

> **Percentage change** = (final − initial) ÷ initial × 100
>
> **Mean annual change** = (final − initial) ÷ number of years
>
> **Compound annual growth rate (CAGR)** = ((final ÷ initial)^(1/n) − 1) × 100
>
> **Doubling time (the rule of 70)** ≈ 70 ÷ annual percentage growth rate

The rule of 70 deserves its own sentence, because exponential growth is the reason this dot point exists. A quantity growing at 2 per cent a year doubles in about 35 years; at 7 per cent a year it doubles in about 10. Between 1950 and 1973 world oil use grew at roughly 8 per cent a year — a doubling every nine years — which is why a resource that looked inexhaustible in 1950 looked finite by 1973 without a single barrel being subtracted from the estimated reserve.

The historical record: three fuels, two centuries

For almost all of human history the energy rate was set by biomass, muscle, wind and water. **Coal** became a significant fuel from about 1800, when steam power made it worth mining at depth. **Oil** dates from the first commercial well in Pennsylvania in **1859**, and only became the dominant transport fuel with the internal combustion engine. **Natural gas** at large scale is a mid-twentieth-century development, requiring long-distance pipelines and, later, liquefaction. Each fuel did not replace the last so much as stack on top of it: world coal use today is higher than it has ever been.

Year	Oil (EJ)	Coal (EJ)	Gas (EJ)	Fossil total (EJ)	All sources (EJ)	Fossil share
1965	60	65	25	150	160	93.8%
1980	130	80	55	265	290	91.4%
2000	155	100	85	340	395	86.1%
2010	170	150	115	435	495	87.9%
2023	195	165	145	505	620	81.5%

World primary energy consumption, rounded to the nearest 5 EJ from the Energy Institute's Statistical Review of World Energy *series (the continuation of the long-running BP dataset). Shares are calculated from the rounded figures. Treat these as the shape of the record, not as exact values. Accurate as at July 2026.*

Read that table for **three different things** and it tells you three different stories.

- **The absolute rate has more than tripled**, from 150 EJ to 505 EJ of fossil energy a year, and it has never sustained a fall for longer than a few years.
- **The share has fallen**, from about 94 per cent to about 81 per cent. But it fell in two bursts, either side of a plateau: the 2000 and 2010 figures differ by less than the rounding in the table, so the robust finding for that decade is not that the share rose but that it **failed to fall**, because Chinese industrialisation added coal roughly as fast as the rest of the world added everything else.
- **The growth rate has slowed.** Fossil use grew about 3.9 per cent a year across 1965–1980 and about 1.7 per cent a year across 2000–2023. Slowing growth is still growth.

The short-term deviations matter as much as the trend, because they show what actually moves a rate. The **1973 OPEC embargo** and the **1979 Iranian revolution** quadrupled and then doubled the oil price; world oil use fell about 10 per cent between 1979 and 1983, the only sustained peacetime decline before 2020, and it did not regain its 1979 level until the early 1990s. The **1990s "dash for gas"** in Europe substituted gas for coal in power generation. The **2000s** were the coal decade, driven almost entirely by China. The **2008–09 global financial crisis** produced a one-year dip. **2020** produced the largest single-year fall in modern energy history — global primary energy down about 4.5 per cent, oil down about 9 per cent — and it was almost entirely reversed within two years. The **2022 invasion of Ukraine** cut Russian pipeline gas to Europe, briefly returned European coal to service, and then accelerated renewables deployment. In 2023 world oil consumption passed **100 million barrels a day** for the first time, and in 2024 world coal consumption reached a record of about **8.8 billion tonnes**.

The lesson from that list is that rates respond to **price, policy, technology and shock**, and that the shocks are sharp while the trends are slow.

Why the rate changes: population, affluence, intensity and mix

"The rate went up" is a description, not an explanation. A rigorous explanation decomposes it. Total fossil energy use can be written as a product of four factors — a form of the **Kaya identity**:

fossil energy use = population × (GDP ÷ population) × (energy ÷ GDP) × (fossil energy ÷ total energy)

Read left to right, the four terms are **population**, **affluence** (output per person), **energy intensity** (energy needed per dollar of output) and **fuel mix** (the fossil share). Every driver of a change in the rate of fossil fuel use acts through one of them, and the identity forces you to say which.

Factor	What pushes it up	What pushes it down
Population	Births, net migration	Demographic transition, falling fertility
Affluence — GDP per person	Industrialisation, rising incomes	Recession, financial crisis
Energy intensity — energy per unit GDP	Heavy industry, sprawl, freight growth	Efficient buildings, vehicles and motors; a shift from manufacturing to services; higher prices
Fossil share	Cheap coal, gas or oil; new fossil capacity	Renewables and nuclear build, electrification of transport and heat, retirement of fossil plant

The identity explains the two most common apparent paradoxes in this topic. First, an economy can grow while its energy use is flat, if intensity falls at least as fast as output rises — which is what has happened in Australia and most OECD countries since about 2008. Second, world fossil use can keep rising while the fossil share falls, if population and affluence together grow faster than intensity and share fall. **Absolute decoupling** — output rising while fossil use falls in absolute terms — requires the last two terms to fall faster than the first two rise, and it is much harder than it sounds.

A boundary worth marking: **energy intensity is not conversion efficiency**. Intensity is a whole-economy ratio of joules to dollars, and it falls partly because factories close and services grow. The efficiency of a *device* — how much of the energy put in comes out as the wanted form — is **12E**'s subject and is a different quantity with a different denominator.

Australia's trajectory, and the accounting boundary that changes the answer

Australia consumes roughly **6200 PJ** of primary energy a year, of which about **91 per cent** is fossil: oil products near 37 per cent, coal near 27 per cent and gas near 27 per cent, with renewables around 9 per cent. That fossil share is well above the world's, and it is the single most important number about Australian energy.

The trajectory has two distinct phases. Australian energy consumption grew at roughly 2.5 per cent a year from the 1970s to **2008–09**, and has been **broadly flat ever since** — a decade and a half in which the rate stopped rising for the first time since records began. Because the population grew from about 21.5 million to over 27 million across the same period, **energy use per person has fallen by roughly a sixth**. Flat total, falling per capita, rising population: three true statements about the same series.

The clearest sectoral change is in electricity.

Year	Total generation (TWh)	Coal	Gas	Renewables
2000	210	83%	9%	8%
2010	245	75%	15%	9%
2023	273	46%	16%	35%

Australian electricity generation by fuel, rounded, from the Australian Energy Statistics *published by the Department of Climate Change, Energy, the Environment and Water. Shares exclude a small oil-products contribution and do not sum to 100 per cent. Accurate as at July 2026.*

Coal's share fell 37 percentage points, but coal-fired generation itself fell by about 28 per cent, from around 174 TWh to around 126 TWh — the difference being that the total grew 30 per cent underneath it. Discrete closures did much of that work: **Hazelwood** in the Latrobe Valley (1600 MW of brown coal) closed in March 2017, **Liddell** in New South Wales in April 2023, and **Yallourn** (1480 MW) is scheduled to close by mid-2028 with **Loy Yang A** to follow by 2035. On the other side of the meter, Australia has more rooftop solar per person than any other country, with over four million systems installed. A rate that looks like a smooth curve at national scale is, up close, a series of steps.

Transport is the part that has not turned. Around three-quarters of Australia's oil goes to transport, and it is the reason the oil share of Australian primary energy has barely moved in thirty years. Australia's own crude oil and condensate production peaked around **2000** and has more than halved; only two refineries remain in operation, at Geelong in Victoria and Lytton in Queensland, after the closures of Kwinana and Altona in 2021; and Australia now imports of the order of **90 per cent** of its refined liquid fuels. This is the country's clearest lived experience of a peak — not a global one, a domestic one.

The accounting boundary. Ask "what is Australia's rate of fossil fuel use?" and there are two defensible answers. Australia *consumes* about 6200 PJ, but it *produces* roughly 20 000 PJ of primary energy a year and **exports about two-thirds of it**, chiefly as coal and LNG. On a **territorial consumption** boundary, Australian fossil use is flat. On a **production** boundary, it has grown enormously, because the LNG export industry barely existed in 2000. Neither figure is wrong; they answer different questions, and any claim about "Australia's fossil fuel use" that does not state its boundary cannot be evaluated. Which boundary a stakeholder chooses usually tells you what they want the number to show.

Instruments that act directly on the rate. Three are worth naming precisely, because they regulate rate rather than stock.

- The **Safeguard Mechanism**, operating under the *National Greenhouse and Energy Reporting Act 2007* (Cth), sets declining emissions baselines — reducing by 4.9 per cent a year to 2030 — for facilities whose covered scope 1 emissions exceed 100 000 t CO_2-e a year. Its reporting architecture is **9D**'s; what matters here is that it constrains a rate at named facilities.
- The *New Vehicle Efficiency Standard Act 2024* (Cth) sets average CO_2 targets for new light vehicles supplied in Australia from 1 January 2025, with credits and penalties accruing from 1 July 2025. It is Australia's first such standard, and transport is where Australian oil use is.
- In Victoria, the *Climate Action Act 2017* (Vic) — renamed from the *Climate Change Act 2017* (Vic) by the amending Act that brought the target forward — legislates a **net zero by 2045** target with interim targets, and the Victorian Renewable Energy Target under the *Renewable Energy (Jobs and Investment) Act 2017* (Vic) requires 65 per cent renewable electricity by 2030 and 95 per cent by 2035. Victoria also has the country's strictest supply-side restriction: the ban on hydraulic fracturing and on coal seam gas exploration and production is **entrenched in the** *Constitution Act 1975* **(Vic)**, inserted by the *Constitution Amendment (Fracking Ban) Act 2021* (Vic), while the moratorium on onshore *conventional* gas was lifted on 1 July 2021. *Accurate as at July 2026.*

Reserves, resources and the reserves-to-production ratio

Before peak oil can be defined, the stock side needs its vocabulary, because most bad arguments about peak oil turn on using one of these words when the other was meant.

Term	Definition
Resource	The total quantity of a fuel believed to be present, whether or not it can be extracted
Reserve	The part of the resource that has been **identified** and that is **technically and economically recoverable under current conditions**
Proved (1P) reserve	A reserve recoverable with high confidence — conventionally at least 90 per cent probability
Unconventional	Resource requiring non-standard extraction — tight oil, oil sands, coal seam gas, shale gas
Ultimately recoverable resource (URR)	Total that will ever be produced: cumulative production to date plus remaining reserves plus expected future additions

The crucial property is that **a reserve is not a physical constant**. Oil moves from resource to reserve when the price rises, when technology improves, or when a survey is done, and moves back when the price falls. Booking a reserve is partly a geological act and partly an accounting one.

The standard summary statistic is the **reserves-to-production ratio**:

R/P ratio (years) = proved reserves ÷ current annual production

World figures are of the order of **50 years for oil, 50 years for gas and 130 years for coal**. These are quoted constantly as "years of oil left", and that reading is wrong twice over.

- **It assumes production stays constant.** If use grows exponentially, the reserve is consumed far sooner than the ratio implies. At 3 per cent annual growth, an 80-year static reserve life is closer to 41 years.
- **It assumes reserves are fixed.** They are not: the world oil R/P ratio has *risen* from about 30 years in 1980 to about 50 years today, despite four decades of continuous production, because reserves were added faster than they were produced.

The two errors point in opposite directions, which is precisely why the ratio should be read as a **snapshot of current adequacy**, not as a countdown.

Peak oil: the concept, Hubbert's model, and what it assumes

Peak oil is the point in time at which the maximum **rate** of oil extraction is reached, after which the rate of extraction enters terminal decline.

Every word of that is load-bearing. It is a statement about a **rate**, not about a stock; about a **maximum**, not about exhaustion; and about **terminal** decline, so a temporary dip such as 2020 is not a peak. At the moment of peak, in the classical model, roughly **half the ultimately recoverable resource is still in the ground**. Peak oil is not the world running out of oil. It is the world running out of the ability to *increase* the rate at which it gets oil.

The concept comes from **M. King Hubbert**, a geophysicist with Shell Development Company, who in **1956** presented a paper to the American Petroleum Institute predicting that crude oil production in the United States would peak between 1965 and 1971. It peaked in **1970**, at about 9.6 million barrels a day. His reasoning has three steps.

1. Production of any finite resource must begin at zero and end at zero, so **cumulative** production traces an S-shaped (logistic) curve and the **rate** — its gradient — traces a roughly symmetrical bell.
2. You cannot produce what you have not found, so production follows **discovery** with a lag of some decades. A discovery peak therefore forecasts a production peak.
3. The bell peaks when about **half the URR** has been produced.

The discovery limb is the strongest evidence in the whole debate, and it is not seriously contested: global discovery of conventional oil peaked in the **mid-1960s**, and since the mid-1980s the world has consumed more oil each year than it has discovered.

The assumptions, which are where the argument lives:

Assumption	Why it can fail
The URR is fixed and known	Reserve growth, better recovery and price changes all revise it upward
Production is limited by geology	OPEC quotas, sanctions, war and investment cycles limit it instead
Technology is static	Horizontal drilling and hydraulic fracturing brought a resource base that was not in the original estimate
The curve is symmetrical	Real provinces often decline faster than they rose, or are held on a plateau by infill drilling
Demand will absorb whatever is produced	Policy, efficiency and substitution can cap demand before geology caps supply

The record of the prediction — and the shift to peak demand

Honesty about the forecasting record is part of teaching this concept properly.

Where it worked. The United States lower-48 peak was called correctly, fourteen years ahead. The model also describes individual fields and provinces well, and it describes Australia's own crude oil production, which peaked around 2000. Provincial and national peaks are ordinary, observed events.

Where it failed. Applied to the world, the model has been wrong repeatedly. A widely read 1998 *Scientific American* article by Campbell and Laherrère forecast a global peak before 2010; the Association for the Study of Peak Oil made similar calls through the 2000s. What actually happened is that **conventional** crude production plateaued from about 2005 — consistent with the model — while **total liquids** kept rising, because tight oil, oil sands, deepwater production, natural gas liquids and biofuels came from outside the resource base Hubbert's estimate described. United States crude production, having fallen to about 5 million barrels a day by 2008, reached a record of roughly 13 million barrels a day by 2024. The model was not so much refuted as **out-scoped**: it correctly describes the depletion of a defined conventional resource, and incorrectly assumes that resource is all there is.

The reframing. The contemporary debate is no longer mainly about when supply will fail. It is about **peak demand** — the point at which the rate of use stops rising because consumers stop wanting more, not because producers cannot deliver more.

	Supply-side (geological) peak	Demand-side peak
Cause	Depletion, falling discovery, rising extraction difficulty	Efficiency, electrification, policy, substitution, saturation
Price signal	Prices **rise** — scarcity	Prices **fall or stay weak** — surplus capacity
Who is exposed	Importers, transport-dependent economies	Exporters and owners of stranded reserves
Evidence to look for	Falling discovery, rising costs per barrel, falling EROI, decline rates outpacing new supply	Falling oil intensity of GDP, EV share of new sales, flat demand despite growth

The International Energy Agency's *World Energy Outlook 2023* was the first edition to project that demand for **all three** fossil fuels would peak before 2030 under its Stated Policies Scenario, and later editions have maintained that projection under the same scenario. OPEC's *World Oil Outlook* continues to project oil demand growing to 2050. Both are honest projections; they differ because they assume different rates of policy delivery, electric vehicle uptake and emerging-economy growth. Noting that a projection is **scenario-dependent** — and naming the assumption that drives the difference — is the analytical move the study design's key science skills are asking for, and it is worth more marks than picking a side.

Net energy: EROI, and why a peak bites before exhaustion

Beyond the study design. **Energy return on investment** appears nowhere in the Units 3 & 4 study design, nowhere in the examination specifications and nowhere in any VCAA examiners' report from 2020 to 2025. It is **not assessed, and no question in this subtopic requires it** — where the term appears in a model answer below it is offered as an alternative, never as the marking point. It is set out here for two reasons: the peak-oil literature you will read is argued in these terms, and it explains something the barrel count cannot — why the peak of *conventional* oil mattered even though total liquids kept rising. Read it for the idea, not for the formula.

Extraction costs energy. The measure of what is left over is **energy return on investment**:

EROI = energy delivered ÷ energy invested to obtain it

It is a **ratio of a source's output to the energy spent getting it**, and it is *not* the conversion efficiency of a device, which is **12E**'s quantity. A power station has an efficiency; an oil province has an EROI.

Source	Approximate EROI
United States conventional oil, 1930s	~100 : 1
United States conventional oil, 1970s	~30 : 1
Global oil and gas at the wellhead, 2000s	~15–20 : 1
Tight (shale) oil	~5–15 : 1
Oil sands, mined and upgraded	~3–5 : 1
Grain ethanol	~1–2 : 1

Published net-energy analyses; ranges are wide because studies draw the system boundary differently. Treat them as orders of magnitude. Accurate as at July 2026.

The fraction of gross energy actually available to society is **1 − 1/EROI**. At 30 : 1 that is 96.7 per cent; at 6 : 1, 83.3 per cent; at 3 : 1, only 66.7 per cent. The loss is not linear — the last few points of EROI cost far more than the first thirty, which is the shape sometimes called the **net energy cliff**.

This is why the peak of *conventional* oil mattered even though total liquids kept rising. The barrels that replaced conventional crude are real barrels, but each one costs more energy, more capital and more water to obtain, and delivers less net energy to the rest of the economy. A society whose reserves are growing while its EROI is falling is not getting richer in energy terms at the rate its reserve figures suggest.

Four ways rate data is misread

The error	What is actually true
"The share is falling, so use is falling"	A falling **share** of a growing total is perfectly consistent with rising **absolute** use — and absolute use is what determines emissions
"Growth is slowing, so use is falling"	A decelerating increase is still an increase. Use falls only when the growth rate turns **negative**
"The R/P ratio is 50, so we have 50 years"	The ratio assumes constant production and fixed reserves; growth shortens it and reserve additions lengthen it
"Peak oil means running out"	It means the maximum **rate** has passed. About half the recoverable resource remains at the peak

Worked examples

The organisations and provinces named below are fictional; the processes, quantities, statistics and legislation are real.

Example 1 — scaffolded

Classify each statement as consistent or inconsistent with the concept of peak oil, and justify each classification: (i) "Peak oil means the world will run out of oil." (ii) "A country can pass its own peak while world production is still rising." (iii) "Proved reserves are larger now than in 1980, so peak oil cannot happen." (iv) "Peak oil could arrive because demand stops growing, not because supply fails." *(4 marks)*

Working	Comment
(i) **Inconsistent.** Peak oil is the maximum **rate** of extraction; at the peak roughly half the recoverable resource is still in the ground.	The classic error. The curve declines after the peak — it does not stop.
(ii) **Consistent.** Peaks are properties of provinces. Australia's crude oil production peaked around 2000 while world production continued to rise.	A peak is defined for whatever production system you specify.
(iii) **Inconsistent.** Reserves are a **stock** and peak oil is about a **rate**; a larger reserve does not establish that the rate of extraction can keep rising, and reserves grow partly by reclassification.	Growing reserves *do* undermine near-term peak forecasts, but they do not refute the concept.
(iv) **Consistent.** A demand-side peak produces the same observation — a maximum rate followed by decline — from the opposite cause, and with falling rather than rising prices.	Same curve, opposite mechanism. The price signal is what distinguishes them.

Example 2 — scaffolded

The table gives rounded world primary energy consumption.

Source	2000 (EJ)	2023 (EJ)
Oil	155	195
Coal	100	165
Gas	85	145
Non-fossil	55	115

Calculate (a) total fossil energy use in each year, (b) the percentage change in fossil energy use, (c) the fossil share of the total in each year, and (d) explain how (b) and (c) can both be correct. *(5 marks)*

Working	Comment
(a) 2000: 155 + 100 + 85 = **340 EJ**. 2023: 195 + 165 + 145 = **505 EJ**.	Non-fossil is excluded from the fossil total but stays in the denominator for (c).
(b) (505 − 340) ÷ 340 × 100 = **+48.5 per cent**.	An increase of 165 EJ — more than the entire 1965 world fossil total.
(c) 2000: 340 ÷ 395 × 100 = **86.1 %**. 2023: 505 ÷ 620 × 100 = **81.5 %**.	Totals are 340 + 55 = 395 and 505 + 115 = 620.
(d) The **total** grew from 395 to 620 EJ, an increase of 57 per cent. Fossil use grew by 48.5 per cent — real growth, but slower than the total — so its **share** fell while its **amount** rose.	Non-fossil grew 109 per cent from a small base. Fast relative growth from a small base moves the share; it does not by itself reduce the absolute quantity of fossil fuel burnt.

Example 3 — unscaffolded

A commentator writes: "Global coal use grew 8 per cent in the first year of this period, then 4 per cent, then 2 per cent, then 1 per cent. Coal is clearly on the way out." Evaluate this claim, using calculation. *(4 marks)*

Take coal use at the start of the period as an index of 100. Applying each growth rate in turn: 100 × 1.08 = 108.0; × 1.04 = 112.3; × 1.02 = 114.6; × 1.01 = **115.7**.

Coal use was therefore about **15.7 per cent higher** at the end of the period than at the beginning, and it was **higher in every single year than in the year before**. The commentator has confused a fall in the **growth rate** with a fall in the **quantity**. The growth rate is the rate of change of the rate of use; it decelerated, but it never became negative, so the curve rose throughout and finished at its highest point in the series.

What the figures *do* support is a weaker and more defensible claim: coal use is decelerating, and if the trend in the growth rate continues it will cross zero and coal use will begin to fall. That is a projection about the future, resting on an assumption that the deceleration continues, and it is a different statement from the one made. *Takeaway:* a quantity falls only when its growth rate is **negative**; until then, "slowing growth" describes a record that is still setting records.

Example 4 — unscaffolded

The table gives two series for one state over twenty years.

	Year 1	Year 21
Fossil energy **consumed** within the state (PJ)	1450	1490
Fossil energy **produced** in the state (PJ)	2100	5400

The state government reports that "our fossil fuel use has been essentially flat for two decades". An environment group reports that "our fossil fuel use has more than doubled". Using calculation, evaluate both claims. *(5 marks)*

Percentage change on each series:

consumption: (1490 − 1450) ÷ 1450 × 100 = **+2.8 per cent** production: (5400 − 2100) ÷ 2100 × 100 = **+157 per cent**, or 5400 ÷ 2100 = **2.6 times** the Year 1 figure

Both claims are **arithmetically correct**, and they disagree because each is computed on a different **accounting boundary**. The government is reporting **territorial consumption** — fuel burnt inside the state's borders — and a rise of 2.8 per cent over twenty years is fairly described as flat. The environment group is reporting **production —** fuel extracted inside the state, most of it exported and burnt elsewhere — and on that boundary the increase is 157 per cent. The gap between the two series *is* the export industry, and it is the whole substance of the disagreement.

Neither boundary is wrong, but neither answers the other's question. A consumption boundary answers "how much fossil energy does activity inside this state require?", which is the right basis for domestic energy policy and for per-capita comparison. A production boundary answers "how much fossil carbon does this state put into circulation?", which is the right basis for any claim about the state's contribution to global emissions, since the carbon reaches the same atmosphere whichever jurisdiction burns it. Note also that the two series are not alternatives to be averaged: adding them would double-count the fuel that is both produced and consumed in the state.

Takeaway: a rate of fossil fuel use is not evaluable until its **boundary** is stated. When two parties report opposite trends for the same jurisdiction, check the boundary before checking the arithmetic — and notice which boundary each party has chosen, because the choice usually tells you what they want the number to show.

Practice questions

Scaffolded

Q1. Define each of the following: (a) the rate of use of a fossil fuel; (b) peak oil; (c) a proved reserve. *(3 marks)*

Q2. Reserves and resources are distinct quantities. (a) Distinguish between a resource and a reserve. (b) State what the reserves-to-production (R/P) ratio measures, and write the relationship used to calculate it. (c) State two assumptions built into the R/P ratio. *(5 marks)*

Q3. World oil consumption rose from about 31 million barrels a day in 1965 to about 100 million barrels a day in 2023, a period of 58 years. (a) Calculate the percentage increase. (b) Calculate the mean annual increase, in million barrels a day per year. (c) Calculate the compound annual growth rate, using CAGR = ((final ÷ initial)^(1/n) − 1) × 100. (d) Use the rule of 70, doubling time ≈ 70 ÷ annual percentage growth rate, to estimate the doubling time at that growth rate. *(5 marks)*

Q4. Hubbert's model underlies the concept of peak oil. (a) State the shape of the production-rate curve the model predicts, and explain why a finite resource must produce that shape. (b) State approximately what fraction of the ultimately recoverable resource has been produced at the peak. (c) State two assumptions of the model. *(5 marks)*

Q5. The table gives Australian electricity generation.

Year	Total generation (TWh)	Coal share	Gas share	Renewables share
2000	210	83%	9%	8%
2023	273	46%	16%	35%

(a) Calculate the electricity generated from coal in each year.
(b) Calculate the percentage change in coal-fired generation between 2000 and 2023.
(c) Calculate the percentage change in total generation.
(d) A student writes: "Coal's share fell by 37 percentage points, so coal-fired generation fell by 37 per cent." Explain why this is wrong. *(6 marks)*

Q6. World proved oil reserves are of the order of 1700 thousand million barrels and world production is about 100 million barrels a day. (a) Calculate annual production in thousand million barrels, taking one year as 365 days. (b) Calculate the R/P ratio. (c) If production grew at 2 per cent a year instead of remaining constant, state whether the reserve would be exhausted in more or fewer years than the R/P ratio suggests, and explain why. (d) State two reasons the world oil R/P ratio has risen since 1980 despite four decades of continuous production. *(6 marks)*

Unscaffolded

Q7. World oil consumption fell about 9 per cent in 2020 and had recovered within two years. State why this does not show that peak oil has occurred. *(1 mark)*

Q8. Explain why reaching peak oil is not the same as running out of oil. *(2 marks)*

Q9. Australia's total energy consumption has been broadly flat since 2008–09, while its population has grown from about 21.5 million to over 27 million. State what has happened to energy use per person over that period, and explain why a flat total and a falling per-person figure are not in conflict. *(2 marks)*

Q10. Between 2000 and 2023 the fossil fuel share of world primary energy fell from about 86 per cent to about 81 per cent, while the absolute quantity of fossil energy used rose by about 165 EJ. Explain how both statements can be true, and state which quantity is the relevant one for atmospheric carbon dioxide. *(3 marks)*

Q11. The International Energy Agency's *World Energy Outlook* projects, under its Stated Policies Scenario, that demand for oil, gas and coal will each peak before 2030. OPEC's *World Oil Outlook* projects oil demand still growing in 2050. Explain how two expert organisations can publish opposite projections without either being dishonest, and state what you should do with a projection of this kind when using it as evidence. *(3 marks)*

Q12. *(Stimulus.)* Corbanek Petroleum Ltd makes the following statement to investors.

> **Stimulus.** "Corbanek booked a further 400 million barrels of proved reserves in the Wendarra Basin this year. World proved reserves are now larger than they were forty years ago. Warnings about peak oil have therefore been disproved, and there is no scientific reason to constrain oil consumption."

Identify two scientific problems with this reasoning and explain each. *(4 marks)*

Q13. *(Stimulus.)* Crude oil production from the Wendarra Basin province is given below.

Stimulus.

Year	1995	2000	2005	2010	2015	2020	2025
Production (thousand barrels day^{-1})	12	48	112	158	164	131	94

Using the data, describe the pattern shown, identify the year of peak production, and determine the five-year period of most rapid growth. *(4 marks)*

Q14. Explain why Hubbert's model correctly anticipated the 1970 peak of United States crude oil production but has repeatedly failed to predict a global peak. *(4 marks)*

Q15. A country holds coal reserves of 4800 Mt and currently burns 60 Mt a year. (a) Calculate the R/P ratio. (b) Consumption is instead growing at 3 per cent a year. Use the rule of 70, doubling time ≈ 70 ÷ annual percentage growth rate, to find the doubling time, and explain what this does to the reserve life. (c) Give two reasons the R/P figure should not be reported as "years of coal left". *(5 marks)*

Q16. Thurlamby Shire Council states in its annual report that the district "has passed peak fossil fuel use". Describe the evidence you would need to gather, and the measurements you would make, to test that claim. *(5 marks)*

Q17. Compare a supply-side (geological) peak in oil with a demand-side peak, referring to the cause, the expected price behaviour, the evidence you would look for, and the consequences for a country that imports most of its liquid fuel. *(6 marks)*

Q18. *(Stimulus.)* Mirranbeen Freight Group has published the following plan.

> **Stimulus.** "Mirranbeen operates 240 heavy diesel prime movers. Diesel is 41 per cent of our operating cost and its price has risen in four of the last six years. Our plan is: (1) remain on diesel and hedge the fuel price on three-year contracts; (2) fit aerodynamic kits and low-rolling-resistance tyres, expected to cut fuel use per kilometre by 9 per cent; (3) review battery-electric prime movers in 2032. Independent modelling

assumes the diesel price returns to its ten-year average by 2029 and that Australian refining capacity is unchanged."

Evaluate this plan as a response to changes in the rate of fossil fuel use and to the concept of peak oil. *(8 marks)*

Q19. The Wendarra Basin province in Q13 supplies 60 per cent of a small nation's liquid fuel, and its production is now falling at about 5 per cent a year. The government is considering three responses: subsidising exploration to find a replacement province; legislating a new-vehicle efficiency standard and supporting electrification of light transport; and building a strategic fuel reserve equivalent to 90 days of net imports. For each option, explain what it does to the rate of fossil fuel use and to fuel security, evaluate its likely effectiveness in the light of the concept of peak oil, recommend one option with justification, and state one limitation of your recommendation. *(10 marks)*

Answers

Q1. (a) The quantity of the fuel consumed per unit time, in units such as PJ yr^{-1}, Mt yr^{-1} or barrels day^{-1}. (b) The point in time at which the maximum rate of oil extraction is reached, after which the rate enters terminal decline. (c) The part of an identified resource that is technically and economically recoverable under current conditions with high confidence — conventionally at least 90 per cent probability.

Q2. (a) A resource is the total quantity believed present; a reserve is the identified part that is technically and economically recoverable now. (b) It measures how many years current reserves would last at the current production rate: R/P = proved reserves ÷ annual production. (c) That production remains constant, and that reserves are fixed (no additions or reclassification).

Q3. (a) (100 − 31) ÷ 31 × 100 = **223 per cent**. (b) 69 ÷ 58 = **1.19 million barrels day^{-1} per year**. (c) (100 ÷ 31)^(1/58) − 1 = 0.0204 → **2.04 per cent per year**. (d) 70 ÷ 2.04 = **about 34 years**.

Q4. (a) A roughly symmetrical bell-shaped curve; production of a finite resource must start at zero and end at zero, so the rate must rise, reach a maximum and fall. (b) About **half** the ultimately recoverable resource. (c) Any two of: the URR is fixed and known; production is limited by geology rather than by policy, quotas or demand; technology is static; the curve is symmetrical.

Q5. (a) 2000: 0.83 × 210 = **174 TWh**. 2023: 0.46 × 273 = **126 TWh**. (b) (126 − 174) ÷ 174 × 100 = **−28 per cent**. (c) (273 − 210) ÷ 210 × 100 = **+30 per cent**. (d) Because a share is a proportion of a total that itself grew by 30 per cent; a change in percentage points is not a percentage change in the absolute quantity, which must be calculated from the absolute figures — here a fall of 28 per cent, not 37 per cent.

Q6. (a) $100 \times 10^6 \times 365 = 36.5 \times 10^9$ = **36.5 thousand million barrels per year**. (b) 1700 ÷ 36.5 = **about 47 years**. (c) **Fewer** — under exponential growth each year consumes more than the last, so the cumulative total reaches the reserve well before the static figure. (d) Any two of: reserve additions from new discovery; reclassification of resource as reserve when prices rise; improved recovery technology raising the recoverable fraction of known fields; unconventional resources becoming economic.

Q7. Peak oil requires a maximum followed by **terminal** decline; the 2020 fall was a temporary, shock-driven dip that was reversed, not the start of a sustained decline.

Q8. Peak oil concerns the maximum **rate** of extraction, not the exhaustion of the stock. At the peak roughly half the ultimately recoverable resource remains in the ground; production continues afterwards but at a declining rate.

Q9. Energy use per person has **fallen**, by roughly a sixth. Per-capita use is the total divided by population, so a total that is broadly flat, divided by a population that has grown by about a quarter, must give a falling ratio: the total and the per-person figure are different quantities measured against different denominators, not contradictory statements about the same one.

Q10. Total world primary energy grew from about 395 EJ to about 620 EJ, so fossil use could grow 48.5 per cent in absolute terms while growing more slowly than the total and therefore losing share. The quantity relevant to atmospheric CO_2 is the **absolute** amount of fossil fuel burnt, not its share.

Q11. Both are **scenario-dependent** projections, not predictions: each states what follows from a set of assumptions — chiefly the rate at which announced policies are actually delivered, electric vehicle uptake and emerging-economy growth — and the two organisations assume different values for those. They differ because their **inputs** differ, not because either has miscalculated. Using one as evidence requires naming the scenario, naming the assumption that drives the result, and treating the projection as conditional on it.

Q12. (i) The reasoning confuses a **stock** with a **rate**: peak oil is a claim about the maximum rate of extraction, and a larger reserve does not establish that the rate can keep rising. (ii) Much of the growth in world reserves is **reclassification** — resource becoming reserve as prices rose or technology improved — which is an accounting change rather than newly found oil, and says nothing about how fast it can be produced. (Also creditable: the binding constraint on consumption is the carbon budget and the policy response to it, not geological availability; and much of the added reserve is unconventional, so the net energy delivered does not grow in proportion to the barrels booked.)

Q13. Production rose steeply from 1995, decelerated after 2010, peaked in **2015** at 164 thousand barrels day^{-1}, and has since declined, with the decline accelerating. Most rapid growth: **2000–2005**, at (112 − 48) ÷ 5 = **12.8 thousand barrels day^{-1} per year**.

Q14. The United States lower-48 was a mature, densely drilled, privately operated, market-driven province with a long discovery record and essentially all conventional resource — conditions matching the model's assumptions. Globally, the URR was not fixed (reserve growth, technology, price), production is set by OPEC quotas and geopolitics as much as by geology, and tight oil, oil sands, deepwater and natural gas liquids came from outside the conventional resource base the model described. Conventional crude did plateau from about 2005, as the model implies; total liquids did not.

Q15. (a) 4800 ÷ 60 = **80 years**. (b) 70 ÷ 3 ≈ **23 years** to double; consumption reaches 120 Mt yr^{-1} by then and keeps rising, so the reserve is exhausted far sooner than 80 years — about 41 years. (c) Any two of: it assumes constant production, which growth contradicts; it assumes fixed reserves, which additions and reclassification contradict; it excludes resources not yet classified as reserves; and it takes no account of policy or carbon constraints that may leave coal unburnt.

Q16. Evidence must show a sustained fall in an absolute rate on a stated boundary: annual fossil energy consumed in the district in PJ, disaggregated by fuel and sector; a run of years long enough to distinguish a trend from a shock; the accounting boundary stated (consumption within the shire, or production including exported fuel); a control for confounders such as population change, weather-driven heating demand, an industrial closure or a change in reporting method; and per-capita as well as total figures. See the fully-worked solution.

