

CO₂ Capture by Vat-Printed and Photopolymer-Derived Structures: Uptake Mechanisms, Mass Transfer, Regeneration and Qualification

Juan Segurola, PhD

3Dresyns by Resyner Technologies S.L.

Registered tax address: General Etxague 15B, 20003 Donostia / San Sebastián, Gipuzkoa, Spain

VAT number: ESB24827511

Correspondence: info@3Dresyns.com · Website: www.3Dresyns.com

Statement of Significance

A printed material described as a carbon-dioxide collector is not qualified by that label alone. CO₂ can be physically adsorbed, dissolved into a polymer or liquid phase, reversibly chemisorbed, or irreversibly converted into carbonate or another product. Those mechanisms require different capacity units, blanks, gas conditions, humidity controls, regeneration tests and mass-balance logic. Additive manufacturing adds a second layer of complexity because architecture changes exposed area, diffusion length, pressure drop and the accessibility of the active phase. This review develops an evidence architecture for CO₂-reactive and CO₂-sorbent printed structures, with particular attention to the difference between an intact photopolymer composite and a photopolymer-derived inorganic sorbent after debinding or conversion.

Keywords: carbon dioxide; CO₂ capture; vat photopolymerisation; DLP; adsorption; absorption; chemisorption; carbonation; mineralisation; sorbent; TPMS; mass transfer; regeneration; working capacity; qualification

Abstract

Additive manufacturing is increasingly used to shape carbon-dioxide capture media into monoliths, lattices and structured reactors. The underlying materials, however, span fundamentally different states. Published work includes direct-ink-written silicone/sodium-carbonate composites that retain the polymer matrix, DLP-printed zeolite 13X and Li₄SiO₄ structures in which a photopolymer enables shaping but is subsequently removed or converted, and 3D-printed activated-carbon monoliths evaluated by adsorption and breakthrough methods. These systems cannot be pooled into a single CO₂-capture number. Uptake depends on gas composition and partial pressure, temperature, humidity, active-phase loading, accessible porosity, specimen geometry, flow regime, equilibration time, reaction stoichiometry and whether the process is reversible. This Engineering Review separates physisorption, absorption, chemisorption and irreversible carbonation/mineralisation; distinguishes equilibrium capacity from working capacity and transient mass gain; maps architecture-to-mass-transfer effects; and proposes minimum mass-balance, cycling and product-identification requirements. 3Dresyn CDC1 is included only as manufacturer implementation context. A manufacturer catalogue statement of up to 300 g CO₂ per kg of material converted into calcite is treated only as manufacturer information, not independent evidence, and is not qualified by this review without a controlled product-specific capture/conversion mass balance.

1. Scope and boundaries

ER-57 addresses the scientific qualification of printed structures whose intended function is to remove carbon dioxide from a gas phase or to convert it into a retained chemical product. The focus is the finished material or sorbent structure and the evidence needed to support a capture claim. The scope includes intact polymer composites, porous printed adsorbents and photopolymer-derived inorganic structures where vat photopolymerisation is part of the manufacturing route.

The scope does not claim that all cited materials are vat-printed thermosets. This distinction is deliberate. The strongest retained-polymer composite example located in the literature is direct-ink-written rather than VPP [1], whereas direct DLP evidence is strong for sorbent architectures in which the photopolymer is removed or converted during thermal processing [2,3]. That evidence can define measurement and architecture questions, but it cannot prove that an intact commercial VPP resin has the same capture chemistry or capacity.

A recent critical review of 3D-printed adsorbents, membranes and catalysts for CO₂ capture, separation and conversion surveys that broader landscape [5]; ER-57 differs by asking what evidence is required before a printed structure may carry a quantitative capture claim.

