Environmental Sustainability in Control Systems

Design choices, energy use and CO_2e in the use phase

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Intended Learning Outcomes

- Explain how control design impacts energy, resources and emissions.
- Define system boundaries and functional units for fair comparisons.
- Select and report energy and quality metrics together.
- Quantify energy and CO_2e with transparent assumptions.
- Compare controllers via sampling trade-off and Pareto views.

Why Sustainability in Control?

- Control decisions (sampling, constraints, supervision) shape actuator duty and computation.
- Small choices accumulate over thousands of hours → large energy impact.
- Goal: efficient, safe, maintainable operation rather than pointwise optimality.
- Typical applications: fans/pumps, thermal batches, autonomous robots, precision systems, HVAC.

System Boundaries & Use-Phase Focus

- Inside: drive, inverter, gearbox, sensors, embedded controller, communications.
- Outside: upstream utilities and central services unless metered.
- Scope: use phase (manufacturing/EoL excluded unless stated).
- Multiple duty profiles? Evaluate separately and report weighted average.

Functional Units & Normalisation

- Report energy per functional unit (U): per cycle, per tonne, per km, per m^3.
- Avoid per-hour unless task value is fixed; otherwise state window and task.
- Example: “0.23 kWh per cycle (±0.02 kWh).”

Metrics & Reporting

- Primary: energy per U; peak/average power; duty; saturations; starts/stops.
- Quality: settling time, overshoot, RMSE, constraint violations, throughput.
- Emissions: $m\_CO_2e = E(kWh) \times g$ (state region/year and source).
- Always present energy together with quality and uncertainty.

Methods: Electrical Energy

- Continuous: $E = \int v(t) \cdot i(t)\, dt$.
- Sampled (rectangle): $E \approx \Sigma\, v[k] \cdot i[k] \cdot \Delta t$.
- Sampled (trapezoidal): $E \approx \Sigma\, 0.5 \cdot [p[k]+p[k+1]] \cdot \Delta t$, $p[k] = v[k] \cdot i[k]$.
- Convert to kWh: $E(kWh) = E / (3.6 \times 10^6)$.
- Align timestamps; validate down-sampling.