Q17. Supply-side: caused by depletion and falling discovery; prices rise; evidence is annual discovery below annual production and rising cost per barrel; an importer faces scarcity and price shock. Demand-side: caused by efficiency, electrification, policy and substitution; prices fall or stay weak; evidence is falling oil intensity of GDP and rising EV share despite economic growth; an importer's exposure falls, while exporters face stranded reserves. See the fully-worked solution.

Q18. Strengths: the efficiency retrofit is real, immediate and cuts fuel use per kilometre 9 per cent; hedging manages short-term price volatility; the firm has quantified its exposure. Weaknesses: hedging manages price, not physical availability, and a three-year contract does not address a structural trend; a 9 per cent efficiency gain is a one-off level shift, not a change in trajectory, and can be partly offset by rebound; deferring electrification to 2032 treats the risk as static, and because **no Australian standard regulates the fuel use or CO_2 of heavy vehicles** — the *New Vehicle Efficiency Standard Act 2024* (Cth) reaches new **light** vehicles only — the deferral is an unhedged commercial bet on diesel price and technology rather than a timetable set by a regulator; the modelling's assumption that diesel returns to its ten-year average contradicts the firm's own observation of rises in four of six years; and "refining capacity unchanged" misidentifies the risk, since Australia has two refineries and imports about 90 per cent of refined fuel, making this an import-chain exposure. See the fully-worked solution.

Q19. Exploration subsidy: sustains the rate of use, may defer the national peak, but is subject to falling discovery and to the higher cost and lower net energy of any replacement, and is the least reliable. Efficiency standard plus electrification: reduces the rate of oil use structurally and permanently, and improves security by shrinking the quantity that must be imported; slower to take effect because it works through fleet turnover. Strategic reserve: does not change the rate of use at all, but buys 90 days of protection against a disruption; a buffer, not a solution. Recommendation with justification and one specific limitation required. See the fully-worked solution.

Fully-worked solutions

Q1. (a) The **rate of use** is the quantity consumed **per unit time** — petajoules per year, tonnes per year, barrels per day. (b) **Peak oil** is the point in time at which the **maximum rate** of oil extraction is reached, after which the rate enters **terminal decline**. (c) A **proved reserve** is the part of an identified resource that is **technically and economically recoverable under current conditions**, with high confidence (conventionally at least 90 per cent probability). *Marker's note:* (a) is not answered without "per unit time" or a rate unit, and (b) is not answered without the word **rate** — "when the oil runs out" scores nothing.

Q2. (a) A **resource** is the total quantity of the fuel believed to be present, whether or not it can be extracted. A **reserve** is the part of that resource that has been **identified** and is **technically and economically recoverable under current conditions**. (b) The **R/P ratio** measures how many years the current proved reserves would last **if production continued at its current rate**: **R/P = proved reserves ÷ annual production**. (c) Any two: production stays **constant**; reserves are **fixed**, with no additions, discoveries or reclassification. *Common error:* treating a reserve as a physical property of the rock. It is partly economic — the same oil moves in and out of the reserve category as the price moves.

Q3. (a) (100 − 31) ÷ 31 × 100 = 69 ÷ 31 × 100 = **223 per cent**. (b) 69 ÷ 58 = **1.19 million barrels day^{-1} per year**. (c) 100 ÷ 31 = 3.226; 3.226^(1/58) = 1.0204; so CAGR = **2.04 per cent per year**. (d) 70 ÷ 2.04 = **34 years**. *Marker's note:* (a) asks for the percentage **increase**, which is 223 per cent — the final value is 323 per cent **of** the initial. Reporting 323 per cent answers a different question. Note also that (b) and (c) describe the same series and disagree about what "the rate of growth" means: the mean annual increase is a constant number of barrels, the CAGR a constant percentage.

Q4. (a) A roughly **symmetrical bell-shaped curve**. Production of a **finite** resource must begin at zero, because nothing has yet been extracted, and must end at zero, because the resource is exhausted; between those endpoints it must therefore rise to a **maximum** and fall. Equivalently, cumulative production traces an S-shaped logistic curve and the production rate is its gradient. (b) About **one half** of the ultimately recoverable resource. (c) Any two: the **URR is fixed and known**; production is limited by **geology** rather than by demand, price, policy or quota; **technology is static**; the curve is **symmetrical** either side of the peak. *Marker's note:* the explanation in (a) is where the second mark sits. "It is a bell curve" states the answer without giving the reason.

Q5. (a) 2000: 0.83 × 210 = **174.3 TWh**. 2023: 0.46 × 273 = **125.6 TWh**. (b) (125.6 − 174.3) ÷ 174.3 × 100 = −48.7 ÷ 174.3 × 100 = **−28 per cent**. (c) (273 − 210) ÷ 210 × 100 = **+30 per cent**. (d) The student has treated a change in **percentage points** as a **percentage change**, and has ignored the denominator. Coal's share is a proportion of a total that itself grew 30 per cent over the period, so the same share now represents more electricity than it used to. Working from the absolute figures, coal-fired generation fell from about 174 TWh to about 126 TWh — a fall of **28 per cent**, not 37. *Marker's note:* this is the single most examinable calculation in the subtopic. Whenever a share and a total both change, the absolute quantity must be recovered before any statement about "how much it fell" can be made.

Q6. (a) 100 × 10^6 barrels day^{-1} × 365 days = 36.5 × 10^9 barrels = **36.5 thousand million barrels per year**. (b) 1700 ÷ 36.5 = **46.6, or about 47 years**. (c) **Fewer years.** The R/P ratio assumes a constant production rate. Under 2 per cent annual growth each year draws more from the reserve than the year before, so the cumulative total reaches 1700 thousand million barrels well before year 47 — the faster the growth, the larger the shortfall. (d) Any two of: **new discovery**; **reclassification** of resource as reserve when prices rise or costs fall; **improved recovery technology** raising the fraction of a known field that can be produced; **unconventional resources** such as tight oil and oil sands becoming economically recoverable and therefore bookable. *Marker's note:* parts (c) and (d) pull in opposite directions, and a strong answer says so — growth shortens the reserve life, reserve additions lengthen it, and the ratio captures neither. That is why it is a snapshot of adequacy, not a countdown.

Q7. The definition requires the maximum rate to be followed by **terminal** decline — sustained and permanent. The 2020 fall was a **temporary** demand shock: consumption not only recovered but passed 100 million barrels a day for the first time in 2023, above its pre-2020 level. A dip that is reversed is not a peak. *Marker's note:* the single mark sits on the word **terminal** (or "sustained"). "Because it went back up" earns it; "because reserves are still large" does not, since that answers a question about the stock.

Q8. Peak oil is a statement about the **rate** at which oil is produced, not about the **stock** that remains. In the classical model roughly **half the ultimately recoverable resource is still in the ground** at the moment of the peak; production continues for decades afterwards, but at a **falling rate**. Running out would mean the rate reaching zero, which is the far end of the curve, not its summit.

Q9. Energy use per person has fallen, by roughly a **sixth**. The two statements are not in conflict because they are **different quantities**: the total is an absolute rate in PJ per year, while per-capita use is that rate **divided by population**. Population grew from about 21.5 million to over 27 million, roughly 26 per cent, so a genuinely flat total would give a per-capita fall of about a fifth (1 ÷ 1.26 = 0.79). "Broadly flat" in fact conceals a rise in the total of a few per cent, which lifts the numerator slightly and brings the fall back to about a sixth. *Marker's note:* the same structure appears in **Q5** with a share against a growing total and in **Q10** with a share against a growing denominator — whenever a ratio and its numerator appear to disagree, the denominator is doing the work. Note which quantity answers which question: per-capita use measures how energy-hungry the average Australian is, while the **total** is what determines the emissions.

Q10. Both are true because they are statements about **different quantities**. Total world primary energy grew from about **395 EJ to about 620 EJ** over the period, an increase of some 57 per cent. Fossil energy use grew from about **340 EJ to about 505 EJ** — an increase of 165 EJ, or 48.5 per cent — which is genuine growth but **slower than the total**, so the fossil **share** of the total fell from 86 per cent to 81 per cent even as the **amount** rose. A share is a ratio; the numerator can rise while the ratio falls, provided the denominator rises faster. For atmospheric carbon dioxide the relevant quantity is the **absolute amount of fossil fuel burnt**, because the atmosphere responds to tonnes of carbon, not to percentages. *Common error:* reading a falling share as evidence of falling emissions. It is evidence only that non-fossil sources are growing faster, which is compatible with record emissions.

Q11. A projection is not a forecast of what will happen; it is a statement of **what follows from a stated set of assumptions**. The IEA's *World Energy Outlook 2023* was the first edition to project all three fossil fuels peaking in demand before 2030, and it did so under the **Stated Policies Scenario**, which assumes that policies governments have already announced are in fact delivered on schedule. OPEC's *World Oil Outlook* projects oil demand growing to 2050 on assumptions of slower policy delivery, slower electric vehicle uptake and stronger demand growth in developing economies.

Both can therefore be **honest**, because neither claims to know the future. Each answers the question "what happens **if** these assumptions hold?", and they have been handed different assumptions. The disagreement is not about arithmetic and not about the resource; it is about **policy delivery and technology uptake**, which are political and economic variables rather than geological ones.

Using such a projection as evidence requires three things: **name the scenario**, **name the assumption that drives the difference**, and treat the result as **conditional** on it — "under STEPS, which assumes announced policies are delivered, the IEA projects …". *Marker's note:* the analytical move the key science skills reward is identifying the assumption, not picking a side. "The IEA is right because it is independent" scores nothing; "they differ because they assume different rates of policy delivery and EV uptake" has done the work.

Q12. First, the argument confuses a stock with a rate. Peak oil is a claim about the **maximum rate of extraction**, and the size of the reserve does not by itself establish anything about how fast oil can be produced. A very large reserve in deep water, in tight rock or in bitumen sand can only be produced slowly and at high cost; a small reserve in an easy conventional field can be produced quickly. Reserves rising while the production rate plateaus is exactly what the concept predicts, not a refutation of it. **Second, reserve additions are not new oil.** Much of the growth in world reserves since 1980 is **reclassification** — resource becoming reserve when prices rose or technology improved — which is an accounting change rather than a discovery, and moves nothing into the ground. Global discovery of conventional oil peaked in the **mid-1960s** and the world has consumed more than it discovered every year since the mid-1980s, so a rising reserve figure across that period is largely a rising *classification*, not a rising *find*. "Booked" is itself the give-away: booking is a ledger entry, and whether new oil was found is a separate question the statement does not answer. *Also creditable:* the binding constraint on consumption is the **carbon budget** and the policy response to it, not geological availability, so "no scientific reason to constrain consumption" does not follow even if the reserve claim were sound; and much of the added reserve is **unconventional**, which delivers less net energy per barrel than the conventional oil it replaces. *Marker's note:* four marks requires **two** problems and an **explanation** of each. Simply asserting "peak oil is about rate" earns one.

Q13. *"Using the data" means the figures must appear.* Production **rose steeply and then declined**, tracing an asymmetrical bell. From 1995 it climbed from 12 to 48 thousand barrels day^{-1} by 2000 (7.2 per year), then fastest to 112 by 2005 (**12.8 per year**), then more slowly to 158 by 2010 (9.2 per year) and 164 by 2015 (1.2 per year), where the curve flattens. It then falls to 131 by 2020 (**−6.6** per year) and 94 by 2025 (**−7.4** per year), with the decline **accelerating**.

Peak production: **2015**, at 164 thousand barrels day^{-1}. Period of most rapid growth: **2000–2005**, at (112 − 48) ÷ 5 = **12.8 thousand barrels day^{-1} per year**.

Marker's note: the question asks for the period of most rapid **growth** — a rate of change — so the answer requires the **differences** between readings, not the largest reading. Choosing 2010–2015 because the numbers there are highest is the standard error. Note also that this province declines faster than it rose, so the curve is **not** the symmetrical bell Hubbert's model assumes.

Q14. The United States lower-48 states matched the model's assumptions almost exactly. It was a **mature, densely drilled province** with a **long discovery record**, so the URR could be estimated reliably; it was **privately operated and market-driven**, with **no production quota**, so output was limited by **geology** rather than by policy; and the resource was **essentially all conventional**, so the technology of the day defined what was recoverable. Under those conditions the discovery peak of the 1930s duly forecast the production peak of **1970**, at about 9.6 million barrels a day.

Globally, every one of those conditions fails. The **URR is not fixed**: reserve growth, improved recovery and price movements have revised it upward continuously. **Production is not set by geology** alone — OPEC quotas, sanctions, war and the investment cycle set it for a large share of world output. **Technology did not stay still**: horizontal drilling combined with hydraulic fracturing unlocked tight oil that was not in the original resource base, taking United States crude production from about 5 million barrels a day in 2008 to a record near 13 million by 2024. And the definition of "oil" widened, so **total liquids** now include natural gas liquids, oil sands, deepwater production and biofuels.

The fair verdict is that the model was **out-scoped rather than refuted**: **conventional** crude oil production did plateau from about 2005, which is what the model describes, but it is not the whole of supply. *Marker's note:* four marks needs both limbs — the specific conditions that made the United States prediction work, and the specific assumption failures that make the global one fail. An answer that says only "he was wrong about the world" has explained nothing.

Q15. (a) R/P = 4800 Mt ÷ 60 Mt yr^{-1} = **80 years**.

(b) Doubling time ≈ 70 ÷ 3 = **about 23 years**. So in roughly 23 years the country is burning 120 Mt a year, in 46 years 240 Mt a year, and so on. Each year consumes more than the last, so the **cumulative** total reaches 4800 Mt far sooner than the static figure suggests — about **41 years**, roughly half the R/P value. The R/P ratio is not merely imprecise under growth; it is optimistic by about a factor of two at this growth rate. (The 41-year figure comes from summing the growing annual amounts and is quoted here for scale — you are not expected to compute it. "Far sooner than 80 years, because each year burns more than the last" is the answer.)

(c) Any two, explained: it **assumes constant production**, which growth contradicts; it **assumes fixed reserves**, whereas discovery, technology and price changes add to them; it **excludes resource** not yet classified as reserve; and it takes no account of **policy or carbon constraints**, which may leave coal in the ground regardless of whether it is recoverable. *Marker's note:* the two reasons in (c) should pull in **opposite** directions if the answer is to show real understanding — growth shortens the life, reserve additions lengthen it.

Q16. Testing "the district has passed peak fossil fuel use" requires showing that an **absolute rate** has reached a maximum and is in **sustained** decline, on a **stated boundary**.

The quantity and its boundary. Measure annual fossil energy consumed within the shire in **PJ**, disaggregated by fuel (petrol, diesel, LPG, natural gas, coal-derived electricity) and by sector (transport, residential, commercial, industrial). State the boundary explicitly: consumption **within** the shire, or production including fuel exported from it. Electricity must be attributed using the **fossil share of the grid** supplying the district, not counted as zero at the meter.

The data sources and the record length. Retail fuel sales and network gas throughput for the district; distribution-network electricity consumption combined with published generation-mix data; council fleet and facility records. A peak cannot be identified from two points — a run of at least **ten years** of consistently measured annual data is needed, because a single year's fall can be produced by a wet winter, a recession or a plant shutdown.

Controls and confounders. Report **per-capita** alongside total figures, since population change alone moves the total; check for a large **industrial closure or opening** in the period, which can produce a step that looks like a trend; check for a change in **reporting method or boundary**, which is the commonest artificial "decline"; and check whether activity has simply **relocated** outside the shire boundary rather than ceased.

The test itself. Fit or inspect the trend across the record and ask whether the **growth rate has turned negative and stayed negative** for several years, not merely slowed. Compare the recent years' mean with the historical maximum and consider whether the difference exceeds the year-to-year variability in the series. *Marker's note:* the claim is about a **maximum followed by sustained decline**, so the answer must address record **length** and **variability**, not just “measure fossil fuel use”.

Q17. *“Compare” means the same points addressed for both, not two separate descriptions.*

The cause. A **supply-side peak** is imposed by **geology and net energy**: discovery has fallen, existing fields are declining, and the resource still available is harder, deeper and more energy-costly to produce, so the rate of extraction cannot be raised further. A **demand-side peak** is imposed by **users**: efficiency standards, electrification of transport, fuel switching, structural change in economies and eventual saturation of vehicle ownership mean less oil is wanted, even though more could be produced.

The price behaviour. This is the sharpest diagnostic. A supply-side peak is a **scarcity**, so prices **rise**, often violently, and stay high; producers earn windfalls. A demand-side peak is a **surplus**, so prices are **weak or falling** despite ample spare capacity; producers compete for a shrinking market. Same production curve, opposite price signal.

The evidence to look for. For a supply-side peak: **annual discovery below annual production**, **rising capital and energy cost per barrel**, and decline rates in existing fields outpacing new supply (falling EROI is a further indicator, but is not needed to answer). For a demand-side peak: falling **oil intensity of GDP**, rising electric vehicle share of new sales, flat or falling consumption in economies that are still growing, and producers revising demand forecasts downward.

Consequences for an importer of liquid fuel. Under a supply-side peak an importer is badly exposed: it faces rising prices, a worsening trade balance, and physical supply risk on a long import chain — the position Australia is in, importing of the order of 90 per cent of its refined liquid fuels with only two refineries operating. Under a demand-side peak the same importer is a **beneficiary**: fuel is cheap and plentiful, and its own exposure shrinks as its fleet electrifies. The parties at risk shift to the **exporters**, who face falling revenue and **stranded** reserves that will never be produced. *Marker’s note:* six marks reward the **parallel structure** — cause, price, evidence, consequence, for both — and the price signal is the point most often missed, because it is the only one where the two peaks look opposite rather than merely different.

Q18. *Model response (8 marks).*

The plan is a competent short-term cost-management response and a weak long-term energy-transition response, and the distinction matters because the risk it faces is structural rather than cyclical.

What the plan gets right. The efficiency retrofit is genuine and immediate. Aerodynamic kits and low-rolling-resistance tyres reduce fuel use per kilometre by a stated 9 per cent, which cuts both cost and the rate of fossil fuel use at once, requires no new technology, and pays back within the current fleet’s life. Quantifying diesel at 41 per cent of operating cost is also good practice — the exposure is measured rather than asserted.

Hedging manages price, not availability. A three-year fuel contract transfers **price** risk to a counterparty for three years. It does nothing about **physical** supply, and it does nothing about a structural upward trend, because when the contract is rolled it is repriced at whatever the market then is. Hedging smooths a cycle; it cannot smooth a trend.

A 9 per cent efficiency gain is a level shift, not a change in trajectory. It moves fuel use per kilometre down once and then stops. If freight volume grows at even 3 per cent a year, total diesel use recovers its pre-retrofit level within about three years, and lower fuel cost per kilometre may itself encourage additional kilometres — a **rebound** effect. Efficiency improves the rate at which fuel is used per unit of work; only substitution changes what the work runs on.

Deferring electrification to 2032 treats the risk as static. It is worth being exact about why, because the obvious regulatory argument does **not** apply here. Neither of the two Commonwealth instruments that act directly on the rate of fossil fuel use reaches this firm. The *New Vehicle Efficiency Standard Act 2024* (Cth) sets average CO_2 targets for new **light** vehicles only; a prime mover is not a light vehicle, so the standard does not touch Mirranbeen’s fleet. The **Safeguard Mechanism** applies to facilities whose covered scope 1 emissions exceed **100 000 t CO_2-e a year**; at a typical 50 000 to 80 000 L of diesel per prime mover, 240 of them burn some 12 to 19 million litres a year, which at roughly 2.7 kg CO_2-e per litre is of the order of **30 000 to 50 000 t CO_2-e** — well under half the threshold. Australia has **no** fuel-efficiency or CO_2 standard for heavy vehicles at all.

That absence makes the deferral weaker, not stronger. With no regulatory timetable to anchor it and nothing external forcing the firm to prepare, element (3) is an **unhedged commercial bet** on diesel price, vehicle technology and residual values — the same three variables the firm has just told us are moving against it. Heavy-vehicle battery and charging technology, the resale value of a diesel prime-mover fleet, and the emissions conditions large customers attach to freight contracts will all move well before 2032, and a firm that reviews only then will be buying into a mature market rather than shaping its own transition. A firm that has correctly identified a structural exposure should not wait for a regulator that is not coming.

The modelling contradicts the firm's own evidence. Mirranbeen reports that diesel prices rose in four of the last six years, and then adopts modelling that assumes the price **returns to its ten-year average** by 2029. Using a historical mean as the input to a forecast whose own observed data show a trend is a systematic optimism, not a rounding error. Separately, the assumption that "Australian refining capacity is unchanged" **misidentifies the risk**: Australia has only two operating refineries and imports of the order of 90 per cent of its refined liquid fuels, so the exposure is an **import-chain** and shipping exposure, not a domestic capacity one. Holding capacity constant in the model conceals the risk rather than testing it.

Judgement. Element (2) should proceed immediately; it is cheap, certain and reduces the rate of use now. Element (1) is reasonable as a cash-flow measure provided it is not mistaken for a solution. Element (3) is the weakness: the review should be brought forward, with a staged trial of electric or alternative-fuel prime movers on short, depot-based routes where the technology is already viable, so the firm learns before it is forced to decide. The plan should also be re-modelled against a rising real diesel price and an import-disruption scenario, since those are the conditions its own data point towards. *Marker's note:* an evaluation must reach a **judgement**, and must engage with the stimulus's internal contradiction between the observed price rises and the assumed reversion to the mean.

Q19. *Model response (10 marks).*

Option 1 — subsidising exploration for a replacement province. This aims to **sustain** the current rate of fossil fuel use by adding new supply, and to improve security by keeping that supply domestic. It is the option most directly contradicted by the concept of peak oil. Global conventional discovery peaked in the mid-1960s and the world has consumed more than it discovered every year since the mid-1980s, so the probability of finding a province comparable to Wendarra is low, and the lead time from discovery to first production is commonly a decade or more — against a decline already running at 5 per cent a year. Anything found is likely to be **smaller, deeper and costlier**, so even success delivers less net energy per barrel than the production it replaces. It also **locks in demand** for a fuel whose price and availability the nation does not control.

Option 2 — a new-vehicle efficiency standard plus support for electrification. This attacks the **demand** side, reducing the quantity of liquid fuel the country needs rather than trying to find more of it. Its security benefit is structural and permanent: every litre not required is a litre that cannot be disrupted, and electricity can be generated domestically from sources the nation controls. Its weakness is **speed**. A standard applies only to **new** vehicles, so it works through fleet turnover over ten to fifteen years and does nothing for the vehicles already on the road. It also shifts demand onto the electricity system, which must itself be built out, and it does little for heavy freight and aviation in the short term.

Option 3 — a strategic reserve of 90 days of net imports. This changes the rate of fossil fuel use **not at all**. It is a buffer against **interruption**, not against depletion or price trend, and 90 days is the emergency stockholding level International Energy Agency member countries are obliged to maintain under the 1974 *Agreement on an International Energy Program*. It is fast to establish, unambiguous in effect, and it is the only one of the three that helps in a sudden shipping or geopolitical disruption next year. But it is expensive to build and hold, it buys days rather than years, and once used it must be refilled from the same market that failed.

Recommendation. I would recommend **Option 2**, the efficiency standard with electrification support, as the primary response. The province's decline is a **supply-side** problem, and the only durable answer to a falling supply of a fuel is to need less of it: exploration gambles against an observed sixty-year decline in discovery, and a reserve postpones a shortage without reducing it. Option 2 also compounds — each year of fleet turnover reduces exposure further — whereas the other two must be repeated or replenished. I would, however, fund the strategic reserve as a **secondary** measure, because Option 2 takes a decade to bite and the reserve covers exactly the interval in which the nation is most exposed. Exploration should not be subsidised: if a province is genuinely commercial, private capital will find it, and if it is not, a subsidy is public money spent lowering the price of the fuel the nation is trying to depend on less.

Limitation. The recommendation assumes that the **electricity system can absorb the transferred demand** — that generation, transmission and charging capacity can be built at least as fast as the vehicle fleet electrifies, and that the generation added is not itself fossil-fuelled. If it is, the policy relocates the fossil fuel use from the vehicle to the power station rather than eliminating it, and the security gain is only partial. Whether that condition holds depends on the nation's generation mix and grid investment pipeline, neither of which is established by the reasoning above, and both of which should be assessed before the standard's timetable is set. *Marker's note:* ten marks require **all three options** treated on **both criteria** — effect on the rate of use, and effect on fuel security — plus explicit use of the **peak oil** concept, a **justified** recommendation, and a **specific** limitation. "More research is needed" is not a limitation; naming the assumption your own recommendation depends on, and saying what happens if it fails, is.

Chapter 12 Energy sources, conversions and efficiency — 12E Energy conversions and energy efficiency calculations

Theory

Energy is never used up. Every joule that enters a power station leaves it again, and the only question worth asking is *in what form and where*. **Energy efficiency** is the accounting answer to that question: it is the fraction of the energy you put in that came out in the form you actually wanted. The study design asks for this as a calculation, and it asks for it twice over — **"energy efficiency calculations of single and multi-step conversions between different forms of energy, including potential, mechanical, kinetic, thermal, and chemical energy, to generate electricity"**. Both halves matter. Single-step calculations are arithmetic you can do in one line. Multi-step calculations are where nearly all the marks are lost, because the stages **multiply** and almost everyone's first instinct is to add them.

Where this subtopic sits. Chapter 12's other subtopics deal with the sources and their consequences: **12A** with the non-renewable sources, **12B** with the renewable ones, **12C** with what fossil fuel combustion does to the carbon cycle, **12D** with rates of use and peak oil, **12F** with what the first and second laws of thermodynamics *imply for the choices a society makes*, and **12G** with the sustainability principles across the supply chain. Chapter 13 then deals with base and peak load (**13B**) and with the options for a lower-emission energy future, including *increasing the efficiency of energy conversion devices* (**13C**). This subtopic is narrower than any of them and prior to all of them: it is the **numeracy**. Given a conversion chain, what fraction of the input survives to the end of it, and how much fuel does a stated output therefore require? Once you can do that, 12F can tell you why the numbers are shaped as they are, and 13C can argue about what to do.

The forms of energy the study design names

Form	What it is	Defining relationship	Typical unit
Gravitational potential energy	Energy stored by position in a gravitational field	$E_p = mgh$	J
Kinetic energy	Energy of a mass in motion	$E_k = \frac{1}{2}mv^2$	J
Mechanical energy	In generation contexts, the rotational shaft work a turbine or rotor delivers	$E = Pt$ at the shaft	J
Thermal energy	Energy associated with the random motion of particles; transferred as heat	$Q = mc\Delta T$	J
Chemical energy	Energy stored in the bonds of a fuel, released on reaction	$E = m \times$ energy content	J
Electrical energy	Energy carried by moving charge — the output every chain in this subtopic aims at	$E = VIt$	J
Radiant energy	Energy carried by electromagnetic radiation	$E =$ irradiance $\times$ area $\times$ time	J
Nuclear energy	Energy released when nuclei fission	$E = m \times$ energy content	J

The study design's list is not a clean taxonomy, and it is worth saying so rather than pretending otherwise. **Mechanical energy** is conventionally defined as the sum of an object's kinetic and potential energy, so listing it alongside both is a redundancy. The convention this subtopic uses — and the one that makes every chain unambiguous — reserves *mechanical energy* for the **rotating shaft** that couples a turbine to a generator, and uses *kinetic* and *potential* for the energy of the working fluid: moving air or water, or water held at height. **Radiant** and

nuclear energy are not in the study design's list, but you cannot write the chain for a solar or a nuclear station without them, so they are here.

Units, and the two quantities students most often swap

Quantity	Symbol	SI unit	Multiples you will meet
Energy	*E*	joule (J)	kJ, MJ, GJ, TJ, **PJ** (10^{15} J) — Australian national energy statistics are published in petajoules
Power — energy per unit time	*P*	watt (W) = J s^{-1}	kW, MW, GW

Power is a rate; energy is an amount. They are related by $E = Pt$, and confusing them is the single commonest source of a wrong answer in this subtopic. A 2400 W kettle does not "use 2400 W an hour"; it uses energy at the rate of 2400 J every second.

The **kilowatt-hour (kWh)** is an energy unit, not a power unit, because it is a power multiplied by a time. It is the unit on every electricity bill in Victoria, so you must be able to move between it and the joule:

1 kWh = 1000 W × 3600 s = 3.6×10^6 J = **3.6 MJ**

1 MWh = 3.6 GJ · 1 GWh = 3.6 TJ · 1 GJ = 277.8 kWh · 1 PJ = 277.8 GWh

Other quantities you will need, and their standard values: $g = 9.8$ m s^{-2}; the specific heat capacity of water $c = 4180$ J kg^{-1} K^{-1}; the density of fresh water 1000 kg m^{-3}; the density of air 1.225 kg m^{-3} at sea level, the standard-atmosphere value also used in **12B**.

Energy density: what a kilogram of fuel is worth

A backwards calculation — *how much fuel does this output need?* — always ends here.

Fuel	Energy content	Note
Latrobe Valley brown coal, as mined	~6–11 MJ kg^{-1}	About 60 per cent water by mass; the moisture is why the figure is so low
Black coal, export grade	~24–30 MJ kg^{-1}	
Natural gas	~38 MJ m^{-3} (about 52 MJ kg^{-1})	Sold by the megajoule in Victoria
Diesel · **Petrol**	~38.6 MJ L^{-1} · ~34.2 MJ L^{-1}	
Ethanol	~23.4 MJ L^{-1}	Lower than petrol, which is why E10 gives slightly poorer fuel consumption
Air-dried wood / biomass pellets	~16–18 MJ kg^{-1}	Falls steeply with moisture content
Uranium-235, complete fission	~8×10^7 MJ kg^{-1}	Of the order of ten million times brown coal

Figures are rounded representative values; energy content varies with grade and moisture. Accurate as at July 2026.

Writing the conversion chain

Before calculating anything, write the chain. It disciplines the arithmetic, and in the examination it is frequently worth a mark on its own.

Source	Conversion chain to electricity
Coal, gas, biomass, biofuel	chemical → thermal → mechanical → electrical
Nuclear	nuclear → thermal → mechanical → electrical
Hydro-electric	gravitational potential → kinetic → mechanical →

Source	Conversion chain to electricity
	electrical
Wind	kinetic → mechanical → electrical
Tidal (barrage)	gravitational potential → kinetic → mechanical → electrical
Geothermal	thermal → mechanical → electrical
Solar thermal (concentrating)	radiant → thermal → mechanical → electrical
Solar photovoltaic	radiant → electrical *(single step)*
Pumped hydro, charging	electrical → mechanical → kinetic → gravitational potential

Two observations follow immediately, and they are the whole reason this dot point exists. First, **the chains differ in length** — one conversion for a photovoltaic module, two for a wind turbine or a geothermal plant, three for a coal station and three for a hydro scheme — **but length on its own settles nothing**: coal and hydro run the same three conversions and end up a factor of three apart. Second, **every chain that passes through a thermal stage loses most of its energy at that stage**, and that, not the step count, is what separates those two. The second observation is quantified below; *why* a thermal stage is intrinsically limited is **12F**'s dot point, not this one.

The efficiency equation

efficiency (%) = (useful energy output ÷ total energy input) × 100

Equivalently, with power in place of energy, provided both are instantaneous or both are averaged over the same interval:

efficiency (%) = (useful power output ÷ total power input) × 100

Four rules govern its use.

1. **The units on top and bottom must be the same.** If the input is in kWh and the output in MJ, one of them has to be converted first. Efficiency is a ratio and therefore **dimensionless**.
2. **"Useful" is defined by the purpose of the device, not by physics.** The thermal energy leaving an incandescent lamp is a loss; the identical thermal energy leaving a bar radiator is the product. State what you are treating as useful.
3. **Efficiency can be written as a percentage or as a decimal**, and multi-step work is far easier in decimals. Be consistent within a calculation.
4. **A single conversion device cannot exceed 100 per cent.** If your answer does, you have swapped the numerator and denominator, or mixed units.

Where the missing energy goes

Because energy is conserved, the input is fully accounted for by the useful output plus the losses:

energy input = useful energy output + energy lost

That identity is what lets you calculate a loss you did not measure. Every stage of a real chain has named loss pathways, and naming the right one is often the difference between a 1-mark and a full-mark answer.

Stage	Where the lost energy actually goes
Combustion in a boiler	Hot flue gas up the stack; **evaporating the fuel's own moisture** — decisive for brown coal; unburnt carbon; radiation from hot surfaces
Steam turbine	Thermal energy rejected to the condenser and thence to cooling water or a cooling tower; friction; steam leakage
Generator	Resistive (I^2R) heating of the windings; friction in bearings; windage
Transformer	Core (hysteresis and eddy-current) losses; resistive

Stage	Where the lost energy actually goes
	losses in the copper
Transmission and distribution	I^2R heating of conductors — the reason high voltage is used, since raising V lowers I for the same power
Station auxiliaries (parasitic load)	Electricity the station consumes itself: coal mills and conveyors, feed pumps, draught fans, precipitators
End-use device	Depends entirely on the device: waste heat from a lamp, exhaust and coolant heat from an engine, friction in a drivetrain

Auxiliaries deserve a note because they are the commonest omission. A generator's **gross output** is what the machine produces; its **sent-out output** is what leaves the site after the station has run its own pumps, mills and fans. Victorian brown coal stations consume of the order of 10 per cent of gross output internally. If a question gives you an auxiliary figure and you ignore it, every subsequent number is too high.

Multi-step conversions: why the stages multiply

Take a three-stage chain with input E_0 and stage outputs E_1, E_2, E_3. The stage efficiencies are E_1/E_0, E_2/E_1 and E_3/E_2. Multiply them:

$$(E_1/E_0) \times (E_2/E_1) \times (E_3/E_2) = E_3/E_0$$

Every intermediate cancels, and what is left is exactly the overall efficiency. So:

overall efficiency = $\boldsymbol{\eta_1 \times \eta_2 \times \eta_3 \times \ldots \times \eta_n}$ (as decimals)

The consequences are worth stating numerically, because they are counter-intuitive.

- Three stages at 90 per cent give 0.90 × 0.90 × 0.90 = 0.729, or **72.9 per cent** — not 90, and not 270.
- **Adding** efficiencies is meaningless: it can produce totals above 100 per cent, which is impossible.
- **Averaging** them is also wrong, and it is the subtler error because it gives a plausible-looking number. For 0.90, 0.85 and 0.60 the average is 0.783 but the true overall efficiency is 0.459.
- The overall efficiency is always **smaller than the smallest stage efficiency** — a one-second check on any multi-step answer.
- Because the stages multiply, **the worst stage dominates**, and improving an already-good stage barely moves the total. Raising a 98 per cent generator to 99 per cent lifts a whole chain by 1 per cent relative; halving the losses in a 38 per cent turbine, to 69 per cent, would lift it by 82 per cent.

A full chain, stage by stage

This is the calculation the study design is asking for, and the way to lay it out. Havershute Power Station is a fictional Latrobe Valley brown coal generator with an input of **1.00 PJ (1000 TJ)** of chemical energy in its fuel over some period.