Neighbouring Engineering Reviews remain separate. ER-17 controls life-cycle assessment and environmental-superiority claims; ER-26 controls generic TPMS/cellular structure-property qualification; ER-36 controls dispersion and rheology of highly filled VPP suspensions; ER-37 controls debinding defects; ER-49 controls direct versus indirect ceramic/metal route selection; and ER-54 controls gas permeability through photopolymer networks. ER-57 owns only the CO₂-capture endpoint and its state-specific evidence requirements.

2. Capture mechanisms must not be conflated

Four broad mechanisms can produce an apparent decrease in gas-phase CO₂ or an increase in specimen mass. Physical adsorption concentrates CO₂ at internal or external surfaces without forming a new bulk chemical product. Absorption dissolves CO₂ into a liquid or polymer phase and may be strongly affected by free volume, water content and diffusivity. Reversible chemisorption forms chemical adducts that can be regenerated under defined conditions. Carbonation or mineralisation converts CO₂ into carbonate or related inorganic products and may be effectively irreversible under the intended service conditions.

The same gravimetric mass gain can therefore represent very different states. A single endpoint weighing step cannot distinguish reversible uptake from retained water, oxidation, carbonate formation or contamination. Where mineralisation is claimed, carbon-containing reaction products must be identified and the carbon balance must close within a stated uncertainty.

Table 1. CO₂ quantities that must not be conflated

Quantity	Definition / measurement	What it does not establish
Equilibrium uptake	Amount retained at defined T, pressure/composition and equilibrium criterion.	Not working capacity under a cyclic process.
Dynamic breakthrough capacity	Uptake derived during a flowing-gas breakthrough experiment.	Not necessarily an equilibrium isotherm value.
Working capacity	Difference between loaded and regenerated states under a defined cycle.	Not total one-way irreversible fixation.
Mass gain	Change in specimen mass after exposure.	Not CO ₂ -specific without blanks/product analysis.
Conversion / mineralisation yield	Fraction of reactive precursor converted to identified carbonate or other product.	Not gas-separation selectivity or regenerability.

Quantity	Definition / measurement	What it does not establish
CO ₂ /N ₂ selectivity	Preference for CO ₂ over N ₂ under a defined model or mixture.	Not absolute capture rate or capacity.
Capture rate	Amount removed per time under stated transport conditions.	Not final capacity without a time/equilibrium endpoint.

3. Retained polymer composites: direct evidence exists, but the printing route matters

Nguyen et al. developed 3D-printable polymer composite inks containing solid sodium carbonate dispersed in uncured silicone and shaped them by direct ink writing [1]. After curing, hydration created aqueous sodium-carbonate domains within the silicone. The printed geometry increased accessible reactive area and produced substantially faster CO₂ absorption than a liquid sodium-carbonate pool under the study conditions. This is important retained-polymer evidence because the polymer remains part of the working capture structure.

It is not VPP evidence. DIW imposes different formulation, rheology, curing and geometry constraints, so ER-57 uses the work to establish the coupled roles of active-phase loading, hydration, exposed area and diffusion rather than to transfer a capacity value to vat-photopolymerised materials.

4. DLP evidence: photopolymer as shaping vehicle for zeolite 13X

Jivraj et al. fabricated self-standing zeolite 13X gyroid monoliths using a zeolite-photopolymer slurry and digital light processing [2]. The printed green structures were debound to remove the polymer and sintered to consolidate the zeolite. The resulting TPMS sorbents were then evaluated for CO₂ adsorption, selectivity, cyclic stability and breakthrough behaviour. The architecture enabled interconnected flow paths and favourable mass-transfer behaviour relative to conventional powder or bead forms under the tested conditions.

The scientific boundary is essential: the final CO₂-capture material is not the original photopolymer network. VPP provides geometric control, but the active final state is an inorganic zeolite body. Therefore these data cannot validate CO₂ capture by an intact photopolymer resin. They do, however, show why specimen architecture, binder removal, accessible active phase and post-processing state must be reported explicitly.

