THE CCECC HANDBOOK

Cradle to Cradle Energy Conceptual Calculations

A first-principles energy ledger, measured in joules, for any project that makes, moves, stores, or dissipates energy.

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This PDF is a faithful, citable rendering of the web handbook at slowtime.dk/ccecc-handbook. Editor's notes added for this edition are shown in amber italics and marked [Ed.]; they flag points for the next revision and are not part of the original text.

i. What CCECC is (and isn't)

CCECC stands for **Cradle to Cradle Energy Conceptual Calculations**. It is a fast, first-principles *energy ledger* for any project that makes, moves, stores, or dissipates energy.

> ***The one rule:*** *every number in a CCECC evaluation is expressed in **joules, watts, or their multiples** (kJ, MJ, GJ, TJ; Wh, kWh, MWh, GWh, TWh). Not kilograms of CO_2. Not dollars. Not qualitative hand-waves. If you cannot state it in energy units, it does not belong in the ledger.*

Why this strictness? Because carbon footprints, cost figures, and vibes all have escape hatches — discount rates, boundary games, offsets, marketing. A joule does not. A joule delivered is a joule; a joule embodied is a joule; a joule recoverable is a joule. The energy ledger is the one accounting system a physicist, an engineer, and a policymaker all have to agree on.

What it is

- An energy-balance worksheet you can fill in over a single afternoon using public data and rough estimates.
- A tool for engineers, founders, planners, and procurement officers at the *feasibility stage* of a project.
- A communication device — the output is two or three energy ratios and a short verdict, not a 200-page report.

What it is not

- Not a replacement for ISO 14040 life-cycle assessment.
- Not a carbon accounting tool. (Carbon follows from energy and grid mix; CCECC deliberately stops at the energy layer.)
- Not a certification scheme.
- Not a substitute for detailed techno-economic modelling once a project is real.

CCECC aims at the ~10% of LCA work that drives ~80% of early energy decisions.

ii. When to use it

Use CCECC when you need a first-principles answer to one of these questions:

- *What is the energy payback time, roughly?*
- *What is the approximate EROEI of this project?*
- *How many joules does this system consume per unit of service delivered, vs. the alternative?*
- *What fraction of the energy flow is fresh vs. waste-stream?*
- *How much of the embodied energy comes back at end of life?*

Don't use CCECC when you need auditable carbon accounting for compliance, detailed techno-economic cost modelling, or product certification — it is not designed for any of those.

iii. The method in four moves

Each move asks an energy-balance question. Answer each one with a number in joules or watt-hours (or the corresponding multiple — MJ, GJ, kWh, GWh, TWh). Rough order-of-magnitude estimates are fine; precision is not the point, the ledger is.

Move 1 — Upstream cradle: E_{in}

What energy goes in before the project delivers a single useful joule?

- **Embodied energy of the hardware** (E_{emb}, in MJ or GJ). Use handbook figures per kg of each material, multiplied by mass.
- **Annual operating input energy** ($E_{op,in}$, in MJ/yr or GWh/yr) — fuel, feedstock, or electricity drawn during normal operation.
- **Fraction of operating input that is fresh vs. waste-stream.** A joule of waste heat you would otherwise vent is not equivalent to a joule of fresh grid electricity; flag which is which.

Move 2 — Use phase: E_{out}

What energy does the system deliver as useful work, heat, or service?

- **Annual useful energy output** (E_{out}, in kWh/yr, GWh/yr, or GJ/yr).
- **Conversion efficiency** (η) — useful E_{out} divided by $E_{op,in}$.
- **Expected operating lifetime** (yr). Lifetime output = E_{out} × years.
- For systems that do not *produce* energy but *consume* it to deliver a service (a server, a tire, a building), record the service-unit and the energy per service unit (J/prompt, MJ/km, kWh/m^2·yr).

Move 3 — Downstream cradle: $E_{recover}$

How much of the embodied energy comes back at end of life?

- **Recoverable material energy** — the fraction of E_{emb} avoided by recycling vs. virgin production.
- **Calorific energy** — if combustible, heating value × mass (MJ/kg).
- **Decommissioning energy cost** (subtract from recovery).
- Net: $E_{recover}$ = recovered material + calorific – decommissioning.