Stage	Conversion	Energy in (TJ)	η	Energy out (TJ)	Lost here (TJ)	Where the loss goes
Boiler	chemical → thermal	1000.0	0.78	780.0	220.0	Flue gas, fuel moisture, radiation
Steam turbine	thermal → mechanical	780.0	0.38	296.4	483.6	Condenser heat rejection, friction
Generator	mechanical → electrical	296.4	0.98	290.5	5.9	I^2R heating, bearings, windage
Auxiliaries	electrical →	290.5	0.90	261.4	29.0	Mills, pumps,

Stage	Conversion	Energy in (TJ)	η	Energy out (TJ)	Lost here (TJ)	Where the loss goes
	electrical					fans, precipitators
Transmission and distribution	electrical → electrical	261.4	0.92	240.5	20.9	I^2R heating of conductors

Overall efficiency, fuel to customer = 0.78 × 0.38 × 0.98 × 0.90 × 0.92 = **0.2405, or 24.1 per cent.** The **sent-out** efficiency, stopping at the station gate, is 0.78 × 0.38 × 0.98 × 0.90 = 0.2614, or **26.1 per cent**.

Check the accounting: 240.5 delivered + (220.0 + 483.6 + 5.9 + 29.0 + 20.9) lost = 240.5 + 759.4 = **1000 TJ**. Nothing has gone missing; three-quarters of it has simply become low-grade heat in a cooling tower, a chimney plume and a warm conductor. And note *where* the loss is concentrated: the turbine stage alone accounts for 483.6 of the 759.4 TJ lost. In a table like this, always read down the "lost here" column before saying anything about what should be improved.

Expressed as delivered electricity, 240.5 TJ = 240.5 × 10^{12} ÷ (3.6 × 10^6) = 6.68 × 10^7 kWh = **66.8 GWh**.

The same ledger drawn to scale is a **Sankey diagram**, and it is worth learning to read one, because it makes the accounting visible at a glance. Figure 12E.1 does exactly what the table does: the width of the flow is the energy in it, so the total width never changes, the useful flow narrows at every stage, and each loss leaves as a ribbon that stays on the page. The turbine's 483.6 TJ needs no calculation to find — it is the widest ribbon on the figure.

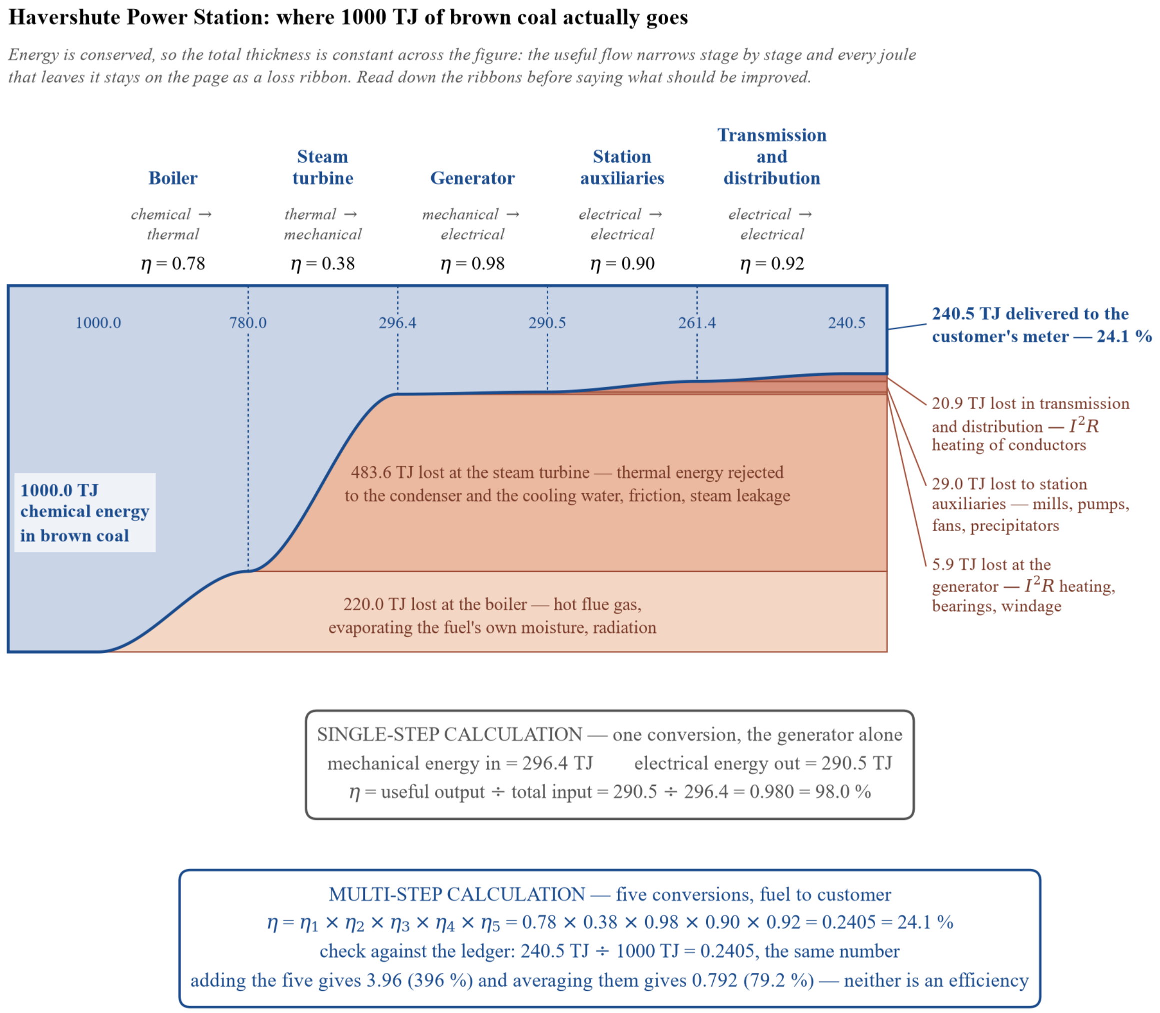


Figure 12E.1 The Havershute ledger as a Sankey diagram, with the efficiency calculation done twice below it: once for a **single** conversion — the generator, 290.5 ÷ 296.4 = 98.0 per cent — and once for the **multi-step** chain, where the five stage efficiencies multiply to 24.1 per cent. The two panels are the two halves of this dot point.

Typical efficiencies, and how to read them

Technology	Chain	Overall (electrical) efficiency
Brown coal, subcritical (Latrobe Valley)	chemical → thermal → mechanical → electrical	**22–28 %** sent out
Black coal, subcritical	as above	33–37 %
Black coal, ultra-supercritical	as above	up to ~45 %
Open-cycle gas turbine	as above	30–38 %
Combined-cycle gas turbine	as above, with the gas turbine's exhaust heat raising steam for a second turbine	**50–60 %**
Nuclear, light-water reactor	nuclear → thermal → mechanical → electrical	33–37 %
Biomass / biofuel steam plant	chemical → thermal → mechanical → electrical	20–28 %
Geothermal	thermal → mechanical → electrical	10–20 %
Concentrating solar thermal	radiant → thermal → mechanical → electrical	15–25 %
Solar photovoltaic module, silicon	radiant → electrical	20–23 %
Wind turbine, whole machine	kinetic → mechanical → electrical	35–45 %
Tidal	gravitational potential → kinetic → mechanical → electrical	20–40 %
Hydro-electric turbine and generator	gravitational potential → kinetic → mechanical → electrical	**85–92 %**
Pumped hydro, round trip	electrical → potential → electrical	70–80 %

Representative ranges for operating plant. Accurate as at July 2026.

Three cautions about reading that table, all of them examinable.

A low efficiency does not mean a large fuel loss when there is no fuel. A wind turbine that converts 41 per cent of the wind's kinetic energy wastes nothing that anyone paid for or dug up, and emits nothing at the point of conversion. A brown coal station that converts 26 per cent burns nearly four tonnes of coal for every tonne's worth of electricity it delivers. The efficiency numbers are the same *kind* of ratio, but for a free flux the number tells you about **land and materials per megawatt-hour**, and for a fuel it tells you about **fuel and emissions per megawatt-hour**. Comparing the raw percentages across that boundary, without saying which, is the classic misuse.

Efficiency is not capacity factor. The **capacity factor** of a plant is

capacity factor = (energy actually generated over a period) ÷ (rated power × that period)

It measures *how much of the time, and at what fraction of nameplate power, the plant ran* — a consequence of wind, sunshine, water availability, demand, maintenance and outages. Efficiency measures *what fraction of the input became electricity while it was running*. A wind farm might have a conversion efficiency of 42 per cent and a capacity factor of 38 per cent; the two numbers are close by coincidence and mean entirely different things. Quoting one as the other is a reported error.

A coefficient of performance is not an efficiency. A heat pump with a **coefficient of performance (COP)** of 4 delivers four joules of thermal energy per joule of electricity consumed. That is not 400 per cent efficiency: the device is *moving* heat from outside to inside rather than converting electricity into it, and the electricity only drives the transfer. Report a COP as a COP; why it breaches no conservation law is **12F**'s.

There is always a longer chain

Where you stop the chain is a choice, and it must be stated. The same brown coal station supports very different-looking true figures depending on where the boundary is drawn:

Boundary	Efficiency
Fuel → gross electrical at the terminals	29.0 %
Fuel → electricity sent out from the station	26.1 %
Fuel → electricity delivered to a customer's meter	24.1 %
Fuel → **visible light** from an incandescent lamp (η ≈ 0.05)	**1.20 %**
Fuel → **visible light** from an LED lamp (η ≈ 0.35)	**8.42 %**

Those last two rows are the most useful pair of numbers in this subtopic. An incandescent lamp delivers about 15 lumens per watt and a modern LED lamp about 105 lumens per watt — a factor of seven — which as a fraction of electrical energy leaving the lamp as visible light is roughly 5 per cent against roughly 35 per cent. Because the stages multiply, that end-of-chain factor of seven propagates all the way back to the mine: **the same light needs about one-seventh of the coal**, a gain no feasible boiler or turbine improvement approaches. This is "the worst stage dominates" in practice, and it is why efficiency regulation in Australia concentrates so heavily on end-use devices and buildings.

Where the real numbers come from, and who requires them

Efficiency figures used in Australia are not casual estimates; several are produced under statutory obligation, and quoting the instrument correctly is part of a full-mark answer.

- Corporations above the reporting thresholds must report their **energy consumption, energy production and greenhouse gas emissions** each year under the *National Greenhouse and Energy Reporting Act 2007* (Cth), administered by the **Clean Energy Regulator**. Facility-level energy input and electricity output data — and therefore station efficiencies — come from this scheme.
- Minimum energy performance standards (**MEPS**) and the star **Energy Rating Label** on appliances are made under the *Greenhouse and Energy Minimum Standards Act 2012* (Cth), which makes it an offence to supply a regulated product that fails the standard or is incorrectly labelled — the reason appliance efficiency claims in Australia are comparable at all.
- In Victoria, the **Victorian Energy Upgrades** program operates under the *Victorian Energy Efficiency Target Act 2007* (Vic), administered by the **Essential Services Commission**. Accredited activities — replacing lighting, upgrading a hot water system, installing an efficient heat pump — create **Victorian Energy Efficiency Certificates (VEECs)**, each representing one tonne of carbon dioxide equivalent abated.
- New Victorian homes must meet the energy efficiency provisions of the **National Construction Code**, applied through the *Building Act 1993* (Vic) and the Building Regulations 2018 (Vic). Victoria adopted the NCC 2022 provisions on **1 May 2024**, lifting the minimum thermal performance requirement for a new dwelling from 6 to **7 stars** under the Nationwide House Energy Rating Scheme and adding a whole-of-home energy budget covering heating, cooling, hot water and lighting.

Accurate as at July 2026.

Presenting the calculation

Show the substitution as well as the answer, carry the units through the working, and state the unit of every quantity that has one. Round only at the end, usually to three significant figures. If the question says *calculate*, working is expected. Examiners' reports name the same failures every year:

Common error	What it looks like	The fix
Adding stage efficiencies	0.78 + 0.38 + 0.98 = 2.14 → "214 %"	Multiply
Averaging stage efficiencies	(0.90 + 0.85 + 0.60) ÷ 3 = 78.3 %	Multiply: 45.9 %
Inverting the ratio	input ÷ output, giving over 100 %	Useful **output** on top
Mixing kWh and MJ	12 kWh ÷ 180 MJ	Convert first: 1 kWh = 3.6 MJ
Confusing power and energy	"the station generated 500 MW last year"	MW is a rate; use MWh or GWh for the year

Common error	What it looks like	The fix
Quoting capacity factor as efficiency	"the wind farm is only 38 % efficient"	Two different ratios; say which
Quoting a COP as an efficiency	"the heat pump is 400 % efficient"	It moves heat; report the COP
Ignoring auxiliaries or network losses	using gross output as delivered energy	State the boundary and apply every stage
Omitting units	"efficiency = 391 248"	Efficiency is dimensionless; give it as % or a decimal

Practical brief — measuring a multi-step conversion chain

Aim. To measure the efficiency of each stage of a multi-step energy conversion — **radiant → electrical → mechanical → gravitational potential** — and to test whether the measured overall efficiency equals the product of the measured stage efficiencies. A lamp or the sun illuminates a photovoltaic module; the module drives a small direct-current motor; the motor winds a thread that raises a known mass through a measured height.

Method — stage 1, radiant → electrical. Measure irradiance at the module face with a pyranometer or calibrated reference cell (W m^{-2}) and the module's active area (m^2). Over a timed interval t, incident radiant energy = irradiance × area × t. Measure the module's output voltage and current simultaneously under the load actually connected; electrical energy = VIt. Log V and I every 10 s rather than taking a single reading, because irradiance drifts.

Method — stage 2, electrical → mechanical → potential. Feed the motor from the module through the same instruments, so its electrical input is measured directly. Have it raise a mass m (0.100–0.500 kg) through a height h measured with a metre rule. Useful output = mgh. Repeat at least five times and report a mean and range.

Method — the overall check. Compute the overall efficiency two ways: as mgh ÷ (incident radiant energy), and as the product $\eta_1 \times \eta_2$. They should agree within the measurement uncertainty; a discrepancy means a stage was measured over a different interval or under a different load.

Method — two further limbs. For **chemical → thermal**, burn a weighed biomass pellet of known energy content under a copper can holding a measured mass of water: thermal energy gained = $mc\Delta T$, chemical energy released = pellet mass × energy content. Expect 40–70 per cent, and account for the shortfall. For a **near-perfect baseline**, run an immersion heater in a lagged calorimeter at extra-low voltage for a timed interval — input VIt, output $mc\Delta T$. Electrical → thermal should approach 100 per cent, which is the control showing the method itself is sound before it is applied to lossy stages.

Equipment. Photovoltaic module and lamp or open sunny site; pyranometer or calibrated reference cell; two digital multimeters or a datalogger; small DC motor with a spindle; slotted masses, thread, clamp stand; metre rule; stopwatch; four-figure balance; copper calorimeter can and lagging; temperature probe (0.1 °C resolution); immersion heater and extra-low-voltage supply; crucible, tripod, gauze, heatproof mat; biomass pellets.

Safety. Risks are assessed and controlled before work begins under the *Occupational Health and Safety Act 2004* (Vic). Electrical work is **extra-low voltage only** — no mains-voltage circuits are built, modified or opened by students. Eye protection for combustion work; hot crucibles, gauzes and water; the fuel handled with reference to its safety data sheet; the lamp and module surfaces become hot. Never look directly at a concentrated light source. Risk-assessment procedure is **1F**.

Analysis. Tabulate, for each stage, the input energy, the output energy, the efficiency and the energy lost, and name the loss pathway for each — a stage ledger in the same form as the Havershute table above. Check that the losses plus the useful output equal the input, then state the overall efficiency both ways and comment on the agreement.

Recording standards. Module area, irradiance readings and their times, the load resistance, mass and height with their instrument resolutions, water mass, initial and final temperatures, and pellet mass before and after all go in the logbook. An efficiency figure with no stated boundary, no stated load and no stated interval cannot be compared with anything.

Escalating this to a Unit 4 Area of Study 3 investigation. The brief already has measurable variables — for example module efficiency (dependent) against irradiance, angle of incidence or module temperature (independent). Frame the research question and hypothesis (**1A**), set the controlled variables and methodology (**14B**), justify the technique and sample size (**14C**), and carry it to the poster (**14H**).

Worked examples

The organisations named below are fictional; the processes, quantities, schemes and legislation are real.

Example 1 — scaffolded

For each of the following, write the sequence of energy conversions from the primary source to electricity, using the energy forms set out in this subtopic, and state how many conversion steps it involves: (i) Havershute Power Station, burning brown coal; (ii) the Glensorrel hydro-electric scheme; (iii) the Vardowie Wind Farm; (iv) a Cobbledean Solar rooftop photovoltaic array. *(4 marks)*

Working	Comment
(i) chemical → thermal → mechanical → electrical: **three conversions**	The chemical energy in the coal is released as thermal energy in the boiler, raising steam that turns a turbine shaft, which drives the generator.
(ii) gravitational potential → kinetic → mechanical → electrical: **three conversions**	Water held behind the dam has potential energy by virtue of its height; falling converts it to kinetic energy; the turbine takes it as shaft work.
(iii) kinetic → mechanical → electrical: **two conversions**	The primary source is already moving, so there is no potential-energy stage.
(iv) radiant → electrical: **one conversion**	A photovoltaic cell converts light directly to electricity — no thermal stage, no moving parts, and hence the shortest chain of the four.

Example 2 — scaffolded

At the Glensorrel hydro-electric scheme, 8.40×10^5 kg of water passes through the turbine each minute, falling through an effective head of 96.0 m. The station's electrical output is 11.8 MW. Take $g = 9.8$ m s^{-2}. Calculate (a) the mass flow rate in kg s^{-1}, (b) the rate at which the water loses gravitational potential energy, in MW, (c) the overall efficiency of the scheme, and (d) state one pathway by which the remaining energy is lost. *(5 marks)*

Working	Comment
(a) 8.40×10^5 kg ÷ 60 s = **1.40×10^4 kg s^{-1}**	Convert per-minute to per-second before anything else; watts are joules per second.
(b) $P = (m/t)gh = 1.40 \times 10^4 \times 9.8 \times 96.0 = 1.317 \times 10^7$ W = **13.2 MW**	$E_p = mgh$, so a mass flow rate gives a power directly.
(c) $\eta = 11.8 \div 13.17 \times 100$ = **89.6 %**	Same units top and bottom (MW and MW), so the ratio is dimensionless.
(d) Friction and turbulence in the penstock and turbine, bearing friction and windage, and resistive heating of the generator windings.	Any one. There is no combustion and no thermal stage, which is why the figure is so high compared with a coal station.

Example 3 — unscaffolded

Havershute Power Station burns brown coal containing 1.00 PJ of chemical energy. Its stage efficiencies are: boiler 0.78; steam turbine 0.38; generator 0.98; station auxiliaries 0.90; transmission and distribution 0.92. Calculate the overall efficiency from fuel to customer and the energy delivered in GWh, identify the stage at which most energy is lost, and explain why a student who reported the overall efficiency as 79.2 per cent — the average of the five stage figures — is wrong. *(5 marks)*

Overall efficiency = 0.78 × 0.38 × 0.98 × 0.90 × 0.92 = 0.2405 = **24.1 per cent**.

Delivered energy = 0.2405 × 1.00 × 10^{15} J = 2.405 × 10^{14} J = 240.5 TJ. Converting, 240.5 × 10^{12} ÷ (3.6 × 10^{6}) = 6.68 × 10^{7} kWh = **66.8 GWh**.

The **steam turbine** loses by far the most. It receives 780 TJ and passes on 296 TJ, so 484 TJ — about 48 per cent of the original fuel energy, and 64 per cent of everything the whole chain loses — is rejected there, chiefly as thermal energy to the condenser cooling water. By comparison the generator loses under 6 TJ. State which denominator you are using: 484 TJ is 48 per cent of the fuel, 64 per cent of the losses and 62 per cent of the thermal energy actually reaching the turbine, and all three are true of the same 484 TJ.

The average is wrong because stage efficiencies are **ratios applied in sequence**, and each stage acts on what the previous stage passed on, not on the original input. Multiplying the ratios cancels every intermediate quantity and leaves output ÷ input, which is the definition of overall efficiency; averaging them has no such interpretation. Concretely, the average of 79.2 per cent claims 792 TJ reaches the customer when in fact 240.5 TJ does — an overstatement by a factor of more than three. *Takeaway:* in a chain, multiply the decimals; the answer is always smaller than the smallest stage.

Example 4 — unscaffolded

A manufacturer needs 96.0 GWh of electricity delivered to its meter each year. Havershute Power Station delivers with an overall efficiency of 0.2405, burning brown coal of energy content 8.0 MJ kg^{-1}. Marrowdyne Energy's combined-cycle gas plant has a thermal efficiency of 0.57, station auxiliaries of 0.975 and the same network efficiency of 0.92, burning natural gas of energy content 38 MJ m^{-3}. Calculate the primary energy each option must consume, the mass of coal and the volume of gas required, and comment on what the comparison does and does not establish. *(6 marks)*

Delivered energy in consistent units: 96.0 GWh = 9.60 × 10^{7} kWh × 3.6 MJ kWh^{-1} = 3.456 × 10^{8} MJ = **345 600 GJ**.

Brown coal. Primary energy = 345 600 ÷ 0.2405 = **1.44 × 10^{6} GJ**. Mass = 1.437 × 10^{9} MJ ÷ 8.0 MJ kg^{-1} = 1.80 × 10^{8} kg = **1.80 × 10^{5} tonnes**.

Combined-cycle gas. Overall efficiency = 0.57 × 0.975 × 0.92 = **0.511**. Primary energy = 345 600 ÷ 0.511 = **6.76 × 10^{5} GJ**. Volume = 6.759 × 10^{8} MJ ÷ 38 MJ m^{-3} = **1.78 × 10^{7} m^{3}**.

The gas option therefore consumes 6.76 × 10^{5} ÷ 1.44 × 10^{6} = **47 per cent** of the primary energy the coal option needs for the same delivered electricity — a factor of **2.13** — essentially because a combined-cycle plant recovers the gas turbine's exhaust heat in a second steam turbine instead of sending it up the stack, and because natural gas does not carry 60 per cent water into the furnace.

What the comparison establishes is the **primary energy**, and hence the **fuel**, each chain consumes per unit delivered. What it does not establish is anything about emissions per megawatt-hour, cost, reliability, upstream fugitive emissions, or whether either plant should be built — those depend on the carbon intensity of each fuel, on the supply chain, and on considerations belonging to **12C**, **12G** and **13C**. *Takeaway:* an efficiency comparison is a statement about the denominator of a chain, and answers only the question it was set up to answer.

Practice questions

Scaffolded

Q1. (a) Define energy efficiency. (b) Write the equation used to calculate it. (c) State the SI unit of energy and the SI unit of power. *(3 marks)*

Q2. Write the sequence of energy conversions, using the energy forms set out in this subtopic, for each of the following generating a supply of electricity: (a) a gas-fired station; (b) a tidal barrage scheme; (c) a concentrating solar thermal station; (d) a geothermal station. *(4 marks)*

Q3. A 2400 W electric kettle is switched on for 3.00 minutes and raises the temperature of 1.20 kg of water from 18.0 °C to 96.0 °C. Take c = 4180 J kg^{-1} K^{-1}. (a) State the number of megajoules in 1 kWh. (b) Calculate the electrical energy supplied to the kettle, in kJ. (c) Calculate the thermal energy gained by the water, in kJ. (d) Calculate the efficiency of the kettle as a water heater. (e) State one pathway by which the remaining energy was lost. *(5 marks)*

Q4. A thermal power station has a boiler efficiency of 0.80, a turbine efficiency of 0.40 and a generator efficiency of 0.98. (a) Calculate the overall efficiency, as a percentage. (b) A student adds the three figures and reports 218 per cent. Explain why this is impossible. (c) Calculate the electrical energy generated from 100 GJ of fuel. (d) Calculate the energy lost across the whole chain. (e) State which single stage should be targeted for improvement, and why. *(5 marks)*

Q5. At the Glensorrel scheme, water flows through the turbine at 45.0 $m^3\ s^{-1}$ from an effective head of 62.0 m. Take the density of water as 1000 kg m^{-3} and g = 9.8 m s^{-2}. (a) Calculate the mass flow rate. (b) Calculate the rate at which gravitational potential energy is released, in MW. (c) The station's electrical output is 24.0 MW. Calculate its efficiency. (d) Over a year the station has a capacity factor of 0.42. Calculate the energy generated, in MWh. (e) Express that energy in kWh. (f) Name the quantity 0.42 in part (d), and state why it must not be multiplied by your answer to (c). *(6 marks)*

Q6. Falkmoor Shire needs 4.20 GWh of electricity delivered to its meters each year. It is supplied from Havershute Power Station, whose stage efficiencies are boiler 0.78, turbine 0.38, generator 0.98, auxiliaries 0.90 and transmission and distribution 0.92. The brown coal has an energy content of 8.0 MJ kg^{-1}. (a) Calculate the overall efficiency from fuel to meter. (b) Convert 4.20 GWh to GJ. (c) Calculate the chemical energy of fuel required, in GJ. (d) Calculate the mass of brown coal required, in tonnes. (e) State one assumption made in this calculation. *(6 marks)*

Unscaffolded

Q7. State what is meant by the energy efficiency of a conversion device. *(1 mark)*

Q8. Convert 1 kWh to megajoules, and convert 750 MJ to kilowatt-hours. *(2 marks)*

Q9. Write the sequence of energy conversions that occurs when a coal-fired station generates electricity, naming the form of energy at each stage. *(2 marks)*

Q10. Distinguish between the conversion efficiency of a wind turbine and its capacity factor, and state why quoting one as the other is an error. *(3 marks)*

Q11. A three-stage conversion chain has stage efficiencies of 0.95, 0.80 and 0.50. A student averages them and reports 75 per cent. Calculate the correct overall efficiency and explain why the student's method is wrong. *(3 marks)*

Q12. *(Stimulus.)* A class measured the energy at each stage of a chain in which a photovoltaic module drove a small motor that raised a mass.

Stimulus.

Point in the chain	Energy (kJ)
Radiant energy incident on the module	45.0
Electrical energy produced by the module	9.20
Mechanical energy delivered by the motor shaft	6.30
Gravitational potential energy gained by the mass	3.15

Calculate the efficiency of each of the three stages and the overall efficiency of the chain, and show that the overall efficiency equals the product of the stage efficiencies. *(4 marks)*

Q13. A household consumes 12.0 kWh of electricity a day, delivered through a chain whose overall efficiency from brown coal to the meter is 24.05 per cent. The coal has an energy content of 8.0 MJ kg^{-1}. Calculate the mass of brown coal, in tonnes, burnt on the household's behalf in a 365-day year. *(4 marks)*

Q14. Compare the conversion chain of a hydro-electric station with that of a brown coal station, and explain why the hydro chain achieves an efficiency of about 90 per cent while the coal chain achieves about 26 per cent. *(4 marks)*

Q15. *(Stimulus.)* A student burnt a pellet supplied by Sedgeburn Biofuels beneath a copper can of water.

> **Stimulus.** Mass of pellet burnt: 2.40 g. Stated energy content of the pellet: 17.0 MJ kg^{-1}. Mass of water in the can: 250 g. Water temperature before: 21.0 °C. Water temperature after: 44.5 °C. Take c = 4180 J kg^{-1} K^{-1}.

Calculate the thermal energy gained by the water, the chemical energy released by the pellet and the efficiency of the transfer, and name two pathways by which the remaining energy was lost. *(5 marks)*

Q16. A turbine at the Vardowie Wind Farm has blades 45.0 m long and operates in an 11.0 m s^{-1} wind. Take the density of air as 1.225 kg m^{-3}. The power available in a wind stream is $P = ½\rho A v^3$, and no turbine can extract more than 16/27 of it. (a) Calculate the power available in the wind passing through the swept area. (b) Calculate the theoretical maximum power the turbine could extract. (c) The turbine's electrical output is 2.10 MW. Calculate its overall conversion efficiency, and express its output as a percentage of the theoretical maximum. *(5 marks)*

Q17. Compare the conversion chains and overall efficiencies of a brown coal station, a combined-cycle gas plant and a wind turbine, and explain what an efficiency figure does and does not tell you about each of them. *(6 marks)*

Q18. *(Stimulus.)* Cobbledean Solar Pty Ltd makes the following claims in a sales brochure.

> **Stimulus.** "Our rooftop system is 22 per cent efficient at the panel, 96 per cent efficient at the inverter and 98 per cent efficient in the cabling, giving a total system efficiency of 216 per cent. Our 6.6 kW system will generate 6.6 kW every day. Compare that with the coal-fired station supplying your suburb, which is only 38 per cent efficient — its capacity factor last year."

Identify and correct four errors in this passage. *(8 marks)*

Q19. *(Stimulus.)* Falkmoor Shire Council is deciding how to reduce the coal burnt on its behalf and has commissioned the following figures.

> **Stimulus.** Electricity reaches the Council's buildings from Havershute Power Station through the chain: boiler 0.78, steam turbine 0.38, generator 0.98, station auxiliaries 0.90, transmission and distribution 0.92. Lighting is the Council's largest single electrical load and is currently provided by halogen floodlights, which convert about 7 per cent of electrical energy into visible light. Equivalent LED floodlights convert about 40 per cent. A boiler refurbishment at Havershute would raise boiler efficiency from 0.78 to 0.86; the lamp replacement would not alter the generation chain.

Calculate the overall efficiency from coal to visible light under the present arrangement, under the boiler refurbishment alone, and under the lamp replacement alone. Determine which option delivers the greater reduction in coal burnt for the same light, explain in terms of multi-step efficiency why this is so, and state one assumption and one limitation of your analysis. *(10 marks)*

Answers

Q1. (a) The fraction of the energy supplied to a device that emerges in the useful form intended. (b) Efficiency (%) = (useful energy output ÷ total energy input) × 100. (c) Energy: joule (J). Power: watt (W).

Q2. (a) chemical → thermal → mechanical → electrical. (b) gravitational potential → kinetic → mechanical → electrical. (c) radiant → thermal → mechanical → electrical. (d) thermal → mechanical → electrical.

Q3. (a) 3.6 MJ. (b) 2400 × 180 = 432 000 J = **432 kJ**. (c) 1.20 × 4180 × 78.0 = 391 248 J = **391 kJ**. (d) 391 248 ÷ 432 000 × 100 = **90.6 %**. (e) Any one of: thermal energy conducted to the kettle body and lost to the room; energy heating the element and jug rather than the water; steam carrying away latent heat; radiation from the outer surface.

Q4. (a) 0.80 × 0.40 × 0.98 = 0.3136 = **31.4 %**. (b) Efficiency cannot exceed 100 per cent, because that would mean more useful energy leaving than entered; stage efficiencies must be multiplied, not added. (c) 100 × 0.3136 = **31.4 GJ**. (d) 100 − 31.36 = **68.6 GJ**. (e) The **turbine**, at 0.40 — it loses the most and, because the stages multiply, the largest proportional gain is available where the efficiency is lowest.

Q5. (a) 45.0 × 1000 = **4.50×10^4 kg s^{-1}**. (b) $4.50 \times 10^4 \times 9.8 \times 62.0 = 2.734 \times 10^7$ W = **27.3 MW**. (c) 24.0 ÷ 27.34 × 100 = **87.8 %**. (d) 24.0 × 8760 × 0.42 = **88 300 MWh** (8.83×10^4 MWh). (e) 8.83×10^7 kWh. (f) 0.42 is the **capacity factor** — the fraction of the energy the station would have generated at rated power for the whole year that it actually generated. It is not an efficiency, and the two ratios have different denominators, so their product is a quantity with no meaning. (c) describes conversion, 0.42 availability.

Q6. (a) 0.78 × 0.38 × 0.98 × 0.90 × 0.92 = 0.2405 = **24.1 %**. (b) 4.20 GWh = 4.20×10^6 kWh × 3.6 MJ = 1.512×10^7 MJ = **15 120 GJ**. (c) 15 120 ÷ 0.2405 = **6.29×10^4 GJ**. (d) 6.287×10^7 MJ ÷ 8.0 MJ kg^{-1} = 7.86×10^6 kg = **7.86×10^3 tonnes**. (e) Any one of: the stage efficiencies are constant at all loads; the coal's energy content is uniformly 8.0 MJ kg^{-1}; all of the Shire's electricity comes from this station; network losses are the same for every delivery point.

Q7. The fraction of the energy supplied to it that is converted into the intended useful form, usually expressed as a percentage.

Q8. 1 kWh = **3.6 MJ**. 750 ÷ 3.6 = **208 kWh**.

Q9. chemical (in the coal) → thermal (in the steam) → mechanical (rotating turbine shaft) → electrical.

Q10. Conversion efficiency is the fraction of the wind's kinetic energy converted to electricity while the turbine is running. Capacity factor is the energy actually generated over a period divided by the energy that would have been generated at rated power for the whole period. They measure conversion and availability respectively, so a low capacity factor indicates intermittent wind, not a poorly performing converter.

Q11. 0.95 × 0.80 × 0.50 = 0.380 = **38.0 %**. Each stage acts on the output of the previous stage, not on the original input, so the ratios compose by multiplication; averaging has no physical meaning and here overstates the result by 37 percentage points.

Q12. η_1 = 9.20 ÷ 45.0 = **20.4 %**; η_2 = 6.30 ÷ 9.20 = **68.5 %**; η_3 = 3.15 ÷ 6.30 = **50.0 %**. Overall = 3.15 ÷ 45.0 = **7.00 %**. Product = 0.2044 × 0.6848 × 0.500 = 0.0700 = 7.00 % ✓.

Q13. 12.0 kWh = 43.2 MJ; 43.2 ÷ 0.2405 = 179.6 MJ of coal per day; × 365 = 65 560 MJ per year; ÷ 8.0 = 8195 kg = **8.20 tonnes**.

Q14. Hydro: gravitational potential → kinetic → mechanical → electrical, with only friction, turbulence and resistive losses, giving 85–92 per cent. Coal: chemical → thermal → mechanical → electrical, where the thermal-to-mechanical stage alone passes on under 40 per cent and the boiler loses further energy to flue gas and to evaporating the coal's 60 per cent moisture, giving 22–28 per cent. The decisive difference is the **thermal stage**, which hydro does not have.

Q15. Q = 0.250 × 4180 × 23.5 = 24 557 J = **24.6 kJ**. Chemical energy = 0.00240 × 17.0 × 10^6 = 40 800 J = **40.8 kJ**. Efficiency = 24 557 ÷ 40 800 × 100 = **60.2 %**. Losses (any two): hot combustion gases escaping past the can; thermal energy heating the can, thermometer and clamp; radiation to the room; incomplete combustion leaving unburnt residue; evaporation of water from the can.

Q16. (a) $A = \pi \times 45.0^2 = 6362$ m²; $P = 0.5 \times 1.225 \times 6362 \times 11.0^3 = 5.19 \times 10^6$ W = **5.19 MW**. (b) 5.186 × 16/27 = **3.07 MW**. (c) η = 2.10 ÷ 5.186 × 100 = **40.5 %**; as a fraction of the theoretical maximum, 2.10 ÷ 3.073 × 100 = **68.3 %**.

