Supplementary Note S2—Estimating Robotics Electricity Demand

Purpose and scope

The concept behind this note is to provide a transparent and reproducible estimate of the annual electricity consumption of robots up to 2035. In order to ensure clarity, the demand is disaggregated into three archetypes, namely industrial arms (I), autonomous mobile robots AMR/AGV (M) and humanoids (H). After the logistic adoption of the installed fleets had been defined and the duty-cycle energy models had been formed, the uncertainty is quantified via Monte Carlo with triangular priors. Finally, the results are designed (i) to be stand-alone, (ii) to remain literature-bounded for the central cases and (iii) to retain a clearly labelled frontier sensitivity for long-run household humanoids.

Method and equations

For class k∈{I,M,H} in year t:

- Adoption (logistic S-curve)
  $N_k(t) = K_k / \{1 + exp[-r_k (t - t_{0,k})]\} \times s_k$
  Where:
  K_k: asymptotic carrying capacity (units);
  r_k: slope;
  $t_{0,k}$: inflection year.

Central parameter sets are chosen to align with installed-base baselines and plausible 2030/2035 ranges from the literature.

- Energy accounting
  $E_k(t) = N_k(t) \times P_k \times h_k \times 365 / 10^9$ *(units: TWh·yr⁻¹)*
  Where:
  $\overline{P_k}$ (kW): average electrical draw while active
  H_k (h/day): average active hours per day
- Uncertainty

For uncertainty Monte Carlo simulation is used with triangular priors and is implemented in MS Excel using the native inverse CDF

For each class:

$$s_k \sim Tri(a_k, c_k, b_k) \text{ (fleet multiplier around central adoption)}$$

$$\bar{P}_k \sim Tri\left(P_{k,min}, P_{k,mode}, P_{k,max}\right),$$

$$h_k \sim Tri\left(h_{k,min}, h_{k,mode}, h_{k,max}\right).$$

The trial year totals are:

$$E_{tot}(t) = \sum_k \frac{s_k N_k^{central}(t) \overline{P_k h_k 365}}{10^9}$$

Excel triangular inverse:

$$X = \begin{cases} a + \sqrt{U(b-a)(c-a)}, \; U \leq \dfrac{c-a}{b-a} \\ b - \sqrt{(1-U)(b-a)(b-c)}, otherwise \end{cases}$$

Parameterization

Adoption baselines:

- Industrial arms (I): anchor N_I(2023) = 4,281,585 operational units (IFR World Robotics 2024) [R1].
- AMR/AGV (M): constrain adoption to pass through 2.7 M in 2027 (ex-Amazon) and >4.2 M in 2030 (Interact Analysis) [R2–R3]. Model years 2024–2026 are obtained by smooth back-casting; no single-year literature value is asserted.
- Humanoids (H): baseline near zero in 2024 with only small pilot fleets, e.g., Agility's Digit deployed in a commercial application and OEM pilots with no production deployments announced [R14–R15].

Duty-cycle anchors (central modes with triangular bounds):

- Industrial arms: P_I ∈ [1.0, 2.0, 3.0] kW (mode 2.0); h_I ∈ [4, 6, 12] h/day (mode 6). Anchors: ABB IRB2600 Product Specification lists measured power consumption near 0.9 kW at maximum speed and 0.15–0.43 kW in calibration/idle states; combined controller/process loads in production environments justify centering 'active' draw around ~2 kW (triangular 1–3 kW). [R10–R11], plus historical per-robot kWh benchmarks [R12].
- AMR/AGV: P_M ∈ [0.10, 0.15, 0.30] kW (mode 0.15); h_M ∈ [4, 6, 10] h/day (mode 6). Anchors: MiR250 battery 1.63 kWh and runtime up to 13 h (implying ≈0.125 kW average) [R5,R6,R9], and AMR energy-modeling literature [R18].
- Humanoids: P_H ∈ [0.20, 0.30, 0.50] kW (mode 0.30); h_H ∈ [1, 3, 4] h/day (mode 3). Anchors: Agility Digit battery ~1.0 kWh with 3–4 h runtime [R7]; Tesla Optimus 2.3 kWh battery (manufacturer claim) [R8] and expert skepticism regarding 'full-day' operation [R9].

These values populate the **Inputs** sheet in the workbook and can be tuned for sensitivity with full traceability.

Deterministic (central) results (order-of-magnitude)

Under the default inputs, the central totals are scaled to the order of tens of TWh/year by 2035. The demand is dominated by industrial arms (I), AMR remains modest, whereas humanoids (H) contribute a non-negligible but still secondary load under conservative duty-cycle assumptions. The exact year-by-year values are computed in the Deterministic sheet.

Uncertainty bands (P10–P90)

The Monte Carlo sheet (*MC*) samples s_k, $\overline{P_k}$, h_k per class and aggregates to total robotics energy. The *Figure* sheet displays a **filled P10–P90 band** around the **central** trajectory and class-wise central lines (industrial, AMR, humanoid).

Sampling: For each class k, we draw s_k, P_k, h_k from independent triangular distributions Tri(min, mode, max). The inverse-CDF is applied piecewise to a uniform u∼U(0,1) to generate samples.

Frontier sensitivity: household humanoids

In order to keep the "billions of robots" narrative analytically anchored, adoption on TCO per service hour is conditioned:

TCO per service hour:

$$TCO_h = \frac{CAPEX \cdot CRF(i,n) + O\&M + Energy}{H_{annual}}$$

- High-wage early markets plausibly adopt at $TCO_h \leq \$15$/h; mass-market parity likely \$3–\$5/h, consistent with global wage levels and recent minimum-wage dynamics (ILO Global Wage Report 2024–25; OECD 2025) [R16–R17].
- Under current costs and utilization, household humanoids remain throughput- and cost-constrained to 2035. Large-scale impact appears post-2035 unless CAPEX and reliability improve markedly.