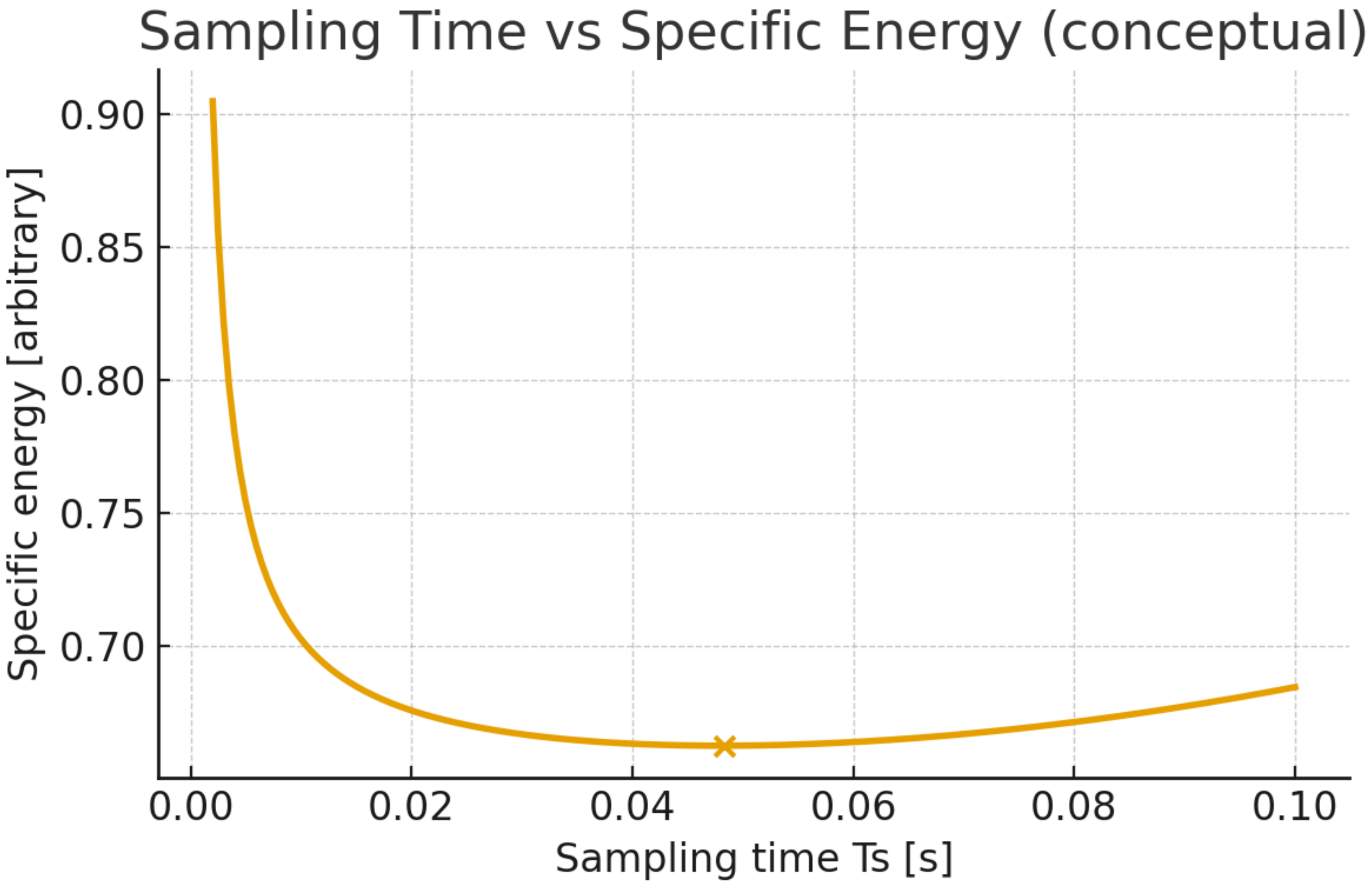
Methods: Emissions & Computation

- Emissions: $m\_CO_2e = E(kWh) \times g$ (region/year, units, source).
- Compute (proxy): $E\_comp \approx P\_idle \cdot T + (P\_load - P\_idle) \cdot u\_CPU \cdot T$.
- Duty-factor quick estimate: $D = t\_active/T \rightarrow E \approx P\_rated \cdot D \cdot T$.
- Include networking/offloaded compute when applicable.

Design Levers: Overview

- Sampling time and anti-windup.
- Set-point shaping and reference governors.
- Constraints (rates/limits) and soft penalties.
- Supervisory switching and scheduling; predictive/adaptive strategies.