Q17. Brown coal: four-form chain through a thermal stage, 22–28 per cent, and the figure translates directly into tonnes of coal and emissions per MWh. Combined-cycle gas: same chain but the gas turbine's exhaust heat raises steam for a second turbine, 50–60 per cent, so roughly half the primary energy per MWh of the coal plant. Wind: kinetic → mechanical → electrical, 35–45 per cent, but the input is a free flux, so the figure says nothing about fuel or emissions and instead bears on swept area, land and materials per MWh. See the fully-worked solution.

Q18. (i) Stage efficiencies multiply, not add: 0.22 × 0.96 × 0.98 = **20.7 %**, not 216 per cent — which is impossible. (ii) 6.6 kW is a power rating, not a daily energy yield; the system produces about 6.6 kW only at full irradiance, and a Victorian rooftop yields roughly 3.6–4.2 kWh per installed kW per day as an annual average. (iii) 38 per cent described as a capacity factor is not an efficiency; the two ratios measure different things. (iv) Comparing a solar panel's efficiency with a coal station's is comparing conversion of a free flux with conversion of a mined fuel — the percentages are not commensurable in the way the passage implies. See the fully-worked solution.

Q19. Present: 0.78 × 0.38 × 0.98 × 0.90 × 0.92 = 0.2405, × 0.07 = **1.68 %**. Boiler refurbishment: 0.86 × 0.38 × 0.98 × 0.90 × 0.92 = 0.2652, × 0.07 = **1.86 %**. Lamp replacement: 0.2405 × 0.40 = **9.62 %**. The lamp replacement is far superior: it multiplies the whole-chain efficiency by 5.71 against the refurbishment's 1.10, and delivers 9.62 ÷ 1.86 = **5.18 times** the improvement. Because efficiencies multiply, a proportional gain at any stage scales the entire chain, so the largest gains are available where a stage is worst — and the 7 per cent floodlight is by far the worst stage. Assumption and limitation required. See the fully-worked solution.

Fully-worked solutions

Q1. (a) **Energy efficiency** is the proportion of the energy supplied to a device or system that emerges in the **useful** form the device is intended to produce. (b) **Efficiency (%) = (useful energy output ÷ total energy input) × 100**; equivalently with powers, provided both are measured over the same interval. (c) Energy: the **joule (J)**. Power: the **watt (W)**, equal to one joule per second. *Marker's note:* "useful" is load-bearing in (a). An answer that says "the energy that comes out divided by the energy that goes in" describes conservation of energy, not efficiency, because *all* of the energy comes out.

Q2. (a) **chemical → thermal → mechanical → electrical.** (b) **gravitational potential → kinetic → mechanical → electrical.** (c) **radiant → thermal → mechanical → electrical.** (d) **thermal → mechanical → electrical.** *Marker's note:* one mark each, and the marks are for the *sequence*. All four end at a turbine driving a generator, so all four carry a **mechanical** stage; omitting it loses the mark, because the turbine shaft is where the working fluid's energy becomes shaft work and the generator acts on that shaft work, not on the steam or the water. Parts (c) and (d) are the discriminating ones. A concentrating solar station is **not** radiant → electrical: unlike a photovoltaic cell it uses the sunlight to raise steam, so the thermal stage must appear. A geothermal station **begins** at thermal, because the heat is drawn from hot rock rather than released from a fuel, so writing a chemical stage in front of it is wrong.

Q3. (a) **1 kWh = 3.6 MJ** (1000 W × 3600 s). (b) $E = Pt$ = 2400 W × 180 s = 432 000 J = **432 kJ**. (c) $Q = mc\Delta T$ = 1.20 kg × 4180 J kg^{-1} K^{-1} × (96.0 − 18.0) K = 1.20 × 4180 × 78.0 = 391 248 J = **391 kJ**. (d) η = 391 248 ÷ 432 000 × 100 = **90.6 %**. (e) Any one, specifically: thermal energy **conducted into the kettle body and element** and then lost to the surroundings; **steam escaping**, carrying latent heat; **radiation and convection** from the outer surface during the three minutes. *Marker's note:* 3.00 minutes must become 180 s before it meets a quantity in watts. Using 3 in place of 180 gives 7.20 kJ and an impossible efficiency above 5000 per cent — which is itself the signal to check the units.

Q4. (a) η = 0.80 × 0.40 × 0.98 = 0.3136 = **31.4 %**. (b) Because 218 per cent would mean **more useful energy leaving the station than entered it**, which no conversion can do. The error is method, not arithmetic: each stage efficiency is a **ratio of that stage's output to that stage's input**, and ratios applied in sequence **compose by multiplication**. (c) 100 GJ × 0.3136 = **31.4 GJ** of electrical energy. (d) 100 − 31.36 = **68.6 GJ**, almost all of it ending as low-grade thermal energy in flue gas and condenser cooling water. (e) The **turbine**, at 0.40. It loses 60 per cent of what reaches it — more than the other two stages combined — and because the stages multiply, a given *proportional* improvement lifts the whole chain by the same proportion wherever it is made, so the practical opportunity lies where the stage efficiency is lowest. The generator can rise from 0.98 only to 0.99, worth 1 per cent relative; the turbine rising from

0.40 to 0.44 is worth 10 per cent. *Marker's note:* (e) asks for a reason, not just a stage. "Because it is the lowest" earns the mark only if it is tied to the size of the available gain.

Q5. (a) Mass flow rate = volume flow rate × density = 45.0 $m^3\ s^{-1}$ × 1000 kg m^{-3} = **4.50×10^4 kg s^{-1}**. (b) $P = (m/t)gh$ = $4.50 \times 10^4 \times 9.8 \times 62.0 = 2.7342 \times 10^7$ W = **27.3 MW**. (c) η = 24.0 MW ÷ 27.342 MW × 100 = **87.8 %**. (d) Energy = rated power × hours in a year × capacity factor = 24.0 MW × 8760 h × 0.42 = **88 300 MWh** (8.83×10^4 MWh, or 88.3 GWh). (e) 88 300 MWh × 1000 = **8.83×10^7 kWh**. (f) The 0.42 is the **capacity factor**: over a year the station generated 42 per cent of what it would have produced running at 24.0 MW continuously, because inflows vary with rainfall and because it is dispatched to meet demand. The 87.8 per cent in (c) is an **efficiency**: of the potential energy released by the falling water, 87.8 per cent becomes electrical energy *while the station is generating*. The two ratios are taken against different denominators — one the energy actually delivered to the turbine, the other the energy a full year at nameplate power would represent — so their product, 0.878 × 0.42 = 0.369, is not the efficiency of anything and not a fraction of any real quantity. A station can have a very high efficiency and a low capacity factor at the same time; the first is about conversion, the second about how much of the time it converts. *Marker's note:* 8760 = 24 × 365. Multiplying the efficiency by the capacity factor is a common conflation and produces a quantity with no meaning.

Q6. (a) η = 0.78 × 0.38 × 0.98 × 0.90 × 0.92 = **0.2405**, or **24.1 per cent**. (b) 4.20 GWh = 4.20×10^6 kWh; × 3.6 MJ kWh^{-1} = 1.512×10^7 MJ = **1.512×10^4 GJ** (15 120 GJ). (c) Fuel energy = delivered ÷ efficiency = 15 120 ÷ 0.2405 = **6.29×10^4 GJ** (62 870 GJ). Note the division: working *backwards* through a chain divides by the efficiency, and the answer must be larger than the delivered energy. (d) 6.287×10^4 GJ = 6.287×10^7 MJ; mass = $6.287 \times 10^7 \div 8.0$ = 7.86×10^6 kg = **7.86×10^3 tonnes**, that is about 7860 t of brown coal for 4.20 GWh delivered. (e) Any one, clearly stated: that the **stage efficiencies are constant**, whereas real plant is less efficient at part load; that the **energy content is uniformly 8.0 MJ kg^{-1}**, whereas as-mined brown coal varies with moisture; that **all** the Shire's electricity comes from this one station, whereas in a connected grid it does not; that network losses are **identical for every delivery point**. *Marker's note:* six marks — one each for (a), (b), (d) and (e), and **two for (c)**, where the direction of the arithmetic is what is being tested. Multiplying by 0.2405 instead of dividing gives 3640 GJ — less fuel energy than the electricity delivered, which is impossible.

Q7. The **fraction of the energy supplied to the device that is converted into the useful form it is intended to produce**, normally expressed as a percentage.

Q8. 1 kWh = 1000 W × 3600 s = 3.6×10^6 J = **3.6 MJ**. Then 750 MJ ÷ 3.6 MJ kWh^{-1} = **208 kWh** (208.3 kWh). *Marker's note:* two marks, one each way. Multiplying by 3.6 in the second conversion gives 2700 kWh and shows the direction was not checked: a megajoule is smaller than a kilowatt-hour, so the number of kilowatt-hours must be smaller.

Q9. Chemical energy stored in the coal is released by combustion as **thermal** energy, which raises steam; the steam expands through a turbine, giving **mechanical** energy as rotation of the shaft; the generator converts that shaft work to **electrical** energy. *Marker's note:* four forms, three conversions, in that order.

Q10. Conversion efficiency is the fraction of the **kinetic energy of the wind passing through the swept area** that leaves the turbine as electrical energy — typically 35–45 per cent for a modern machine, with a theoretical ceiling of 16/27, or 59.3 per cent. **Capacity factor** is the **energy actually generated over a period divided by the energy the turbine would have generated at its rated power for that whole period** — typically 30–45 per cent for Australian onshore wind. The first is a property of the machine as a converter; the second is dominated by the resource and by how often the wind blows at usable speeds. Quoting one as the other is an error because it attributes a **resource characteristic to the technology**: a turbine with a capacity factor of 0.30 is not converting badly, it is simply not always in wind. *Common error:* concluding that wind is "only 30 per cent efficient" from capacity factor data. The two figures can be numerically similar and still be about different things.

Q11. Overall efficiency = 0.95 × 0.80 × 0.50 = **0.380 = 38.0 per cent**.

The student's method is wrong because each stage efficiency is the ratio of that stage's **output to its own input**, and each stage receives only what the previous one passed on. Chaining the ratios algebraically — $(E_1/E_0) \times (E_2/E_1) \times (E_3/E_2)$ — cancels every intermediate energy and leaves E_3/E_0, the definition of the overall efficiency. An average has no such interpretation: it weights the stages equally when they are not equally placed, and ignores that the poorest stage acts on a quantity the good stages have already delivered. Here it overstates the result by 37 percentage points, and the true answer must always be **smaller than the smallest stage efficiency** — a useful check. *Marker's note:* the explanation mark is for *why* multiplication is the correct operation, not for the instruction to multiply.

Q12. *Each stage efficiency uses the energy at the start of that stage as its denominator, not the energy at the start of the chain.*

- Stage 1, radiant → electrical: 9.20 ÷ 45.0 = 0.2044 = **20.4 %**
- Stage 2, electrical → mechanical: 6.30 ÷ 9.20 = 0.6848 = **68.5 %**
- Stage 3, mechanical → gravitational potential: 3.15 ÷ 6.30 = 0.500 = **50.0 %**
- Overall, measured directly: 3.15 ÷ 45.0 = 0.0700 = **7.00 %**

Check by product: 0.2044 × 0.6848 × 0.500 = 0.0700 = **7.00 %**, which agrees exactly — the cancellation shown algebraically in Q11, appearing in real data. *Marker's note:* dividing every value by 45.0 is the standard error and gives 20.4, 14.0 and 7.00 per cent, a set of numbers that no longer multiply to the overall figure. Note also how brutal a three-stage chain is: a 20 per cent, a 69 per cent and a 50 per cent stage together deliver 7 per cent.

Q13. Daily delivered energy = 12.0 kWh × 3.6 MJ kWh^{-1} = **43.2 MJ**.

Daily fuel energy = 43.2 ÷ 0.2405 = **179.6 MJ**.

Annual fuel energy = 179.6 × 365 = **65 560 MJ**.

Mass of coal = 65 560 ÷ 8.0 MJ kg^{-1} = 8195 kg = **8.20 tonnes**.

Marker's note: four marks, one each for the unit conversion, the division by the efficiency, the scaling to a year, and the division by energy content. Notice the size of the result — a modest household load of 12 kWh a day is more than eight tonnes of brown coal a year, and it is the 24 per cent chain, not the household, that makes it so.

Q14. The chains. Hydro: **gravitational potential → kinetic → mechanical → electrical**. Water held at height falls, the falling water turns a turbine, and the turbine drives a generator. Brown coal: **chemical → thermal → mechanical → electrical**. Combustion releases the fuel's chemical energy as thermal energy, the steam drives a turbine, and the turbine drives a generator.

Where the difference lies. Both chains end identically, with a turbine and a generator whose efficiencies are high — 90–95 per cent and 98–99 per cent respectively — losing energy only to friction, turbulence, windage and resistive heating of the windings. The hydro chain contains **nothing else**, which is why the whole scheme reaches **85–92 per cent**.

The coal chain adds two lossy stages. The **boiler** loses roughly a fifth of the fuel's energy to hot flue gas, radiation and, for Latrobe Valley brown coal specifically, to **evaporating the fuel's own moisture**, about 60 per cent of its mass. Then the **thermal-to-mechanical** stage passes on only about 38 per cent of the thermal energy reaching it, rejecting the rest to condenser cooling water. Because the stages multiply, those two figures alone cap the chain at 0.78 × 0.38 = 0.30 before the generator and auxiliaries are considered, giving **22–28 per cent** sent out.

The decisive difference is therefore that the coal chain **passes through a thermal stage and the hydro chain does not**. Why a thermal stage is intrinsically limited in this way, rather than merely badly engineered, is the second law of thermodynamics — **12F**'s dot point. *Marker's note:* four marks require both chains written out and the thermal stage identified as the locus of the difference, with a quantity attached. "Hydro is more efficient because water is free" does not answer the question; the efficiency of a conversion has nothing to do with what the input costs.

Q15. Thermal energy gained by the water. $Q = mc\Delta T$ = 0.250 kg × 4180 J kg^{-1} K^{-1} × (44.5 − 21.0) K = 0.250 × 4180 × 23.5 = 24 557 J = **24.6 kJ**.

Chemical energy released. E = mass × energy content = 2.40 g = 0.00240 kg; 0.00240 × 17.0 × 10^6 J kg^{-1} = 40 800 J = **40.8 kJ**.

Efficiency of the transfer. η = 24 557 ÷ 40 800 × 100 = **60.2 %**.

Two loss pathways, any two clearly stated: **hot combustion gases rising past the sides of the can** and out into the room rather than transferring their energy through its base — usually the largest single loss; **thermal energy absorbed by the can, clamp, gauze and thermometer** rather than by the water; **radiation and convection from the**

outer surface of the can while it is hot; **incomplete combustion**, leaving unburnt carbon in the residue so that less than 40.8 kJ was actually released; **evaporation** of water from the can, carrying away latent heat. *Marker's note:* masses must be converted to kilograms to match the units of c and of the energy content. Note the direction of the incomplete-combustion point — it means the *denominator* was smaller than assumed, so the true transfer efficiency is higher than 60.2 per cent. Losses that cut the numerator and losses that cut the denominator are different in kind, and the strongest answers say so.

Q16. (a) Swept area $A = \pi r^2 = \pi \times (45.0\text{ m})^2 = \pi \times 2025 =$ **6362 m²**.

$P = \frac{1}{2}\rho A v^3 = 0.5 \times 1.225\text{ kg m}^{-3} \times 6362\text{ m}^2 \times (11.0\text{ m s}^{-1})^3 = 0.5 \times 1.225 \times 6362 \times 1331 = 5.186 \times 10^6\text{ W} =$ **5.19 MW**.

(b) Theoretical maximum = 16/27 × 5.186 = 0.5926 × 5.186 = **3.07 MW**.

(c) Overall conversion efficiency = 2.10 ÷ 5.186 × 100 = **40.5 %**. As a fraction of the theoretical maximum, 2.10 ÷ 3.073 × 100 = **68.3 %**.

Marker's note: the blade length is the **radius**, not the diameter — using 45.0 m as a diameter quarters the area and quarters the power. The wind speed is **cubed**, so a small error in v propagates heavily. And note what (c) shows: 40.5 per cent sounds unimpressive against a hydro turbine, but it is more than two-thirds of the theoretical ceiling for *any* device in a free wind stream, and the 59.5 per cent not converted is wind that keeps blowing.

Q17. *"Compare" means the same points addressed for all three, not three separate descriptions.*

The chains. The **brown coal station** and the **combined-cycle gas plant** share the same sequence of forms — **chemical → thermal → mechanical → electrical** — but not the same architecture. The coal plant burns fuel to raise steam for a single turbine. The combined-cycle plant burns gas in a gas turbine and then uses that turbine's hot exhaust to raise steam for a **second, steam turbine**, so thermal energy that a single-cycle plant sends up the stack is converted a second time. The **wind turbine** has the shortest chain of the three, **kinetic → mechanical → electrical**, with no combustion and no thermal stage at all.

The efficiencies. Brown coal, subcritical: **22–28 per cent** sent out, held down by a boiler that must evaporate the fuel's roughly 60 per cent moisture and by a steam turbine passing on under 40 per cent of the thermal energy reaching it. Combined-cycle gas: **50–60 per cent**, roughly twice the coal figure, from the recovered exhaust heat and a drier, higher-quality fuel. Wind turbine: **35–45 per cent** of the kinetic energy in the swept area, against a theoretical ceiling of 59.3 per cent.

What the figure tells you. For the two fuelled plants the efficiency is a statement about **fuel and emissions per unit of electricity**: at 24 per cent delivered, about 7860 tonnes of brown coal are required per 4.2 GWh, while the gas plant needs roughly half the primary energy for the same output. The number converts directly into tonnes mined, cubic metres burnt and, with a carbon intensity, into emissions.

What it does not tell you. For the wind turbine the input is a **free, continuously renewed flux** that is not depleted, not paid for and not combusted, so a "loss" of 59 per cent is wind that carries on past the rotor. The efficiency figure for wind therefore bears on **swept area, land and materials per megawatt-hour**, not on fuel or emissions. For all three, efficiency is silent on **capacity factor, dispatchability, cost, land use, water use and upstream emissions**. Comparing 26 per cent with 41 per cent as though they were the same measure of merit is the error the numbers invite. *Marker's note:* six marks reward the **parallel structure** — chain, efficiency, what the figure means — for all three, and the highest-scoring answers make the fuelled-versus-flux distinction explicitly rather than ranking the three percentages.

Q18. *Model response (8 marks).*

Error 1 — the stage efficiencies have been added. Efficiencies in series **multiply**: 0.22 × 0.96 × 0.98 = **0.207**, so the system efficiency from sunlight to alternating current is about **20.7 per cent**. The stated 216 per cent is not merely inaccurate, it is impossible — it would mean the system delivered more energy than the sunlight supplied. A single arithmetic check catches this: an overall efficiency can never exceed the smallest stage efficiency, here 22 per cent.

Error 2 — a power rating has been quoted as a daily energy yield. "6.6 kW" is the array's **rated power**, its output at standard test conditions; "generate 6.6 kW every day" confuses a **rate** with an **amount**. Energy is $P \times t$, so the claim needs a time: a Victorian rooftop yields of the order of **3.6–4.2 kWh per installed kilowatt per day** averaged over a year, so about **24–28 kWh per day** for a 6.6 kW array — and far less in mid-winter than in mid-summer. A daily yield is measured in kilowatt-hours.

Error 3 — a capacity factor has been presented as an efficiency. The passage itself concedes the 38 per cent is "its capacity factor last year", so it is the fraction of the station's rated output actually generated over the year, not the fraction of the coal's chemical energy converted to electricity. A brown coal station's conversion efficiency is about **22–28 per cent** sent out, while its capacity factor can be **60–90 per cent** because it runs close to continuously. The passage has taken the station's most flattering available number and mislabelled it as the very quantity on which coal performs worst.

Error 4 — the two efficiencies are not commensurable as a merit comparison. Even with both figures corrected, setting a photovoltaic module's 20.7 per cent against a coal station's 26 per cent invites the inference that coal converts "better". The denominators are different in kind: the module's input is a **free, undiminished solar flux** whose unconverted fraction costs nothing and emits nothing, while the station's input is **mined fuel** whose unconverted fraction is coal dug up, paid for and combusted for no delivered energy. Solar efficiency governs roof area; coal efficiency governs tonnes and emissions.

A defensible version of the claim. "This system converts about 21 per cent of the sunlight reaching the panels into usable alternating current, and a 6.6 kW array on a Victorian roof typically delivers about 8700–10 000 kWh a year, or roughly 24–28 kWh a day averaged across the seasons." *Marker's note:* eight marks, two per error — the identification and the correction, with the correct value calculated where the passage gives one. Listing the four errors without correcting them earns half.

Q19. *Model response (10 marks).*

The present chain, coal to visible light.

Generation and delivery: 0.78 × 0.38 × 0.98 × 0.90 × 0.92 = **0.2405**.

Adding the lamp: 0.2405 × 0.07 = 0.01684 = **1.68 per cent**.

Of every 100 joules of chemical energy in the coal, about **1.7 joules leave the lamp as visible light**.

Option A — boiler refurbishment alone (0.78 → 0.86).

0.86 × 0.38 × 0.98 × 0.90 × 0.92 = **0.2652**, so delivered efficiency rises from 24.1 to 26.5 per cent.

Coal to visible light: 0.2652 × 0.07 = 0.01856 = **1.86 per cent**.

Option B — lamp replacement alone (0.07 → 0.40).

0.2405 × 0.40 = 0.09620 = **9.62 per cent**.

Which reduces coal burnt for the same light. Because the same quantity of light is required in each case, the coal required is inversely proportional to the whole-chain efficiency. Option A raises it by a factor of 0.2652 ÷ 0.2405 = **1.10**, cutting coal by about **9 per cent**. Option B raises it by a factor of 0.40 ÷ 0.07 = **5.71**, cutting coal by **83 per cent** — the same light for about one-sixth of the fuel. Comparing the two directly, 9.62 ÷ 1.86 = **5.18**, so **the lamp replacement is worth about five times the boiler refurbishment**, and Option B is clearly the better investment on these figures.

Why, in terms of multi-step efficiency. Overall efficiency is the **product** of the stage efficiencies, so improving any one stage by a factor k multiplies the whole chain by k regardless of where in the chain that stage sits. What matters is therefore not how large a stage's efficiency is in absolute terms but **how much proportional headroom it has**. The boiler is already at 0.78, so the absolute best available there is a factor of 1/0.78 = 1.28. The floodlight is at 0.07, so its headroom is a factor of up to 14, and a commercially available LED realises a factor of nearly 6 of it. The **worst stage dominates the chain**, and in this chain the worst stage by a wide margin is at the very end, in the Council's own buildings — which is exactly why Australian efficiency regulation concentrates on end-use devices, through minimum energy performance standards under the *Greenhouse and Energy Minimum Standards Act 2012* (Cth) and, in Victoria, through lighting upgrade activities accredited under the Victorian Energy Upgrades program made under the *Victorian Energy Efficiency Target Act 2007* (Vic).

One assumption. That the Council's lighting demand is measured in **light delivered** and stays constant after the change. The calculation compares chains at equal light output; if brighter or longer-used lighting is installed once running costs fall, part of the saving is taken as more light rather than less coal.

One limitation. The analysis is **confined to lighting and to conversion efficiency**. It ignores the embodied energy and materials of manufacturing and disposing of several thousand LED floodlights, the capital cost and outage of a boiler refurbishment, and every other load in the Council's buildings — so it identifies the better of these two lighting interventions but does not establish that either is the best available use of the Council's money. Nor do the figures address whether the electricity should come from Havershute at all, which is a separate question about the supply mix rather than about efficiency. *Marker's note:* ten marks require all **three efficiencies calculated** (1.68, 1.86 and 9.62 per cent), a **quantified comparison** rather than an assertion that LEDs are better, the **multiplicative argument** about proportional headroom, and a **specific** assumption and limitation. "More research is needed" is not a limitation; naming the rebound in light demand, or the boundary of the analysis, is.

Chapter 12 Energy sources, conversions and efficiency — 12F The first and second laws of thermodynamics in energy choices

Theory

Two statements govern every energy decision ever made. The first is that you cannot get something for nothing. The second is that you cannot even break even. They are the **first and second laws of thermodynamics**, and the study design asks not for the laws in the abstract but for **"the implications of the first and second laws of thermodynamics in making energy choices"** — which is to say, what the two laws force a household, a company or a government to conclude when it is choosing between one energy option and another.

Where this subtopic sits. Chapter 12's other subtopics describe the options and count the joules: **12A** the non-renewable sources, **12B** the renewables, **12C** what combustion does to the carbon cycle, **12D** the rate of fossil fuel use and peak oil, **12E** the arithmetic of efficiency for single and multi-step conversions, and **12G** the sustainability principles as they apply across the energy supply chain. This subtopic supplies the **physics underneath 12E's arithmetic** and the **reasoning that turns it into a decision**. Base and peak load are **13B**; the catalogue of options for a sustainable energy future is **13C**; the stakeholder tensions around those options are **13D**. Here the question is prior to all of them: given that these two laws hold, which energy choices are physically sensible and which are not? One **method** used below also sits outside the study design's own vocabulary — the **Carnot ceiling**, and the kelvin arithmetic that goes with it — and is tagged as such where it is introduced.

The quantities, before the laws

Energy is measured in **joules (J)**. Power — energy per unit time — is measured in **watts (W)**, one watt being one joule per second. Two conversions recur throughout this chapter and are worth committing to memory:

1 kilowatt hour (kWh) = 3.6 megajoules (MJ)

1 petajoule (PJ) = 10^{15} J — the unit the *Australian Energy Statistics* uses for national totals

The study design names the forms energy takes: **potential**, **mechanical**, **kinetic**, **thermal** and **chemical**, to which the energy system adds **electrical**, **radiant** and **nuclear**. The laws below are about what happens when one of these is turned into another.

The first law: energy is conserved

The first law of thermodynamics states that **energy cannot be created or destroyed, only converted from one form to another**; the total energy of an isolated system is constant. Formally, the change in a system's internal energy equals the heat added to it minus the work it does:

$$\Delta U = Q - W$$

Three implications follow immediately, and each one changes how an energy claim should be read.

One — nothing "generates" energy. A power station converts energy that was already there: chemical energy in ancient plant matter, the kinetic energy of moving air, gravitational potential energy in stored water. Even "renewable" is a statement about the *rate at which a store is replenished*, not about energy being created. "Generation" is entrenched in the industry and in this workbook, but a student who reads it literally has already made a first-law error.

Two — the books must balance. For any device, **energy in = useful energy out + losses**. Nothing disappears. Any claim that a device delivers more energy than it consumes is a claim that energy has been created; such a machine would be a **perpetual motion machine of the first kind**, and none has ever worked.

Three — the first law says nothing about direction or usefulness. It is an accounting rule, perfectly happy to count the 55 GJ of heat drifting out of a cooling tower as energy — rightly, since that energy is still there. What it cannot tell you is that nobody wants it. For that you need the second law, and the gap between the two is where almost all real energy decision-making lives.

The second law: energy is degraded

The second law of thermodynamics can be stated in several equivalent ways, and each is useful for a different kind of question.

- **The Clausius statement.** Heat flows spontaneously from a hotter body to a colder one, and never the reverse without work being done. A cup of tea cools; a cool cup of tea does not spontaneously reheat by drawing warmth from the room.
- **The Kelvin–Planck statement.** No device operating in a cycle can take heat from a single reservoir and convert **all** of it into work. Some heat must always be rejected to a colder reservoir. This is the statement that sets the ceiling on every power station that burns something.
- **The entropy statement. Entropy** is a measure of how dispersed and disordered energy is, and the total entropy of an isolated system never decreases. Every real process is **irreversible** and increases the entropy of the universe.

The single sentence that ties these together, and the one to write in an answer, is this: **energy is conserved in quantity but degraded in quality every time it is converted.** The joules survive; their usefulness does not.

Energy quality — the concept that makes the second law usable

If the second law is going to change a decision, it needs a handle. That handle is **energy quality**, sometimes called **exergy**: the fraction of a quantity of energy that could in principle be converted into useful work. High-quality energy is ordered and fully convertible; low-quality energy is dispersed and largely not.

Grade	Form	Fraction convertible to work	Comment
Highest	Electricity; mechanical work	Effectively 100 per cent	Fully ordered; can become any other form
High	Chemical energy in a fuel; concentrated sunlight	~90 per cent	Releases high-temperature heat on demand
Medium	Heat at 500–1500 °C (a furnace, a flame)	~60–80 per cent	Enough temperature difference to drive an engine
Low	Heat at 60–150 °C (process hot water, steam)	~15–30 per cent	Useful for heating tasks, marginal for work
Lowest	Heat within 20 °C of ambient	Nearly 0 per cent	Vast in quantity, almost worthless for work

Read the bottom row carefully, because it is the row that decides arguments. The cooling water leaving a Victorian power station carries an enormous *quantity* of energy and almost no *quality*. That is why it is dumped: not because engineers have failed to think of using it, but because heat only a few degrees above its surroundings has almost no capacity to do anything. **A joule is not a joule.** The first law counts joules; the second law tells you what they are worth.

The Carnot limit: the ceiling no engineering can lift

Any device that converts heat into work — a coal or gas or nuclear plant, a car engine, a geothermal turbine — is a **heat engine**, and every heat engine takes heat from a hot reservoir, converts part of it to work, and rejects the rest to a cold reservoir. The second law fixes the best it can possibly do. The **Carnot efficiency** is the theoretical maximum:

$\eta(max) = 1 - T(cold) \div T(hot)$, with both temperatures in **kelvin** (K = °C + 273)

Two features of that expression matter more than the arithmetic. First, the ceiling depends **only on the two temperatures** — not on the fuel, not on the turbine design, not on how much money is spent. Second, it is always **less than one**, because T(cold) can never reach absolute zero. No heat engine can be 100 per cent efficient, ever, and the shortfall is not a fault to be engineered away.

Beyond the study design, and worth the effort anyway. The words **"Carnot"**, **"kelvin"**, **"exergy"** and **"coefficient of performance"** appear nowhere in the study design, and no VCAA examination paper from 2002 to 2025 has asked for a Carnot calculation or a conversion to kelvin. Every thermodynamics item VCAA has actually set has been **qualitative** — most often a multiple-choice question on what the first law states, occasionally a short-answer asking how a law relates to efficiency. You will not be handed two temperatures and asked for a ceiling under examination conditions. The expression is set out here, and worked in the examples and in **Q2**, **Q15** and **Q18**, because the dot point asks for the *implications* of the second law, and its central implication cannot be argued convincingly without it: that the gap between a Victorian unit's 27 per cent and perfection is **physics, not an engineering failure**, and that no amount of money spent on the machine will close it. What VCAA does mark is the substance underneath the arithmetic — that no heat engine can convert all its heat into work, that the limit is fixed by the **two reservoir temperatures alone**, and that raising the hot side is therefore the only route to a higher ceiling. Use the calculation as the shortest way to see why those three statements are true, and write the statements, not the formula, when a question asks for implications.

Plant type	Hot side	Cold side	Carnot ceiling	Typical real efficiency	Fraction of ceiling
Victorian brown coal, subcritical	540 °C (813 K)	35 °C (308 K)	62 per cent	22–29 per cent	~40 per cent
Australian black coal, supercritical	600 °C (873 K)	30 °C (303 K)	65 per cent	33–39 per cent	~55 per cent
Open-cycle gas turbine	1200 °C (1473 K)	30 °C (303 K)	79 per cent	33–38 per cent	~45 per cent
Combined-cycle gas turbine	1400 °C (1673 K)	30 °C (303 K)	82 per cent	55–60 per cent	~70 per cent

Efficiencies are rounded sent-out figures consistent with published Australian generation data; treat them as ranges, not exact values. Accurate as at July 2026.

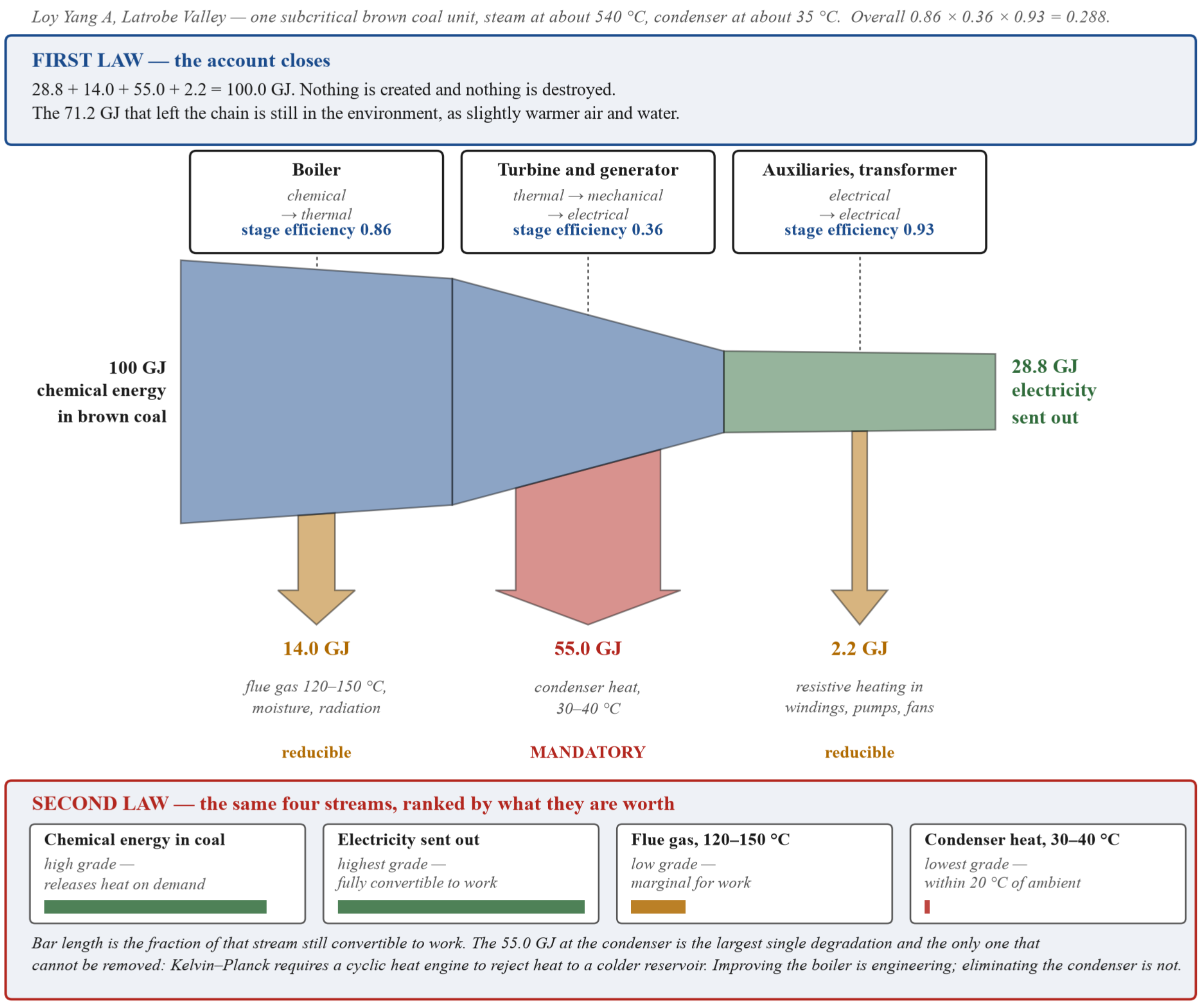
The gap between ceiling and reality is caused by **irreversibilities**: friction, heat transfer across finite temperature differences, turbulence, incomplete combustion, hot flue gases up the stack, and electricity consumed by the station's own pumps and fans. Brown coal sits at the bottom of the table for an additional and specifically Victorian reason: Latrobe Valley brown coal is roughly 60 per cent water by mass, and much of the fuel's chemical energy is spent boiling that water off before steam can be raised.

