Energy from fuels

Reactivity 1.3 · shared SL and HL content

Which fuel is better?

Choose the service before choosing the fuel

One fuel releases more energy per mole, another more per gram. A third has low direct emissions but high production emissions. What would be a fair comparison?

Reactivity 1.3: combustion equations, useful energy, fossil and biofuels, life-cycle decisions and fuel-cell half-equations. Shared SL and HL content.

Use mole calculations and oxidation–reduction. Scenarios are invented; rounded thermochemical values are provided in the handout.

Combustion is not only for hydrocarbons

1. **A metal.** $2\mathrm{Mg} + \mathrm{O_2} \rightarrow 2\mathrm{MgO}$.
2. **A non-metal.** $\mathrm{C} + \mathrm{O_2} \rightarrow \mathrm{CO_2}$.
3. **A hydrocarbon.** $\mathrm{CH_4} + 2\mathrm{O_2} \rightarrow \mathrm{CO_2} + 2\mathrm{H_2O}$.

Decision

Bond breaking absorbs energy. Product bond formation releases more energy overall in these examples.

Balance ethanol without forgetting its oxygen

1. **Carbon and hydrogen.** $\mathrm{C_2H_5OH} \rightarrow 2\mathrm{CO_2} + 3\mathrm{H_2O}$ before balancing oxygen.
2. **Oxygen count.** Products need 7 O atoms. Ethanol already supplies 1; external oxygen must supply 6.
3. **Balanced.** $\mathrm{C_2H_5OH(l)} + 3\mathrm{O_2(g)} \rightarrow 2\mathrm{CO_2(g)} + 3\mathrm{H_2O(l)}$.

Decision

Match water state when using combustion enthalpy data. Condensation also releases energy.

Check: two more fuels

Balance on paper first

Write complete-combustion equations for propane, $\mathrm{C_3H_8}$, and methanol, $\mathrm{CH_3OH}$, forming liquid water.

Check C, H and O separately. Why is multiplying every coefficient sometimes useful?

Complete-combustion reasoning

1. **Propane.** $\mathrm{C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O(l)}$.
2. **Methanol.** $\mathrm{2CH_3OH + 3O_2 \rightarrow 2CO_2 + 4H_2O(l)}$.
3. **Check.** Methanol has 2 oxygen atoms on the reactant side before adding $\mathrm{3O_2}$; both sides total 8.

Two idealized methane pathways

1. **Carbon monoxide.** $2\mathrm{CH_4} + 3\mathrm{O_2} \rightarrow 2\mathrm{CO} + 4\mathrm{H_2O(g)}$.
2. **Carbon.** $\mathrm{CH_4} + \mathrm{O_2} \rightarrow \mathrm{C} + 2\mathrm{H_2O(g)}$.
3. **Real flames.** May produce mixtures of CO_2, CO, soot and unburned fuel; oxygen availability and mixing vary.

Decision

More energy remains in incompletely oxidized carbon products: less heat is released per mole fuel.

A flame is not a carbon-monoxide detector

Different hazards need different explanations

Carbon monoxide is colourless and odourless. It binds strongly to haemoglobin and impairs oxygen transport.

Soot particles damage health. A sooty flame can indicate incomplete combustion, but no visible soot does not prove no CO.

Longer-chain alkanes have a higher C:H ratio and tend to soot more under comparable conditions; vaporization and mixing also matter.

Use appropriate oxygen supply and ventilation. Never test oxygen restriction in an enclosed or unsafe apparatus.