Limitations and external validity

- Data sparsity for humanoids: power/duty profiles are evolving. As a result, triangular priors are used with conservative modes and explicit bounds.
- Correlation structure among parameters (e.g., higher utilization ↔ charging logistics) is not modeled here. Independence is a reasonable first pass.
- Adoption ceilings K_k are scenario-dependent. Inputs can be changed and the Excel sheet recomputes all series automatically.

Data

Class	Anchor year(s)	Literature anchor(s)	Value(s)	Use in model
Industrial arms (I)	2023	[R1] IFR World Robotics 2024	N_I(2023) = 4,281,585 units	Fix baseline; tune (K_I, r_I, t0_I, s_I) to match
AMR/AGV (M)	2027, 2030	[R2–R3] Interact Analysis	N_M(2027) ≈ 2.7M; N_M(2030) > 4.2M	Constrain trajectory through these points
Humanoids (H)	2024	[R14–R15] Pilot deployments	Near zero (small pilots)	Supply-limited; t0_H ≥ 2036; K_H ≤ 0.2–0.5M by 2035

References

[R1] International Federation of Robotics (IFR). World Robotics 2024 – Industrial Robots, Executive Summary. Frankfurt: IFR, 2024. Available at: https://ifr.org/img/worldrobotics/Executive_Summary_WR_2024_Industrial_Robots.pdf

[R2] Interact Analysis. 'Macro-economic factors cause slowdown in global mobile robot market.' Jan 15, 2025. Installed base projected to exceed 4.2 million by end-2030. https://interactanalysis.com/macro-economic-factors-cause-slowdown-in-global-mobile-robot-market/

[R3] Interact Analysis (quoted). 'Mobile robots to remain strong segment...' Power & Motion, June 3, 2024. By 2027, ≈2.7 million mobile robots installed worldwide (ex-Amazon). https://www.powermotiontech.com/...

[R4] International Federation of Robotics (IFR). 'Sales of Service Robots up 30% Worldwide' (World Robotics 2024 – Service Robots). Oct 8, 2024. https://ifr.org/ifr-press-releases/news/sales-of-service-robots-up-30-worldwide

[R5] Mobile Industrial Robots (MiR). MiR250 Specifications (Battery 1.63 kWh; runtime). 2024. https://mobile-industrial-robots.com/products/robots/mir250/specifications

[R6] Locus Robotics. 'Locus Origin – Operating Time 14 hours per charge.' 2024. https://locusrobotics.com/locusone/fleet/locus-origin-collaborative-robot

[R7] Agility Robotics. 'Agility Robotics announces new innovations for Digit' (battery lasts up to four hours). Mar 31, 2025. https://www.agilityrobotics.com/content/agility-robotics-announces-new-innovations-for-market-leading-humanoid-robot-digit

[R8] The Verge. 'Tesla's Optimus prototype contains a 2.3 kWh battery pack...' Sep 30, 2022. https://www.theverge.com/2022/9/30/23374729/tesla-bot-ai-day-robot-elon-musk-prototype-optimus-humanoid

[R9] IEEE Spectrum. 'What Robotics Experts Think of Tesla's Optimus' (skepticism on full-day operation). 2025. https://spectrum.ieee.org/robotics-experts-tesla-bot-optimus/dennis-hong

[R10] ABB. IRB 2600 Product Specification (PF>0.95 above 2 kW; energy 3.4 kW). 2025. https://search.abb.com/library/Download.aspx?DocumentID=3HAC035959-001

[R11] Ruzarovský, R., et al. 'Evaluating Energy Efficiency and Optimal Positioning of ABB IRB 1600.' Journal of Manufacturing and Materials Processing 2024;8(6):276. https://doi.org/10.3390/jmmp8060276

[R12] ACEEE. 'Direct and Indirect Impacts of Robots on Future Electricity Use.' 2017 Summer Study on Energy Efficiency in Industry. https://www.aceee.org/files/proceedings/2017/data/polopoly_fs/1.3687904.1501159084%21/fileserver/file/790278/filename/0036_0053_000029.pdf

[R13] IFR. World Robotics 2024 – Service Robots (205,000 professional service robots sold in 2023). Oct 2024. https://ifr.org/ifr-press-releases/news/sales-of-service-robots-up-30-worldwide

[R14] The Robot Report. 'Digit is first humanoid deployed in a commercial application.' 2025. https://www.therobotreport.com/rbr50-company-2025/digit-is-first-humanoid-deployed-in-a-commercial-application/

[R15] Manufacturing Dive. 'BMW tests Figure 02 humanoid on production line; no deployments yet.' Aug 12, 2024. https://www.manufacturingdive.com/news/bmw-completes-sucessful-pilot-humanoid-robots-spartanburg-plant-figure-02/723819/

[R16] International Labour Organization. Global Wage Report 2024–25. Geneva: ILO, 2024. https://www.ilo.org/publications/flagship-reports/global-wage-report-2024-25-wage-inequality-decreasing-globally

[R17] OECD. 'Real wages continue to recover' (2025). https://www.oecd.org/content/dam/oecd/en/publications/reports/2025/03/real-wages-continue-to-recover_3a8a464b/8f8ec0e4-en.pdf

[R18] Sperling, M.; Furmans, K. 'Energy Requirement Modeling for Autonomous Mobile Robots Considering Material Flow and Layout Data.' Designs 2024;8:48. https://doi.org/10.3390/designs8030048

Excel Sheet



Robotics.xlsx