5. DLP-derived Li₄SiO₄ structures: capture can depend on thermal conversion

Cai et al. used DLP within a polymer-derived-ceramics strategy to fabricate cellular Li₄SiO₄ sorbents for CO₂ capture [3]. The study examined phase evolution and calcination strategy in addition to the capture response. This again demonstrates that the photopolymerisation step can be upstream of the actual sorbent chemistry: the capture-active state is created through thermal conversion and cannot be inferred from the green or cured photopolymer state.

For qualification this creates a mandatory state chain: printable slurry -> green printed body -> debound/converted intermediate -> final sorbent -> cycled sorbent. Chemical phase, mass and dimensions can change at every transition. A capture result belongs to the exact state tested.

6. Carbonaceous monoliths show why capacity and working capacity differ

Zafanelli et al. evaluated 3D-printed activated-carbon monoliths for post-combustion CO₂ capture using equilibrium and fixed-bed methods [4]. Thermal activation changed surface area, CO₂/N₂ selectivity and working capacity, and consecutive adsorption-desorption experiments were used to test regenerability. The work illustrates a general rule for printed sorbents: the largest equilibrium uptake is not automatically the best process metric because selectivity and regeneration conditions can move in a different direction.

7. Architecture is part of the capture system

Printed geometry changes external area, internal flow path, boundary-layer thickness, diffusion length, pressure drop and the fraction of active phase that is reachable on the experimental timescale. TPMS or lattice designs can therefore improve kinetics even when the intrinsic chemistry is unchanged. Conversely, a thick, dense part can contain a high theoretical loading of reactive material while exposing only a small fraction during the intended service time.

ER-57 therefore separates chemistry-normalised capacity from structure-normalised performance. At minimum, a capture paper should report specimen mass, active-phase mass fraction where known, external dimensions, architecture parameters, accessible porosity or an appropriate structural descriptor, gas-flow configuration and the time criterion used to define completion.

8. Humidity and water state are first-order variables

Water can promote, suppress or qualitatively change CO₂ uptake depending on the chemistry. In the sodium-carbonate/silicone composite of Nguyen et al., hydration creates the aqueous reactive domains that enable rapid absorption [1]. In other adsorbents, water competes for sites or changes transport and regeneration energy. For an intact photopolymer, water uptake can additionally plasticise the network and change gas diffusion.

Accordingly, dry-gas and ambient-air claims are not interchangeable. Relative humidity or water activity, preconditioning, specimen water content where material, and exposure temperature must accompany any capacity or kinetics result intended for comparison.

9. Reversible capture, irreversible fixation and regeneration

A reusable sorbent requires a defined regeneration step and retention of useful working capacity over cycles. An irreversible mineralising material instead consumes reactive capacity as carbonate or another product accumulates. Both can remove CO₂, but they are different technologies and require different service-life metrics.

For reversible systems the core endpoint is cycle-resolved working capacity together with regeneration temperature, pressure, purge gas or vacuum conditions and performance retention. For irreversible fixation the core endpoints are stoichiometric conversion, carbon-containing product identification, maximum reacted fraction, reaction-front progression where relevant and the residual mechanical/functional state of the printed part.

10. A defensible mass balance

The capture claim should begin with a closed accounting boundary. Gas-in/gas-out analysis, gravimetry, product analysis or combinations of these can be used, but each has different interferences. Gravimetry requires humidity and blank controls; gas analysis requires calibrated flow and concentration measurement; carbonate formation requires chemical or phase evidence rather than mass gain alone. If the denominator is total printed-part mass, active-phase mass or dry sorbent mass, that basis must be stated.

A numerical claim such as grams of CO₂ per kilogram is incomplete unless the kilogram basis, starting state, gas composition, CO₂ partial pressure, humidity, temperature, exposure time/equilibrium criterion, blank correction and confirmation of retained carbon are given. For a reactive mineralising system, theoretical stoichiometric capacity and measured converted capacity should be reported separately.

