

Primary-Data Carbon Accounting for Photopolymer Additive Manufacturing: Energy, Materials, Yield and Allocation

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Abstract

Carbon accounting for photopolymer additive manufacturing is only as defensible as its primary inventory. Electricity, resin input, failed builds, support structures, washing solvent, post-cure energy, consumables, recovered material, machine utilisation and accepted-part yield can each dominate a result under different boundaries. This review defines a measurement-first carbon-accounting architecture for vat photopolymerisation and related photopolymer AM. It separates direct measured quantities from database proxies, defines accepted-part and job-level reference flows, requires time- and location-specific electricity factors where material, and treats yield, utilisation and allocation as explicit model choices rather than hidden corrections. ISO 14040, ISO 14044 and ISO 14067 provide the governing LCA and product-carbon-footprint framework [1-3]. Polymer-AM studies show that printer utilisation, electricity demand and material choice can materially change per-part burdens [4-6]. The review does not claim a universal carbon advantage for photopolymer AM; it defines the primary-data chain needed before such a comparison is credible.

Keywords: carbon accounting; life-cycle inventory; vat photopolymerisation; additive manufacturing; electricity; resin yield; allocation; primary data; carbon footprint

1. Significance and scope

ISO 14040 and ISO 14044 require goal/scope, inventory, impact assessment and interpretation to remain consistent with the declared study question [1,2]. ISO 14067 applies those principles to product carbon-footprint quantification [3]. For photopolymer AM, the engineering problem is not the arithmetic conversion of kWh and kilograms into CO₂-equivalents; it is preserving the physical identity of what was measured, which accepted output it supports, and what losses or shared burdens were allocated to that output.

1.1 Corpus boundary

ER-17 retains full life-cycle assessment, functional units, system boundaries, inventory quality, uncertainty and environmental-superiority interpretation. ER-173 retains photoresin batch manufacture; ER-175 retains washing-system engineering; ER-181 retains post-cure process engineering; ER-183 and ER-198 retain mechanical recycling and material-loop closure; ER-178 retains waste classification and disposal. ER-271 is narrower: it owns primary-data carbon accounting for photopolymer AM operations, especially measured energy, material throughput, yield and allocation records used as inventory inputs. ER-272 owns solvent-recovery mass balances rather than carbon interpretation. Forward roadmap identifiers are planning boundaries only.

2. Define the accounting object before collecting data

Choose whether the result is per print job, per as-built part, per accepted finished part, per unit mass, or per delivered function. These are not interchangeable denominators. A job containing ten parts does not create ten equal outputs if scrap, support mass or downstream processing differs by part. The carbon record should therefore link every inventory quantity to a declared reference flow and state whether the study is gate-to-gate, cradle-to-gate or broader.

3. Meter electricity by process state

Printer nameplate power is not a primary energy measurement. Record idle, warm-up, exposure/build, recoating, pumping, chamber conditioning, washing, drying, post-curing and ancillary loads where they are inside scope. Integrate measured power over time or use validated equipment logs. Shi and Faludi showed that utilisation can strongly alter impact per part in polymer AM because machine burdens are spread over different output levels [4]. Baltrocchi and co-workers likewise demonstrated that print settings that lengthen processing time increase electricity-driven impacts in their measured polymer-AM system [6].

$$E = \int P(t) dt$$

where E is measured electrical energy over the declared interval and P(t) is measured power as a function of time. A single average wattage multiplied by slicer time is a model, not primary metering, unless validated against measured traces. The foreground record should preserve process-state decomposition rather than collapse resin conditioning, build preparation, idle/warm-up, exposure and recoating, washing, drying, post-curing, support handling, failed-build handling, equipment cleaning, solvent handling, ancillary conditioning and inter-campaign cleaning into one undifferentiated “printing energy” value. Collapsing distinct states prevents causal interpretation and weakens transfer between laboratories.