Where the energy actually goes — one chain, quantified

Take a real machine: a **Loy Yang A** unit in the Latrobe Valley, one of the four subcritical brown coal units that make up the station's 2210 MW, raising steam at about 540 °C and condensing against cooling water at about 35 °C. Follow 100 GJ of chemical energy in coal from the moment it reaches the boiler.

Stage	Conversion	Stage efficiency	Energy passed on	Energy rejected	Form and grade of the loss
Boiler	Chemical → thermal (steam)	0.86	86.0 GJ	14.0 GJ	Flue gas at 120–150 °C, plus moisture and radiation
Turbine and generator	Thermal → mechanical → electrical	0.36	31.0 GJ	55.0 GJ	Condenser heat at 30–40 °C — lowest grade
Auxiliaries and transformer	Electrical → electrical	0.93	28.8 GJ	2.2 GJ	Resistive heating in windings, pumps and fans
Sent out		**0.288 overall**	**28.8 GJ**	**71.2 GJ**	

Loy Yang A: four brown coal units, 2210 MW registered capacity, Latrobe Valley, commissioned 1984 and 1987 (AEMO, Generation Information — National Electricity Market*). The 28.8 per cent sent-out figure sits inside the 22–29 per cent band for Victorian brown coal generation (Department of Climate Change, Energy, the Environment and Water,* Australian Energy Statistics*, Table O). Retrieved July 2026. The stage-by-stage split is a worked chain typical of a unit of this class, not metered plant data; treat the three stage efficiencies as representative and the arithmetic as exact.*



The first and second laws applied to one real conversion chain: 100 GJ of brown coal followed through the boiler, turbine and generator, and auxiliaries and transformer of a Loy Yang A unit, with every rejected stream quantified and labelled with its temperature and grade.

Two readings of that table are available and only one is right. The wrong reading is that 71.2 GJ has been "lost" — it has not; every joule is still in the universe, mostly as slightly warmer air and water. The right reading is that 71.2 GJ has been **degraded** from a high-quality chemical store into low-grade heat, and that the largest single degradation, 55 GJ at the condenser, is **mandatory**: Kelvin–Planck requires heat to be rejected to a cold reservoir for the cycle to run at all. Improving the boiler is engineering; eliminating the condenser loss is impossible.

Why renewable "efficiency" is a different quantity

Wind turbines and photovoltaic panels are **not heat engines**, so the Carnot limit does not apply to them at all. They have ceilings of their own — the **Betz limit** of 16/27 for a wind rotor and the **Shockley–Queisser limit** of about 33 per cent for a single-junction silicon cell — but these arise from momentum and from semiconductor physics respectively, not from the rejection of heat to a cold reservoir. Both are **12B**'s to derive and quantify. What belongs here is the one second-law observation they share: in a photovoltaic cell, photons carrying more energy than the band gap give up the excess as heat, and that **thermalisation** is an energy-quality degradation happening inside the cell. Where no heat engine is involved at all, efficiencies are far higher than anything on the Carnot table — a large water turbine converts 90–95 per cent of the water's energy, a generator 97–99 per cent, a large electric motor 90–96 per cent.

Now the implication, one of the most-tested and most-misunderstood ideas in this dot point. A brown coal unit at 22 per cent and a solar farm at 21 per cent are **not equally wasteful**, because efficiency is a ratio and their denominators are not comparable. The coal plant's unconverted 78 per cent is fuel mined, dewatered, transported and burnt for no return, with the carbon dioxide emitted anyway. The solar farm's unconverted 79 per cent is sunlight that fell on the site regardless and cost nothing. **Conversion efficiency is a decision-relevant criterion when the input is scarce, costly or damaging, and much less relevant when it is a free, non-depleting flow.** For a solar farm the ratios that matter are energy delivered per dollar and per hectare, not joules out per joule of sunlight in.

Matching energy quality to the task — the central decision rule

If the second law implies one practical rule for choosing between energy options, it is this: **do not use high-quality energy for a task that only needs low-quality energy.** The classic violation is **resistive electric heating**, and it repays close attention because it is a trap dressed up as a virtue.

An electric panel heater converts very nearly 100 per cent of the electricity reaching it into heat. By the first law it is as efficient as a device can be, which is exactly the claim its marketing makes. By the second law it is close to the worst available choice, for two reasons. First, that electricity may have been made in a heat engine that threw away roughly 70 per cent of its fuel, so the primary-energy efficiency of the whole chain is around 26 per cent, not 100. Second — and this holds whatever generated the electricity — a joule of electricity is fully convertible to work, while the task is to raise a room from 12 °C to 21 °C, which needs almost no work at all. The **second-law efficiency** of resistive space heating, measured as exergy delivered against exergy consumed, is only a few per cent.

Heat pumps are the counter-example that proves the rule. A reverse-cycle air conditioner does not *make* heat; it **moves** heat from cool outdoor air into a warm room, using electricity only to drive the compressor that forces the transfer in the direction heat would not go on its own. Its performance is reported not as an efficiency but as a **coefficient of performance (COP)**:

COP = useful heat delivered ÷ work (electrical energy) input

A COP of 4 means four joules of heat delivered per joule of electricity. That does **not** violate the first law, because three of those four joules came from the outdoor air, not from the electricity. Nor does it violate the second law, because work was supplied to drive the transfer uphill — which is exactly what the Clausius statement requires. Heat pumps have ceilings too:

COP(max, heating) = T(hot) ÷ [T(hot) − T(cold)] and COP(max, cooling) = T(cold) ÷ [T(hot) − T(cold)]

Both ceilings collapse as the temperature difference grows, which is why a heat pump performs superbly on a mild morning and poorly on a frosty one, and why the honest figure to quote is a **seasonal** COP rather than a best-case one.

This is not a theoretical preference; regulators have written it into law. Under the *Greenhouse and Energy Minimum Standards Act 2012* (Cth), administered by the **GEMS Regulator**, it is unlawful to supply a **covered product** in Australia unless it meets the minimum energy performance standards and carries the energy rating label set for it by a **GEMS determination**. One of those labels is worth naming here because it exists *because* a heat pump's COP varies with the temperatures it works between. For air conditioners of **65 kW capacity and under**, the *Greenhouse and Energy Minimum Standards (Air Conditioners up to 65kW) Determination 2019* requires the **Zoned Energy Rating Label**, which reports performance separately for three climate zones rather than as a single figure. A single national number would misdescribe the physics, so the label does not use one. Two limits on that obligation matter when you go looking for a figure: the label is **mandatory on single-phase non-ducted units** but **voluntary on ducted systems**, whose performance is published in the GEMS Registration Database instead, and equipment above 65 kW falls under a separate determination with no zoned label at all.

The wider policy architecture that follows from this — minimum performance standards, the Victorian Energy Upgrades certificates that subsidise substituting heat pumps for resistive and gas water heating, and the planning rules restricting new gas connections — belongs to **12E** and **13C**, which treat those instruments as efficiency and sustainable-energy options rather than as thermodynamics. *Accurate as at July 2026.*

Cascading and cogeneration: using the heat you cannot avoid rejecting

The second law says heat must be rejected. It does not say the rejected heat must be wasted, and it does not fix the *temperature* at which it is rejected. That gap is the opportunity.

Cogeneration, also called **combined heat and power (CHP)**, runs an engine or turbine to make electricity and then captures its rejected heat at a temperature high enough to be useful — typically 80–120 °C — for space heating, process hot water, sterilising or drying. A gas engine converting 38 per cent of its fuel to electricity and recovering another 44 per cent as usable hot water reaches a **total fuel utilisation of 82 per cent**. Burn the same gas in a power-only station and the comparable figure is that station's electrical efficiency — **33–38 per cent** open-cycle or **55–60 per cent** combined-cycle from the table five sections above, and roughly a tenth of that is lost again on the way to a customer. State which quantity you are quoting: 82 per cent is fuel *utilisation*, counting heat and electricity together, while 55–60 per cent is *electrical* efficiency alone. Even against the best power-only plant, the cogeneration unit puts a further 44 per cent of the fuel to work that would otherwise have gone up a cooling tower. Adding an absorption chiller driven by the same heat makes it **trigeneration**.

Nothing here breaks the Carnot limit, and an answer that says it does has misread the situation: the *electrical* efficiency is still 38 per cent and still below its ceiling. What CHP changes is that the rejected heat is put to a task matched to its grade instead of being thrown at the sky. The constraint is geographic — heat cannot travel far without losing the temperature that makes it useful — so **cogeneration only works where the electricity demand and a steady heat demand share a site**. Hence dairies, hospitals, breweries and universities, and not a generator two hundred kilometres from anyone who wants hot water.

Two further implications: where savings count, and why energy cannot be recycled

Because conversion efficiencies **multiply** along a chain — the arithmetic is **12E**'s — a joule saved at the point of use saves several joules of primary energy upstream. If electricity reaches a building after generation at 0.29 and delivery at 0.91, every joule not consumed avoids about $1 \div (0.29 \times 0.91) = 3.8$ J of coal, which is why replacing an incandescent lamp at about 5 per cent conversion to visible light with an LED at 30–40 per cent cuts primary energy far more than the lamp's rating suggests. Two qualifications apply: the multiplier holds only where the electricity comes from a thermal chain, shrinking as a grid decarbonises; and the **rebound effect** means cheaper energy services tend to be used more, so a 40 per cent efficiency gain rarely delivers a 40 per cent cut in energy use. Efficiency is a necessary lever, not a self-executing one — the options for acting on it are **13C**'s.

Second, combustion is strongly **irreversible**: it converts a compact, ordered chemical store into hot gases dispersed through the atmosphere, and reassembling carbon dioxide and water into a fuel would take **more** energy than the combustion released. Hence one of the sharpest implications in this dot point — **materials can be recycled; energy cannot.** Aluminium can be melted and recast indefinitely, using about 5 per cent of the electricity needed to smelt it from bauxite, but that electricity is gone, degraded to warm air, and a fresh supply is needed every time. Circular economy thinking, taught at **8E**, applies to the material loop and not to the energy that drives it.

The first law licenses a whole-of-project audit

Because energy is conserved it can be **accounted for**, and the accounting need not stop at the device. Building a power station itself takes energy — mining and refining materials, manufacturing, constructing, operating and decommissioning — so a first-law audit can be drawn around a whole project and ask whether it delivers more energy than it consumed, and by how much. That ratio is **energy return on investment (EROI)**, and its values, its use in the peak oil argument and its pitfalls are **12D**'s dot point. The point to carry from here is only that the first law is what makes such an audit meaningful in the first place: an option whose own supply chain consumes most of its output delivers little **net energy** to society however attractive its headline capacity looks.

Storage: paying the second law twice

Every store-and-retrieve cycle converts energy at least twice, and each conversion degrades some of it. The **round-trip efficiency** is what survives.

Store	Round-trip efficiency	Where the losses go
Lithium-ion battery	85–95 per cent	Internal resistance, heat, inverter losses
Pumped hydro	70–80 per cent	Pump and turbine losses, friction, evaporation
Compressed air	55–70 per cent	Heat of compression, throttling
Electricity → hydrogen →	30–40 per cent	Electrolysis ~65–75 per cent,

Store	Round-trip efficiency	Where the losses go
electricity		compression, fuel cell ~50–60 per cent

The pattern is clear: the more conversions between different *forms* of energy, the worse the round trip. (What these losses mean for *sizing* storage against a daily demand peak is **13B**'s dot point; the question here is only why the loss is unavoidable.) The implication is not that hydrogen is bad but that it should be chosen for tasks direct electrification cannot serve — high-temperature industrial heat, chemical feedstock for steel making, long-duration seasonal storage, long-distance export — and not for tasks a battery or a wire can do. Losing two-thirds of the energy is a reasonable price for reaching 1500 °C or crossing an ocean; it is not a reasonable price for running a car.

The decision rules, collected

Everything above reduces to six rules a decision-maker can actually apply.

1. **Check that the accounting closes.** Any option claiming output greater than input is claiming energy has been created. It has not.
2. **Compare like with like.** Efficiency is meaningful only against a stated input; never set a thermal plant's fuel efficiency against a solar farm's conversion efficiency as though they measured the same thing.
3. **Match the grade of the source to the grade of the task** — high-quality energy for work and high-temperature processes, low-grade heat for low-temperature heating.
4. **Prefer fewer conversion steps**, because losses multiply, and prefer moving heat to making it wherever a heat pump can do the job.
5. **Use the heat you must reject**, by siting conversion where a matched heat demand exists.
6. **Count the whole chain, including the energy the option cost to build** — and remember that the laws set physical limits, not priorities. What the second law rules out is settled; what to do with what remains involves cost, emissions, equity and risk, the ground of **12G**, **13C** and **13D**.

Worked examples

The organisations named below are fictional; the laws, quantities, schemes and legislation are real.

Example 1 — scaffolded

For each statement, identify whether it follows from the first law, the second law, both or neither, and justify your choice: (i) "A wind farm does not create energy; it converts the kinetic energy of moving air." (ii) "No power station can turn all the heat from its boiler into electricity." (iii) "The 30 °C water leaving a cooling tower carries a great deal of energy but is almost useless." (iv) "A device producing 104 per cent of the energy put into it is impossible." *(4 marks)*

Working	Comment
(i) **First law.** Energy cannot be created; the turbine converts kinetic energy already present in the air into electrical energy.	"Generation" is industry shorthand, not physics. Nothing is made.
(ii) **Second law**, specifically the Kelvin–Planck statement. A cyclic heat engine must reject some heat to a colder reservoir.	The first law would happily permit 100 per cent conversion. Only the second law forbids it.
(iii) **Second law.** The *quantity* of energy is large but its *quality* is almost nil, because it is only a few degrees above ambient and so has virtually no capacity to do work.	This is the energy-quality distinction; the first law cannot make it, since it counts joules only.
(iv) **First law.** Output greater than input means energy has been created — a perpetual motion machine of the first kind.	Contrast with (ii): a claim of *exactly* 100 per cent from a heat engine breaches the second law, not the first.

Example 2 — scaffolded

Extension: the Carnot arithmetic in (a) and (b) is beyond the study design — see the tagged note in The Carnot limit *above. Parts (c) and (d) are the examinable substance, and they are what an implications question actually asks for.*

A brown coal generating unit raises steam at 540 °C and condenses it against cooling water at 35 °C. Its actual sent-out efficiency is 27 per cent. (a) Calculate the maximum theoretical efficiency. (b) Calculate what fraction of that ceiling the unit achieves. (c) Explain why the actual figure falls short. (d) Identify one change that would raise the ceiling itself, and one Victorian factor that depresses this unit's performance. *(5 marks)*

Working	Comment
(a) T(hot) = 540 + 273 = 813 K; T(cold) = 35 + 273 = 308 K. η(max) = 1 − 308 ÷ 813 = 1 − 0.379 = **0.621, or 62.1 per cent**.	Both temperatures must be in kelvin. Using degrees Celsius gives 1 − 35/540 = 94 per cent, which is the standard error here.
(b) 27 ÷ 62.1 = **0.43, or about 43 per cent of the Carnot ceiling**.	The plant is not "27 per cent of the way to perfect"; it reaches under half of what the second law would allow.
(c) The Carnot figure assumes a reversible cycle. A real unit suffers **irreversibilities** — friction, turbulence, heat transfer across finite temperature differences, hot flue gas up the stack, incomplete combustion, and station auxiliaries drawing power.	The shortfall is engineering; the 62.1 per cent ceiling is physics.
(d) Raise the ceiling by **increasing T(hot)** (supercritical steam conditions) or **lowering T(cold)** (colder cooling water), since only the two temperatures appear in the expression. Victorian brown coal is about **60 per cent water by mass**, and evaporating that moisture consumes a large share of the fuel's chemical energy before any steam is raised.	Lowering T(cold) is limited by ambient conditions — you cannot cool below the environment without spending work.

Example 3 — unscaffolded

A supplier advertises resistive electric panel heaters as "100 per cent efficient — every joule of electricity becomes heat in your room, unlike a gas heater at 85 per cent". Evaluate this claim. *(4 marks)*

The claim is **true as stated and misleading as an argument**, and the distinction is entirely a second-law one.

By the **first law** the supplier is right: a resistive element converts essentially all the electrical energy reaching it into thermal energy in the room, so its point-of-use efficiency really is close to 100 per cent, against about 85 per cent for a gas heater that sends some combustion products up a flue.

The argument fails on **two second-law grounds**. First, it ignores what happened upstream of the power point: if the electricity came from a thermal generator at roughly 29 per cent and was delivered at about 91 per cent, the **primary-energy efficiency of the whole chain** is 0.29 × 0.91 ≈ **26 per cent** — worse, on that measure, than burning the gas in the room. Second, and independently of how the electricity was made, **electricity is the highest-quality energy there is**, fully convertible into work, and it is being spent on a task that requires almost no work: warming a room to about 21 °C. Measured as exergy delivered against exergy consumed, resistive heating achieves only a few per cent.

The decisive point is that a better option exists using the same electricity: a **heat pump** with a seasonal COP of 3.5 delivers the same heat for **less than a third** of the electrical input, because it moves heat already in the outdoor air rather than creating it. *Takeaway:* "100 per cent efficient" answers a first-law question nobody needed to ask. The right question is how much heat you get per joule of electricity, and the answer can be far greater than one.

Example 4 — unscaffolded

Norbeck Creamery Pty Ltd installs a gas engine that consumes 100 GJ of natural gas, produces 38 GJ of electricity and recovers 44 GJ as 88 °C hot water used for pasteurising and plant washdown; 18 GJ leaves in the flue and as radiated heat. Calculate the electrical efficiency and the total fuel utilisation, and explain why the second law is not contradicted by a figure of that size. *(5 marks)*

Electrical efficiency = 38 ÷ 100 = **38 per cent**. **Total fuel utilisation** = (38 + 44) ÷ 100 = **82 per cent**. Check that the accounting closes, as the first law requires: 38 + 44 + 18 = 100 GJ. ✓

An 82 per cent figure looks at first sight as though it has beaten a Carnot ceiling of roughly 80 per cent for an engine of this kind, but the two numbers describe different things. The **Carnot limit applies to the conversion of heat into work**, and the work output here is the 38 GJ of electricity, which sits comfortably below its ceiling. The remaining 44 GJ was never converted into work at all — it is **heat that stayed heat**, captured at 88 °C on its way out instead of being dumped. The second law requires a heat engine to reject heat to a colder reservoir; it says nothing about what that reservoir must be, and a pasteurising circuit needing 80 °C water is a perfectly good one.

That is the logic of **cascading**: match each energy stream to a task needing exactly its grade. High-grade combustion heat drives the engine, medium-grade reject heat runs the plant's hot water, and only the low-grade flue loss is discarded. The binding constraint is **geographic**, not thermodynamic — hot water cannot travel far without cooling to uselessness, so the electrical and heat loads must share a site. A creamery, with continuous demand for both, is close to ideal. *Takeaway:* you cannot avoid rejecting heat, but you can choose the temperature you reject it at and find a task that needs it.

Practice questions

Scaffolded

Q1. State each of the following: (a) the first law of thermodynamics; (b) one valid statement of the second law of thermodynamics; (c) what is meant by the quality of a quantity of energy. *(3 marks)*

Q2. A generating unit raises steam at 520 °C and rejects heat to cooling water at 25 °C. (a) Write the relationship for the maximum theoretical efficiency of a heat engine. (b) Convert both temperatures to kelvin and calculate that maximum efficiency. (c) The unit's actual efficiency is 31 per cent. State what fraction of the theoretical maximum this represents. (d) Explain why no engineering improvement could raise the unit above the figure calculated in (b). *(4 marks)*

Q3. A supercritical **black coal** unit in New South Wales receives 100 GJ of chemical energy in fuel. Its boiler is 88 per cent efficient, its turbine and generator together 40 per cent efficient, and its auxiliaries and transformer 95 per cent efficient. (a) Calculate the overall efficiency and the electrical energy sent out. (b) Calculate the total energy rejected. (c) Identify the largest single loss, state its magnitude, and state the form and approximate temperature of that loss. (d) Explain why the loss identified in (c) cannot be eliminated. (e) State which law tells you that the rejected energy still exists, and which tells you it is largely useless. *(5 marks)*

Q4. A heat pump with a coefficient of performance of 4.2 delivers 12 MJ of heat to a room. (a) State what COP measures. (b) Calculate the electrical energy the heat pump consumes. (c) Calculate the electrical energy a resistive heater would consume to deliver the same 12 MJ. (d) Calculate how much heat the heat pump drew from the outdoor air, and use this to explain why a COP above 1 does not breach the first law. (e) State which law makes the heat pump the better choice, and why. *(5 marks)*

Q5. Garrowmede Glassworks Pty Ltd has four energy demands on one site: melting glass in a furnace at 1500 °C; holding an annealing lehr at 550 °C; heating the amenities block to 21 °C; and driving conveyor motors. Three supplies are available: grid electricity; natural gas burnt in air; and 85 °C water recovered from the furnace cooling circuit. (a) Match each demand to the most thermodynamically appropriate supply. (b) Justify each of your four choices by reference to energy quality. (c) State the general rule your four answers illustrate, and name the statement of the second law that rules out using the 85 °C water for the furnace. *(6 marks)*

Q6. Ingleforth Regional Energy Trust is assessing a cogeneration unit for a regional hospital. The unit consumes 300 GJ of natural gas and produces 105 GJ of electricity and 132 GJ of recoverable heat at 95 °C; 63 GJ is lost in the flue and as radiation. (a) Calculate the electrical efficiency. (b) Calculate the total fuel utilisation. (c) Supplied separately, the same services would need grid electricity generated at 33 per cent and delivered at 92 per cent, plus heat from a gas boiler at 90 per cent. Calculate the primary energy that separate supply would require, and hence the percentage saved by cogeneration. (d) Explain why a total fuel utilisation of this size does not breach the Carnot limit. (e) State the constraint that determines whether a site can use cogeneration at all. *(6 marks)*

Unscaffolded

Q7. State what the **entropy** of a system measures, and what the second law of thermodynamics requires of the entropy of an isolated system. *(1 mark)*

Q8. Explain why the statement "a coal-fired power station loses 70 per cent of its energy" is imprecise, and give a more accurate statement. *(2 marks)*

Q9. Explain why no heat engine can convert all of the heat supplied to it into work. *(2 marks)*

Q10. Explain, referring to both laws, why the warm water leaving a power station's cooling tower cannot simply be returned to the boiler to raise more steam. *(3 marks)*

Q11. A resistive electric heater converts almost all of the electricity supplied to it into heat. Explain why it is nevertheless regarded as a poor use of electricity. *(3 marks)*

Q12. *(Stimulus.)* Oxhaven Dynamics Pty Ltd advertises a new device.

> **Stimulus.** "The Oxhaven Recirculator captures the waste heat from its own generator and returns all of it to the turbine. Once started with a single charge of fuel, it produces 40 kW continuously with no further fuel input, at an overall efficiency of 104 per cent."

Identify the laws breached by this advertisement and explain each breach. *(4 marks)*

Q13. *(Stimulus.)* The table gives round-trip efficiencies for four storage technologies.

> **Stimulus.**

Technology	Lithium-ion battery	Pumped hydro	Compressed air	Flywheel
Round-trip efficiency	90 per cent	78 per cent	60 per cent	85 per cent

(a) Explain, in terms of the second law, why none of these figures reaches 100 per cent.
(b) An operator recovers 600 MWh from pumped hydro. Calculate the electricity that had to be stored, and hence the energy degraded to low-grade heat over the cycle.
(c) Explain why that loss is not evidence of poor design. *(4 marks)*

Q14. A Victorian brown coal unit operates at 26 per cent efficiency and a nearby solar farm converts 24 per cent of the sunlight falling on its panels. Explain why these two figures do not show that the two installations are equally wasteful. *(4 marks)*

Q15. Plant A raises steam at 535 °C; Plant B is a combined-cycle gas turbine with a turbine inlet temperature of 1330 °C. Both reject heat at 33 °C. Plant A achieves 26 per cent and Plant B 57 per cent. Calculate the Carnot ceiling for each and the fraction of it each achieves, and explain what the two comparisons together tell a decision-maker. *(5 marks)*

Q16. Larkmount Hydrogen Pty Ltd proposes to store surplus renewable electricity as hydrogen. Electrolysis is 68 per cent efficient, compression and storage 92 per cent, and the fuel cell that returns electricity to the grid 55 per cent. A battery alternative has a round-trip efficiency of 90 per cent. Calculate the round-trip efficiency of the hydrogen pathway and the electricity returned from 100 MWh stored by each route, and explain a duty for which the hydrogen pathway would nevertheless be the correct choice. *(5 marks)*

Q17. Compare the first and second laws of thermodynamics, referring to what each law states, what each rules out, what each implies for energy choices, and one worked illustration of each. *(6 marks)*

Q18. *(Stimulus.)* Bexholme Cold Chain Pty Ltd operates a refrigerated distribution centre. Its board has approved the following plan.

> **Stimulus.** "1. Replace the office block's gas boiler with resistive electric panel heaters, because they are 100 per cent efficient whereas the boiler is only 82 per cent efficient. 2. Use surplus rooftop solar to run a resistance element heating a wash-bay tank to 70 °C. 3. Reject the proposal to recover heat from the refrigeration condensers, because the refrigerant condenses at only 45 °C and that heat is low-grade waste.

4. Accept that the refrigeration plant, with a coefficient of performance of 2.8, is already 280 per cent efficient and cannot be improved. The cold rooms are held at −20 °C and the plant ultimately rejects its heat to outside air at 35 °C."

Evaluate this plan using the first and second laws of thermodynamics. *(8 marks)*

Q19. Elverstoke Shire Council must heat a 50 m pool and its change rooms, a demand of 2400 GJ per year, and is considering three options: a condensing gas boiler at 94 per cent point-of-use efficiency; a resistive electric boiler supplied under a 100 per cent renewable retail contract; and an air-source heat pump array with a seasonal COP of 3.4. For each option, identify the energy conversion involved, calculate the annual energy input required, and evaluate it against both laws; recommend one option with justification; and state one specific limitation of your recommendation. *(10 marks)*

Answers

Q1. (a) Energy cannot be created or destroyed, only converted from one form to another. (b) Any one of: heat flows spontaneously only from hotter to colder; no cyclic device can convert heat entirely into work; the entropy of an isolated system never decreases. (c) The fraction of that energy that could be converted into useful work.

Q2. (a) η(max) = 1 − T(cold) ÷ T(hot), temperatures in kelvin. (b) 793 K and 298 K; 1 − 298 ÷ 793 = **62.4 per cent**. (c) 31 ÷ 62.4 = **about 50 per cent** of the maximum. (d) The ceiling depends only on the two temperatures, so no improvement to the machine — only a change to T(hot) or T(cold) — can lift it.

Q3. (a) 0.88 × 0.40 × 0.95 = **0.334**, so **33.4 GJ** sent out. (b) 100 − 33.4 = **66.6 GJ**. (c) The turbine and condenser stage: 88.0 − 35.2 = **52.8 GJ**, rejected as low-grade heat in the condenser cooling water at about 30 °C. (d) A heat engine must reject heat to a cold reservoir to complete its cycle (Kelvin–Planck), so the condenser loss is required, not a defect. (e) The **first law** says the energy still exists; the **second law** says it has been degraded to a quality too low to be useful.

Q4. (a) The ratio of useful heat delivered to the work (electrical energy) supplied. (b) 12 ÷ 4.2 = **2.86 MJ**. (c) **12 MJ**. (d) 12 − 2.86 = **9.14 MJ** drawn from the outdoor air; the heat pump moves existing heat rather than creating it, so no energy is created and the first law holds. (e) The **second law** — the heat pump matches a low-grade task to a small input of high-grade energy, whereas the resistive heater destroys the exergy of every joule it uses.

Q5. (a) Furnace → natural gas (or electricity); lehr → natural gas (or electricity); amenities block → 85 °C recovered water; conveyor motors → grid electricity. (b) The furnace and lehr need high-temperature heat that only a flame or resistance heating can supply; the amenities block needs warmth barely above ambient, for which the recovered water is exactly matched and high-grade sources are wasteful; the motors need mechanical work, which electricity supplies at 90–96 per cent while heat-to-work conversion is Carnot-limited. (c) Match the grade of the source to the grade of the task. The **Clausius statement** rules out heating a 1500 °C furnace with 85 °C water, since heat does not flow spontaneously from cold to hot.

Q6. (a) 105 ÷ 300 = **35 per cent**. (b) (105 + 132) ÷ 300 = 237 ÷ 300 = **79 per cent**. (c) Electricity: 105 ÷ (0.33 × 0.92) = **345.8 GJ**; heat: 132 ÷ 0.90 = **146.7 GJ**; total **492.5 GJ**, against 300 GJ for cogeneration — a saving of 192.5 GJ, or **39 per cent**. (d) The Carnot limit applies only to the conversion of heat into **work**, which here is the 105 GJ of electricity at 35 per cent, well below its ceiling; the 132 GJ was never converted into work at all — it is heat that stayed heat and was captured rather than dumped. (e) A **steady demand for heat on the same site as the electrical demand**, because heat cannot be transported far without losing the temperature that makes it useful.

Q7. Entropy measures how **dispersed and disordered** the energy of a system is; the second law requires that the entropy of an isolated system **never decreases**.

Q8. The energy is not lost — the first law guarantees it all still exists. It is **degraded**: about 70 per cent of the fuel's chemical energy is converted into low-grade heat in flue gases and condenser cooling water rather than into electricity.

Q9. By the Kelvin–Planck statement of the second law, a device operating in a cycle must reject some heat to a colder reservoir in order to return to its starting state, so some of the heat supplied can never appear as work.

Q10. By the Clausius statement, heat does not flow spontaneously from the 30 °C cooling water to the 540 °C boiler; forcing it would require work, and the second law guarantees the work needed exceeds any extra output gained. The first law confirms the energy is still present, but its quality — only a few degrees above ambient — is far too low to raise steam.

Q11. Its first-law efficiency is near 100 per cent, but electricity is the highest-quality energy form, fully convertible to work, and it is being used for a task requiring almost no work. If the electricity came from a thermal chain the primary-energy efficiency is only about 26 per cent, and in any case a heat pump would deliver the same heat for a third or less of the electricity.

Q12. "104 per cent" and "produces 40 kW with no further fuel input" both breach the **first law** — output exceeds input, so energy is being created; this is a perpetual motion machine of the first kind. "Captures the waste heat and returns all of it to the turbine" breaches the **second law** twice: heat cannot flow unaided from the cooler exhaust back to the hotter turbine inlet (Clausius), and no cyclic device can convert rejected heat entirely back into work (Kelvin–Planck).

Q13. (a) Every conversion is irreversible — friction, turbulence, electrical resistance and heat transfer across finite temperature differences all degrade some energy to low-grade heat, and the total entropy must increase. (b) 600 ÷ 0.78 = **769.2 MWh** in; loss = **169.2 MWh**. (c) The loss is required by the second law, not caused by poor design; no store can be built with a round-trip efficiency of 100 per cent.

Q14. The two percentages have different denominators. The coal plant's unconverted 74 per cent is fuel that was mined, transported and burnt for no return, with the carbon dioxide released anyway; the solar farm's unconverted 76 per cent is sunlight that fell on the site regardless and cost nothing. Efficiency earns its place as a criterion in proportion to what the input costs, so it is decisive for the coal unit and nearly irrelevant for the solar farm, where energy per dollar and per hectare are the ratios that decide.

Q15. Plant A: T(hot) 808 K, T(cold) 306 K, ceiling **62.1 per cent**, achieving 26 ÷ 62.1 = **42 per cent** of it. Plant B: T(hot) 1603 K, ceiling **80.9 per cent**, achieving 57 ÷ 80.9 = **70 per cent** of it. Plant B is better on both counts — it has a higher ceiling because it runs far hotter, and it also captures a greater share of that ceiling. See the fully-worked solution.

Q16. 0.68 × 0.92 × 0.55 = **0.344, or 34.4 per cent**. From 100 MWh: hydrogen returns **34.4 MWh**, the battery **90 MWh**. Hydrogen is nevertheless correct where a battery cannot serve the duty at all — high-temperature industrial heat, chemical feedstock for steel making, long-duration seasonal storage or long-distance export. See the fully-worked solution.

Q17. First law: energy is conserved, ruling out output exceeding input and requiring the energy account to balance. Second law: energy is degraded and heat flows only from hot to cold, ruling out complete conversion of heat to work and setting the Carnot ceiling. Implications: the first law says count every joule; the second says judge each joule by its quality and match it to the task. See the fully-worked solution.

Q18. Point 1 compares point-of-use efficiencies while ignoring the upstream chain and the exergy destroyed; a heat pump is the correct comparison. Point 2 repeats the same error with the solar surplus. Point 3 contradicts points 1 and 2 — 45 °C heat is precisely the right grade for the 21 °C space heating and for pre-heating wash water. Point 4 misdescribes COP as an efficiency and is wrong that no improvement is possible: the ideal COP for cooling from −20 °C to 35 °C is 253 ÷ 55 = **4.6**, so 2.8 is only about 61 per cent of the ceiling. See the fully-worked solution.

Q19. Gas boiler: chemical → thermal, 2400 ÷ 0.94 = **2553 GJ** of gas. Resistive electric boiler: electrical → thermal, **2400 GJ** = **667 MWh**. Heat pump: electrical work moving ambient heat, 2400 ÷ 3.4 = **706 GJ** = **196 MWh**. Recommend the heat pump, with a justification from both laws and one specific limitation. See the fully-worked solution.

Fully-worked solutions

Q1. (a) The **first law**: energy **cannot be created or destroyed, only converted from one form to another**; the total energy of an isolated system is constant. (b) Any **one** valid statement of the **second law**: heat flows spontaneously only from a hotter body to a colder one (Clausius); no cyclic device can convert heat entirely into work, so some must always be rejected to a colder reservoir (Kelvin–Planck); the entropy of an isolated system never decreases. (c) **Energy quality**, or exergy, is the **fraction of a given quantity of energy that could be converted into useful work** — high for electricity and mechanical work, near zero for heat close to ambient temperature. *Marker's note:* one statement of the second law is enough, but it must be a statement, not a consequence. "Energy is lost as heat" is neither of the two laws.