Table 2. Minimum qualification architecture for a printed CO₂-capture material

Layer	Minimum record	Why it matters
Material state	Intact polymer composite, green body, converted ceramic, carbon monolith, coating, etc.	Prevents transfer of results between fundamentally different states.
Capture chemistry	Physical adsorption, absorption, chemisorption or identified conversion reaction.	Defines reversibility, analysis and capacity basis.
Gas condition	CO ₂ concentration/partial pressure, balance gas, flow or static mode, temperature, humidity.	Capacity and kinetics depend on the exposure environment.
Geometry	Mass, dimensions, architecture, wall/strut scale and porosity descriptor.	Controls accessible area, diffusion and pressure drop.
Capacity method	Isotherm, breakthrough, gravimetry, gas balance or product analysis.	Different methods do not measure identical quantities.
Blank / interference	Unreactive blank, water correction, oxidation/volatile control where applicable.	Prevents non-CO ₂ mass or signal change from being assigned to capture.
Regeneration / endpoint	Cycle protocol or irreversible conversion endpoint.	Separates reusable sorption from consumptive fixation.
Retained function	Mechanical integrity and capture response after cycling/exposure.	Links material-level uptake to usable service state.

11. Environmental benefit is a separate claim

Demonstrating CO₂ uptake does not by itself demonstrate net climate benefit. Feedstock production, printer energy, failed builds, washing or thermal conversion, regeneration energy, service life and end-of-life can outweigh or reduce the significance of the captured mass. ER-17 therefore remains the controlling review for life-cycle assessment. ER-57 does not use a capture-capacity result as evidence that a material is carbon negative, eco-friendly or environmentally superior.

The distinction is particularly important for one-way mineralisation: gross CO₂ chemically fixed in a specimen is a material balance, whereas net greenhouse-gas benefit is a system-level life-cycle result.

12. 3Dresyns implementation boundary

The controlled 3Dresyns catalogue contains 3Dresyn CDC1, Carbon Dioxide Collector, as an SLA/DLP/LCD material implementation candidate [M1]. Catalogue material has also carried an approximate statement of up to 300 g CO₂ per kg of material converted into calcite. That numerical statement is manufacturer information, not independent evidence, and ER-57 does not validate or reproduce it as a qualified performance result. A quantitative public capture claim for any such product would first require the exact capture mechanism, dry-mass basis, gas and humidity conditions, kinetics, maximum capacity, identified conversion product, blank correction and retained function to be established under the architecture set out in §10 and Table 2.

13. Minimum reporting checklist

- exact material state tested and whether the photopolymer remains in the final capture structure;
- active sorbent/reactive phase identity and loading to the extent disclosure permits;
- printing route, post-processing and any debinding, sintering, activation or hydration step;
- dry specimen mass and denominator used for capacity;
- CO₂ concentration or partial pressure, balance gas, temperature and humidity/water state;
- static or flowing exposure geometry, flow rate where applicable, and equilibration/time criterion;

- capture method and calibration: isotherm, breakthrough, gravimetry, gas balance, product analysis or combination;
- blank/control capable of detecting water uptake, oxidation, volatilisation or non-specific mass change;
- capacity, rate and selectivity reported as separate endpoints;
- for reversible systems, regeneration protocol and cycle-resolved working-capacity retention;
- for irreversible systems, reaction-product identification and stoichiometric carbon balance;
- geometry/porosity descriptor sufficient to interpret mass-transfer effects;
- mechanical/structural condition before and after the claimed exposure or cycling;
- clear separation of gross CO₂ uptake from any life-cycle or carbon-negative claim.

