Energy from fuels

International Baccalaureate · IB Diploma · Chemistry · SL

Scope and prerequisites

This handout teaches Reactivity 1.3, Energy from fuels, for the course first assessed in 2025. The understandings in this unit are shared by SL and HL. It also develops the life-cycle comparisons and functional-unit reasoning in the course objectives.

Prerequisites: balancing equations, mole calculations, enthalpy changes and oxidation–reduction. Numerical scenarios are original and invented unless a reference value is explicitly identified. They are not official examination questions.

Combustion: where the energy comes from

A **fuel** stores chemical energy that can be transferred in a useful process. During **combustion**, a substance reacts with oxygen. Many metals, non-metals and organic substances burn when sufficiently heated. Examples include

$$2\mathrm{Mg(s)} + \mathrm{O_2(g)} \rightarrow 2\mathrm{MgO(s)},$$

$$\mathrm{C(s)} + \mathrm{O_2(g)} \rightarrow \mathrm{CO_2(g)},$$

$$\mathrm{CH_4(g)} + 2\mathrm{O_2(g)} \rightarrow \mathrm{CO_2(g)} + 2\mathrm{H_2O(l)}.$$

These reactions release energy overall because forming the product bonds releases more energy than breaking the reactant bonds requires. The energy is not released simply by "breaking the fuel's bonds". An ignition source overcomes an activation barrier; a fuel that releases much energy can still be relatively unreactive during safe storage.

Complete combustion of a hydrocarbon or an alcohol produces carbon dioxide and water. Balance carbon first, hydrogen second and oxygen last. An alcohol already contains oxygen, so include that oxygen when calculating the external oxygen supply.

Worked example: ethanol

Ethanol is $\mathrm{C_2H_5OH}$, with two carbon atoms, six hydrogen atoms and one oxygen atom per molecule. Two carbon atoms give $2\mathrm{CO_2}$; six hydrogen atoms give $3\mathrm{H_2O}$. The products contain seven oxygen atoms. One comes from ethanol, leaving six to be supplied by three oxygen molecules:

$$\mathrm{C_2H_5OH(l)} + 3\mathrm{O_2(g)} \rightarrow 2\mathrm{CO_2(g)} + 3\mathrm{H_2O(l)}.$$

Water may leave a hot flame as vapour. If using a tabulated combustion enthalpy, match its specified water state; a value for liquid water includes the additional energy released on condensation. Do not compare fuel values defined with different product states without accounting for that difference.

Limited oxygen and incomplete combustion

Incomplete combustion occurs when carbon is not fully oxidized to carbon dioxide. Carbon monoxide and/or solid carbon can form, usually alongside some carbon dioxide and water. The following equations are idealized limiting cases, not a claim that a real flame produces only one carbon-containing product:

$$2\mathrm{CH_4(g)} + 3\mathrm{O_2(g)} \rightarrow 2\mathrm{CO(g)} + 4\mathrm{H_2O(g)},$$

$$\mathrm{CH_4(g)} + \mathrm{O_2(g)} \rightarrow \mathrm{C(s)} + 2\mathrm{H_2O(g)}.$$

Carbon monoxide is colourless and odourless and is toxic because it binds strongly to haemoglobin, impairing oxygen transport. Soot consists of carbon-rich particles; inhaled particles damage health. A yellow, sooty flame can indicate incomplete combustion, but the absence of visible soot does not prove the absence of carbon monoxide.

Hydrocarbons with higher carbon-to-hydrogen ratios, such as longer-chain alkanes, tend to soot more under comparable burning conditions. Oxygen delivery, vaporization and mixing also affect the outcome.

More chemical energy remains in CO or carbon than in fully oxidized products, so incomplete combustion releases less heat per mole of original fuel than complete combustion to the same final water state. It wastes fuel as well as increasing health risks. Provide a suitable oxygen supply and ventilation; never use an unvented flame in an enclosed room. This is a reason to improve apparatus, not an instruction to experiment with unsafe oxygen restrictions.

