Environmental Sustainability in Control Systems

Technical Handout

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1. Abstract

This handout explains how design and tuning choices in feedback control influence energy use, operating cost and climate-relevant emissions during the **use phase** of engineered systems. It provides a practical procedure for defining what is included in the analysis, choosing a meaningful basis for comparison, measuring or estimating energy flows with defensible assumptions, and comparing alternative controllers fairly. The approach emphasises transparency and reproducibility in laboratory and industrial settings. Equations are given in plain text with Unicode symbols so the document can be pasted into a word processor without formatting issues.

2. Introduction and Scope

2.1 **Why this matters.** Even when hardware remains unchanged, control choices determine actuator duty, switching losses, thermal cycling and computation. These effects accumulate over thousands of operating hours and can dominate the life-cycle use-phase energy. Making them visible allows engineers to improve efficiency without compromising safety or product quality.

2.2 **Typical applications.** Variable-speed drives for pumps and fans, thermal processes with batch operation, autonomous robots, precision positioning systems, and building services (heating, ventilation and air conditioning).

2.3 **Scope of the assessment.** Unless stated otherwise, our boundary includes sensing, actuation, embedded computation and any input/output overhead introduced by the control strategy. Manufacturing and end-of-life are excluded. When cloud or edge offloading is used, its energy must be accounted for explicitly.

2.4 **Objective.** Provide a step-by-step recipe to quantify energy and **carbon-dioxide equivalent** emissions (written “CO_2e”) per functional unit, and to trade them against control quality (settling time, overshoot, constraint violations) when selecting a controller.

3. System Boundaries and Functional Unit

3.1 **Boundary definition.** Enumerate what is inside (e.g., motor, inverter, gearbox, sensors, embedded controller, communications) and what is outside (e.g., upstream utilities, chilled-water plant). Briefly justify each exclusion. A simple diagram helps reviewers understand responsibilities.

3.2 **Operating profile.** Fix a representative profile (drive cycle, batch duration, occupancy pattern, ambient conditions). All alternatives must use **the same profile**. If multiple profiles are credible (e.g., weekdays vs weekends), evaluate them separately and report a weighted average with weights stated.

3.3 **Functional unit (U).** Normalise results so they are portable, e.g., kWh **per cycle**, **per tonne** of product, **per kilometre** travelled, or **per cubic metre** processed. Reporting **per hour** is acceptable only when it corresponds to a task of fixed value; otherwise state both the time window and the task.

3.4 **Baselines and comparators.** Define a baseline controller (e.g., PID tuned for nominal load, sampling time T_s = 10 ms) and list all configuration details: gains, filters, limits, anti-windup method, set-point pre-filters. This prevents hidden degrees of freedom that would confound comparisons.

3.5 **Data retention.** Decide what logs and metadata you will keep (firmware versions, solver tolerances, calibration certificates). Store them with the results so other engineers can reproduce the study.

4. Metrics and Reporting Conventions

4.1 **Primary indicators.** Energy per functional unit; average and peak power; actuator duty; the number and duration of saturations; cumulative starts/stops.

4.2 **Quality indicators.** Settling time, overshoot, **Root-Mean-Square Error (RMSE)**, frequency and magnitude of constraint violations, throughput, and product quality proxies (e.g., temperature uniformity). Always report energy **together** with these indicators to avoid misleading trade-offs.

4.3 **Emissions.** Convert energy in kilowatt-hours to **CO_2e** using a grid factor **g** (kilograms of CO_2e per kWh) specific to region and year: **$m\_CO_2e = E_{(kWh)} \times g$**. State the source and any adjustments (on-site renewables, power-purchase agreements) and explain the allocation used.

4.4 **Uncertainty.** Distinguish **measurement error** (instrument accuracy, resolution, sampling jitter) from **modelling uncertainty** (assumed efficiencies, envelope conditions). When possible, report a range or **± value**. Example: “0.23 kWh per cycle ± 0.02 kWh; RMSE 0.9 °C.”

4.5 **Reporting style.** Bind numbers to the functional unit within the same sentence; give units for all quantities; avoid mixing energy and power terms. Prefer tables for scenario summaries and short paragraphs for interpretation.