Move 4 — Systemic loop check: EROEI and EPBT

Two headline ratios tell you whether the ledger closes:

- **EROEI** (Energy Return on Energy Invested) = (lifetime E_{out} + $E_{recover}$) / (E_{emb} + lifetime $E_{op,in}$ – waste-stream contribution)
- **EPBT** (Energy Payback Time) = E_{emb} / annual net E_{out}, in years.
- Also record: *what fraction of $E_{op,in}$ is genuinely waste-stream*, not fresh extraction. This is the circularity question the ratios alone don't capture.

iv. The one-page worksheet

Copy this for each project. Every blank is filled with a number in joules, watt-hours, or their multiples. Use a plain unit suffix (MJ, GJ, kWh, GWh) next to each figure.

```
PROJECT NAME:
DATE / ANALYST:
SYSTEM BOUNDARY (what's in, what's out):

[1] UPSTREAM CRADLE - energy in
    Embodied energy of hardware (E_emb) ......... ___ GJ
    Annual operating input (E_op,in) ............ ___ GWh/yr
        of which waste-stream (not fresh) ........ ___ %
    Expected lifetime ........................... ___ yr

[2] USE PHASE - energy out
    Annual useful output (E_out) ................ ___ GWh/yr
    Conversion efficiency  eta = E_out / E_op,in . ___ %
    Lifetime output = E_out x lifetime .......... ___ GWh
    Service-unit (if non-energy output) ......... ___ J per unit

[3] DOWNSTREAM CRADLE - energy recoverable
    Recoverable material energy ................. ___ GJ
    Calorific energy (if combustible) ........... ___ GJ
    Decommissioning energy cost ................. ___ GJ
    Net E_recover ............................... ___ GJ

[4] SYSTEMIC LOOP - ratios
    EROEI = (lifetime E_out + E_recover)
            / (E_emb + lifetime fresh E_op,in) ... ___
    EPBT = E_emb / annual net E_out ............. ___ yr
    Fresh-joule fraction of input ............... ___ %

VERDICT (<= 100 words, anchored in the ratios above):
```

Scoring thresholds

Scores follow from the ratios, not from intuition. Typical cut-offs for energy-producing systems:

Move	Strong	Medium	Weak
Upstream (waste-stream share of E_op,in)	> 75%	25–75%	< 25%
Use phase (η, relative to best-in-class)	≥ 0.9× BIC	0.6–0.9×	< 0.6×
Downstream (E_recover / E_emb)	> 60%	20–60%	< 20%
Systemic (EROEI)	> 10	3–10	< 3

For systems that consume energy to deliver a non-energy service (servers, vehicles, tires, buildings), EROEI is undefined. State this explicitly, and evaluate on *joules per service-unit* compared to the next-best alternative, using the same Strong/Medium/Weak bands relative to that alternative.

v. Worked example — Chaotan One

sCO_2 waste-heat power, Liupanshui, China

Upstream	**Strong**
Use phase	**Strong**
Downstream	**Medium**
Systemic	**Strong**

Project: Chaotan One — 2 × 15 MW supercritical CO_2 waste-heat power plant, Liupanshui, Guizhou, China. Developer: Nuclear Power Institute of China (CNNC). Commercial operation from December 20, 2025. Coupled to a Shougang Shuicheng steel sinter line.

Move 1 — Upstream: E_{in}

- **$E_{op,in}$:** ~250 GWh/yr of thermal waste heat at 300–400 °C (calculated from ~70 GWh_e/yr output at ~28% thermal-to-electric efficiency, typical for sCO_2 Brayton at these temperatures).
- **Waste-stream share:** ~100%. The sinter line dumps this heat to atmosphere without Chaotan One; the fresh-joule fraction of input is effectively 0%.
- **E_{emb} of hardware:** 30 MW × ~3 GJ/kW for high-alloy sCO_2 plant (nickel superalloys, printed-circuit heat exchangers, >73-atm vessels) ≈ **90 GJ = 25 GWh embodied**. About 2× a steam Rankine plant of the same capacity (~1.5 GJ/kW), reflecting exotic metallurgy.

[Ed.] Unit check for v0.2: 30 MW × 3 GJ/kW = 90 TJ (≈ 25 GWh), not 90 GJ. The downstream ratios below use the 90 GJ figure; reconcile E_{emb} to 90 TJ so the GWh and the joule figures agree, and re-derive EROEI accordingly.