■ Worked example: balancing an incomplete reaction

For ethanol producing only CO and water as the carbon/hydrogen products, begin with $C_2H_5OH \rightarrow 2CO + 3H_2O$. Products contain five oxygen atoms; ethanol supplies one, so two O_2 molecules supply the remaining four:

$$C_2H_5OH(l) + 2O_2(g) \rightarrow 2CO(g) + 3H_2O(g).$$

Check every atom after balancing. A smaller oxygen coefficient than in the complete-combustion equation is consistent with incomplete oxidation.

Compare fuels on the same basis

A more negative molar enthalpy does not automatically identify the most useful fuel. A large molecule can release more energy per mole simply because it contains more atoms. **Specific energy** compares energy per unit mass; **energy density** compares energy per unit volume. Storage volume, safety, cost, availability, transport and conversion efficiency also matter.

Use positive magnitudes when comparing energy released. For molar mass M and molar combustion enthalpy ΔH_c,

$$\text{specific energy} = \frac{|\Delta H_c|}{M}.$$

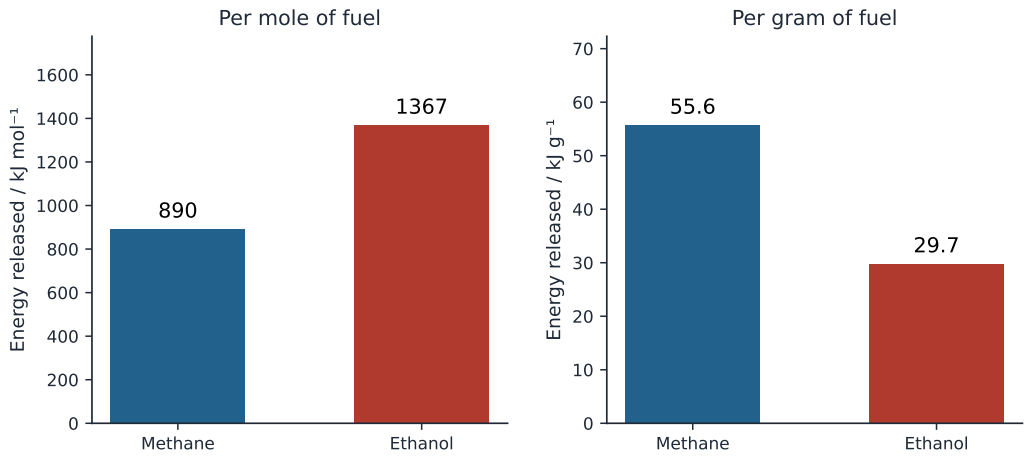
If ΔH_c is in $\mathrm{kJ\,mol^{-1}}$ and M in $\mathrm{g\,mol^{-1}}$, the result is in $\mathrm{kJ\,g^{-1}}$, numerically equal to $\mathrm{MJ\,kg^{-1}}$.

■ Worked comparison: methane and ethanol

Use rounded comparison values of $-890\ \mathrm{kJ\,mol^{-1}}$ for methane and $-1367\ \mathrm{kJ\,mol^{-1}}$ for liquid ethanol, both for complete combustion to liquid water. Use $M = 16.0$ and $46.0\ \mathrm{g\,mol^{-1}}$, respectively.

$$E_{\text{methane}} = \frac{890}{16.0} = 55.6\ \mathrm{kJ\,g^{-1}},$$

$$E_{\text{ethanol}} = \frac{1367}{46.0} = 29.7\ \mathrm{kJ\,g^{-1}}.$$



The denominator changes the question being answered; use a common basis before comparing fuels.

Ethanol releases more per mole, but methane more per gram. Methane is a gas under ordinary conditions, requiring a storage strategy such as compression; ethanol is a liquid. The mass comparison alone does not settle a vehicle-storage decision.