5. Methods and Mathematical Modelling

Use SI units unless stated. Symbols are defined in Section 12.

5.1 **Electrical energy — continuous time**

$E = \int v(t) \cdot i(t)\, dt$ (integration over the task duration). To express in kWh: **$E_{(kWh)} = E / (3.6 \times 10^6)$**.

Good practice. Integrate power directly when available; otherwise, compute instantaneous power as **$p(t) = v(t) \cdot i(t)$** and integrate.

5.2 **Electrical energy — sampled data**

Rectangle rule: $E \approx \Sigma [\, v[k] \cdot i[k] \cdot \Delta t \,]$.

Trapezoidal rule (often better): $E \approx \Sigma\, 0.5 \times [\, p[k] + p[k+1] \,] \times \Delta t$, where **$p[k] = v[k] \cdot i[k]$**.

Ensure the same sampling window for voltage and current; align timestamps to compensate for clock drift. Validate down-sampling by checking that the integration error is negligible relative to uncertainty.

5.3 **Mechanical proxy (when electrical power is unavailable)**

$E \approx \int \tau(t) \cdot \omega(t)\, dt$. If gearbox or inverter efficiencies are known, include them; otherwise report mechanical energy as a **lower bound** and provide a bracket for total electrical input: **$E_{elec} \approx E_{mech} / \eta$**, with **$\eta$** stated.

5.4 **Emissions**

$m\_CO_2e = E_{(kWh)} \times g$. Give **$g$** with region, year, units and source. If a different allocation rule (market-based vs location-based) is used, state it explicitly.

5.5 **Controller/edge computation (proxy)**

$E_{comp} \approx P_{idle} \cdot T + (P_{load} - P_{idle}) \cdot u_{CPU} \cdot T$. Include networking and storage; for offloaded computation, add the external energy per task. Record solver settings (for predictive controllers), sampling time and fixed background services that influence **P_{idle}**.

5.6 **Duty factor — quick estimate**

$D = t_{active} / T$, hence **$E \approx P_{rated} \cdot D \cdot T$**. This estimate is useful for early comparisons but should be replaced by measurements for final reporting.

5.7 **Sampling requirements**

Log at least **10–20 samples across the fastest transient** of interest. For switching drives, log the electrical side at a lower bandwidth but verify with a higher-rate spot check.

6. Control Design Levers and Their Impact on Energy

6.1 **Sampling time (T_s).** Smaller T_s typically improves disturbance rejection but increases input/output overhead and central-processing usage; larger T_s can degrade tracking, increase oscillations and inflate energy per task. Evaluate a small set of T_s candidates under identical constraints (e.g., 2 ms, 5 ms, 10 ms) and select near the **knee** of the energy–error curve.

6.2 **Set-point shaping and feed-forward.** Smoother references reduce peak currents and component stress. Use s-curve ramps or trajectory generators; add feed-forward terms for load and friction where models are trustworthy. Document the shaping parameters so others can reproduce the result.

6.3 **Anti-windup and saturation.** Integral wind-up causes prolonged saturation and wasteful oscillations. Choose an anti-windup scheme (back-calculation, conditional integration, or clamping) and verify that recovery from saturation is monotonic. Record limits for actuators and their rates.

6.4 **Constraint handling.** Where possible, represent physical limits as explicit constraints (e.g., speed, torque, rate). Soft constraints with well-chosen penalties can reduce chatter and switching losses compared with hard clipping.

6.5 **Dead-band/hysteresis.** Introduce small dead-bands to prevent high-frequency switching. Excessive dead-band degrades accuracy; tune using measured power rather than relying on rules of thumb.

6.6 **Overshoot versus energy.** Lower overshoot often correlates with lower energy and wear, but overly conservative settings may prolong the task and increase total energy. Confirm with measurements at equal throughput.

6.7 **Controller class.** Advanced strategies (predictive or gain-scheduled) can reduce energy **when** they exploit constraints, previews or variable tariffs. Otherwise, the extra computation may offset gains. Always measure end-to-end results.

