PHOTON ACADEMY

Topic A.3

WORK, ENERGY & POWER

Every Formula, Trick & Trap on a Page
& IB-Style Quick Reference

Topics Covered	**Exam Relevance**
Work & the Force–Distance Graph	P1 & P2 (with & without GDC)
Kinetic Energy & Work–Energy Theorem	Area under an F–s graph
Gravitational & Elastic PE	Energy bar charts
Conservation of Mechanical Energy	$P = Fv$; efficiency %
Power, Efficiency & Energy Density	Sankey & fuel comparisons

The Big Picture — How A.3 Fits Together

WORK, ENERGY & POWER
energy is transferred, stored, and conserved

- **Work**: $W = Fs\cos\theta$ $=$ area under F–s; $W_{\text{net}} = \Delta E_K$
- **Energy Stores**: KE $\frac{1}{2}mv^2$; grav $mg\Delta h$; elastic $\frac{1}{2}kx^2$
- **Conservation**: $E_{\text{mech}} = E_K + E_p$; friction removes it as heat
- **Power**: $P = \frac{\Delta W}{\Delta t} = Fv$
- **Efficiency & Fuel**: $\eta = \frac{\text{out}}{\text{in}}$; Sankey; energy density

§1 — Work Done

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Core Formula

$$W = Fs\cos\theta$$

W: work (J) F: force (N) s: displacement (m)
θ: angle between **force** and **displacement**

θ	$\cos\theta$	Work
0°	1	$W = Fs$ (max)
90°	0	$W = 0$
180°	-1	$W = -Fs$ (opp.)

TRICK Only the component of force *along* the displacement does work. Normal force and weight do **zero work** on a horizontal surface.

TRAP θ is the angle between $\vec{F}$ and $\vec{s}$, NOT the angle of the incline. Draw a diagram!

TRICK **Two ways to find work:** $W = Fs\cos\theta$ for a *constant* force, OR the *area under the F–s graph* for a *varying* force (e.g. a spring). For constant F the area is just the rectangle Fs.

Work-Energy Theorem

$$W_{\text{net}} = \Delta E_K$$

Net work = change in kinetic energy.

FROM THE PHOTON QUESTION BANK

The angle in $Fs\cos\theta$ is between force and *displacement*, not the slope. State that normal force & weight do zero work on a horizontal path.

§2 — Kinetic Energy

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KE Formulas

$$E_K = \frac{1}{2}mv^2 = \frac{p^2}{2m}$$

NOTE $E_K = p^2/(2m)$ is essential for comparing energies of two objects with the same momentum (e.g., explosion problems).

TRICK Same momentum $\Rightarrow$ lighter mass has **more** KE. Same KE $\Rightarrow$ lighter mass has **less** momentum.

TRAP Doubling speed **quadruples** KE. Doubling mass only **doubles** KE.

§3 — Potential Energies

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Gravitational PE (near surface)

$$\Delta E_p = mg\Delta h$$

$\Delta h > 0$: moving up (PE increases)

Elastic PE (Hooke's Law spring)

$$E_H = \frac{1}{2}k(\Delta x)^2$$

Always ≥ 0 (extension or compression).

TRAP $\Delta E_p = mg\Delta h$ is valid only near Earth's surface where $g \approx$ const.

TRICK **Two ways to see grav PE:** $\Delta E_p = mg\Delta h$ *is* the work done against gravity ($=$ area under the constant weight–height graph). Only Δh matters, never the path.

NOTE E_H = area under F–x graph = area of triangle = $\frac{1}{2} \times k\Delta x \times \Delta x$.

§4 — Conservation of Mechanical Energy

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Mechanical Energy

$$E_{\text{mech}} = E_K + E_p + E_H$$

Conserved when only conservative forces act (no friction, no air resistance).

With friction:

$$\Delta E_{\text{mech}} = W_{\text{non-cons}} < 0$$

TRICK At maximum height (zero velocity): all KE has converted to PE. Use $mgh = \frac{1}{2}mv_0^2$ to find $h_{\max}$.

TRICK **Final speed — 3 ways:** (1) energy conservation (best with heights/springs, no time needed); (2) work–energy theorem $W_{\text{net}} = \Delta E_K$ (forces + distance); (3) SUVAT (when you need time or acceleration). Height and no time $\Rightarrow$ use energy.