Move 2 — Use phase: E_{out}

- **Annual E_{out}:** ~70 GWh_e/yr = 252 TJ/yr.
- **η (thermal → electric):** ~28%, vs. ~18–22% for conventional sinter-waste steam cycles — genuinely best-in-class at this heat source and scale.
- **Assumed lifetime:** 20 yr (with the caveat in Move 3 below).
- **Lifetime E_{out}:** 70 × 20 = **1,400 GWh = 5,040 TJ**.

Move 3 — Downstream: $E_{recover}$

- **Nickel-alloy recovery:** high-grade superalloys have embodied energy ~200 MJ/kg. Assuming ~80 t of superalloy in the hot end and ~80% recovery efficiency at end-of-life → ~13 GJ recoverable as avoided-virgin energy.
- **Steel structure:** ~500 t structural steel at ~25 MJ/kg embodied, ~90% recovery → ~11 GJ.
- **Decommissioning cost:** ~2 GJ (crane, transport, cutting).
- **Net $E_{recover}$** ≈ **22 GJ**, or about 24% of E_{emb}. Sits in the Medium band. The uncertainty: if hot-end creep or sCO_2 corrosion halves the 20-year lifetime, $E_{recover}$ is unchanged but EROEI roughly halves — this is the real open question for the technology.

Move 4 — Systemic: EROEI and EPBT

- **EROEI** = (lifetime E_{out} + $E_{recover}$) / (E_{emb} + fresh $E_{op,in}$) = (5,040 + 0.022 TJ) / (0.090 TJ + 0 TJ) ≈ **56**. (Waste-heat input contributes 0 to the denominator by definition.)
- **EPBT** = E_{emb} / annual E_{out} = 90 GJ / 252,000 GJ·yr^{-1} ≈ **0.36 yr (~4 months)**.
- If lifetime halves to 10 yr, EROEI drops to ~28 — still solidly Strong.
- Fresh-joule fraction of input: ~0%. This is what makes the ratios so favourable.

Verdict

On a pure energy ledger, Chaotan One is the best kind of CCECC project: a ~4-month energy payback and an EROEI of ~56 because its fuel side contributes zero fresh joules. The embodied energy of the alloy-heavy hot end (~25 GWh) is only ~0.5% of lifetime output (~1,400 GWh). The single open question is lifetime — if sCO_2 corrosion and creep shorten hardware life to under ten years, EROEI halves but remains comfortably Strong. Downstream recovery at ~24% of E_{emb} is Medium and has room to improve with better alloy-recycling streams.

vi. One AI prompt vs. the sulphur in one winter tire

Comparing a digital service to a physical material on common cradle-to-cradle terms

> *Why this odd pairing? CCECC is most useful when it forces us to compare unlike things on a common cradle-to-cradle basis. Setting one AI prompt — a digital, ephemeral service — against the sulphur in one winter tire — a physical, durable material input — reveals something that per-kilogram carbon comparisons miss: whether the impact is happening inside a loop or outside one.*

Side A — One typical AI prompt

A median-length query to ChatGPT, Claude, or Gemini in 2026.

Upstream	**Weak**
Use phase	**Medium**
Downstream	**Weak**
Systemic	**Weak**

*Note: a prompt consumes energy but produces no joules of useful energy output. EROEI is therefore **undefined**. CCECC evaluates this on **joules per service-unit** (J/prompt) against alternatives, not on an energy-return ratio.*

Move 1 — Upstream: E_{in} per prompt

- **Inference electricity:** 0.24–0.34 Wh = 860–1,225 J at the chip (Google Gemini: 0.24 Wh; Sam Altman/ChatGPT: 0.34 Wh; Epoch AI: ~0.3 Wh).
- **× data-centre PUE (~1.2):** ~1,050–1,470 J at the grid.
- **+ Amortised GPU embodied energy:** a data-centre GPU has ~1–2 GJ embodied and serves in the low millions of prompts over 3–5 yr life. Adds roughly 300–1,000 J per prompt.
- **Total E_{in} per median prompt: ~1,500–2,500 J**, i.e. ~0.4–0.7 Wh.
- **Waste-stream share:** ~0%. Every joule is freshly drawn from grid generation.

Move 2 — Use phase: J per service-unit

- **E_{out} (useful joules):** 0 J. The output is bits.
- **Alternative comparisons (J per “equivalent answer”):** reading a well-chosen Wikipedia article ~200–500 J (≈0.05–0.14 Wh end-to-end); driving 1 km to a library ~2,000,000 J (~2 MJ), ~1,000× the prompt; asking a domain expert by phone for 3 min ~5,000–20,000 J.
- A prompt is a very efficient J/service-unit compared to physical-movement alternatives, and modestly worse than a pre-existing web page. Hence Medium on this move — context-dependent.