4. Preserve resin and consumable mass balance

Record resin charged, resin remaining, resin transferred to parts, supports, drips, filters, wipes, wash solvent and discarded or recovered fractions. A low nominal material-use ratio can result from recoverable uncured resin, unrecoverable contamination or simply inventory uncertainty; those states must not be collapsed. The inventory should distinguish gross resin input, net resin loss and accepted-product mass.

5. Yield belongs in the denominator and in the history

Failed builds, rejected parts and rework consume energy and materials but do not deliver the intended functional output. Accepted yield should therefore be measured over the declared production interval. A pilot study with one successful print cannot be used as a production yield without evidence. If scrap is experimentally excluded, that exclusion should remain visible in sensitivity analysis.

$$Y_{\text{mass}} = M_{\text{accepted}} / M_{\text{input_allocated}}$$

$$Y_{\text{build}} = N_{\text{accepted}} / N_{\text{started}}$$

Y_{mass} is the accepted-product mass divided by the input mass allocated to that output; Y_{build} is the number of accepted builds or parts divided by the number started on the declared basis. Mass yield and build yield answer different questions and should not be substituted for one another.

6. Allocation is a model choice, not a measurement

Shared machine idle time, chamber heating, solvent baths, filters, facility loads and multi-part jobs require allocation. Possible bases include time, mass, occupied build area, part count or a causal engineering driver. ISO 14044 requires allocation choices to be transparent and consistent with study purpose [2]. ER-271 does not prescribe one universal basis; it requires the basis and sensitivity to be declared.

7. Primary data and database data must remain distinguishable

Resin production, electricity generation, solvent production and upstream transport often require secondary databases or supplier data. Their provenance, geography, year and technology should be recorded separately from on-site measurements. ISO 14067 explicitly frames carbon-footprint work as LCA-consistent quantification [3]. A precise foreground measurement does not remove uncertainty in an upstream proxy, and a database value should not be presented as directly measured plant data.

8. Grid and time assumptions can change the result

Electricity carbon intensity can vary by region, contract, time and marginal-versus-average accounting method. The chosen factor should match the study question. When print time changes materially, the same kWh-per-part result may still produce a different carbon result under time-varying electricity. Sensitivity analysis should separate process energy reduction from electricity-source substitution.

9. Non-compensatory qualification matrix

Gate	Required evidence	Blocking failure
G1 Functional output	Reference flow and accepted-part definition frozen	Inventory divided by an undefined or changing denominator
G2 Energy	Measured or validated time-resolved equipment energy inside scope	Nameplate power substituted for actual process energy
G3 Materials	Resin, supports, solvent and consumables mass-balanced	Gross input or recovered fraction omitted without disclosure
G4 Yield	Failed, rejected and reworked output recorded	Successful trial treated as production yield
G5 Allocation	Shared burdens assigned by declared rule with sensitivity	Allocation hidden inside spreadsheet totals
G6 Background factors	Electricity and upstream datasets carry geography/year/provenance	Secondary factors presented as primary plant data

10. Minimum reporting set

Report study purpose, reference flow, system boundary, production interval, printer and ancillary equipment, measured energy by process state, resin and consumable mass balance, supports and failed parts, accepted yield, utilisation, allocation rule, electricity factor and provenance, upstream dataset provenance, treatment of recovered material, uncertainty and sensitivity cases. Report both raw activity data and calculated carbon results so that recalculation remains possible when background factors change.

11. Knowledge boundary

The cited standards and studies establish accounting principles, inventory requirements and system-specific evidence that utilisation, process time and material choice can change additive-manufacturing burdens [1-6]. They do not establish a universal carbon factor, a universal yield correction, an allocation rule that is valid for every production system, or environmental superiority of photopolymer additive manufacturing. ISO/ASTM AWI 52964 remains an approved work item under development rather than a published standard [7]; it is recorded as a developing methodological boundary, not as current normative authority.

12. Conclusions

Primary-data carbon accounting for photopolymer AM is a custody problem before it is a calculation problem. Metered energy, material genealogy, yield and allocation must remain linked to the accepted output. LCA standards govern the broader model; ER-271 supplies the operational measurement architecture that prevents hidden scrap, shared loads or proxy values from masquerading as direct carbon evidence.

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