■ Carbon dioxide per unit energy

From the balanced equations, one mole methane makes one mole CO_2, while one mole ethanol makes two. With $M_{CO_2} = 44.0\ \mathrm{g\,mol^{-1}}$,

$$I_{\text{methane}} = \frac{44.0}{0.890} = 49.4\ \mathrm{g\ CO_2\,MJ^{-1}},$$

$$I_{\text{ethanol}} = \frac{88.0}{1.367} = 64.4\ \mathrm{g\ CO_2\,MJ^{-1}}.$$

These are **direct combustion** emissions per energy released, not full life-cycle emissions. The carbon source in ethanol and energy used during production have not yet been counted.

A **functional unit** specifies a common service, such as 1 MJ of useful heat, rather than one mole or one tank. If a heater transfers only a fraction η of the fuel energy usefully,

$$\text{direct } CO_2 \text{ per useful MJ} = \frac{\text{direct } CO_2 \text{ per released MJ}}{\eta}.$$

For invented efficiencies of 80% for methane and 90% for ethanol, the respective intensities become $49.4/0.80 \approx 61.8$ and $64.4/0.90 \approx 71.6$ g per useful MJ. Write percentages as fractions. Comparing released energy on one side with useful energy on the other is unfair.

Fossil fuels and biofuels

Fossil fuels are formed from ancient biological material over geological timescales and are non-renewable on human timescales. Coal is a carbon-rich solid with impurities; crude oil is a mixture refined into useful fractions; natural gas is methane-rich, with composition varying by source.

- Coal can be stored as a solid but produces substantial direct CO_2 per released energy; impurities and ash create additional pollution concerns.
- Oil-derived liquid fuels are convenient for transport and energy storage, but combustion emits CO_2 and spills can damage ecosystems.
- Natural gas generally emits less direct CO_2 per released energy than coal, but extraction and transport can leak methane, itself a greenhouse gas. Lower combustion emissions do not remove the need for life-cycle assessment.

CO_2 absorbs and emits infrared radiation at particular wavelengths. Increasing its atmospheric concentration initially reduces net energy escaping to space; warming changes the energy balance towards a new equilibrium. This enhanced greenhouse effect is distinct from ozone depletion. Direct CO_2 accounting therefore addresses a climate impact, while CO and soot introduce additional health and pollution effects.

A **renewable** source is replenished on a timescale relevant to its use; a finite source is not made renewable merely by using it more slowly. Solar energy captured by plants can become a **biofuel**. Photosynthesis fixes atmospheric carbon into biological material:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2.$$

Light supplies energy; photosynthesis is not an energy source independent of sunlight. Fermentation can convert glucose into ethanol and carbon dioxide:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2.$$

Biomass can regrow, but this does not guarantee that a biofuel is carbon neutral. Growing, harvesting, fertilizer production, processing and transport consume energy and may emit greenhouse gases. Land-use change can release stored carbon or displace food production; regrowth and land availability matter. Waste-derived fuels may have different impacts from crops grown specifically for fuel. Carbon taken up during growth must be counted consistently with carbon released later, without counting the same uptake twice.

Life-cycle assessment and a defensible decision

A **life-cycle assessment** follows impacts from raw materials and production through transport, use and end-of-life processes. Specify the boundary and functional unit before comparing options. Carbon dioxide alone does not describe water demand, land use, toxicity, local air pollution or waste.

Worked comparison: useful heat with upstream emissions

In an invented comparison per 1 MJ of useful heat, fuel A has 62 g direct CO_2 and 14 g CO_2-equivalent upstream emissions. Fuel B has 72 g direct CO_2; its stated accounting credits 60 g of uptake during feedstock growth, and assigns 25 g CO_2-equivalent upstream emissions.