6.8 **Supervision and scheduling.** Simple supervisory logic (sleep modes, batch alignment with low-tariff periods, warm-up management) often delivers large savings with minimal risk. Document the logic and triggers.

7. Measurement, Logging and Validation

7.1 **Instrumentation.** Prefer true-RMS power meters on the electrical input. If not available, derive power from voltage and current with validated models and check against a calibrated handheld meter.

7.2 **Calibration and synchronisation.** Record calibration certificates and the logging resolution; synchronise clocks (e.g., network time) and correct for drift.

7.3 **Test design.** Execute replicates under identical conditions; randomise the order of controller alternatives to avoid thermal or ageing bias. Document ambient conditions and load variations.

7.4 **Sanity checks.** Verify non-negative energy, plausible peaks, consistent energy balance between electrical input and mechanical output within efficiency brackets.

7.5 **Data hygiene.** Keep a lab notebook (digital is fine) with assumptions, units and data sources. Store raw logs and processed results with version numbers.

8. Analysis and Visualisation

8.1 **Normalisation.** Express energy and quality metrics relative to the baseline for rapid reading, e.g., "Energy 0.92 (−8%) vs baseline; RMSE 1.04 (+4%)."

8.2 **Pareto view.** Plot **normalised energy** against **normalised tracking error** for all alternatives under identical workloads and constraints. Identify the **knee**, where further energy savings require disproportionate performance sacrifice.

8.3 **Statistical confidence.** When replicates are available, add error bars (e.g., ± one standard deviation) to the Pareto points. If differences are within uncertainty, prefer the simpler design.

8.4 **Narrative.** Summarise the main reasons for the chosen design (e.g., "5 ms sampling with ramped set-points reduced energy by 7% at equal settling time; anti-windup eliminated saturation-induced oscillations").

9. Worked Examples

9.1 **Electrical energy and emissions (single-phase device)**
A device draws **2.0 A** at **230 V** for **30 minutes** (= 1 800 s).
E = 230 × 2.0 × 1 800 = 828 000 J ≈ 0.23 kWh.
With **g = 0.25 kg CO_2e/kWh**: **m_CO_2e = 0.23 × 0.25 = 0.058 kg** (≈ 58 g) **per cycle**.

9.2 **Mechanical proxy with efficiency bracket**
A drive delivers **τ = 5.0 N·m** at **ω = 120 rad/s** for **60 s**.
E_mech ≈ 5.0 × 120 × 60 = 36 000 J ≈ 0.01 kWh.
If overall efficiency is **η = 0.8**, estimate **E_elec ≈ E_mech / η ≈ 0.0125 kWh** (range 0.012–0.014 kWh if **η** ∈ [0.75, 0.85]).

9.3 **Computation energy (proxy)**
P_idle = 20 W, **P_load = 50 W**, **u_CPU = 0.4**, **T = 1 h**.

E_comp ≈ 20 × 3 600 + (50 − 20) × 0.4 × 3 600 = 115 200 J ≈ 0.032 kWh.
Use mainly for relative comparisons.

9.4 **Duty-factor estimate**
P_rated = 200 W, **D = 0.3**, **T = 2 h**.
E ≈ 200 × 0.3 × 7 200 = 432 000 J ≈ 0.12 kWh.

9.5 **Mini case study — variable-speed pump**

Scenario. A centrifugal pump runs two batch cycles per hour. Baseline control uses abrupt set-point changes; the alternative adds ramped set-points (4 s s-curve) and anti-windup back-calculation.

Profile. Each batch: 5 minutes at high flow, 10 minutes at low flow, then idle. Ambient unchanged.

Instrumentation. Input power logged at 1 Hz; flow and pressure logged at 2 Hz; clocks synchronised.

Results (per batch; illustrative).

- Energy: baseline **0.62 kWh**, alternative **0.57 kWh** (−8%).
- Peak power: baseline **2.3 kW**, alternative **1.9 kW** (−17%).
- Quality: settling time to high-flow set-point unchanged (≈ 6 s); overshoot reduced from **12%** to **4%**; constraint violations eliminated.