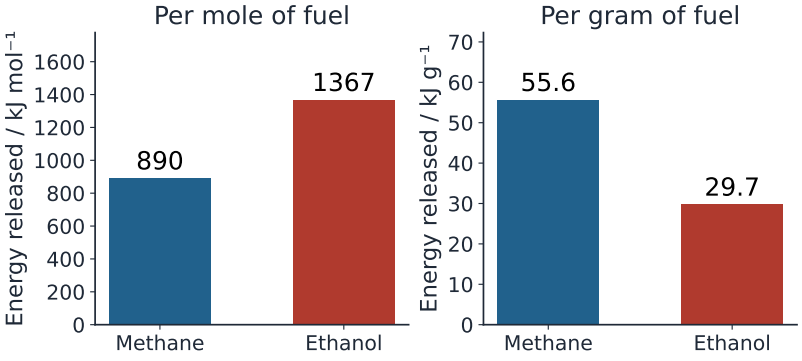
Complete and incomplete combustion

complete: alkane $+ O_2 \rightarrow CO_2 + H_2O$

incomplete: alkane $+$ less $O_2 \rightarrow CO +$ soot $+ H_2O$

> Limited oxygen means incomplete combustion

Two denominators, two rankings



Ethanol releases more per mole; methane releases more per gram. Compare the same service.

From molar enthalpy to specific energy

1. **Given.** Methane: 890 kJ mol^{-1}, 16.0 g mol^{-1}. Ethanol: 1367 kJ mol^{-1}, 46.0 g mol^{-1}.
2. **Specific energy.** $E = |\Delta H_c|/M$: methane $890/16.0 = 55.6$ kJ g^{-1}.
3. **Ethanol.** $E = 1367/46.0 = 29.7$ kJ g^{-1}. A mole-based ranking does not decide a mass-based question.

Decision

Energy density uses volume instead; methane and ethanol also have different storage needs.

CO_2 per released energy

1. **Methane stoichiometry.** 1 mol fuel $\rightarrow$ 1 mol CO_2: 44.0 g from 0.890 MJ.
2. **Ethanol stoichiometry.** 1 mol fuel $\rightarrow$ 2 mol CO_2: 88.0 g from 1.367 MJ.
3. **Normalize.** Methane $44.0/0.890 = 49.4$; ethanol $88.0/1.367 = 64.4$ g CO_2 per released MJ.

Decision

These are direct combustion emissions. Production and transport are outside this boundary.

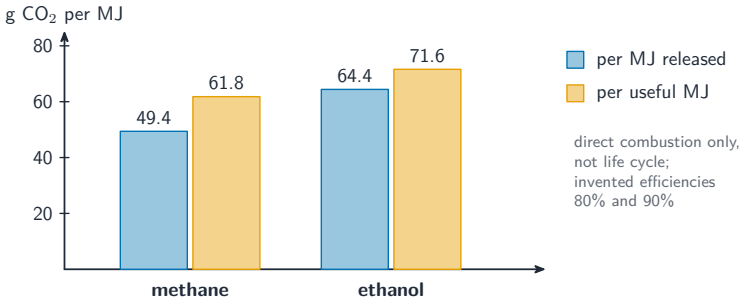
Useful heat changes the denominator again

1. **Functional unit.** Deliver 1 MJ useful heat; efficiency $\eta = E_{\text{useful}}/E_{\text{released}}$.
2. **Invented methane heater.** At 80%: $I = (44.0/0.890)/0.80 \approx 61.8$ g per useful MJ.
3. **Invented ethanol heater.** At 90%: $I = (88.0/1.367)/0.90 \approx 71.5$ g per useful MJ.

Decision

Use the same delivered service and convert percentage efficiency to a fraction.

Carbon dioxide per megajoule



Compare fuels on the same basis

Why more CO_2 affects the energy balance

Greenhouse effect is distinct from ozone depletion

CO_2 absorbs and emits infrared radiation at particular wavelengths.

More atmospheric CO_2 initially reduces net energy escaping to space. Warming changes the balance towards a new equilibrium.

CO and soot add health and pollution concerns. Direct CO_2, local air quality and life-cycle greenhouse-gas emissions answer different questions.