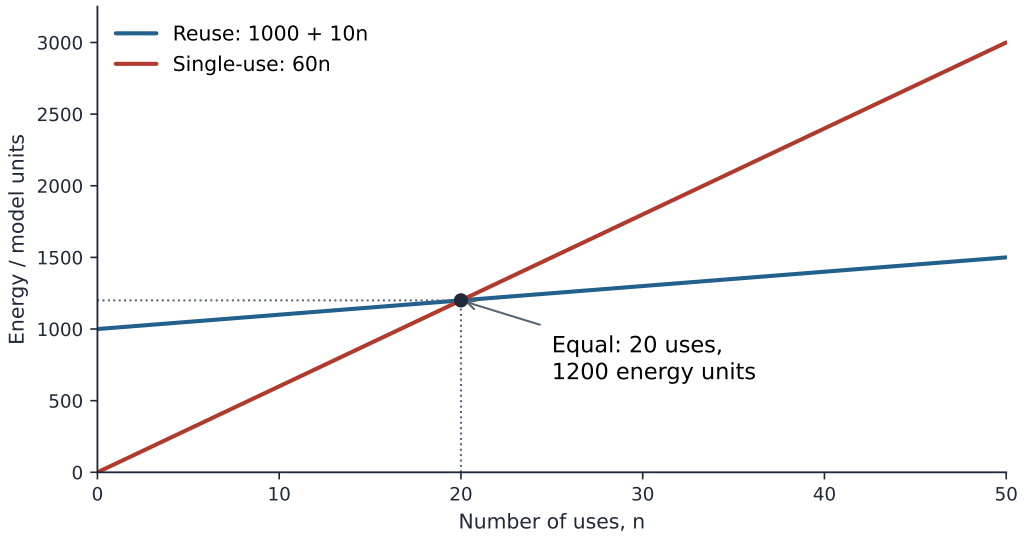
$$I_A = 62 + 14 = 76 \text{ g } CO_2\text{-equivalent},$$

$$I_B = 72 - 60 + 25 = 37 \text{ g } CO_2\text{-equivalent}.$$

B has lower net greenhouse-gas emissions under these assumptions, despite higher direct CO_2. This is a conditional result: the uptake credit, land-use boundary and upstream data must be justified. CO_2-equivalent is an accounting measure combining greenhouse gases on a stated basis; it is not a claim that the exhaust contains that mass of CO_2 alone.

The same logic applies beyond fuels. In a simplified invented reusable-container model, manufacturing costs 1000 energy units and cleaning costs 10 per use, whereas a disposable costs 60 per use. With the same delivered service,

$$E_{\text{reuse}} = 1000 + 10n, \qquad E_{\text{single}} = 60n.$$

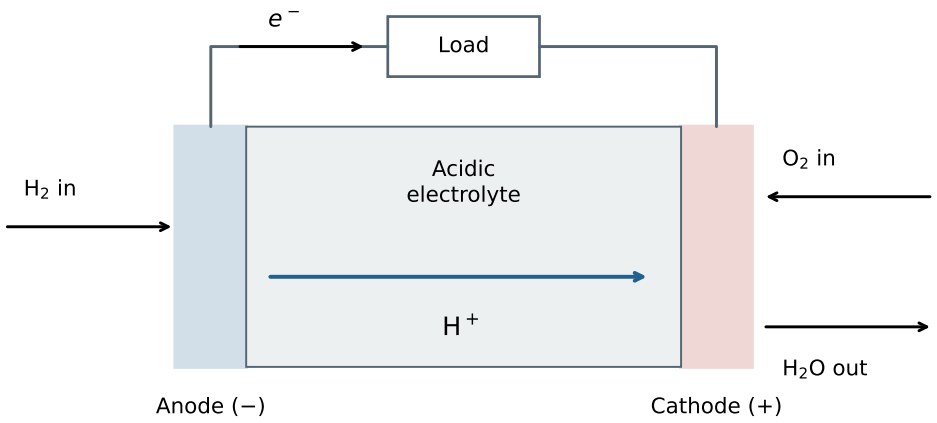


Equal at 20 uses; the reusable option uses less energy after that point.

Equality occurs at $n = 1000/(60 - 10) = 20$ uses. The reusable option uses less energy only **after** 20 uses. Cleaning assumptions, transport and disposal can change the crossover; energy break-even does not establish break-even for water or emissions. "Recyclable" describes a possibility, not proof of collection and recycling. State which impacts and priorities support the final judgement.