Interpretation. The energy reduction comes primarily from smoother acceleration and the removal of wind-up after valve saturations.

10. Implementation checklist

- Define boundary, operating profile and functional unit (Section 3).
- Select a baseline and record all controller settings, limits and filters.
- Instrument power and synchronise logs; document calibration (Section 7).
- Evaluate a small set of alternatives; keep the workload identical.
- Plot the Pareto view and report uncertainty (Section 8).
- Write a short narrative interpreting causes of improvement.

11. Conclusions

A structured procedure—clear boundaries, well-chosen functional units, sound measurements and **knee-based** trade-offs—enables control designs that reduce energy and emissions without sacrificing essential performance or robustness. Because the method makes assumptions explicit and results reproducible, it supports continual improvement across laboratory prototypes and industrial deployments.

12. Glossary — Symbols and Units

E — energy [J] or [kWh]
v(t), v[k] — voltage [V] (continuous / sampled)
i(t), i[k] — current [A] (continuous / sampled)
p(t), p[k] — electrical power [W] (continuous / sampled)
Δt — sampling interval [s]
τ (tau) — torque [N·m]
ω (omega) — angular speed [rad/s]
m_CO_2e — mass of carbon-dioxide equivalent [kg CO_2e]
g — grid factor [kg CO_2e/kWh] (specify year/region and source)
U — functional unit (tonne, km, m^3, cycle)
$E_{(kWh)}$ — energy expressed in kilowatt-hours [kWh]
P_idle, P_load — idle / load power [W]
u_CPU — CPU utilisation (0–1) [–]
T — time or task duration [s] or [h]
D — duty factor (time active / total time) [–]
T_s — sampling time [s]
RMSE — Root-Mean-Square Error (define once; avoid elsewhere)

13. References (selected)

[1] Chen, J.; Patton, R. J. *Robust Model-Based Fault Diagnosis for Dynamic Systems*. Kluwer, 1999.

[2] Simani, S.; Fantuzzi, C.; Patton, R. J. *Model-Based Fault Diagnosis in Dynamic Systems Using Identification Techniques*. Springer, 2002.

[3] Skogestad, S.; Postlethwaite, I. *Multivariable Feedback Control*. Wiley, 2005.

Appendix A

System and boundary. Brief description; inside/outside elements; exclusions and justification.

Operating profile. Duty cycle, batches, and ambient conditions.

Functional unit. Definition and rationale.

Baseline. Controller type and parameters (gains, filters, limits, sampling time).

Alternatives. List each with only the changes relative to baseline.

Instrumentation. Meters, logging rates, calibration, synchronisation.

Results table (per functional unit). Energy; peak/average power; duty; quality metrics (settling time, overshoot, RMSE); constraint violations; emissions (state **g** and source).

Uncertainty. Measurement vs modelling; numeric range.

Interpretation. Two or three sentences explaining *why* the winner performs better.

Reproducibility pack. Where logs, scripts and configuration files are stored.

Appendix B — Data logging template (fields)

Run metadata: date/time, operator, firmware versions, ambient conditions.

Controller settings: gains, filters, limits, anti-windup scheme, sampling time, solver tolerances.

Signals and rates: voltage [V], current [A], computed power [W], torque [N·m], speed [rad/s], process variables (with units), set-points, actuator commands; logging rate for each.

Synchronisation: time source, drift correction method.

Calibration: instruments, certificates, last calibration date.

Notes: anomalies, restarts, safety events.

Appendix C — Step-by-step energy calculation (sampled data)

1. Compute instantaneous power: **p[k] = v[k] × i[k]**.
2. Integrate with trapezoidal rule: **E ≈ Σ 0.5 × [p[k] + p[k+1]] × Δt**.
3. Convert to kilowatt-hours: $\mathbf{E_{(kWh)} = E / (3.6 \times 10^6)}$.
4. Compute emissions: $\mathbf{m\_CO_2e = E_{(kWh)} \times g}$ (state **g** with source).
5. Report: “Energy **X kWh per U**, emissions **Y kg** $\mathbf{CO_2e}$ **per U**, RMSE **Z**; uncertainty **± δ**.”