TRAP Do NOT cancel mass m from energy equations if the problem involves *two different* masses.

NOTE "Change in total mechanical energy = work done by non-conservative forces". Friction always reduces mechanical energy.

FROM THE PHOTON QUESTION BANK

If a height or spring is given and no time is asked, use energy conservation — the track shape is irrelevant. Loss in mechanical energy $=$ average resistive force $\times$ distance.

§5 — Power

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Power

$$P = \frac{\Delta W}{\Delta t} = Fv$$

Units: W = J s^{-1}

TRICK At **terminal velocity**: driving force = resistive force. $P = F_{\text{drive}} \times v_{\text{terminal}}$ gives minimum engine power.

TRICK For a motor lifting mass at constant speed: $P_{\text{useful}} = mgv$ (gravitational PE gained per second).

TRICK **Two forms of power:** $P = \Delta W/\Delta t$ (energy $\div$ time — *average*); $P = Fv$ (force $\times$ velocity — *instantaneous*). Same law: $\Delta W/\Delta t = F\,\Delta s/\Delta t = Fv$.

TRAP $P = Fv$ only when F is *parallel* to v. In general: $P = Fv\cos\theta$.

FROM THE PHOTON QUESTION BANK

At constant speed the driving force balances resistance, so $P = F_{\text{res}}v$ is the minimum power to hold that speed. Rate of wasted (thermal) power $= P_{\text{in}}(1-\eta)$.

§6 — Efficiency

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Efficiency

$$\eta = \frac{E_{\text{output}}}{E_{\text{input}}} = \frac{P_{\text{output}}}{P_{\text{input}}} \le 1$$

NOTE Sankey diagram: arrow *width* $\propto$ energy. The useful output arrow is always narrower than the input arrow.

TRAP Efficiency cannot exceed 1 (100%). If you calculate $\eta > 1$, check your substitution.

TRICK $E_{\text{waste}} = E_{\text{input}}(1-\eta)$. Useful for finding thermal energy produced.

§7 — Fuel Sources

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Specific Energy vs Energy Density

$$\text{specific energy} = \frac{E_{\text{released}}}{m_{\text{fuel}}}\ (\text{J kg}^{-1})$$

$$\text{energy density} = \frac{E_{\text{released}}}{V_{\text{fuel}}}\ (\text{J m}^{-3})$$

NOTE **per mass** $=$ specific energy (weight-limited: rockets); **per volume** $=$ energy density (space-limited: fuel tanks). Linked by density: e. d. $=$ sp. e. $\times\rho$.

Fuel	MJ kg^{-1}
Hydrogen	~142
Petrol	~46
Coal	~27
Li-ion battery	~0.6

TRICK Mass of fuel = total energy needed $\div$ specific energy. Units: J $\div$ J kg^{-1} = kg.

NOTE High specific energy = less fuel mass needed. Batteries are very low compared to fossil fuels.

FROM THE PHOTON QUESTION BANK
Mass of fuel = energy ÷ specific energy (convert MJ→J); divide by efficiency first — the fuel must supply more than the useful energy.

NOTE **Degraded energy**: each cycle dumps low-grade heat that can no longer do work (2nd law). Energy is still conserved — just spread out. So no station is 100% efficient (~30% typical).

NOTE **Sankey to scale**: output-arrow width = efficiency × input width; label every loss branch.

§8 — Power Generation & Sources

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Thermal Power Station Chain

fuel → thermal → steam → turbine → electrical

Boiler → turbine → generator → condenser.

TRICK **Renewable** (solar, wind, hydro, tidal, wave, geothermal): no CO_2, free source, but often unreliable / area-hungry. **Non-renewable** (coal, oil, gas, nuclear): high specific energy but finite.

TRAP **Pumped storage** is a *store*, not a source — it does not generate new energy.

A.3 Master Formula Summary

$$W = Fs\cos\theta \qquad \Delta E_p = mg\Delta h \qquad P = \Delta W/\Delta t$$

$$W_{\text{net}} = \Delta E_K \qquad E_H = \tfrac{1}{2}k(\Delta x)^2 \qquad P = Fv$$

$$E_K = \tfrac{1}{2}mv^2 = \frac{p^2}{2m} \qquad E_{\text{mech}} = E_K + E_p + E_H \qquad \eta = E_{\text{out}}/E_{\text{in}}$$