A practical fuel choice has several constraints

Fuel	**Useful property**	**Concern**
Coal	Solid storage	CO_2, impurities, ash
Oil-derived liquids	Transport/storage	CO_2 and spills
Natural gas	Lower direct CO_2 than coal	Methane leakage; infrastructure

Trace the biological carbon

1. **Photosynthesis.** $6\mathrm{CO_2} + 6\mathrm{H_2O} \rightarrow \mathrm{C_6H_{12}O_6} + 6\mathrm{O_2}$, with light supplying energy.
2. **Fermentation.** $\mathrm{C_6H_{12}O_6} \rightarrow 2\mathrm{C_2H_5OH} + 2\mathrm{CO_2}$.
3. **Combustion.** Ethanol releases $\mathrm{CO_2}$ again; regrowth can take up carbon over a relevant timescale.

Decision

Renewable describes replenishment. Carbon neutral requires a justified emissions balance.

Why biofuel need not mean carbon neutral

Count the production pathway

Harvesting, processing and transport may use fossil energy; fertilizer and land-use change can add greenhouse-gas emissions.

Crop land can compete with food production. Waste-derived fuels can have different impacts from dedicated crops.

Specify the land-use boundary and timescale. Do not count feedstock carbon uptake twice.

Life-cycle accounting can reverse a direct-emissions ranking

1. **Common service.** All invented values below are per 1 MJ useful heat, in g CO_2-equivalent.
2. **Fuel A.** Direct 62 + upstream 14: total $I_A = 76$.
3. **Fuel B.** Direct 72 − credited uptake 60 + upstream 25: total $I_B = 37$.

Decision

B is lower under these assumptions. Check uptake, land-use boundary and upstream uncertainty.

Change the assumptions before making a recommendation

Try a sensitivity check

Keep A at 76 g CO_2-equivalent per useful MJ. For B, retain direct emissions 72, reduce the uptake credit to 50 and increase upstream emissions to 70.

Recalculate B and decide whether the ranking survives. Name another impact that the greenhouse-gas total does not describe.

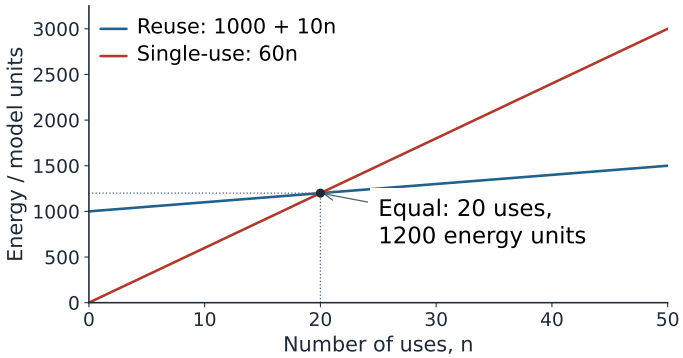
A conditional conclusion

1. **Recalculate.** $I_B = 72 - 50 + 70 = 92$ g CO_2-equivalent per useful MJ.
2. **Compare.** 92 exceeds A's 76: the ranking reverses.
3. **Evaluate.** Water use, land, toxicity, local air pollution and waste may also matter.

Decision

Life-cycle assessment needs a boundary, a **functional unit** and uncertainty, not a universal slogan.

Reuse: equality is not yet a saving



Invented energy model: equal at 20 uses; reuse is lower only after 20 uses.

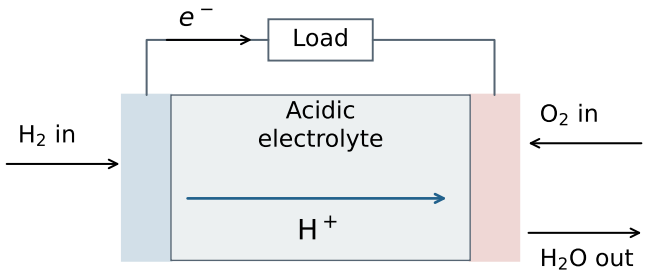
Break-even is specific to its assumptions

1. **Invented model.** $E_{\text{reuse}} = 1000 + 10n$; $E_{\text{single}} = 60n$.
2. **Equality.** $1000 + 10n = 60n$, so $n = 20$ uses.
3. **Limit.** Cleaning, transport and disposal change the model. Energy break-even need not match water or emissions break-even.