Q2. (a) **η(max) = 1 − T(cold) ÷ T(hot)**, with both temperatures in **kelvin**. (b) T(hot) = 520 + 273 = **793 K**; T(cold) = 25 + 273 = **298 K**. η(max) = 1 − 298 ÷ 793 = 1 − 0.376 = **0.624, or 62.4 per cent**. (c) 31 ÷ 62.4 = **0.50 — about half** the theoretical maximum. (d) Because the expression contains **only the two reservoir temperatures**. Better bearings, better blades, better insulation and better control all reduce the *irreversibilities* that keep the plant below 62.4 per cent, but none of them changes T(hot) or T(cold), so none can lift the ceiling itself. Only raising the steam temperature or lowering the heat-rejection temperature does that. *Common error:* working in degrees Celsius. 1 − 25/520 gives 95 per cent, which is not a possible efficiency for this plant and should be recognised as wrong on sight. *(Extension: parts (a)–(c) work the Carnot arithmetic, which is beyond the study design — see the tagged note in* The Carnot limit*. Part (d) is the examinable substance, and it can be answered in full without calculating anything.)*

Q3. (a) Overall efficiency = 0.88 × 0.40 × 0.95 = **0.334**, so **33.4 GJ** of the 100 GJ is sent out as electricity. (b) Rejected = 100 − 33.4 = **66.6 GJ**. (c) Boiler loss = 100 − 88.0 = 12.0 GJ; turbine and condenser loss = 88.0 − 35.2 = **52.8 GJ**; auxiliaries and transformer = 35.2 − 33.4 = 1.8 GJ. The **largest is the 52.8 GJ rejected at the condenser**, as **low-grade thermal energy in cooling water at about 30 °C**. (Check: 12.0 + 52.8 + 1.8 = 66.6 GJ. ✓) (d) **Kelvin–Planck** requires a cyclic heat engine to **reject heat to a colder reservoir**; without a condenser the steam cannot be returned to liquid and the cycle cannot repeat. The loss is a **condition of operating at all**, not an engineering failure, and is bounded below by the Carnot relationship. (e) The **first law** tells you the 66.6 GJ still exists in the environment; the **second law** tells you it has been degraded to a quality too low to be useful. *Marker's note:* the marks in (d) and (e) are for naming the laws and their roles. An answer that only recomputes percentages has answered 12E, not this question. Worth comparing with the Latrobe Valley chain in the theory: this unit sends out 33.4 GJ against that one's 28.8 GJ, and almost the whole difference is the turbine stage, 0.40 against 0.36. That is what higher steam conditions and a drier fuel buy — and note that the condenser is still by a wide margin the largest loss in both.

Q4. (a) The **coefficient of performance** is the ratio of **useful heat delivered to the work (electrical energy) supplied**. (b) Electrical input = 12 ÷ 4.2 = **2.86 MJ**. (c) A resistive heater is essentially 100 per cent efficient at the point of use, so it needs the full **12 MJ**. (d) Heat drawn from the outdoor air = 12 − 2.86 = **9.14 MJ**. The heat pump **moves** heat that already exists in the outside air rather than creating it, so the energy account balances exactly: 2.86 MJ of electricity plus 9.14 MJ of ambient heat gives the 12 MJ delivered. **No energy is created, so the first law is not breached.** (e) The **second law**. Both devices satisfy the first law, but only the heat pump matches the grade of the energy to the grade of the task, spending a small amount of high-quality electricity purely to drive heat in the direction it would not travel on its own — precisely what the Clausius statement says work is needed for. The resistive heater instead destroys the full work potential of every joule it consumes. *Common error:* claiming a COP above 1 breaks the first law. It does not, because the extra energy comes from the environment, and identifying that source is what part (d) is worth.

Q5. (a) and (b), taken together:

Demand	Supply	Justification
Furnace at 1500 °C	**Natural gas** burnt in air (electric resistance is also thermodynamically valid)	Only a flame or resistance heating reaches this temperature; the task genuinely requires the highest available grade, so no quality is squandered.
Annealing lehr at 550 °C	**Natural gas** (or electricity)	Still well above any recoverable waste stream on the site; requires medium-to-high-grade heat.
Amenities block at 21 °C	**85 °C recovered water**	The task needs warmth barely above ambient. The recovered water is already at a suitable temperature and would otherwise be discarded, so using electricity or a flame here would destroy a large amount of exergy for no gain.
Conveyor motors	**Grid electricity**	The task is mechanical work. Electricity converts to work at 90–96 per cent in a large motor, whereas any heat-to-work route is Carnot-limited to a far lower figure.

(c) The general rule is to **match the grade of the energy source to the grade of the task** — reserve high-quality energy for work and high-temperature processes, and meet low-temperature demands with low-grade heat that would otherwise be wasted. The **Clausius statement** rules out using the 85 °C water for the furnace: heat will not flow spontaneously from colder to hotter. *Marker's note:* credit is available for choosing electricity for the furnace provided the justification is about temperature grade. What is not creditable is using the 85 °C stream anywhere above 85 °C.

Q6. (a) Electrical efficiency = 105 ÷ 300 = **0.35, or 35 per cent**. (b) Total fuel utilisation = (105 + 132) ÷ 300 = 237 ÷ 300 = **0.79, or 79 per cent**. (Check that the account closes, as the first law requires: 105 + 132 + 63 = 300 GJ. ✓)

(c) **Separate supply.** Electricity: the grid chain delivers 0.33 × 0.92 = 0.3036 of its primary energy, so 105 GJ of delivered electricity needs 105 ÷ 0.3036 = **345.8 GJ**. Heat: 132 ÷ 0.90 = **146.7 GJ**. Total = 345.8 + 146.7 = **492.5 GJ** of primary energy, against **300 GJ** for the cogeneration unit. Saving = 492.5 − 300 = 192.5 GJ, or 192.5 ÷ 492.5 × 100 = **39 per cent**.

(d) Because **the Carnot limit governs only the conversion of heat into work**. The work output here is the **105 GJ of electricity**, an efficiency of 35 per cent, which sits well below the ceiling for an engine of this kind. The other **132 GJ was never converted into work at all** — it is heat that stayed heat, captured at 95 °C on its way out instead of being rejected to the atmosphere. The second law requires a heat engine to reject heat to a colder reservoir but says nothing about what that reservoir must be, and a hospital's hot water and space heating circuits are a perfectly good one.

(e) A **steady demand for heat on the same site as the electrical demand**. Heat cannot be transported far without losing the temperature that makes it useful, so the constraint is geographic rather than thermodynamic — which is why hospitals, dairies, universities and breweries suit cogeneration and a remote generator does not.

Marker's note: (c) is where the marks concentrate, and the standard error is dividing by 0.33 alone and forgetting the delivery stage. (d) must identify **which** energy stream the Carnot limit applies to; an answer asserting that 79 per cent "beats Carnot" has misread what the ceiling constrains.

Q7. Entropy is a measure of how **dispersed and disordered** the energy of a system is. The **entropy statement** of the second law is that the total entropy of an **isolated system never decreases**: it increases in every real process, because every real process is **irreversible**, and it is constant only in the reversible limit that no real machine attains. *Common error:* defining entropy as "disorder" alone. It is the energy that is dispersed, and it is that dispersal which makes the energy progressively less able to do work.

Q8. The energy is **not lost** — the first law guarantees that all 100 per cent of it still exists. What has happened is **degradation**: roughly 70 per cent of the fuel's chemical energy has been converted into **low-grade thermal energy** in flue gases and condenser cooling water, dispersed into the environment at a temperature too close to ambient to be useful. *Marker's note:* the second mark is for supplying the accurate wording, not merely for objecting to the loose one.

Q9. By the **Kelvin–Planck statement** of the second law, a device operating in a **cycle** must **reject some heat to a colder reservoir** in order to return to its initial state and repeat. The rejected heat can never appear as work, so the fraction converted is bounded above by the Carnot efficiency, 1 − T(cold) ÷ T(hot), which is always less than one because T(cold) cannot be absolute zero.

Q10. By the **Clausius statement**, heat does not flow spontaneously from a colder body to a hotter one, and the cooling water at about 30 °C is hundreds of degrees below the boiler's 540 °C steam. Transferring it "uphill" would require **work input**, and the second law guarantees that the work needed exceeds any additional electricity the returned heat could produce — otherwise the plant would be a perpetual motion machine of the second kind. The **first law** confirms the energy is genuinely still there; the **second law** explains why its quality, only a few degrees above ambient, makes it useless for raising steam. *Common error:* answering only that "the water is not hot enough". True, but the question asks why, and the reason is the direction of spontaneous heat flow plus the exergy of the stream.

Q11. By the **first law** the heater is close to 100 per cent efficient at the point of use, and that much is correct. The objection is a **second-law** one, on two grounds. **Energy quality:** electricity is the **highest-grade** energy there is, fully convertible into work, and it is being spent on a task — warming a room to about 21 °C — requiring almost no work; as exergy delivered against exergy consumed, resistive heating achieves only a few per cent. **The upstream chain:** where the electricity comes from thermal generation the whole-chain primary-energy efficiency is only about 0.29 × 0.91 ≈ **26 per cent**. Decisively, a **heat pump** delivers the same heat for **a third or less** of the electricity, because it moves heat rather than making it. *Marker's note:* three marks require the quality argument, not just the upstream one — the quality argument holds even on a fully renewable grid, which makes it the stronger.

Q12. The first law is breached twice. An "overall efficiency of 104 per cent" means the device delivers more energy than it receives, which requires energy to be **created**; and producing **40 kW continuously with no further fuel input**

means indefinite output from zero input. Either claim describes a **perpetual motion machine of the first kind**, which is impossible.

The second law is breached twice. Returning the generator's rejected heat **to the turbine** would require heat to flow from the cooler exhaust to the hotter inlet unaided, contrary to the **Clausius statement**. And even with a pump doing that work, capturing **all** the waste heat and converting it back into work would mean a cyclic device converting heat entirely into work with no rejection to a cold reservoir, contrary to **Kelvin–Planck** — a perpetual motion machine of the second kind.

Marker's note: four marks means both laws identified **and** each mechanism explained. Note the discrimination being tested: a claim of *more than* 100 per cent is a first-law breach, while a claim of *exactly* 100 per cent from a heat engine is a second-law breach. Treating every impossible machine as "breaking the first law" loses half the marks.

Q13. (a) Every step in a store-and-retrieve cycle is **irreversible**. Electrical resistance in cells and cables, friction and turbulence in pumps and turbines, heat generated on compression, and heat transfer across finite temperature differences all convert part of the stored energy into **low-grade heat** dispersed to the surroundings. The second law requires the **total entropy to increase** at every such step, so some degradation is unavoidable and the round trip must return less than it received. (b) Electricity required = 600 ÷ 0.78 = **769.2 MWh**. Energy lost = 769.2 − 600 = **169.2 MWh**. (c) Because a round-trip efficiency of 100 per cent is **forbidden by the second law**, not merely difficult. Pumped hydro at 78 per cent is close to the practical ceiling for that technology, and the right question is not whether a store loses energy but whether the loss is smaller than the value of having the energy available when it is wanted. *Marker's note:* (c) tests whether a student can distinguish a physical limit from an engineering shortcoming — the same distinction as Q3's condenser.

Q14. The two figures are **ratios with different denominators**, so they cannot be compared directly.

For the coal unit the input is a **finite, extracted, carbon-bearing stock**. The unconverted 74 per cent is coal that was mined, dewatered, transported and burnt for **no return at all**, with the carbon dioxide from it released just the same; every point of efficiency lost costs fuel, money, land disturbance and emissions. For the solar farm the input is an **incident flow** that arrived regardless of whether the panels were there. Its unconverted 76 per cent is reflected or absorbed as heat exactly as it would have been on bare ground, so **no resource is consumed and no emission caused** by failing to convert it.

The general principle is that **efficiency earns its place as a criterion in proportion to what the input costs**: where the input is scarce, purchased or damaging, every point lost is paid for twice over, and where it is a free, non-depleting flow the ratio decides almost nothing. For the solar farm the ratios that matter are energy delivered per dollar and per hectare, and a cheap, durable 24 per cent module may beat a 30 per cent one that is neither. *Marker's note:* four marks require the *reason* the denominators differ, not merely that "solar is renewable". The strongest answers name what replaces efficiency as the relevant criterion.

Q15. Plant A. T(hot) = 535 + 273 = 808 K; T(cold) = 33 + 273 = 306 K. Ceiling = 1 − 306 ÷ 808 = 1 − 0.379 = **62.1 per cent**. Fraction achieved = 26 ÷ 62.1 = **42 per cent**.

Plant B. T(hot) = 1330 + 273 = 1603 K; T(cold) = 306 K. Ceiling = 1 − 306 ÷ 1603 = 1 − 0.191 = **80.9 per cent**. Fraction achieved = 57 ÷ 80.9 = **70 per cent**.

The two comparisons say different things and a full answer needs both. The **ceilings** differ because the Carnot expression depends only on the two temperatures, and Plant B's turbine inlet is nearly 800 °C hotter — running hotter is the only way to raise the physical limit, which is why combined-cycle plant exists at all. The **fractions of ceiling** differ because Plant B also suffers fewer irreversibilities relative to its potential, recovering its turbine exhaust heat in a second steam cycle instead of discarding it.

The implication for a decision-maker is that **Plant B converts more than twice as much of each joule of fuel into electricity**, so for the same output it burns less than half the fuel and emits correspondingly less carbon dioxide per unit of electricity — before any difference between the fuels is considered. It also shows where effort should go: raising T(hot) lifts the ceiling, better engineering only closes the gap beneath it. *Marker's note:* both ceilings, both fractions, and an interpretation using both. Calculating four numbers and stopping earns three of the five marks. *(Extension: the four calculations are beyond the study design — see the tagged note in* The Carnot limit*. The interpretation in the last two paragraphs is the examinable substance, and it is also where the marks are.)*

Q16. Hydrogen round trip = 0.68 × 0.92 × 0.55 = **0.344, or 34.4 per cent**. From 100 MWh stored, the hydrogen route returns **34.4 MWh** and the battery returns **90 MWh**. So the hydrogen pathway discards about **two-thirds** of the electricity — 65.6 MWh against the battery's 10.0 MWh, or **more than six times as much** — while the battery returns about **two and a half times** as much usable electricity as hydrogen does (90 ÷ 34.4 = 2.6).

The reason is structural, not a matter of poor equipment: the hydrogen route makes **three conversions between different forms of energy** — electrical to chemical, mechanical work of compression, then chemical back to electrical — and each is a separate opportunity for the second law to take its cut, with the efficiencies multiplying rather than adding. A battery stores and returns energy electrochemically with far less conversion between forms.

Hydrogen is nevertheless correct for **duties a battery cannot serve at all**. Any one of these would answer the question: **high-temperature industrial heat** above about 1000 °C, where electrification is difficult and hydrogen combustion reaches the required temperature; use as a **chemical feedstock**, for instance as the reducing agent in direct reduced iron for low-emission steel, where what is needed is a molecule and not stored electrons; **long-duration or seasonal storage** over weeks to months, where a battery's cost per unit of stored energy becomes prohibitive; and **long-distance export**, where hydrogen or its derivatives can be shipped and electricity cannot. *Marker's note:* the final marks require a duty for which the **alternative is unavailable**, with a reason. "Hydrogen is cleaner" does not answer it, since both routes store the same renewable electricity.

Q17. *"Compare" means the same points addressed for both laws, not two separate descriptions.*

What each states. The **first law**: energy cannot be created or destroyed, only converted between forms, so the total energy of an isolated system is constant. The **second law**: heat flows spontaneously only from hotter to colder, no cyclic device can convert heat entirely into work, and total entropy never decreases — in short, every conversion **degrades** energy quality even though it preserves quantity.

What each rules out. The first law rules out any device whose **output exceeds its input** — a perpetual motion machine of the first kind — and requires every energy account to balance. The second law rules out **complete conversion of heat into work**, rules out heat flowing uphill unaided, and imposes the **Carnot ceiling**, η(max) = 1 − T(cold) ÷ T(hot), on every heat engine.

What each implies for energy choices. The first law implies that nothing "generates" energy, that every claimed saving must appear somewhere in the balance, and that a whole-of-life energy audit of a project is a legitimate test (the metric is **12D**'s). The second law implies that a joule is not a joule: energy must be judged by **quality** as well as quantity, so high-grade energy is reserved for work and high-temperature processes, low-grade waste heat is **cascaded** into tasks that suit it, and conversion steps are minimised because their losses multiply.

An illustration of each. *First law:* a heat pump with a COP of 4 delivering 12 MJ consumes 12 ÷ 4 = **3.00 MJ** of electricity and draws the other **9.00 MJ** from outdoor air — the account balances exactly, and none of the 12 MJ was created. *Second law:* a brown coal unit with steam at 540 °C and a condenser at 35 °C cannot exceed 1 − 308 ÷ 813 = 62 per cent however well engineered, and in practice reaches about 27 per cent.

Marker's note: six marks reward the **parallel structure —** statement, prohibition, implication, illustration, for both laws. The most valuable sentence is that the first law governs **quantity** and the second governs **quality**.

Q18. *Model response (8 marks).*

The plan contains one point that is correct but misapplied, two that follow from the same error, and one that is simply wrong. Each fails on the second law rather than the first.

Point 1 — a real comparison, but the wrong one. By the first law the board is right that a resistive panel converts essentially 100 per cent of the electricity reaching it into heat, against 82 per cent for the boiler. But upstream, if any of that electricity comes from thermal generation the **primary-energy efficiency of the whole chain** is around 26 per cent, worse than burning the gas on site. More fundamentally, **electricity is the highest-grade energy available**, fully convertible into work, and the task is to warm an office to about 21 °C, which requires almost no work. The correct comparison is not resistance against gas but either of them against a **heat pump**, which delivers the same heat for roughly a third of the electricity by moving ambient heat instead of creating it.

Point 2 — the same error, applied to the solar surplus. A resistance element heating water to 70 °C converts high-grade electricity straight into medium-grade heat; a heat pump water heater at a COP of about 3 would produce **three**

times as much hot water from the same surplus. There is a legitimate counter-argument the board has not made — if the surplus would otherwise be spilled and earns nothing, even a poor use of it beats no use — but that is an economic case, and it would not survive the heat pump comparison.

Point 3 — this contradicts points 1 and 2. The board dismisses 45 °C condenser heat as "low-grade waste" in the same plan in which it proposes to **manufacture** 21 °C space heat and 70 °C wash water out of electricity. Heat at 45 °C is exactly the right grade for the space-heating duty and for **pre-heating** the wash-bay tank before a smaller top-up, and the refrigeration plant must reject it somewhere regardless, so **cascading** it into a task that needs warmth costs nothing extra. Discarding a low-grade stream while creating low-grade heat from the highest-grade source available is the plan's central inconsistency.

Point 4 — the COP is misdescribed and the conclusion is wrong. A **coefficient of performance is not an efficiency**, and 2.8 does not mean "280 per cent efficient": it is the ratio of heat moved to work supplied, and exceeds one because most of the heat is transported rather than generated. Nor is the plant at its limit. The ceiling is set by the **two reservoir temperatures** — the cold room the plant draws heat from and the outside air it finally dumps that heat into — not by the temperature the refrigerant happens to condense at on the way. So use −20 °C (253 K) and 35 °C (308 K), not the 45 °C of point 3:

COP(max) = T(cold) ÷ [T(hot) − T(cold)] = 253 ÷ (308 − 253) = 253 ÷ 55 = **4.6**

so 2.8 is only about **61 per cent** of the thermodynamic ceiling. The 45 °C in point 3 is the **condensing temperature**, which is the grade of the recoverable stream and is a further 10 °C above ambient precisely because heat will not flow into 35 °C air unless it is pushed above it. Lowering that condensing temperature, cleaning condensers, floating head pressure control or reducing heat ingress would all move the COP upwards — which is also why the two temperatures answer two different questions: 35 °C tells you how good the plant *could* be, 45 °C tells you what the rejected heat is *good for*. *(The ceiling calculation is extension material; see the tagged note in* The Carnot limit*. The examinable substance here is that a COP is not an efficiency and that the plant is not at its limit.)*

Judgement. The plan should not proceed as approved. Its own numbers point to a better one: recover the 45 °C condenser heat for space heating and wash-water pre-heating, replace the panel heaters and the resistance element with heat pumps, and treat the refrigeration COP as having roughly a third of its ceiling still available. Two of these would attract support under the **Victorian Energy Upgrades** program, administered by the Essential Services Commission under the *Victorian Energy Efficiency Target Act 2007* (Vic). *Marker's note:* eight marks require all four points addressed and a judgement reached. The highest-value observation is the **internal contradiction between points 1–2 and point 3**; an answer that finds it has understood energy quality rather than merely recited it.

Q19. *Model response (10 marks).*

Option 1 — condensing gas boiler at 94 per cent. The conversion is **chemical energy in natural gas → thermal energy** in the pool water. Annual input = 2400 ÷ 0.94 = **2553 GJ of gas**. By the first law the accounting is sound and point-of-use efficiency is genuinely high, since a condensing boiler recovers the latent heat in its flue gases. By the second law it is a **poor match of grade to task**: a flame at well over 1000 °C has its exergy largely destroyed warming water to 28 °C. It also commits a long-lived public asset to fossil fuel at a time when new residential buildings requiring a planning permit have been unable to connect to reticulated natural gas since **Amendment VC250** took effect on **1 January 2024**.

Option 2 — resistive electric boiler on a renewable retail contract. The conversion is **electrical → thermal** at essentially 100 per cent at the point of use. Annual input = **2400 GJ**, or 2400 ÷ 3.6 = **667 MWh of electricity**. This looks attractive on a first-law reading and the renewable contract removes the emissions objection, but it is the **weakest option thermodynamically**: it takes the highest-quality energy form there is and destroys its entire work potential to produce warmth barely above ambient. The contract does not change the physics — it changes who else could have used those 667 MWh, every one of which is then unavailable to displace fossil generation elsewhere on the grid.

Option 3 — air-source heat pump array, seasonal COP 3.4. This is barely a conversion at all: electrical energy does **work to move existing thermal energy** from outdoor air into the pool. Annual input = 2400 ÷ 3.4 = **706 GJ**, or **196 MWh**; the remaining 1694 GJ comes from the ambient air, so the first law balances exactly. Against Option 2 that is a **71 per cent reduction in electricity** for an identical duty. By the second law it is the only option that respects the grade of the task, spending a little high-quality energy purely to drive heat in the direction it will not travel unaided — precisely what the Clausius statement identifies as requiring work.

Recommendation. The Council should install the **heat pump array** — but the justification has to be built carefully, because the two comparisons available are not the same comparison, and decision rule 2 forbids treating them as though they were.

Against **Option 2** the case is decisive and genuinely like-for-like: both options buy electricity, and the heat pump delivers the identical 2400 GJ for **196 MWh** against **667 MWh**, a 71 per cent reduction for no change in service. Whatever supplies the grid, that is 471 MWh released for another use.

Against **Option 1** the comparison is **not** like with like: 706 GJ of *delivered electricity* is not the same quantity as 2553 GJ of *gas at the burner*. Put both on a common basis and the wide margin disappears. On a wholly thermal supply, using this chapter's chain of $1 \div (0.29 \times 0.91) = 3.8$, the heat pump's 706 GJ stands for about **2680 GJ of primary energy** — slightly *more* than the boiler's 2553 GJ. Emissions at today's published factors tell the same story: 2553 GJ of gas at 51.5 kg CO_2-e GJ^{-1} is about **131 t CO_2-e**, while 196 MWh at Victoria's 0.78 kg CO_2-e kWh^{-1} is about **153 t**. Against a *condensing* boiler, and at present grid intensity, the heat pump is line-ball at best.

Two things decide it that a single-year comparison cannot show. First, **grade matched to task**: the heat pump is the only option that does not destroy the work potential of what it consumes, and that argument holds whatever generates the electricity. Second, **the life of the asset**: pool plant installed now runs for decades, over which the gas figure is fixed by chemistry while the electricity figure falls with the grid — renewables already supplied 44.6 per cent of Victoria's generation in 2025, against legislated targets of 65 per cent by 2030 and 95 per cent by 2035. The boiler's emissions are locked in the day it is commissioned; the heat pump's are not. The Council can also put the array on the same renewable retail contract offered for Option 2, and would then be buying under a third as much of it. *Accurate as at July 2026.*

Limitation. The recommendation rests on the **seasonal COP of 3.4 being achieved in practice**. COP falls as the temperature difference widens, so on the cold winter mornings when the pool loses heat fastest the instantaneous COP may be nearer 2 — and that is also when solar output is lowest and grid demand highest. If real winter performance is materially below the annual average, both the electricity required and the **peak** electrical demand, which drives network charges and may force a supply upgrade, are understated above. Before committing funds the Council should obtain the manufacturer's **certified performance data at stated test conditions**, covering the range of ambient air and pool water temperatures this site actually sees rather than a single rating point, require a **seasonal COP modelled for this climate** and written into the contract as a performance guarantee, and verify it by metering after commissioning. Size the array on winter performance, not on an annual mean. Note what cannot be used here: the **Zoned Energy Rating Label** does report performance by climate zone, but it is required by the *Greenhouse and Energy Minimum Standards (Air Conditioners up to 65kW) Determination 2019* for space-conditioning air conditioners, and this is not one — it is pool-heating plant, and at 2400 GJ a year its thermal duty is well above 65 kW in any case.

Marker's note: ten marks require **all three options** treated on **conversion, calculated input and both laws**, plus a **justified** recommendation and a **specific** limitation. "It might be expensive" is not specific; the strongest answers name the assumption their own recommendation depends on, say what would happen if it failed, and identify how it could be tested.

§2A RECORDED SCOPE DECISION

Aboriginal and Torres Strait Islander knowledge — deliberately not covered (ICIP). This workbook does not reproduce Aboriginal and Torres Strait Islander knowledge, cultures or histories. The Study Design's Aboriginal and Torres Strait Islander knowledge and perspectives requirement is therefore not covered here. Real Aboriginal and Torres Strait Islander knowledge must be sourced by teachers directly with the relevant community under the appropriate protocols; any Indigenous-looking example in this book is fictitious and must not be taken as real.

Theory

What this subtopic is for. The dot point is the longest in the Area of Study and every clause in it is examinable: *"sustainability principles as they apply to accessing, extracting, processing, transporting, and using energy resources: conservation of biodiversity and ecological integrity; efficiency of resource use; intergenerational equity; intragenerational equity; precautionary principle; and user pays principle"*. Read the shape of it. There are **six principles** and there are **five stages**, and the dot point joins them. Neither list on its own is the answer. A response that defines the six principles has answered **3B**; a response that describes an energy industry has answered **12A** or **12B**. What is asked here is the **join** — what each principle demands *at each stage of an energy supply chain*, and whether a particular chain honours it there.

This matters more than its position at the end of the chapter suggests, because Unit 4 Outcome 2 is written in its language: students must *"compare the advantages and disadvantages of using a range of energy sources, and evaluate the suitability and impacts of their use* ***in terms of upholding sustainability principles****"*. The six principles are the marking criteria for the whole Area of Study. Everything Chapter 12 has built — the sources at **12A** and **12B**, the carbon-cycle consequences at **12C**, depletion rates at **12D**, conversion efficiency at **12E**, the two laws at **12F** — becomes evidence to be run through the six tests here.

Boundaries — what belongs elsewhere. This chapter reads as one chapter, and this subtopic is the last of it. Keep to your own ground.

Not this subtopic	Where it belongs
The six principles' definitions, discriminators and the analysis routine	**3B**
Value systems — anthropocentric, biocentric, ecocentric, technocentric	**3C**
Turning a principle into a requirement, an instrument and an indicator	**8C**
The same principles applied to *biodiversity conservation*	**7F**
Population, food, water and energy as *challenges* to upholding principles	**8D**
Circular economy thinking, risk analysis, cost–benefit analysis	**8E**
What the sources *are*, and the Victorian gas and nuclear prohibitions	**12A**, **12B**
Combustion and the carbon cycle; life-cycle emissions figures	**12C**, **12B**
Peak oil, depletion rates and **EROI**	**12D**
Conversion efficiency calculations; the two laws; energy quality and exergy	**12E**, **12F**

Not this subtopic	Where it belongs
Rehabilitating energy extraction sites, and rehabilitation bond adequacy	**13A**
Whether a source can carry base and peak load	**13B**
The four option families for a sustainable energy future, GEMS/MEPS, VEU	**13C**
Stakeholder values, regulatory tensions, contested data, new technologies	**13D**

12G owns the supply chain as an analytical axis: the five stages, what changes between them, and the fact that a principle can be upheld at one stage and breached at another by the same chain.

The five stages, defined precisely

Students lose marks by treating the first two stages as one word. The study design names five, and they are different activities with different impacts, different regulators and different principles biting hardest.

1 — Accessing. Securing the legal right and the physical ability to reach an energy resource, *before any of it is removed*. This covers exploration and appraisal — seismic survey, geophysical survey, exploration drilling, resource assessment — and the whole apparatus of tenure and consent: exploration licences, production licences, planning permits, environmental assessment, heritage approval under the *Heritage Act 2017* (Vic) where a place on the Victorian Heritage Register is affected, land access agreements with landholders, and for electricity projects, a connection agreement to the grid. Accessing has real physical impacts of its own: seismic lines cut through vegetation, exploration pads and access tracks cleared, drilling fluids to manage, marine seismic noise. It also has a property no later stage has — **at the accessing stage the option not to proceed is still cheap**. That single fact is why the precautionary principle lives here.

2 — Extracting. Removing the resource from the Earth, or capturing the natural flux. For fuels this is open-cut and underground mining, drilling and production, and the harvesting of biomass. For flow resources it is the capture itself: a turbine taking kinetic energy from moving air, a panel intercepting sunlight, a dam impounding water. The distinction matters and is examinable. Extracting a **stock** resource depletes it permanently; capturing a **flux** does not deplete anything, but it still occupies land, displaces other land uses, and modifies the local environment. It follows that **the impacts the capture hardware causes while it is working are extracting-stage impacts**: collision risk to birds and bats at an operating wind turbine, and altered flow and thermal regimes and barriers to fish passage at a dam, arise where the flux is captured, not where the electricity is finally consumed. "Renewables have no extraction stage" is wrong, and so is treating their extraction stage as costless.

3 — Processing. Converting the raw resource into a usable **fuel** — a form that can be stored, moved and burnt where it is wanted. Coal is crushed, washed and, for Victorian brown coal, largely *dried*; crude oil is refined into petrol, diesel and jet fuel; raw gas is conditioned to remove water, carbon dioxide and hydrogen sulfide, and may be liquefied; uranium ore is milled, converted, enriched and fabricated into fuel; biomass is chipped, dried and pelletised, or fermented and distilled into ethanol. **Manufacturing the conversion hardware belongs here too** — smelting silicon into polysilicon and then into cells, casting turbine towers, refining lithium and nickel into cathode material. Fix the far boundary as well: processing *prepares* a fuel and *builds* the hardware, so burning that fuel to generate electricity is **not** processing — the fuel is consumed there, which makes it *using*. This is the stage most often left out of an evaluation, and leaving it out is what makes some chains look cleaner than they are.

4 — Transporting. Moving the resource, the energy, or the residues. Conveyors, rail, road tankers, ships, slurry lines and pipelines carry fuels; **transmission and distribution networks** carry electricity; and the same stage carries the wastes away and the hardware in. Two features make this stage distinctive. Its infrastructure is **linear**, so its ecological signature is fragmentation rather than area loss. And for electricity it is **lossy in transit** — of the energy entering a transmission and distribution system, roughly 8–10 per cent is dissipated as heat before it reaches a customer.

5 — Using. The conversion of the resource into an energy service — motion, heat, light, refrigeration, computation — together with the emissions and residues that conversion produces. Two boundaries need fixing here. For a **fuel**, the point of consumption is the boiler, furnace, engine or reactor in which it is burnt or fissioned, so a power station's conversion efficiency and its combustion emissions are counted at *using*, even though the electricity it makes is then transported onward to an appliance. And the study design names **five** stages and no separate “end of life” stage, so the residues left behind when a service ends — ash, spent fuel, retired panels and cells — are counted here, as residues of using, while the taking of the materials inside them is counted back at extracting and processing. Using is the only stage most people ever see, which is precisely the problem the next section describes.

A chain runs across all five. Judging it at one is the characteristic error of this dot point.

What each principle asks at each stage

Read this table as the instrument of the subtopic. The middle column is the question; the right-hand column is the stage where examiners most often set it and the breach that typically appears there.

Principle	The question it asks of a stage	Where it bites hardest, and how it fails
Conservation of biodiversity and ecological integrity	Does this stage reduce species abundance or genetic diversity, or impair the system’s ability to keep its organisation and function and renew itself unaided?	**Extracting** (area cleared, hydrology altered, capture hardware operating) and **transporting** (linear fragmentation). Fails when losses are compensated on paper but the remaining system cannot function without continuing intervention
Efficiency of resource use	Does this stage deliver the same energy service using smaller amounts of physical resources — energy, water, land and materials — while minimising environmental impact?	**Processing** and **using**. Fails through self-consumption, flaring and venting, and matching a high-grade source to a low-grade task (**12F**)
Intergenerational equity	Does this stage leave the resource base and the environment able to serve future generations, or does it move a cost forward in time?	**Extracting** (depletion, voids, tailings) and **using** (long-lived emissions and wastes). Fails whenever the benefit is taken now and the liability matures later
Intragenerational equity	Among people alive now, are the burdens of this stage borne by the same people who receive the benefit?	**Accessing**, **extracting** and **transporting** — burdens are local and rural; the benefit is dispersed and largely metropolitan. Also **using**, through who can afford the service
Precautionary principle	Is the risk of harm from this stage high while the evidence remains uncertain — and if so, have preventive measures been taken and has the *proponent* provided proof of no or minimal harm?	**Accessing**, overwhelmingly, because that is where refusal is still available. Fails when uncertainty is read as permission, or the onus of proof is left with objectors
User pays principle	Do those who use the resource or service pay directly for the amount they use, rather than the cost being shared across a community that did not?	**Extracting** and **using**. Fails when a cost arising at one stage is met by people at another stage, or by the public, or by nobody until it is too late

Three points about this table are worth more than the table itself.

First, **the principles are not independent**. Efficiency of resource use is often the cheapest way to serve all five of the others, because a chain that needs less input has less of every stage.

Second, **the wording of each definition is doing work**. Efficiency of resource use concerns *physical resources*, not only energy, so land and water count. The precautionary principle contains two obligations, not one — take measures, *and* place the proof on the proposer. The user pays principle is about paying for *the amount you use*, which is why an equal charge to everybody can breach it.

Third, **intergenerational and intragenerational equity are separated by time, not by severity**. Both use the words "preserving natural resources and the environment for the benefit of"; the only difference is *future generations* against *the current generation*. Mixing them is the single most common terminology error on this dot point.

Principle 1 — biodiversity and ecological integrity along the chain

The two halves of this principle come apart along a supply chain, and the marks are in the second half. **Conservation of biodiversity** asks how much variety remains — species abundance and richness in the region, genetic diversity within populations. **Ecological integrity** asks whether the system still *works*: whether it holds its biotic and abiotic organisation and function as conditions change, and whether it can renew itself without help.