Fuel cells: chemical energy directly to electricity

A **fuel cell** separates fuel oxidation from oxygen reduction at electrodes. Electrons travel through an external circuit and can do electrical work; ions carry charge through an electrolyte. The electrolyte must not provide an electron short circuit. Fuel and oxidant are supplied continuously, unlike the finite stored reactants of a primary cell. A fuel cell is not simply a battery that must be recharged after consuming its original reactants.



Oxidation supplies electrons; reduction consumes them.

Oxidation at the anode supplies electrons to the external circuit; oxygen is reduced at the cathode.

Hydrogen in acidic conditions

At the anode, hydrogen is oxidized:

$$H_2 \rightarrow 2H^+ + 2e^-.$$

At the cathode, oxygen is reduced:

$$\tfrac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O.$$

Add and cancel electrons and hydrogen ions to obtain $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$. Check both atoms and charge in each half-equation. In this operating cell the anode is negative and the cathode positive; the definitions oxidation/anode and reduction/cathode remain valid in other electrochemical cells too.

In alkaline conditions, balance using hydroxide ions. At the anode:

$$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-.$$

At the cathode:

$$\tfrac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-.$$

The overall reaction is unchanged. Keep both half-equations in the same medium.

Methanol as a fuel

For a direct methanol cell in acidic conditions, anode oxidation is

$$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-.$$

Multiply the acidic oxygen-reduction equation by three:

$$\tfrac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O.$$

After cancelling species, the overall reaction is $CH_3OH + \frac{3}{2}O_2 \rightarrow CO_2 + 2H_2O$. Methanol is a convenient liquid to store, but it is toxic and its use produces CO_2. It is incorrect to say all fuel cells emit only water.

Hydrogen cells have no direct CO_2 from the hydrogen–oxygen reaction. However, hydrogen is an **energy carrier**: producing, compressing, transporting and storing it require resources and energy. Emissions depend on the production pathway and energy supply. Fuel cells can avoid an intermediate combustion heat engine, but still have losses; neither direct conversion nor a water-only cell product proves 100% efficiency or zero life-cycle impact.

Practice

Use the rounded fuel data above where needed. All additional scenarios are invented.

1. Balance complete combustion equations for propane, C_3H_8, and methanol, CH_3OH. Include water as a liquid.
2. Balance separate idealized equations for propane forming (a) only CO and water vapour and (b) only carbon and water vapour as products. Why can a real flame differ from both equations?
3. Explain why an exothermic fuel can need ignition. Identify the error in "energy is released when fuel bonds break".

4. Compare methane and ethanol on energy released per mole and per gram, using the given data. Why do the rankings differ?
5. Calculate direct CO_2 produced when methane releases 4.45 MJ and when ethanol releases 4.101 MJ. Then express each as g per released MJ.
6. A methane heater has efficiency 70%. Calculate direct CO_2 per useful MJ and the mass of methane required to deliver 7.00 MJ useful heat.
7. Explain one advantage and one limitation each of coal, oil-derived fuels and natural gas. Distinguish a combustion-emissions comparison from a life-cycle comparison.
8. Write the photosynthesis and ethanol-fermentation equations. Explain two reasons why crop-derived ethanol need not be carbon neutral.
9. A reusable product needs 900 energy units to manufacture and 6 per use; a disposable needs 36 per use. Find the equality point and the first whole number of uses for which reuse consumes less energy. State two model limitations.
10. For the life-cycle example, suppose B's upstream emissions rise to 70 g CO_2-equivalent and its uptake credit falls to 50 g, all per useful MJ. Recalculate B's total and compare with A. What does this show about the decision?
11. Write and add acidic hydrogen-cell half-equations. Identify the electron direction, the oxidation electrode and the species carrying charge through the electrolyte.
12. Derive the acidic methanol-cell overall equation from its two half-equations. Explain why "fuel cells have no carbon emissions" is too broad.
13. A cell receives 100 kJ chemical energy and supplies 58 kJ electricity and 30 kJ useful heat. Find electrical efficiency and total useful-energy efficiency. Explain why neither value alone establishes the lower-impact fuel supply.