Decision

Recyclable does not mean actually collected and recycled.

Keep electron and ion paths separate



Oxidation supplies electrons; reduction consumes them.

> Oxidation supplies electrons at the anode; reduction consumes them at the cathode.

Hydrogen fuel cell in acidic conditions

1. **Oxidation at anode.** $\mathrm{H_2} \to 2\mathrm{H^+} + 2\mathrm{e^-}$.
2. **Reduction at cathode.** $\frac{1}{2}\mathrm{O_2} + 2\mathrm{H^+} + 2\mathrm{e^-} \to \mathrm{H_2O}$.
3. **Add and cancel.** $\mathrm{H_2} + \frac{1}{2}\mathrm{O_2} \to \mathrm{H_2O}$. $\mathrm{H^+}$ carries charge through the acidic electrolyte.

Decision

Electrons pass through the external load from anode to cathode. The electrolyte must not short-circuit them.

Alkaline electrolyte: use a consistent medium

1. **Anode.** $\mathrm{H_2 + 2OH^- \rightarrow 2H_2O + 2e^-}$.
2. **Cathode.** $\mathrm{\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-}$.
3. **Overall.** Cancel $\mathrm{OH^-}$, electrons and one water: $\mathrm{H_2 + \frac{1}{2}O_2 \rightarrow H_2O}$.

Decision

Do not mix acidic and alkaline half-equations without converting the medium.

Methanol cell: oxidation supplies six electrons

1. **Acidic anode.** $\mathrm{CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-}$.
2. **Acidic cathode.** $\mathrm{\frac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O}$.
3. **Overall.** $\mathrm{CH_3OH + \frac{3}{2}O_2 \rightarrow CO_2 + 2H_2O}$ after cancellation.

Decision

A methanol cell directly produces $\mathrm{CO_2}$. “All fuel cells emit only water” is false.

Direct conversion still has a supply chain

Separate the device from its fuel source

A fuel cell receives fuel and oxidant continuously. A primary cell contains a finite original supply of reactants.

Hydrogen is an energy carrier. Production, compression, transport and storage use resources and energy.

A hydrogen–oxygen cell makes no direct CO_2, but upstream emissions depend on the pathway. Direct electricity generation does not imply 100% efficiency.

Account for every energy output

1. **Invented inputs.** 100 kJ chemical energy gives 58 kJ electricity and 30 kJ useful heat.
2. **Electrical efficiency.** $\eta_{\text{electrical}} = (58/100) \times 100 = 58\%$.
3. **Total useful efficiency.** $\eta_{\text{useful}} = ((58 + 30)/100) \times 100 = 88\%$. Remaining 12 kJ is not useful output here.

Decision

Credit heat only if it is actually useful. Efficiency alone does not measure life-cycle impact.

Transfer the comparison

Attempt before checking the handout

A methane heater is 70% efficient. Use 49.4 g direct CO_2 per released MJ and 890 kJ per mole fuel.

Find direct CO_2 per useful MJ and methane mass needed for 7.00 MJ useful heat. Use molar mass 16.0 g mol^{-1}.

Then attempt the handout's 13 questions, including incomplete-combustion equations and the changed life-cycle assumptions.

Transfer reasoning

1. **Emissions.** $I = 49.4/0.70 \approx 70.6$ g per useful MJ.
2. **Fuel energy.** $E_{\text{released}} = 7.00/0.70 = 10.0$ MJ.
3. **Fuel mass.** $n = 10000/890 = 11.24$ mol; $m = nM \approx 180$ g.

Decision

Normalize to the delivered service; do not multiply released-energy intensity by efficiency.

Check yourself

A defensible fuel answer

Balance atoms and charge; count oxygen already in alcohols. State whether you use acidic or alkaline half-equations.

Normalize energy and emissions to the same functional unit. Separate direct emissions from life-cycle emissions.

Give a conditional judgement supported by data and assumptions; distinguish renewable from carbon neutral.