Stage by stage the mechanism differs, and naming the mechanism is what earns the mark:

- **Accessing** — seismic lines and exploration tracks cause **edge effects** and open corridors for weeds and predators far out of proportion to the area cleared. Marine seismic survey introduces high-intensity noise into a water column.
- **Extracting** — direct habitat loss over the mined or occupied footprint; **altered hydrology**, which for an open cut means depressurising groundwater over an area much larger than the pit; acid and metalliferous drainage from exposed overburden; for biomass, removal of the coarse woody debris and hollow-bearing material that many species depend on; and, where the resource is a flux, the impacts of the capture itself — **collision risk to birds and bats** at an operating wind turbine, and altered flow and thermal regimes and barriers to fish passage at a dam.
- **Processing** — point-source discharges to air and water, thermal discharge, and the impacts of the *material* supply chains for hardware, which usually sit in another jurisdiction entirely.
- **Transporting** — **fragmentation**. A transmission easement or pipeline right-of-way removes a narrow strip but divides a population, and a divided population loses genetic exchange. This is an integrity failure that an area-based accounting will not detect.
- **Using** — for combustion, deposition of nitrogen and sulfur compounds downwind, acidifying soils and waters well beyond the plant boundary; and, once the service ends, the retired hardware itself, whose materials are either recovered or lost.

The instrument that carries this principle in Victoria is the **mitigation hierarchy** — *avoid*, then *minimise*, then *offset* — expressed for native vegetation through **clause 52.17** of planning schemes and the *Guidelines for the removal, destruction or lopping of native vegetation* (2017), and at Commonwealth level through assessment of a **controlled action** under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) where a matter of national environmental significance is significantly affected. The hierarchy is taught at **6A**, **7E** and **8C**; what belongs here is the observation that **it is applied stage by stage, and the stages are approved by different decision-makers at different times**. A project can satisfy the hierarchy at extraction, having avoided and minimised carefully within its mine footprint, and breach it at transport because the easement was assessed years later as a separate permit against a separate baseline. Ecological integrity is a property of a landscape, not of a permit.

The land-occupation comparison, handled honestly. Renewables occupy more land per unit of energy at the extraction stage than thermal plant does; thermal plant imposes its load through a smaller footprint plus emissions, depletion and long-lived residues. Neither observation settles anything on its own, because the *quality* of occupation differs: a wind farm's turbines and tracks physically occupy a small percentage of the land they sit within, and cropping and grazing continue around them, whereas an open cut removes everything within its boundary for decades. Compare **exclusive** occupation with exclusive occupation and **compatible** occupation with compatible occupation, and say which you are doing.

Principle 2 — efficiency of resource use along the chain

The study design's definition is *"use of smaller amounts of physical resources to produce the same product or service while minimising environmental impact"*. Two things follow immediately. It is not the same quantity as conversion efficiency, which **12E** calculates and **12F** bounds; and it is not confined to energy, because **physical resources** include water, land and materials.

Efficiency along a chain compounds, and that is the examinable idea. Each stage passes on only what it does not consume or lose, so the whole-chain figure is the *product* of the stage figures. For a representative black coal chain delivering electricity to a customer:

$$\eta_{\text{chain}} = 0.97 \times 0.92 \times 0.99 \times 0.33 \times 0.91 = 0.265$$

— that is, mine own-use 97 per cent, preparation 92 per cent, rail 99 per cent, generation 33 per cent, transmission and distribution 91 per cent, for about **26.5 per cent** of the coal's chemical energy arriving as electricity at the point of use.

Two decisions follow from that single number. First, **the conversion stage dominates**, so effort spent there returns more than effort spent on haulage. Second, and less obvious, **a unit of energy saved at the using stage avoids about 1 ÷ 0.265 ≈ 3.8 units of primary energy at the extracting stage**. The leverage runs backwards up the chain. **12F** establishes why savings at the end of the chain count most; the point *here* is what that implies for where to regulate — an efficiency requirement imposed on end-use appliances reaches back and reduces extraction, which is why end-use standards are among the most powerful biodiversity and depletion instruments available even though they say nothing about either. The instruments themselves are **13C**'s.

Characteristic efficiency failures by stage:

- **Extracting** — self-consumption of the resource to run the operation, and **fugitive** losses: methane vented or leaked from coal seams and gas infrastructure, and gas **flared** because no market or reinjection option exists. Flaring converts a resource into nothing but carbon dioxide and heat, which is a failure of resource efficiency before it is anything else.
- **Processing** — energy and water consumed to make the fuel usable. Victorian brown coal is roughly 60 per cent water by mass, and evaporating that moisture consumes a large share of the fuel's own chemical energy (**12F**). Refining, liquefaction and enrichment each carry their own parasitic load.
- **Transporting** — resistive losses in transmission, pumping energy in pipelines, and diesel in haulage. For low-energy-density feedstocks such as green biomass, haulage distance can decide whether the chain is worth running at all.
- **Using** — the largest single source of waste in most chains, and almost always a **grade mismatch**: high-quality energy spent on a task needing none of its work potential (**12F**).

Expressed as a ratio of energy returned to energy invested this becomes **EROI**, which is **12D**'s quantity; the framing here is the principle, not the ratio.

Principle 3 — intergenerational equity along the chain

Preserving natural resources and the environment for the benefit of future generations. Energy supply chains breach this principle by a single, consistent mechanism worth stating in one line and then applying: **the benefit is taken in the present and the cost matures in the future.** Every serious intergenerational problem in this dot point is an instance of that asymmetry, and identifying the asymmetry explicitly is what distinguishes a scoring answer from a description.

The asymmetry appears at four stages:

- **Extracting** — a **stock** resource used now is not available later. This is depletion, and **12D** quantifies it. Extraction also creates the physical legacies: open voids, tailings storage facilities that must remain stable indefinitely, depressurised aquifers that take generations to recover, and land whose contamination outlives the company that caused it.

- **Processing** — long-lived residues created in *making* the fuel, distinct from the mine's own waste at extracting. Milling uranium ore leaves tailings whose radium-226 keeps generating radon for thousands of years and which must therefore be contained by people who will never use the electricity; refining, liquefaction and enrichment leave residues of their own.
- **Transporting** — infrastructure with an asset life of fifty years or more, built to serve a present pattern of demand, which either serves future generations well or **locks them in**. A transmission easement acquired now shapes what can be built for a century; a gas distribution network expanded now leaves either a stranded asset or a captive customer base to a generation that may want neither.
- **Using** — emissions and residues that outlast the service they bought. A tonne of carbon dioxide emitted to run an appliance for a decade continues to influence the climate for centuries (**12C**), and the risks it creates are managed at **11B** and **11C**. The clearest case of all is **spent nuclear fuel**: the fuel is consumed in a reactor to make one generation's electricity, and what comes out requires isolation and monitoring over periods vastly longer than any institution has yet survived. Note carefully that this is an intergenerational point about **stewardship duration**, not a claim about accident risk, which is a precautionary matter.

The instrument designed to defeat the asymmetry is the **financial assurance** — a bond or security lodged before disturbance, sized to the full cost of returning the site to its agreed end state, so that the money exists whether or not the operator does. **13A** works the adequacy of Victorian rehabilitation bonds and should be cited rather than repeated. What belongs here is the *logic*: a bond converts a future environmental obligation into a present financial one, which is exactly the transformation intergenerational equity requires. When the security is smaller than the true cost, the transformation is incomplete and the remainder transfers forward regardless of what the licence says.

A caution about time scales. The Area of Study asks for consequences over **short** (seconds to years), **medium** (multiple years to hundreds of years) and **long** (thousands to millions of years) time scales. Attach the scale to the mechanism. Fugitive methane is a short-to-medium-scale problem because methane's atmospheric lifetime is about a decade; carbon dioxide is medium-to-long; a tailings facility or a high-level waste repository is long. A generic "future generations will suffer" earns nothing.

Principle 4 — intragenerational equity along the chain

Preserving natural resources and the environment for the benefit of the current generation. Same sentence as the last principle, different beneficiary: people alive **now**. Along an energy chain the failure mechanism is not deferral but **separation** — the burdens of a stage and the benefits of the chain accrue to different people at the same time.

The separation is structural, not accidental. Accessing, extracting and transporting happen where the resource and the corridor are: in regional and rural areas, on farmland, on the coast and offshore. Using happens where the load is: overwhelmingly in cities. So the community that hosts the mine, the well pad, the easement, the haul road, the dust, the noise and the truck traffic is systematically **not** the community that consumes most of the electricity or fuel. Regional Victoria hosts the generation and transmission that Melbourne's demand requires. The **Western Renewables Link** runs entirely within Victoria — some 190 km of 500 kV line from Bulgana, north of Ararat, to the Sydenham terminal station on Melbourne's north-western fringe — so its easement costs fall on western Victorian landholders while the electricity it carries is consumed overwhelmingly at the metropolitan end of it. **VNI West**, the Victoria–New South Wales interconnector that joins it at Bulgana, spreads its benefits across two states while its burden again falls on the farmland it crosses. Same principle, two different geographies of the same separation.

Four specific intragenerational questions, one per stage, are reliably examinable:

- **Accessing** — who is entitled to say no, and is their consent genuine? Consent comes in grades, and the grade decides the equity outcome. A landholder negotiating a private access agreement can refuse; a neighbour with an objection right under a planning scheme can be heard but cannot refuse; a community with neither has only what the proponent chooses to offer. Statutory approvals sit in the same list, including a heritage permit under the *Heritage Act 2017* (Vic) where a registered place is affected. **A fictitious worked referent.** Take the **Harrowmede Commons**, an invented settlement whose shared grazing and woodland commons is protected by an invented statutory instrument, the **Commons Protection Statement**, which a proponent must prepare jointly with the Harrowmede community and have approved before high-impact work may begin. Both the community and the instrument are fictitious inventions of this workbook and represent no real community, culture or heritage law. The examinable point they carry is structural: an instrument requiring *agreement with the affected community before approval* turns an equity question into a consent question at the one stage where refusal is still cheap, whereas a duty merely to consult leaves the burden exactly where it fell.

- **Extracting and transporting** — is the host community compensated at a level that reflects what it bears, and does it receive any of the benefit? Landholder payments along easements, community benefit funds and local employment and procurement commitments are the instruments; whether they are proportionate is the evaluation.
- **Processing —** where does the hardware come from, and under what conditions? A chain that is clean at every Australian stage but depends on mining and refining elsewhere has not upheld intragenerational equity; it has **relocated** the question.
- **Using —** can everybody actually afford the service? Electricity is an essential service, and the same price rise is not the same burden across households. The **Essential Services Commission** administers the **Energy Retail Code of Practice**, whose payment difficulty framework obliges retailers to offer assistance before disconnection is contemplated. The deeper failure is structural: the households facing the highest bills are frequently renters and apartment dwellers who cannot install the rooftop system or the heat pump that would insulate them, so a program that lowers average costs can still widen the gap. The mechanism is worked at **13C** and the stakeholder dimension at **13D**.

Principle 5 — the precautionary principle along the chain

The study design's definition is unusually specific and should be learned as three conditions and two obligations. It *"is triggered when the risk of harm to the environment due to a proposed action is high but the scientific evidence is uncertain, requiring that measures be taken to prevent environmental damage and that the proof of no, or minimal, harm be provided by the proposer"*.

The trigger has two limbs and both must be present: high risk of harm **and** uncertain evidence. This is where most answers go wrong. Where harm is established rather than uncertain, the operative principle is conservation of biodiversity and ecological integrity, or user pays — not precaution. Where the risk is trivial, uncertainty alone does not trigger anything. And the **reversal of the onus of proof** is half the principle: the proponent must demonstrate no or minimal harm, rather than an objector being required to demonstrate harm. An answer that omits the onus reversal has given half the definition.

Precaution is the accessing-stage principle. This is the structural insight of the subtopic. Uncertainty is greatest before anything has been built, and that is also the only moment at which refusing, deferring or staging the decision costs little. Once wells are drilled, capital is sunk, contracts are signed and a workforce is employed, the same decision carries a very different price, and the practical effect is that precaution stops being available. So precaution is the principle that decides **whether the chain starts at all**, and its instruments cluster at the front:

- **Environmental assessment before approval** — an **environment effects statement** under the *Environment Effects Act 1978* (Vic) for projects capable of significant environmental effects, and assessment of a controlled action under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth). Both place the burden of investigation and documentation on the proponent, which is the onus reversal made operational.
- **A general, forward-looking duty rather than a fixed limit.** Under the *Environment Protection Act 2017* (Vic), in force from 1 July 2021, a person conducting an activity that may give rise to risks of harm to human health or the environment from pollution or waste owes the **general environmental duty** — to eliminate or minimise those risks *so far as reasonably practicable*. **3B** establishes why this is a precautionary instrument; what matters along a supply chain is *where* it reaches, which is every stage that generates pollution or waste, and that it binds whether or not a specific limit has been set for the substance in question. It does not wait for the evidence to become certain.
- **Prohibition, where the risk is judged unacceptable.** Victoria's bans on hydraulic fracturing and coal seam gas exploration and production are the strongest precautionary instruments in the Australian energy sector, and are set out with their entrenchment and their limits at **12A** — including the point that the moratorium on onshore *conventional* gas was lifted while the unconventional prohibitions were not.

- **Staging and reversibility.** Trial and pilot phases, adaptive licence conditions, and monitoring with pre-committed triggers all allow a chain to proceed while keeping the option to stop.

Two errors to avoid. **Precaution is not prohibition** — proportionate preventive measures satisfy it, and a proposal can be approved precautionarily with conditions. And precaution **is not a general licence to refuse**: the trigger requires a high risk of harm, and an answer must say what the potential harm is and why the evidence about it is uncertain.

Principle 6 — the user pays principle along the chain

Calls upon the user of a service or resource to pay directly for the amount they use, rather than the cost being shared by all the users or a community equally. The principle has a precise structure: payment should be **direct**, and **proportionate to the amount used**. A flat charge unrelated to consumption breaches it even if everyone pays something.

Along a supply chain, user pays fails by externalisation: a cost arises at one stage and is met by somebody at a different stage, or by the public, or by nobody at all until the bill can no longer be avoided. Name the stage where the cost arose and the party who actually paid, and the analysis is most of the way done.

- **Accessing and extracting** — royalties, licence fees and financial assurances are the mechanisms by which a producer pays for the resource and for the state it leaves the land in. Where a bond is set below the true cost, the shortfall is a transfer to the public.
- **Processing and transporting** — network tariffs and access charges. These are also where user pays and intragenerational equity collide, because network costs are largely **fixed**: as some customers reduce their volumetric consumption, the same fixed cost is recovered over a smaller volume and the unit charge rises for everyone else. That is worked at **13C**.
- **Using** — fuel excise, road user charges, tariffs and, where they exist, carbon prices. A **volumetric** charge upholds user pays; a **fixed** charge does not.

Distinguish user pays from polluter pays. They are not synonyms, and the difference is examinable. User pays asks the *user of a resource or service* to pay for *the amount they use*. Polluter pays asks the *party who caused harm* to pay for *the harm*. A chain can satisfy one and breach the other. The clearest Australian illustration is the **Northern Endeavour**, a floating production, storage and offtake facility serving the Laminaria and Corallina oil fields in Commonwealth waters. When its owner was placed into liquidation in February 2020, neither the company nor its security could meet the cost of decommissioning, and the Commonwealth assumed responsibility for the facility and the wells. The Commonwealth then recovered the cost through the *Offshore Petroleum (Laminaria and Corallina Decommissioning Cost Recovery Levy) Act 2022* (Cth): a temporary levy of **48 cents per barrel of oil equivalent**, administered by the Australian Taxation Office, payable by holders of offshore petroleum production licences on the petroleum they recover under those licences in Commonwealth waters, imposed for the financial years beginning 1 July 2021 through to 1 July 2029.

Work out what that instrument does and does not achieve, because it is a model answer in itself. It **repairs user pays at the level of the industry** — the cost of decommissioning offshore petroleum infrastructure is met by offshore petroleum producers rather than by taxpayers generally, and it is levied volumetrically, per barrel, so it is proportionate to use. It **does not deliver polluter pays at the level of the firm**, because the company that produced the oil, took the profit and left the liability is gone, and the levy falls on competitors who did nothing wrong and on their customers through prices. And it is a **retrospective** correction: the cost had already transferred before the instrument existed, which is the intergenerational point — a liability created by one period's production is paid for out of a later period's. The precautionary reading is that the security should have been set at the full estimated cost of decommissioning from the outset, with the onus on the titleholder to demonstrate it was sufficient.

Displacement: the error that costs the most marks

Almost every weak response to this dot point makes the same mistake, and it is worth a name. **Displacement** is judging a chain at the stage where it looks best, when the principle load has moved to a stage the evaluation did not examine.

The stage most people see is **using**, so that is where displacement usually hides:

- An **electric vehicle** or a **rooftop solar panel** is genuinely close to impact-free at the using stage. Its principle load sits at **processing** — polysilicon smelting, cell and cathode manufacture, all energy-intensive and mostly performed on grids more emissions-intensive than Australia's — and at **extracting**, in the mining of lithium, nickel, cobalt, copper and rare earth elements, with the intragenerational equity questions those raise wherever the mining occurs. The correct conclusion is not that the technology is bad; it is that the claim must be stated at the stage it is true and evaluated across all five.
- A **"100 per cent renewable" retail electricity contract** changes the accounting of the using stage and changes nothing physical at any stage. **12F** makes the thermodynamic version of this point.
- **Biomass described as carbon neutral** is neutral only if the carbon is actually re-sequestered on a matched time scale, which is a claim about the extracting stage, not the using stage (**12B**, **12C**).
- Conversely, coal is often judged only at using and extracting, where its record is worst, while its *fuel-haulage* limb — a conveyor from the mine to the boiler beside it — is genuinely benign. Say which limb you mean, because the same chain's *network* limb, the transmission and distribution that carries the electricity to the load, is no better than any other electricity chain's. Displacement cuts both ways, and an even-handed answer says so.

The discipline that defeats displacement is mechanical: **state the stage with every claim**. "Low emissions at the point of use, with the emissions load displaced to processing" is a scoring sentence. "Low emissions" is not.

Three chains compared, stage by stage

Use this table as a worked model of the analysis, not as content to memorise. Each cell names the *principal* principle stress at that stage — there are always others.

Stage	Latrobe Valley brown coal → electricity	Offshore gas → electricity and heat	Utility solar + battery → electricity
Accessing	Licensing and work plan approval; resource long known, so uncertainty is low and precaution is weakly engaged	Seismic survey noise in a marine environment; genuine evidential uncertainty, so **precaution** is strongly engaged	Planning permit, grid connection, native vegetation and heritage approvals; land access by agreement rather than compulsion
Extracting	**Biodiversity and integrity** — large exclusive footprint, groundwater depressurisation; **intergenerational** — void and depletion	**Intergenerational** — depletion of a stock; **user pays** — decommissioning liability created here	**Biodiversity** — large but largely non-exclusive footprint; no depletion, since the flux is not a stock
Processing	**Efficiency** — about 60 per cent moisture must be driven off, consuming the fuel's own energy	**Efficiency** — conditioning and compression parasitic load; **user pays** — fugitive and flared gas priced by nobody	**Intragenerational and efficiency** — the load sits offshore in polysilicon, cell and cathode manufacture
Transporting	Two limbs. Fuel: a short conveyor from mine to boiler, genuinely efficient.	Two limbs. Pipelines; **biodiversity** — linear fragmentation along the	**Biodiversity and intragenerational** — new transmission fragments

Stage	Latrobe Valley brown coal → electricity	Offshore gas → electricity and heat	Utility solar + battery → electricity
	Electricity: **efficiency** — 8–10 per cent dissipated across transmission and distribution to Melbourne; **biodiversity** — easement fragmentation	right-of-way. Electricity: the same transmission and distribution losses and easements as any other chain	habitat and concentrates costs on host landholders; the same 8–10 per cent network loss applies
Using	**Intergenerational** — highest carbon dioxide per unit electricity of any source; **efficiency** — low conversion efficiency	**Intergenerational** — lower but substantial emissions; **efficiency** — good, especially where heat is cascaded	**Efficiency** — high; **intergenerational** — retired panels and cells are the chain's least resolved residue

Read the rows, not the columns, and the lesson appears: **no chain is uniformly good or bad, and the stages where each is strongest are different**. Brown coal's *fuel* haulage is as short as haulage gets; solar's processing stage is its weakest; offshore gas engages precaution at a stage where coal barely does. That is why the dot point names five stages instead of asking which source is best.

Note what the transporting row required to be comparable. All three chains deliver electricity to a load, so all three carry a transmission and distribution limb, and charging that limb to solar alone would have made brown coal's transport stage look excellent by an accounting choice rather than by a result. **Compare chains on the same boundaries**, or the comparison measures the boundary instead of the chain.

Where the principles conflict

Six tests applied to one decision will not all point the same way, and questions worth six marks and above usually turn on the conflict rather than the compliance. Four conflicts recur.

Precaution against intragenerational equity. Prohibiting or deferring an extractive industry protects an uncertain environmental value and simultaneously removes employment and income from the region that would have hosted it. The people protected and the people who bear the cost are both alive now.

Intergenerational against intragenerational equity. Requiring full-cost financial assurance, or retiring a plant early, protects future generations and raises present costs — which fall hardest on the households least able to absorb them. Almost every decarbonisation decision has this shape.

Efficiency of resource use against biodiversity. The most efficient site is usually the windiest ridge, the sunniest plain or the shortest transmission route, and those are frequently the sites of greatest ecological value. Efficiency pushes towards concentration; biodiversity often requires avoidance.

User pays against intragenerational equity. Strict user pays, applied to an essential service, charges a low-income household the full cost of the electricity it cannot do without. This is the standard argument for concessions and payment-difficulty protections, and it is a genuine breach of user pays accepted on equity grounds — which is the honest way to describe it.

When you find a conflict, **name both principles, say which stage the conflict arises at, and say which one you are giving priority to and why**. Value systems decide that priority, and value systems are **3C**; declaring the trade-off is what the marks are for. Never resolve a conflict by pretending it is absent.

The four-move routine

Every question on this dot point yields to the same sequence.

1. **Locate the stage.** Which of accessing, extracting, processing, transporting or using does the information concern? If a claim is made without a stage, supply the stage.

2. **Name the principle, in the study design's words.** Use the exact term. "Fairness to people later" is not intergenerational equity for marking purposes.
3. **State the mechanism.** How, causally, does this stage uphold or breach that principle? Groundwater depressurisation over an area larger than the pit; a bond below the true cost; a fixed charge unrelated to consumption. The mechanism is the mark.
4. **Check the other four stages for displacement, then check for conflict.** Has the load moved somewhere the claim did not look? Does another principle now point the other way?

For an evaluation, add a fifth move: **reach a judgement and name the assumption it depends on.**

Common errors

- **Defining the principles instead of applying them.** The definitions are 3B's. Marks here are for the join between a principle and a stage.
- **Treating accessing and extracting as one stage.** They have different impacts, different approvals and different principles biting hardest — precaution at accessing, biodiversity and equity at extracting.
- **Confusing intergenerational with intragenerational equity.** Time separates them.
- **Giving half the precautionary principle.** Both trigger limbs, and both obligations, including the reversal of the onus of proof onto the proposer.
- **Treating user pays as polluter pays.** Amount used, not harm caused.
- **Omitting the processing stage** for renewables and omitting the transporting stage for electricity. Every electricity chain has a network limb, so charging it to one column of a comparison and not the others makes the comparison measure the boundary rather than the chain.
- **Asserting that renewables have no extraction stage.** Capturing a flux is extraction under this dot point and occupies land.
- **Filing the capture hardware's impacts at *using*.** Blade strike at a turbine and barriers to fish passage at a dam arise where the flux is captured, so they are **extracting**; combustion in a boiler, furnace, engine or reactor is where a fuel is consumed, so its emissions and its conversion efficiency are **using**.
- **Inventing a sixth stage.** There is no "end of life" stage. Retired hardware is a residue of **using**, and the materials in it were taken at extracting and processing.
- **Resolving conflicts silently.** If two principles disagree, say so and say which you prefer.

Worked examples

The organisations named below are fictional; the principles, quantities, schemes, agencies and legislation are real.

Example 1 — scaffolded

For each statement, identify the supply chain stage it concerns and the sustainability principle most directly engaged, and justify your choice: (i) "The company's exploration programme cut 40 km of seismic lines through remnant woodland." (ii) "Raw gas is compressed before entering the pipeline, consuming about 3 per cent of the gas produced." (iii) "The rehabilitation bond was set at one-tenth of the estimated closure cost." (iv) "Marine seismic survey may affect whale migration, but the evidence is inconclusive." *(4 marks)*

Working	Comment
(i) **Accessing**; **conservation of biodiversity and ecological integrity**. Seismic lines fragment remnant woodland and create edges that admit weeds and predators, impairing the system's capacity for self-renewal.	Exploration is *accessing*, not extracting — nothing has been removed. The integrity limb matters more than the area cleared.
(ii) **Processing**; **efficiency of resource use**. Energy consumed to make the resource transportable is a physical resource used without producing any additional	Compression before transport sits at the processing–transporting boundary; either is acceptable if justified.

Working	Comment
energy service.	
(iii) **Extracting**; **intergenerational equity** (and **user pays**). A bond below true cost leaves the difference to be met by a future public rather than by the operator that created the liability.	Both principles are legitimately available. The stage is *extracting*, because that is where the liability is created.
(iv) **Accessing**; the **precautionary principle**. Both trigger limbs are present — potentially serious harm and uncertain evidence — so preventive measures are required and the proponent must show no or minimal harm.	Contrast with (i), where the harm is established rather than uncertain, so precaution is *not* the operative principle.

Example 2 — scaffolded

Sarrowmoor Bioenergy Pty Ltd burns plantation harvest residue. For every 100 GJ of chemical energy in residue collected at the coupe, 8 GJ of that residue is burnt to dry the remainder; chipping consumes 1.2 GJ of electricity and haulage over 140 km consumes 2.4 GJ of diesel. The station converts the delivered fuel to sent-out electricity at 26 per cent. (a) Calculate the electricity sent out. (b) Calculate the net energy delivered after external inputs, and express it as a percentage of the residue collected. (c) Identify which principle these figures test, and at which stages. (d) State the condition on which the chain's intergenerational equity depends, and one condition on which its intragenerational equity depends. *(6 marks)*

Working	Comment
(a) Fuel delivered to the boiler = 100 − 8 = **92 GJ**. Electricity sent out = 0.26 × 92 = **23.92 GJ**.	The drying energy comes out of the resource itself, so subtract it before applying the conversion efficiency. Applying 26 per cent to 100 GJ is the standard error.
(b) External inputs = 1.2 + 2.4 = 3.6 GJ. Net energy = 23.92 − 3.6 = **20.32 GJ**, which is 20.32 ÷ 100 = **20.3 per cent** of the residue collected.	Chipping electricity and haulage diesel are inputs from outside the chain and must be counted separately from the fuel's own self-consumption.
(c) **Efficiency of resource use**, tested at **processing** (the 8 GJ of drying and 1.2 GJ of chipping), **transporting** (2.4 GJ of diesel over 140 km) and **using** (the 26 per cent conversion, the dominant loss).	Haulage distance is the variable that most easily decides whether a low-density feedstock chain is worth running. As a ratio of return to investment this is EROI, which is **12D**'s quantity.
(d) **Intergenerational equity** depends on the harvested plantation actually being **replanted and regrown**, so the carbon is re-sequestered on a time scale matched to its release, and on sufficient coarse woody debris being left on site to maintain soil carbon and habitat. **Intragenerational equity** depends on the burden borne by communities along the 140 km haul route — truck movements, noise, dust, road wear — being matched by benefit, through local employment, procurement or road funding.	Unreplanted harvest makes the emission permanent, which converts a renewable chain into a depleting one.

Example 3 — unscaffolded

A retailer advertises a household battery as "completely sustainable — zero emissions, zero fuel, zero impact". Evaluate this claim using sustainability principles across the energy supply chain. *(5 marks)*

The claim is **true of one stage and asserted of all five**, which is the defining error of this dot point.

At the **using** stage the advertisement is essentially accurate. A battery discharging into a household circuit produces no combustion products, consumes no fuel and has no local emissions, and its round-trip losses appear as a small amount of low-grade heat. Judged there and only there, "zero emissions" is fair.

The principle load has been **displaced upstream to processing and extracting**, and the advertisement is silent about both. **Processing** — cell manufacture, cathode production and the refining of lithium, nickel, cobalt, graphite and copper are highly energy-intensive and are mostly carried out on electricity grids more emissions-intensive than Australia's, so the product embodies emissions that were real, merely elsewhere. **Extracting** — those same materials are mined, with the habitat loss, water demand and community impacts mining entails, raising **intragenerational equity** questions wherever it occurs and, because the ore bodies are stocks, **intergenerational equity** questions too. "Zero impact" is not a defensible statement about either stage.

Two further principles are engaged that the claim does not address. **Efficiency of resource use** is not zero-cost: every stored kilowatt hour is subject to round-trip loss, so storage always returns less than it takes (**12F**), and the materials themselves are physical resources within the study design's definition. **Intergenerational equity** also reaches the battery's **end of life** — which is not a sixth stage but a residue of **using**: whether the cells are recycled or landfilled determines whether the materials remain available to a later generation, and it is the least resolved part of the whole chain.

A fair evaluation says what the product is good for. A household battery genuinely reduces emissions over its life where it shifts self-generated solar into the evening peak and displaces gas or coal generation, and its upstream load is incurred once while the benefit recurs daily for a decade or more. The correct verdict is that the **advertisement is misleading and the product may still be worthwhile** — and the way to say so is to attach a stage to every claim. *Takeaway:* "zero emissions **at the point of use**, with the emissions load displaced to processing and extraction" is both honest and worth marks.

Example 4 — unscaffolded

Tannerook Petroleum Pty Ltd operated an offshore field in Commonwealth waters, produced petroleum for 14 years, and was placed into liquidation leaving a floating facility and 11 wells to be made safe. The estimated decommissioning cost is $780 million; the security held by the regulator is $60 million. The Commonwealth completes the work and recovers the shortfall through an industry-wide levy of 48 cents per barrel of oil equivalent on all offshore petroleum production. Calculate the production the levy must be applied to, and evaluate the arrangement against the user pays, intergenerational equity and precautionary principles. *(6 marks)*

Shortfall = 780 − 60 = **$720 million**. At $0.48 per barrel of oil equivalent, the production required is 720 000 000 ÷ 0.48 = **1.5×10^9 barrels of oil equivalent** — 1.5 billion boe of offshore production levied to cover one operator's default.

User pays — partly upheld, and at the wrong level. The principle asks the user of a resource to pay directly for the amount they use. The levy is genuinely **volumetric**, charged per barrel, so as between the producers who pay it the cost is proportionate to use, and it keeps the cost inside the offshore petroleum industry rather than sending it to taxpayers generally. But the party that used the resource, took the revenue and created the liability is **Tannerook**, and Tannerook has paid $60 million of a $780 million cost. The levy therefore restores user pays **at the level of the industry** while leaving it breached **at the level of the firm** — and this must be distinguished from **polluter pays**, which asks the party who caused the harm to pay for the harm and which the arrangement plainly does not deliver. Competitors that did nothing wrong, and their customers through prices, meet the balance.

Intergenerational equity — breached, then partly repaired. The liability was created across 14 years of production and is met afterwards, out of a later period's output, by producers and consumers who received none of the benefit. That is the standard asymmetry of this principle: the benefit was taken in one period and the cost matured in another. The levy repairs it only in the sense that the cost is eventually paid by somebody other than the general public.

Precautionary principle — the failure that caused all of this, and it sat at the accessing stage. The risk that a titleholder would be unable to meet decommissioning costs was foreseeable and the eventual cost was uncertain, which is exactly the trigger. The precautionary response is to require **financial assurance sized to the full estimated cost, reviewed as the estimate changes, with the onus on the titleholder to demonstrate that the security is sufficient** — the onus reversal that the definition requires. A security at under 8 per cent of cost meant the obligation existed on paper and the money did not.

Takeaway: the real Australian instance is the **Northern Endeavour**, recovered through the *Offshore Petroleum (Laminaria and Corallina Decommissioning Cost Recovery Levy) Act 2022* (Cth), and its lesson is that a liability created at one stage of a chain does not disappear when a company does — it simply changes who pays.

Practice questions

Scaffolded

Q1. State each of the following: (a) the five stages of an energy supply chain named in the study design; (b) the difference between intergenerational and intragenerational equity; (c) the two conditions that together trigger the precautionary principle. *(3 marks)*

Q2. A company undertakes an airborne geophysical survey and drills three exploration wells. (a) Identify which supply chain stage this activity belongs to. (b) Explain why this stage, rather than any later stage, is where the precautionary principle principally operates. (c) State the two obligations the precautionary principle imposes once triggered. (d) Identify one Victorian and one Commonwealth instrument that place the burden of environmental investigation on the proponent. *(4 marks)*

Q3. A black coal chain has the following stage efficiencies: mine own-use 96 per cent; coal preparation 90 per cent; rail haulage 99 per cent; generation 34 per cent; transmission and distribution 92 per cent. (a) Calculate the whole-chain efficiency, expressed as a percentage. (b) Identify the stage responsible for the largest single loss. (c) Calculate how many units of chemical energy in coal must be extracted for one unit of electricity delivered to a customer. (d) Using your answer to (c), explain why an efficiency standard applied to household appliances is also a biodiversity and depletion measure. (e) State which sustainability principle these calculations test, and why land and water fall within it. *(5 marks)*

Q4. Glenmarrick Transmission Pty Ltd proposes a 165 km overhead transmission line across farmland and remnant woodland to connect a new renewable energy zone to the grid. (a) Identify the supply chain stage. (b) Explain why the ecological signature of this stage is fragmentation rather than area loss, and why an area-based assessment may not detect the harm. (c) Name the mitigation hierarchy and state its three steps in order. (d) Explain why the host landholders raise an intragenerational equity question rather than an intergenerational one. (e) State one instrument that could address the equity concern in (d). *(5 marks)*

Q5. Pethwick Fuels Pty Ltd operates a refinery. Its licence sets no numerical limit for a solvent vapour it has begun emitting, and the health effects of that solvent at ambient concentrations are not well characterised. (a) Identify the supply chain stage. (b) Explain why the absence of a numerical licence limit does not mean the company has no obligation, naming the relevant Victorian duty and the Act that creates it. (c) Explain why this duty is properly described as a precautionary instrument. (d) State the standard to which the duty requires risks to be eliminated or minimised. (e) Identify one sustainability principle other than precaution that is engaged, and state the stage at which it arises. *(6 marks)*

Q6. Wraybourne Storage Pty Ltd markets a grid-scale battery system as “emissions-free energy”. (a) Identify the stage at which the claim is accurate. (b) Identify the two stages to which the principle load has been displaced, and state the impact arising at each. (c) Explain why round-trip losses mean efficiency of resource use is engaged even though no fuel is burnt. (d) The system will eventually be retired. Identify which of the five stages carries the intergenerational equity question its retirement raises, and state that question. (e) State the general rule that this question illustrates, and write one sentence that states the company’s claim accurately. *(6 marks)*

Unscaffolded

Q7. State the user pays principle. *(1 mark)*

Q8. Explain why the statement “solar power has no extraction stage” is incorrect. *(2 marks)*

Q9. Distinguish between the user pays principle and the polluter pays principle, using an energy example. *(2 marks)*

Q10. Explain why a rehabilitation bond set below the true cost of closure breaches intergenerational equity even though the licence requires rehabilitation. *(3 marks)*

Q11. Explain why the burdens of the accessing, extracting and transporting stages of Victorian electricity supply, and the benefits of the using stage, fall on different populations, and name the principle engaged. *(3 marks)*

Q12. A gas producer flares gas at the wellhead because no pipeline connection exists. Identify the stage and evaluate the practice against two sustainability principles. *(4 marks)*

Q13. *(Stimulus.)* Halstenmoor Renewables Pty Ltd publishes the following statement about a proposed wind farm.