Move 3 — Downstream: $E_{recover}$

- The prompt itself leaves no recoverable artefact. $E_{recover}$ per prompt = **0 J**.
- The serving GPU has ~1–2 GJ embodied; precious-metal recovery at end-of-life returns perhaps 5–10% of that as avoided-virgin energy — but this is pooled across millions of prompts, not attributable to any one.

Move 4 — Systemic

- **EROEI:** undefined (no energy output).
- **Aggregate system draw:** ~15 TWh in 2025, projected to ~347 TWh by 2030 per Schneider Electric. That's the scale of Argentina's national electricity demand.
- Fresh-joule fraction of input: ~100% globally (slightly better where hyperscalers contract dedicated renewables, but grid-equivalent accounting still attributes the fresh draw).

Side B — The sulphur in one passenger-car winter tire

~150 g of elemental sulphur in a ~10 kg tire.

Upstream	**Strong**
Use phase	**Strong**
Downstream	**Medium**
Systemic	**Strong**

*A tire doesn't produce energy either. But the sulphur's **role** is to avoid a tenfold increase in tire consumption — so the meaningful energy ledger is "joules of future tire manufacturing avoided" per joule of sulphur invested.*

Move 1 — Upstream: E_{in} for 150 g of sulphur

- **Embodied energy of recovered Claus sulphur:** ~0.5–1 MJ/kg (it's a by-product of oil & gas desulphurisation; the energy is almost entirely attributable to the host refining process).
- **150 g × ~1 MJ/kg = 0.15 MJ = 150 kJ per tire.**
- **Waste-stream share:** ~95%. The refining industry has to remove sulphur regardless; the tire industry absorbs it productively.
- Energy to distribute the sulphur during vulcanisation: ~30–50 MJ for the whole tire, but only a fraction attributable to sulphur. Net marginal energy of "using sulphur" vs. "not": essentially the 150 kJ above.

Move 2 — Use phase: functional leverage in joules

- **Embodied energy of a 10 kg tire:** ~750 MJ (rubber compound ~75 MJ/kg including synthetic rubber, carbon black, steel belt, processing).
- **Without sulphur cross-linking,** the tire would fail in ~1/10 the distance (soft in summer, brittle in winter — exactly the 1839 problem Goodyear solved).
- **Avoided manufacturing energy:** 9 × 750 MJ = **6,750 MJ** over the same driving distance.
- **Rolling-resistance energy over tire life** (~60,000 km): ~3,000 MJ dissipated as heat (~50 J/m × 60 × 10^6 m).

Move 3 — Downstream: $E_{recover}$

- **Calorific energy:** 10 kg tire × ~32 MJ/kg heating value = **~320 MJ recoverable** as tyre-derived fuel.
- But: burning sulphur-vulcanised rubber releases SO_2 unless scrubbed (an environmental, not energy, cost).
- Material recycling of the crosslinked rubber is essentially zero — vulcanisation is irreversible by design.
- $E_{recover}$ / E_{emb} ≈ 320 / 750 = **43%**. Medium, all of it as low-grade fuel rather than material.

Move 4 — Systemic: leverage ratio

- **Energy-leverage ratio** (the sulphur equivalent of EROEI, for a material that enables rather than produces energy) = avoided manufacturing energy / energy invested in the sulphur = 6,750 MJ / 0.15 MJ ≈ **45,000**.
- Fresh-joule fraction of input: ~5%.
- Caveat: as oil & gas peak, Claus sulphur supply shrinks. If the tire industry has to mine virgin sulphur (Frasch process), input-side embodied energy rises roughly 10× — still excellent leverage, but worth watching.