Sampling Time vs Specific Energy

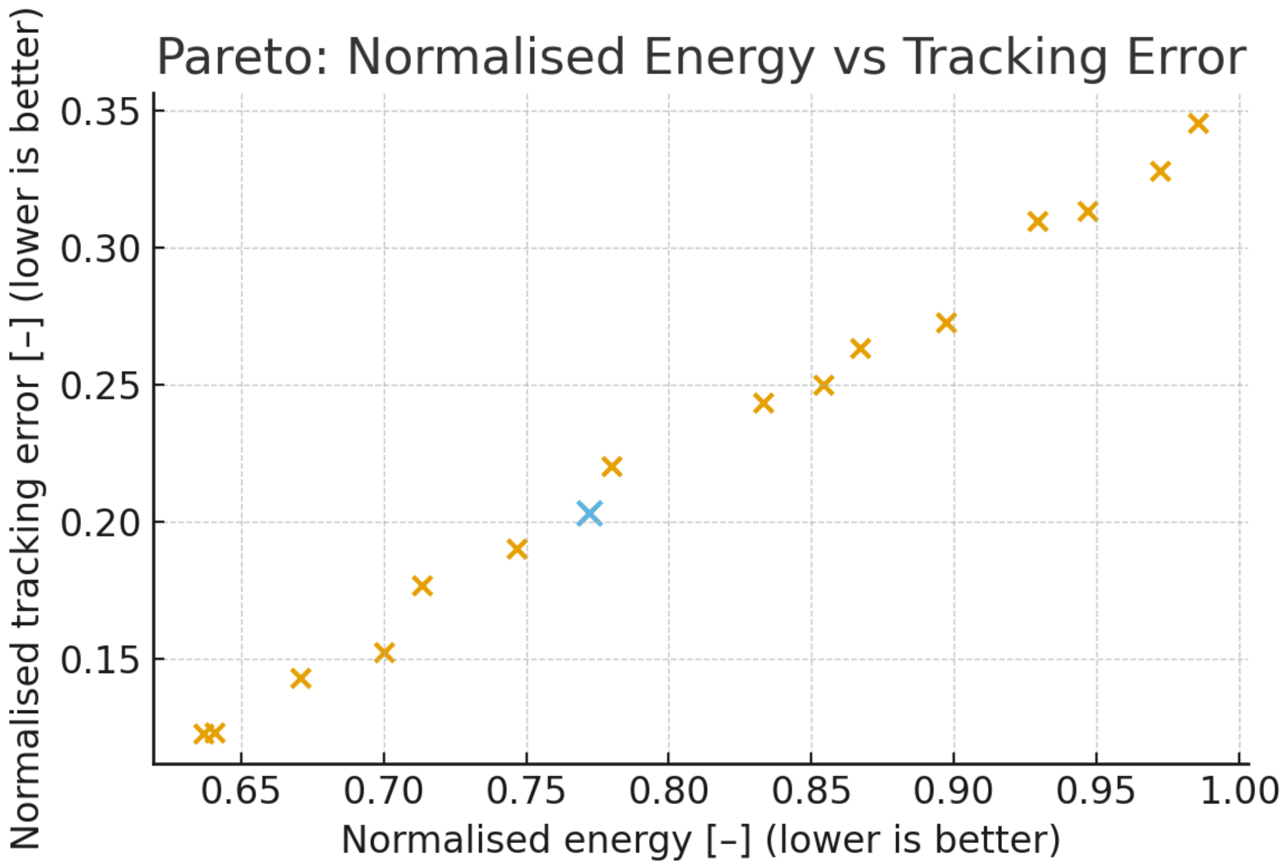


Choose T_s by comparing 2–3 candidates under the same workload.
Target the knee region.

Reading the Sampling Trade-off

- Small T_s ↑ I/O and CPU overhead.
- Large T_s ↓ disturbance rejection → longer tasks/oscillations.
- Pick near the knee; confirm with measurements.

Pareto: Normalised Energy vs Tracking Error



Same constraints/workload across alternatives.
Prefer points near the knee; add error bars.

Measurement & Logging

- Use true-RMS meters; calibrate and record certificates.
- Synchronise clocks; declare log rates; replicate runs.
- Sanity checks: non-negative energy; plausible peaks; efficiency bracket.

Worked Example: Electrical + CO_2e

- Given V = 230 V, I = 2.0 A, t = 1 800 s → E ≈ 0.23 kWh.
- With g = 0.25 kg CO_2e/kWh → m_CO_2e ≈ 0.058 kg per cycle.
- Report uncertainty band and the source of g.

Worked Example: Mechanical Proxy

- Given $\tau = 5.0$ N·m, $\omega = 120$ rad/s, $T = 60$ s → $E_{mech} \approx 0.01$ kWh.
- If $\eta = 0.8$ → $E_{elec} \approx 0.0125$ kWh (range 0.012–0.014 kWh).
- Mechanical energy is a lower bound unless efficiencies are known.

Mini Case Study: Variable-Speed Pump

- Baseline: abrupt set-points; Alternative: s-curve (4 s) + anti-windup.
- Energy per batch: 0.62 → 0.57 kWh (−8%). Peak power: 2.3 → 1.9 kW (−17%).
- Overshoot: 12% → 4%; constraint violations eliminated.

Summary & Takeaways

- Define boundaries and functional units; document assumptions.
- Tune with energy and robustness in mind (sampling, shaping, wind-up).
- Use Pareto views; choose the knee region.
- Report energy/CO_2e with uncertainty; sustain efficiency with supervision.

Discussion

- Where is your Pareto knee and how sensitive is it?
- Which small change yields the largest saving?
- Which assumptions dominate uncertainty?
- How will supervision/maintenance sustain gains over time?