> **Stimulus.** "This project is fully sustainable. It burns no fuel, emits nothing, and will supply 90 000 homes. Because the turbines sit on grazing land that remains in production, the project has no environmental impact whatsoever."

Identify two stages at which the claim that the project has "no environmental impact whatsoever" is false, and state the principle engaged at each. *(4 marks)*

Q14. Explain why the precautionary principle is more readily applied at the accessing stage of a supply chain than at the extracting or using stages, and state one consequence of that fact for how energy decisions should be sequenced. *(4 marks)*

Q15. A regulator must choose between two sites for a solar farm. Site A is the sunnier and lies 8 km from an existing substation; it contains 60 ha of a threatened grassland community. Site B receives 6 per cent less solar radiation, requires 45 km of new transmission line, and is cleared pasture. Analyse the choice using sustainability principles across the supply chain, and identify the conflict the regulator cannot avoid. *(5 marks)*

Q16. An offshore petroleum titleholder is placed into liquidation, leaving decommissioning obligations estimated at $640 million against a security of $48 million. The shortfall is recovered by a levy of 48 cents per barrel of oil equivalent on all offshore production. Calculate the production the levy must be applied to, and explain in what sense the arrangement upholds the user pays principle and in what sense it does not. *(5 marks)*

Q17. Compare the conservation of biodiversity and ecological integrity principle with the efficiency of resource use principle as they apply across an energy supply chain, referring to what each principle requires, the stage at which each bites hardest, the mechanism by which each is typically breached, and one situation in which the two point in opposite directions. *(6 marks)*

Q18. *(Stimulus.)* Dellamont Shire Council has published a sustainability statement for a proposed biomass plant.

> **Stimulus.** "1. The plant is carbon neutral, because the fuel is biomass. 2. There is no extraction impact, because we are using waste residue that would otherwise be burnt in the open. 3. Uncertainty about the effect of residue removal on soil carbon is not a reason to delay, because no study has yet demonstrated harm. 4. Costs will be recovered through a flat annual levy of $85 on every rateable property in the Shire, which satisfies the user pays principle. The plant will be built 60 km from the Shire's main town, in the Shire's smallest settlement."

Evaluate this statement using sustainability principles across the energy supply chain. *(8 marks)*

Q19. Dellamont Shire Council must supply 42 000 GJ per year of heat and electricity to its aquatic centre, depot and offices, and is choosing between three options: extending the existing reticulated natural gas supply; a biomass boiler fuelled by residue hauled 130 km; and a rooftop and ground-mounted solar array with a battery, imported and installed. For each option, evaluate the chain across the five stages against the sustainability principles, identify the principal conflict, recommend one option with justification, and state one limitation of your recommendation. *(10 marks)*

Answers

Q1. (a) **Accessing, extracting, processing, transporting and using.** (b) Both concern preserving natural resources and the environment for the benefit of a group; **intergenerational** equity concerns **future generations**, **intragenerational** equity concerns the **current generation**. (c) The risk of harm to the environment from the proposed action is **high**, **and** the scientific evidence is **uncertain** — both limbs are required.

Q2. (a) **Accessing** — exploration and appraisal, before any resource is removed. (b) Uncertainty is greatest before anything is built and the option not to proceed is still cheap; once capital is sunk and contracts and employment are in place, the same decision carries a very different cost and precaution ceases to be practically available. (c) Take **measures to prevent environmental damage**, and require the **proof of no, or minimal, harm to be provided by the proposer**. (d) Victorian: an **environment effects statement** under the *Environment Effects Act 1978* (Vic). Commonwealth: assessment of a **controlled action** under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth).

Q3. (a) 0.96 × 0.90 × 0.99 × 0.34 × 0.92 = **0.2676, or about 26.8 per cent**. (b) **Generation**, at 34 per cent. (c) 1 ÷ 0.2676 = **about 3.7 units** of coal energy per unit of electricity delivered. (d) Because the leverage runs backwards up the chain: one unit saved at the using stage avoids about 3.7 units of extraction, so an end-use standard reduces the area mined, the groundwater drawn down and the stock depleted without mentioning any of them. (e) **Efficiency of resource use** — the definition refers to *physical resources*, not only energy, so land, water and materials are within it.

Q4. (a) **Transporting.** (b) The easement removes a narrow strip but divides populations either side of it; a divided population loses genetic exchange and the system loses integrity, which an assessment counting only hectares removed will not detect. (c) The **mitigation hierarchy**: **avoid**, then **minimise**, then **offset**. (d) Because the landholders bearing the cost and the customers receiving the electricity are all alive now — the burden and benefit are separated in **space**, not in time. (e) Any one of: landholder easement payments proportionate to impact; a community benefit fund; local employment and procurement commitments; undergrounding or rerouting to reduce the burden.

Q5. (a) **Processing.** (b) Under the *Environment Protection Act 2017* (Vic) the company owes the **general environmental duty**, which applies to risks of harm to human health or the environment from pollution or waste whether or not a numerical limit has been set. (c) Because it does not wait for the evidence to become certain or for a limit to be prescribed — it obliges the duty holder to act on a risk that is still uncertain, and places the responsibility on the person conducting the activity. (d) **So far as reasonably practicable.** (e) **Intragenerational equity**, arising at **processing**: the health burden of the emission falls on the community around the refinery, not on the users of the fuel. (Efficiency of resource use, at processing, is also acceptable — solvent lost to air is a resource lost.)

Q6. (a) **Using.** (b) **Processing** — energy-intensive cell and cathode manufacture and metal refining, largely on more emissions-intensive grids; and **extracting** — mining of lithium, nickel, cobalt, graphite and copper, with habitat loss, water demand and community impacts. (c) Because storage returns less than it takes: round-trip losses degrade some of every stored unit to low-grade heat, and the materials themselves are physical resources within the definition. (d) **Using** — the retired cells are a residue of the using stage, since there is no separate end-of-life stage among the five. The question is whether they are recycled, returning the lithium, nickel, cobalt and copper to a later generation, or landfilled, removing them permanently. (**Extracting** is also creditable where the answer is framed as depletion of the stocks those metals came from.) (e) Attach a stage to every claim. For example: "Emissions-free **at the point of use**, with the emissions load displaced to processing and extraction."

Q7. It calls upon the user of a service or resource to pay directly for the amount they use, rather than the cost being shared by all the users or a community equally.

Q8. Capturing a natural flux is the extraction stage for a renewable chain: a panel intercepts sunlight over an area, and that area is occupied and its previous land use displaced. What is absent is **depletion of a stock**, not extraction itself.

Q9. User pays asks the *user of a resource or service* to pay directly for *the amount they use*; **polluter pays** asks the *party that caused harm* to pay for *the harm*. A volumetric electricity tariff delivers user pays; requiring the operator of a defaulted offshore field to fund its own decommissioning would deliver polluter pays, and an industry-wide levy that spreads the cost across other producers delivers the first without the second.

Q10. The licence creates the obligation but the bond is what makes the money exist independently of the operator. If the security is less than the cost and the operator does not or cannot complete the work, the difference is met by a future public — so the benefit is taken now and the cost matures later, which is exactly the asymmetry intergenerational equity forbids.

Q11. The resource, the corridor and the site are in regional and rural areas, so accessing, extracting and transporting impose dust, noise, traffic, land occupation and fragmentation locally; the load is overwhelmingly metropolitan, so the benefit of the using stage is dispersed elsewhere. The burdens and benefits are separated in space among people alive now, which engages **intragenerational equity**.

Q12. Extracting (at the wellhead). **Efficiency of resource use** — the gas is a physical resource converted to nothing but carbon dioxide and heat, producing no energy service at all, which is the most complete failure of this principle available. **Intergenerational equity** — a finite stock resource is permanently destroyed and its carbon released, so a future generation loses both the gas and the atmospheric budget. (**User pays** is also creditable: the atmospheric cost is borne by nobody.)

Q13. Any two of: **processing** — manufacture of towers, blades, nacelles, magnets and cabling is energy- and materials-intensive, engaging **efficiency of resource use** and, where the materials are mined and refined overseas, **intragenerational equity**; **transporting** — new transmission and access tracks fragment habitat, engaging **conservation of biodiversity and ecological integrity**, and concentrate costs on host landholders, engaging **intragenerational equity**; **extracting** — the operating turbines carry collision risk to birds and bats, which the grazing-compatibility point does not answer, engaging **conservation of biodiversity and ecological integrity**.

Q14. Because at accessing the evidence is most uncertain and the option not to proceed is still inexpensive, so both trigger limbs are live and preventive measures remain available; by extracting and using, capital is sunk, contracts and employment are in place, and the harm is often established rather than uncertain, so the operative principles change and refusal carries a cost that makes it unlikely. The consequence is that **assessment, evidence-gathering and the reversal of the onus of proof must be completed before approval**, because a precautionary decision deferred to a later stage is effectively a decision not to be precautionary.

Q15. Site A: better **efficiency of resource use** (more output per unit of panel, land and materials; 8 km of line rather than 45 km) but it destroys 60 ha of a threatened grassland community, breaching **conservation of biodiversity and ecological integrity** at the extracting stage — and a grassland community is very difficult to offset in a way that restores integrity rather than area. Site B: upholds biodiversity at extracting on already-cleared land, but 45 km of new easement moves the biodiversity cost to the **transporting** stage as fragmentation, raises the **intragenerational equity** burden on landholders along the route, and costs 6 per cent of output plus the materials for the line. **The unavoidable conflict is efficiency of resource use against conservation of biodiversity and ecological integrity**: efficiency pushes towards the sunniest, closest site, which is the ecologically valuable one. Site B is generally preferable because grassland integrity, once lost, cannot be reconstructed, whereas fragmentation along an easement can be reduced by routing and design.

Q16. Shortfall = 640 − 48 = **$592 million**; production required = 592 000 000 ÷ 0.48 = **1.233×10^9 barrels of oil equivalent** (about 1.23 billion boe). It **upholds** user pays in that the levy is volumetric, so cost is proportionate to the amount produced, and the cost stays within the industry that uses the resource rather than falling on taxpayers generally. It **does not** uphold it in that the titleholder that used the resource and took the revenue paid only $48 million of a $640 million cost, so the burden falls on other producers and their customers, who did not create it — user pays restored at industry level, still breached at firm level, and polluter pays not achieved at all.

Q17. Biodiversity and ecological integrity requires species abundance, genetic diversity and a system that keeps its organisation and function and can self-renew; efficiency of resource use requires the same service from smaller amounts of physical resources — energy, water, land and materials. Biodiversity bites hardest at **extracting** (area occupied, hydrology altered) and **transporting** (linear fragmentation); efficiency at **processing** (self-consumption, flaring) and **using** (the largest loss in most chains). Biodiversity is typically breached through the **integrity** limb — offsets replace area but leave a system that cannot function unaided; efficiency through **grade mismatch** and loss compounding along the chain. They oppose each other when the most efficient site — windiest ridge, sunniest plain, shortest corridor — is also the ecologically valuable one: efficiency favours concentration, biodiversity requires avoidance.

Q18. Claim 1: carbon neutrality is conditional on the harvest being **regrown on a matched time scale**, which is an extracting-stage condition, not a property of the word "biomass". Claim 2: ignores the extracting stage — coarse woody debris is not waste to the ecosystem, and removing it engages ecological **integrity** and self-renewal. Claim 3: inverts the **precautionary principle** — uncertainty plus potentially significant harm is the trigger, absence of evidence is not evidence of absence, and the **onus of proof rests on the proposer**; proportionate measures (residue retention, soil monitoring, triggers) satisfy it. Claim 4: a **flat** $85 charge is unrelated to the amount used, which is the arrangement user pays is defined against, and is regressive, so **intragenerational equity** fails too. The unexamined siting sentence concentrates burdens on the smallest settlement while all ratepayers pay. Judgement: should not proceed as stated, though a properly conditioned version could satisfy all six principles.

Q19. Gas: depleting stock, fugitive methane at processing, pipeline fragmentation, unavoidable long-lived emissions — worst on **intergenerational equity** and it locks in a long-lived public asset. Biomass: acceptable only if residue is genuinely replanted, weakened by drying self-consumption at processing and by 130 km of haulage (diesel plus an **intragenerational** burden on route communities). Solar with battery: no depleting extraction, no ongoing fuel transport, no using-stage emissions; weakest at **processing** (polysilicon, cell and cathode manufacture, metals mined offshore — equity relocated, not avoided) and in the using stage's residues, where **end-of-life recycling** of panels and cells is unresolved. Principal conflict: **intergenerational against intragenerational equity** — the best option for the future carries the highest up-front cost for present ratepayers. Recommend the **solar array with battery**, because its weak stage is a **one-off** load while the other options' weaknesses recur annually. Limitation: it assumes the system can meet the **shape** of the load, especially the aquatic centre's continuous winter **heat** demand; obtain metered half-hourly profiles, size on winter performance, and evaluate a heat pump for the pool (**13B**).

Fully-worked solutions

Q1. (3 marks) One mark each. (a) The five stages in the study design's order: **accessing, extracting, processing, transporting, using**. Listing four, or merging accessing and extracting, earns nothing. (b) Both definitions read "preserving natural resources and the environment for the benefit of…"; the difference is **future generations** against **the current generation**. (c) **High risk of harm** to the environment **and uncertain scientific evidence** — both, since either alone does not trigger the principle.

Q2. (4 marks) (a) **Accessing.** Exploration, survey and appraisal precede extraction; nothing has been removed for use. (b) The trigger and the remedy are both most available early. Uncertainty is greatest before construction, and the option not to proceed is still cheap; once wells are drilled, capital sunk, contracts signed and a workforce employed, refusal carries a very different price and precaution ceases to be a live option. (c) **Preventive measures** must be taken, **and** the **proof of no, or minimal, harm must be provided by the proposer** — the reversal of the onus of proof. (d) An **environment effects statement** under the *Environment Effects Act 1978* (Vic); assessment of a **controlled action** under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth). Both require the proponent to investigate and document, which is the onus reversal made operational.

Q3. (5 marks) (a) 0.96 × 0.90 = 0.864; × 0.99 = 0.8554; × 0.34 = 0.2908; × 0.92 = **0.2676**, so about **26.8 per cent**. (b) **Generation**, at 34 per cent, is by far the largest single loss, and is bounded by the second law rather than by poor engineering (**12F**). (c) 1 ÷ 0.2676 = **about 3.7 units**. (d) Because the multiplier runs backwards: saving one unit at the point of use avoids about 3.7 units of coal extracted, and therefore a proportionate reduction in the area disturbed, the groundwater depressurised and the stock consumed. An appliance standard that never mentions biodiversity or depletion is nonetheless one of the more effective instruments for both — the instruments themselves are **13C**'s. (e) **Efficiency of resource use**: *"use of smaller amounts of physical resources to produce the same product or service while minimising environmental impact"*. **Physical resources** is broader than energy, so land, water and materials count.

Q4. (5 marks) (a) **Transporting** — networks that carry electricity are the transport stage of an electricity chain. (b) Transmission infrastructure is **linear**. It removes a narrow strip, so the area lost is small, but it **divides** populations either side of the easement; a divided population loses genetic exchange and the ecosystem loses the organisation and self-renewal capacity that the **ecological integrity** limb protects. An assessment counting hectares removed measures the small quantity and misses the large one. (c) The **mitigation hierarchy**: **avoid**, then **minimise**, then **offset**, in that order — offsetting is a last resort, not an alternative to avoidance. (d) Because the landholders bearing the easement and the customers receiving the electricity are **all alive now**; the separation is spatial, not temporal, which is intragenerational equity by definition. (e) Any one of: easement payments proportionate to the impact borne; a community benefit fund or shared-ownership arrangement; local employment and procurement; rerouting or undergrounding sections to reduce the burden.

Q5. (6 marks) (a) **Processing** — a refinery converts a raw resource into usable fuels. (b) Under the *Environment Protection Act 2017* (Vic), in force from 1 July 2021, a person engaging in an activity that may give rise to risks of harm to human health or the environment from pollution or waste owes the **general environmental duty**. It applies to the risk itself, so the absence of a prescribed numerical limit for this solvent removes no obligation. (c) Because it is triggered by **risk under uncertainty** rather than by exceedance of a known threshold, and it places the responsibility to identify and control that risk on the **person conducting the activity** — the same onus allocation the precautionary principle requires. (d) **So far as reasonably practicable.** (e) **Intragenerational equity** at the **processing** stage: the health risk falls on the community living around the refinery, while the benefit of the fuel is enjoyed by users elsewhere. Accept **efficiency of resource use** at processing — solvent vapour lost to air is a physical resource paid for and not used.

Q6. (6 marks) (a) **Using** — a battery discharging into a circuit burns no fuel and emits nothing locally. (b) **Processing**: cell and cathode manufacture and metal refining are highly energy-intensive and mostly occur on grids more emissions-intensive than Australia's, so real emissions are embodied in the product. **Extracting**: lithium, nickel, cobalt, graphite and copper must be mined, with habitat loss, water demand and community impacts wherever that occurs. (c) Because **efficiency of resource use** covers physical resources and not only fuel. Round-trip losses mean every stored unit returns less than it took, the deficit appearing as low-grade heat (**12F**), and the metals in the cells are themselves physical resources within the definition. (d) **Using.** There is no sixth "end of life" stage — the study design names five, and the retired hardware is a **residue of the using stage**, in the same way that ash and spent fuel are. The question is whether the cells are recycled, which returns the lithium, nickel, cobalt and copper to use by a later generation, or landfilled, which removes them permanently; it is the least resolved part of the chain. Accept **extracting** where the answer is argued as depletion of the metal stocks the cells were made from, since that is where those stocks were drawn down. Do not accept "end of life" on its own, which names no stage. (e) The rule is **attach a stage to every claim**. An accurate sentence: *"Emissions-free at the point of use; the emissions and materials load is incurred at the processing and extracting stages, and is offset over the system's life where it displaces fossil generation."*

Q7. (1 mark) It calls upon the user of a service or resource to pay directly for the amount they use, rather than the cost being shared by all the users or a community equally.

Q8. (2 marks) One mark for identifying that capturing the flux **is** the extraction stage — a panel intercepts solar radiation over an occupied area, displacing the previous land use. One mark for the correct distinction: what solar lacks is **depletion of a stock**, since the flux is not diminished by being used, but absence of depletion is not absence of extraction.

Q9. (2 marks) One mark for the distinction: **user pays** charges the *user* for *the amount used*; **polluter pays** charges the *party that caused harm* for *the harm*. One mark for a working energy example — a volumetric electricity tariff is user pays; an industry-wide decommissioning levy that recovers a defaulted operator's costs from other producers delivers user pays at industry level while failing polluter pays at firm level.

Q10. (3 marks) One mark: the licence creates an **obligation**, but the bond is what makes the **money** exist independently of the operator's solvency. One mark: if the security is below the true cost and the operator does not or cannot complete the work, the shortfall is met by the public, or the site is left unrehabilitated. One mark: either way the **benefit was taken now and the cost matures later**, which is the asymmetry intergenerational equity exists to prevent — the paper obligation does not change who ends up paying. The adequacy of Victorian bonds in practice is **13A**.

Q11. (3 marks) One mark: accessing, extracting and transporting occur where the resource and the corridor are — regional and rural land, farmland, the coast and offshore — imposing land occupation, dust, noise, traffic and fragmentation on those communities. One mark: the electrical load is overwhelmingly metropolitan, so the benefit of the using stage accrues elsewhere. One mark: because burdens and benefits are separated in **space** among people **alive now**, the principle engaged is **intragenerational equity**, not intergenerational.

Q12. (4 marks) **Stage: extracting**, at the wellhead. **Efficiency of resource use** (2 marks): the definition requires smaller amounts of physical resources for the same product or service, and flaring produces **no energy service at all**

— a finite resource is converted entirely into carbon dioxide and low-grade heat. This is the most complete failure of the principle available, and it is worse than an inefficient conversion, which at least delivers something. **Intergenerational equity** (2 marks): the gas is a **stock**, so a unit flared is permanently unavailable to a future generation, and its carbon is released to an atmosphere in which it persists (**12C**) — the future bears both a smaller resource base and a larger climate burden, with no offsetting benefit taken by anyone. Accept **user pays** for the same marks: the atmospheric cost of the flare is paid by nobody, and the producer's own gain is the avoided cost of a pipeline connection or reinjection.

Q13. (4 marks) Two marks per stage — one for the stage, one for the principle with its impact. Any two of: **Processing** — manufacturing towers, blades, nacelles, permanent magnets and cabling is energy- and materials-intensive, engaging **efficiency of resource use**; where the rare earths and steel are mined and refined overseas, **intragenerational equity** is engaged and merely relocated rather than avoided. **Transporting** — the connection line and internal access tracks fragment habitat, engaging **conservation of biodiversity and ecological integrity** through the integrity limb, and concentrate costs on host landholders, engaging **intragenerational equity**. **Extracting** — capturing the wind flux is the extraction stage, and the operating turbines carry **collision risk to birds and bats**, engaging **conservation of biodiversity and ecological integrity**. *Marker's note:* "no environmental impact whatsoever" is the statement's fatal claim. The grazing-compatibility point is legitimate and should be credited as such rather than dismissed, but it answers only for **land occupation** at the extracting stage; it says nothing about what the blades do while they turn, which is why extracting remains creditable here. A student who files blade strike at *using* has misread the stage: the turbine is where the flux is captured, not where the electricity is consumed.

Q14. (4 marks) Two marks for the mechanism, one for the contrast, one for the consequence. **Why accessing.** Both limbs of the trigger are strongest before construction: the evidence about a proposed action is at its most uncertain, and the harm is prospective rather than established. Just as importantly the **remedy is still cheap** — refusing, deferring, staging or requiring more information costs little when nothing has been built. **Why not later.** By extracting and using, capital is sunk, contracts are signed and employment is committed, so the same precautionary decision now carries a heavy cost and is unlikely to be made; and by then the harm is often **established** rather than uncertain, so the operative principle becomes conservation of biodiversity and ecological integrity, or user pays, and precaution has ceased to be the right tool. **Consequence for sequencing.** Assessment, evidence-gathering and the **reversal of the onus of proof** must be completed **before approval**, not during operation, because a precautionary decision postponed to a later stage is in practice a decision not to be precautionary. Adaptive conditions and monitoring triggers set at approval are the way to keep some of the option open.

Q15. (5 marks) **Site A.** Stronger on **efficiency of resource use**: higher radiation means more output per unit of panel, land and embodied material, and 8 km of connection rather than 45 km saves conductor, steel and easement. But it breaches **conservation of biodiversity and ecological integrity** at the **extracting** stage by removing 60 ha of a threatened grassland community — and grassland is among the hardest communities to offset in a way that restores **integrity** rather than merely replacing **area**, since the soil profile, species assemblage and fire and grazing regime cannot be reconstructed quickly. **Site B.** Upholds biodiversity at extracting by using already-cleared pasture, but does not escape the principle: 45 km of new easement moves the biodiversity cost to the **transporting** stage as **fragmentation**, adds the materials and losses of a longer line, concedes 6 per cent of output, and imposes an **intragenerational equity** burden on the landholders along the route. **The unavoidable conflict** is **efficiency of resource use against conservation of biodiversity and ecological integrity**: efficiency pushes towards the sunniest, best-connected site, and those sites are frequently the ecologically valuable ones — concentration is efficient and avoidance is protective. **Judgement.** Site B is the better choice, because the mitigation hierarchy requires **avoidance first** and the loss at Site A is effectively irreversible, whereas fragmentation along an easement can be materially reduced by routing, span design and revegetation, and 6 per cent of output can be recovered by adding array area on land of low ecological value. *Marker's note:* five marks require both sites analysed at more than one stage, the conflict named as a conflict, and a judgement. An answer that treats Site B as impact-free has repeated the displacement error.

Q16. (5 marks) **Calculation** (2 marks): shortfall = 640 − 48 = **\$592 million**; barrels required = 592 000 000 ÷ 0.48 = **1.233×10^9 boe**, about **1.23 billion barrels of oil equivalent**. **Upheld** (1½ marks): the levy is **volumetric**, charged per barrel produced, so the cost borne is proportionate to the amount of the resource used, which is what the principle requires; and it keeps the cost within the offshore petroleum industry rather than transferring it to taxpayers who never used the resource. **Not upheld** (1½ marks): the titleholder that used the resource and took 14 years of revenue paid **\$48 million of a \$640 million cost**, under 8 per cent, so the party whose use created the liability has not paid for it. The balance falls on **other producers and their customers**, who are not the users whose activity caused the cost —

user pays is restored at the level of the **industry** and remains breached at the level of the **firm**, and **polluter pays** is not achieved at all. The real instance is the **Northern Endeavour**, recovered under the *Offshore Petroleum (Laminaria and Corallina Decommissioning Cost Recovery Levy) Act 2022* (Cth) at 48 cents per barrel of oil equivalent.

Q17. *Model response (6 marks).*

What each requires. Conservation of biodiversity and ecological integrity requires that a stage maintain the abundance of different species in the region, the genetic diversity within populations, and the ecosystem's ability to hold its biotic and abiotic organisation and function as conditions change, including a capacity for **self-renewal**. It is therefore two tests: how much variety remains, and whether the system still works unaided. **Efficiency of resource use** requires that the same product or service be produced from **smaller amounts of physical resources** while minimising environmental impact — and "physical resources" extends beyond energy to water, land and materials.

Where each bites hardest. Biodiversity and integrity bite hardest at **extracting**, where land is occupied and hydrology altered, and at **transporting**, where linear infrastructure fragments populations. Efficiency bites hardest at **processing**, through self-consumption, flaring and parasitic loads, and at **using**, which is the largest loss in most chains.

How each is typically breached. Biodiversity is typically breached through the **integrity** limb rather than the abundance limb: losses are compensated on paper through offsets while the remaining system cannot function without continuing watering, weeding or restocking, and an area-based accounting cannot detect it. Efficiency is typically breached by **grade mismatch** — spending high-quality energy on a task requiring almost none of its work potential (**12F**) — and by loss compounding along the chain, since the whole-chain figure is the product of the stage figures and a representative thermal chain delivers only about a quarter of the primary energy as electricity.

Where they oppose each other. The most efficient site is usually the windiest ridge, the sunniest plain or the shortest transmission route, and those are frequently the sites of greatest ecological value; efficiency pushes towards **concentration** and shorter corridors, while biodiversity often requires **avoidance** and therefore a longer route or a poorer resource. Choosing cleared pasture over a threatened grassland community accepts a lower yield and a longer line precisely in order to satisfy the mitigation hierarchy's requirement to avoid first.

Marker's note: six marks require all four elements. The highest-value observations are the **integrity limb** as the usual site of breach, and the recognition that the two principles are **not always aligned** — students who assume every sustainability principle points the same way lose marks on exactly this comparison.

Q18. *Model response (8 marks).*

The statement contains four claims. One is conditionally true and stated as unconditional, one ignores a stage, one inverts the precautionary principle, and one misstates the principle it invokes.

Claim 1 — "carbon neutral, because the fuel is biomass." Conditionally true, and the condition is at the **extracting** stage, not the using stage. Combustion releases carbon regardless of the fuel; biomass is only near-neutral if the harvested material is **actually regrown on a time scale matched to the release**, so that the carbon is re-sequestered. If the residue comes from a plantation that is replanted, the claim is defensible; if it comes from unreplanted harvest or native forest, the emission is permanent and the chain depletes a stock. "Because the fuel is biomass" is not a reason — it is the assumption that needs proving, and under the precautionary principle the burden of proving it rests on the Council as proponent. The life-cycle emissions figures are **12B**'s and the carbon-cycle mechanism **12C**'s.

Claim 2 — "no extraction impact, because we are using waste residue." This ignores the extracting stage rather than answering for it. The counterfactual argument is legitimate as far as it goes: residue burnt in the open releases its carbon anyway, and combustion under emission controls is better than open burning for local air quality. But **coarse woody debris is not waste to the ecosystem**. It stores soil carbon, retains moisture, and provides habitat and substrate, so removing it engages **conservation of biodiversity and ecological integrity** through the integrity limb — the site's capacity for **self-renewal** depends partly on the material being taken away. Calling a resource "waste" is a claim about human use, not about ecological function.

Claim 3 — "uncertainty is not a reason to delay, because no study has demonstrated harm." This is the precautionary principle stated backwards, and it is the statement's most serious error. The principle is triggered

precisely by the combination the Council describes: a risk of harm to the environment that may be significant, and **uncertain** scientific evidence. Absence of evidence of harm is not evidence of absence of harm. Further, the principle requires that **the proof of no, or minimal, harm be provided by the proposer** — so the burden is on the Council to demonstrate that residue removal will not degrade soil carbon, not on objectors to demonstrate that it will. The correct response is not necessarily refusal: proportionate measures satisfy the principle — retain a specified proportion of residue on site, monitor soil carbon against a pre-approval baseline, and set a trigger at which removal rates reduce.

Claim 4 — "a flat $85 levy on every rateable property satisfies the user pays principle." It does not, and it inverts it. User pays requires payment **directly for the amount used**; a **flat** charge identical for every property is unrelated to consumption, so a household using very little pays the same as one using a great deal. That is the cost "being shared by all the users or a community equally", which is the arrangement the principle is defined **against**. It also creates an **intragenerational equity** failure, since an identical dollar amount is a far heavier burden on a low-income household. A volumetric charge, or rates scaled to property value with a concession pathway, would serve both principles better.

The siting sentence, which the statement does not defend. Placing the plant 60 km from the main town in the Shire's **smallest settlement** concentrates the local burdens — truck movements, noise, dust, road wear and stack emissions — on the community with the least capacity to absorb them and the smallest share of the benefit, while the levy is paid by everyone. This is a textbook **intragenerational equity** breach at the **processing**, **transporting** and **using** stages simultaneously, and the statement's silence about it is itself a finding.

Judgement. The proposal should not proceed on this statement. Three of its four claims are unsound as written and the fourth requires a condition it does not state. None of this means the plant is a bad proposal: a biomass plant fuelled by genuinely replanted plantation residue, with a residue-retention specification and soil monitoring, a volumetric charge, and a siting and compensation arrangement negotiated with the host settlement, could satisfy all six principles. *Marker's note:* eight marks require all four claims addressed and a judgement reached. The highest-value observation is claim 3 — a student who recognises the **onus of proof reversal** has understood the precautionary principle rather than recited it. Identifying the unexamined siting sentence distinguishes the strongest responses.

Q19. *Model response (10 marks).*

Option 1 — extend reticulated natural gas. *Accessing and extracting*: gas is a **stock**, so every unit used is permanently unavailable later, engaging **intergenerational equity**; extraction imposes land occupation and, offshore, engages the **precautionary principle** through seismic survey. *Processing*: conditioning and compression carry a parasitic load, and fugitive methane is a resource lost and a short-to-medium-scale climate forcing. *Transporting*: pipeline easements fragment habitat linearly. *Using*: direct combustion is efficient and, for heating a pool, a reasonable match of grade to task (**12F**) — but the emissions are unavoidable and long-lived. The decisive problem is **intergenerational equity**: the Council would commit a long-lived public asset to a depleting, emitting fuel, and Victorian policy is moving the other way (**13C**).

Option 2 — biomass boiler, residue hauled 130 km. *Accessing and extracting*: no depletion **if** the source is replanted plantation residue, which is the condition the whole option rests on; removing coarse woody debris engages **conservation of biodiversity and ecological integrity** through the integrity limb. *Processing*: chipping and drying consume a significant fraction of the fuel's own energy, weakening **efficiency of resource use**. *Transporting*: 130 km of haulage for a low-energy-density feedstock is the stage most likely to undermine the option, both in diesel consumed and in the burden of truck movements on communities along the route — an **intragenerational equity** cost. *Using*: combustion is efficient for heat, and matching a boiler to a heating load is thermodynamically sound. Overall the option is defensible but **conditional on two things the Council does not control**: replanting, and haulage distance.

Option 3 — solar array with battery, imported. *Accessing and extracting*: no depletion of a stock; occupation is rooftop plus ground-mounted, largely on land already committed to Council use, so the biodiversity load is the smallest of the three. *Processing*: this is the option's weak stage — polysilicon, cell, and battery cathode manufacture are energy- and materials-intensive, mostly on more emissions-intensive grids, and the metals are mined elsewhere, so **intragenerational equity** questions are **relocated rather than avoided**. *Transporting*: shipping the hardware once, then no ongoing fuel transport and — because the generation sits on the Council's own roofs and land — no transmission and distribution limb either, where both other options continue to draw their electricity across the network at an 8–10 per cent loss. That is a structural advantage over both of them. *Using*: no emissions, no fuel, high

efficiency of resource use, and the strongest **intergenerational** position — subject to the using stage's own residue, the **end-of-life recycling** of panels and cells, which is the least resolved part of the chain and not a sixth stage.

The principal conflict. It is **intergenerational against intragenerational equity**, and it is unavoidable. Option 3 is much the best for future generations and carries the highest **up-front** cost, which a Shire must recover from ratepayers now; Option 1 is cheapest to install and worst for those who come later. A secondary conflict sits between **efficiency of resource use** and **intragenerational equity** in Option 2, where the cheapest fuel source imposes 130 km of truck movements on communities that receive no benefit.

Recommendation. The Council should adopt **Option 3**, the solar array with battery. It is the only option with no depleting extraction stage, no ongoing fuel transport, and no combustion at the using stage, so it upholds intergenerational equity, efficiency of resource use and biodiversity better than the alternatives across four of the five stages. Its weak stage — processing — is a **one-off** load incurred at installation, whereas the weaknesses of Options 1 and 2 recur every year of operation, which is the decisive comparison across a 42 000 GJ annual demand over an asset life of decades. Option 2 should be preferred over Option 1 if Option 3 proves unaffordable, but only with a **contractual residue-retention and replanting specification** and a haulage distance materially below 130 km.

Limitation. The recommendation depends on an assumption the Council has not tested: that a solar and battery system can actually meet the **shape** of the load, in particular an aquatic centre's substantial and continuous **heat** demand, which electricity serves well only through a heat pump and which peaks in winter when solar output is lowest. If the array and battery must be sized for winter heat, the capital cost, the roof and ground area required, and the embodied processing load all rise, and the comparison narrows. Before committing funds the Council should obtain the aquatic centre's metered half-hourly heat and electricity profile, size the system against **winter** performance rather than an annual average, and evaluate a heat pump for the pool explicitly. Whether the resulting system can serve that load at all is a base-load and peak-load question, which is **13B**'s.

Marker's note: ten marks require **all three options** treated **across the stages**, the conflict named as a conflict, a **justified** recommendation and a **specific** limitation. The strongest answers make the one-off-versus-recurring distinction about Option 3's processing load, and name the assumption their own recommendation depends on rather than listing generic risks.