Verdict — the comparison in joules

Per service-unit, an AI prompt costs ~1,500–2,500 J and produces zero joules of return. The sulphur in one tire costs ~150 kJ and enables ~6,750 MJ of manufacturing to be avoided — a leverage ratio near 45,000. CCECC's verdict is stark: a 19th-century material intervention has an energy-leverage ratio four orders of magnitude higher than a 21st-century digital service. This is not an argument against AI — it is an argument that AI's energy ledger only closes when a prompt leads to an action that itself saves joules (a better route, a correct part number, a trip avoided). If the prompt's output is discarded or replaces nothing, every one of its ~2,000 J is a pure net draw on fresh energy. The pedagogy: joules-per-service-unit is the only unit in which unlike systems can be honestly compared.

vii. Worked example — Second-life EV batteries

Repurposed for grid storage

Upstream	**Strong**
Use phase	**Strong**
Downstream	**Strong**
Systemic	**Strong**

Project: Lithium-ion battery packs retired from electric vehicles (at ~70–80% of original capacity) repurposed as stationary grid-scale or behind-the-meter storage. Reference pack: 60 kWh NMC, ~400 kg. Real deployments include Nissan/Eaton xStorage, BMW's Leipzig plant storage, Renault/Connected Energy.

Move 1 — Upstream: E_{in} for second life

- **Original E_{emb} (first-life manufacturing):** 60 kWh NMC pack × ~150 MJ/kg × 400 kg = **~60 GJ embodied** (≈16,700 kWh of manufacturing energy, or ~280 kWh per kWh of pack capacity).
- **Attributed to second life:** 0 GJ. The pack already exists; repurposing is pure deferral of new manufacturing.
- **Refurbishment energy:** ~0.5–2 GJ per pack (disassembly, cell grading, BMS installation, enclosure). Call it **1 GJ**.
- **Waste-stream share of E_{in}:** ~98%. The only fresh joules are the refurbishment step.

Move 2 — Use phase: E_{out}

- **Residual usable capacity:** 60 kWh × 75% = 45 kWh per pack.
- **Second-life duration:** ~7 years.
- **Assume 1 full-cycle-equivalent per day** in grid-storage duty (solar shifting or peak shaving).
- **Lifetime second-life throughput:** 45 kWh × 365 × 7 = **~115 MWh = 414 GJ** delivered.
- **Round-trip efficiency:** ~82% (slightly below a new pack's ~90% due to degradation).

Move 3 — Downstream: $E_{recover}$

- After second life, the pack still enters the same recycling stream as a first-life pack. Second life *defers* recycling, it does not avoid it.
- **Hydrometallurgical recovery (2026 state of the art):** ~60–70% of E_{emb} recoverable as avoided-virgin-material energy.
- **$E_{recover}$:** 0.65 × 60 GJ = **~39 GJ**.

Move 4 — Systemic: EROEI for the second-life intervention

- Treating the intervention as “the decision to run a second life instead of scrapping”:
- **EROEI** = second-life E_{out} / refurbishment E_{in} = 414 GJ / 1 GJ ≈ **414**.
- **EPBT** for refurbishment energy: 1 GJ / (414 GJ / 7 yr) ≈ **6 days**.
- Even if you attribute 20% of the original E_{emb} (12 GJ) to second life as a crediting approach, EROEI is still ~32 — solidly Strong.
- Fresh-joule fraction: ~2%.

Verdict

The energy ledger for second-life EV batteries is almost unbeatable: a ~1 GJ refurbishment investment returns ~414 GJ of grid storage over seven years before the pack enters recycling at ~65% embodied-energy recovery. EROEI ≈ 400, EPBT ≈ 6 days. This is what “cradle to cradle” looks like when expressed in joules — the original manufacturing energy is amortised over *two* productive lives plus a recycling tail, rather than one life and a shredder. The only risks are economic (narrowing price gap against new cells) and regulatory (lack of standardised battery passports). Policy should protect the energy logic from economic logic until recycling capacity matures.

viii. How to contribute

This handbook is a living document. The three examples here are seeds, not the canon.

Ways to contribute

1. **Submit a worked example** using the one-page worksheet above. Aim for 500–800 words.
2. **Challenge a score.** If you think one of the scores above is wrong, send a revised radar with reasoning.
3. **Translate.** Danish, German, Spanish, Mandarin, Hindi, and French translations are priorities.
4. **Build tooling.** Spreadsheets, web tools, API integrations, and batch-compare utilities are all high-leverage next steps.

Target domains for next examples

- Heat pumps replacing gas boilers (building scale).
- Biogas from food waste (agriculture + energy).
- Green hydrogen via electrolysis vs. grey hydrogen from steam reforming.
- Timber construction vs. reinforced concrete.
- Single-use vs. returnable packaging systems.

> ***Core principle for all contributions:*** *Fast, honest, and first-principles. A CCECC that takes a month to produce is not a CCECC.*

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