■ Worked answers

1. $C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O(l)$; $2CH_3OH + 3O_2 \rightarrow 2CO_2 + 4H_2O(l)$. Carbon and hydrogen balance first; then count oxygen already present in methanol.
2. (a) $2C_3H_8 + 7O_2 \rightarrow 6CO + 8H_2O(g)$. (b) $C_3H_8 + 2O_2 \rightarrow 3C + 4H_2O(g)$. Real flames can produce mixtures of CO_2, CO, soot and unburned fuel because mixing and oxygen availability vary.
3. Ignition supplies the activation energy needed to begin a pathway. Bond breaking absorbs energy; product bond formation releases energy. A negative net enthalpy does not imply a negligible barrier.
4. Per mole: ethanol 1367 > methane 890 kJ mol^{-1}. Per gram: $E = |\Delta H_c|/M$ gives methane $890/16.0 = 55.6$ and ethanol $1367/46.0 = 29.7$ kJ g^{-1}. The molar masses differ; neither ranking alone describes storage or life-cycle impact.
5. Methane: $n = 4450/890 = 5.00$ mol, giving $m_{CO_2} = 5.00 \times 44.0 = 220$ g; $220/4.45 = 49.4$ g MJ^{-1}. Ethanol: $n = 4101/1367 = 3.00$ mol, giving $m_{CO_2} = 2 \times 3.00 \times 44.0 = 264$ g; $264/4.101 = 64.4$ g MJ^{-1}.
6. Intensity $= 49.4/0.70 \approx 70.6$ g per useful MJ. Released energy $= E_{useful}/\eta = 7.00/0.70 = 10.0$ MJ. $n = 10000/890 = 11.24$ mol and $m = nM = 11.24 \times 16.0 \approx 180$ g methane. Guard digits avoid premature rounding.
7. Coal: solid storage is straightforward, but combustion and impurities create CO_2/pollution concerns. Oil fuels: convenient liquid transport, but CO_2 and spills matter. Gas: lower direct CO_2 per released energy than coal in a suitable comparison, but methane leakage and storage/infrastructure matter. Life-cycle assessment also counts production, transport and other upstream/downstream impacts.
8. $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$ using light; $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$. Fossil energy in production and transport can emit CO_2; fertilizer use and land-use change can add greenhouse-gas emissions. Biomass uptake must be assessed over the stated boundary and timescale.
9. $900 + 6n = 36n$, so $n = 900/30 = 30$. Totals are equal at 30 uses; reuse uses less from 31 whole uses onwards. Cleaning and transport assumptions may change the result; energy equality does not establish equality in water use or waste impacts.
10. $I_B = 72 - 50 + 70 = 92$ g CO_2-equivalent per useful MJ, exceeding A's 76. The ranking reverses when the assumptions change. State the boundary, uncertain inputs and priorities rather than declaring one fuel universally preferable.
11. Anode: $H_2 \rightarrow 2H^+ + 2e^-$. Cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$. Overall: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$. Electrons travel from the oxidation anode through the load to the reduction cathode; hydrogen ions carry charge through the acidic electrolyte in this model.
12. Add $CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$ to $\frac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$. Cancel electrons, hydrogen ions and one water: $CH_3OH + \frac{3}{2}O_2 \rightarrow CO_2 + 2H_2O$. Methanol cells directly produce CO_2; even hydrogen cells can have upstream emissions.
13. Electrical efficiency $= 58/100 \times 100 = 58\%$. Total useful efficiency $= (58+30)/100 \times 100 = 88\%$; the remaining 12 kJ is not useful output in this boundary. A full comparison also needs fuel production emissions, storage/transport and a common service; useful heat is only credited if there is an actual use for it.

Exam tips

- Balance all atoms, including oxygen already in alcohols, and check charge in half-equations. Use one electrolyte medium consistently.
- Compare the same functional unit. Distinguish direct emissions from life-cycle impacts, and renewable supply from a justified carbon-neutral claim.
- Support a conditional judgement with data, boundaries and uncertain assumptions. Hydrogen cells have no direct CO_2, but fuel production can emit it; methanol cells directly produce CO_2.

References: IB guide, R1.3; NIST ethanol data; DOE fuel cells.