14. Failure-mode and discrimination matrix

Table 3. Common observations and discriminating evidence

Observation	Competing explanations	Discriminating evidence
Specimen gains mass in CO ₂	CO ₂ uptake; water uptake; oxidation; contamination.	Humidity-matched blank + gas balance + carbon/product analysis.
Fast initial uptake, early plateau	Surface reaction; diffusion limitation; depleted accessible sites.	Thickness/geometry series + time-resolved uptake + active-phase normalisation.
High equilibrium uptake, poor cycling	Irreversible reaction; incomplete regeneration; structural damage.	Cycle mass balance + regenerated-state chemistry + morphology/mechanics.
Printed lattice outperforms powder per reactor volume	Improved mass transfer; lower pressure drop; different packing density.	Separate material-normalised and reactor-volume-normalised metrics.
Capacity changes with humidity	Hydration-assisted chemistry; competitive adsorption; polymer swelling.	Controlled RH series + water-only blanks + dimensional/mass monitoring.
Carbonate detected after exposure	Intended mineralisation; pre-existing carbonate; surface contamination.	Pre/post phase/composition analysis with unexposed control and carbon balance.
Good coupon, poor large part	Diffusion length; inaccessible interior; gas-channel maldistribution.	Scale/geometry series + spatial reaction mapping or sectioning.

15. Research and standardisation priorities

- VPP-specific studies in which the intact cured photopolymer remains the CO₂-capture matrix, rather than serving only as a sacrificial shaping binder;
- paired dry- and humid-gas datasets for the same printed composition and geometry;
- round-robin reporting of equilibrium capacity, breakthrough capacity and working capacity on common structured sorbents;
- blank-corrected gravimetric protocols for reactive/mineralising printed polymers;
- spatial mapping of reaction fronts through thick VPP parts;
- coupled capture/mechanical testing to determine whether mineralisation or sorption changes stiffness, cracking or dimensional stability;
- comparison of chemistry-normalised versus reactor-volume-normalised performance for TPMS and conventional geometries;
- life-cycle studies that use experimentally measured capture and regeneration data rather than nominal product labels.

16. Conclusions

CO₂ capture in an additively manufactured structure is a coupled chemistry-transport-geometry problem. Printed polymer composites, DLP-derived inorganic sorbents and activated-carbon monoliths show that additive manufacturing can change mass-transfer behaviour and reactor architecture, but their capture numbers are not interchangeable. The first qualification step is therefore to identify the actual material state and mechanism: physisorption, absorption, reversible chemisorption or irreversible conversion.

A defensible quantitative claim requires a defined mass basis, gas composition and partial pressure, temperature, humidity, time/equilibrium criterion, blank correction, analytical method and geometry. Reusable sorbents additionally require cycle-resolved working capacity and regeneration conditions; mineralising systems require reaction-product identification and a stoichiometric carbon balance. Gross CO₂ uptake must remain separate from life-cycle environmental benefit.

For 3Dresyns implementation, CDC1 provides a real commercial motivation for this qualification framework, but its product description is not used as scientific proof of mechanism or capacity. Product-specific evidence must close the capture/conversion mass balance before a numerical capacity is treated as independently validated.

Limitations

Direct literature on intact vat-photopolymerised thermoset parts whose primary function is CO₂ capture is limited. The review therefore uses adjacent additive-manufacturing evidence only where the mechanism or measurement question is transferable, and labels the printing/material-state boundary explicitly. No performance value from DIW, zeolite, Li₄SiO₄ or activated-carbon studies is assigned to a 3Dresyns product. This review reports no new capture experiments and makes no life-cycle superiority claim.

Author contributions

Juan Seguro: conceptualisation, literature synthesis, engineering framework, writing and critical review.

Competing interests

The author is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. Manufacturer documentation is included only as implementation context and is separated from independent scientific evidence.

Data availability

No new experimental dataset was generated for this review. Scientific statements derive from the cited literature; manufacturer examples derive from controlled public 3Dresyns documentation.

Company information

3Dresyns by Resyner Technologies S.L. · General Etxague 15B, 20003 Donostia / San Sebastián, Gipuzkoa, Spain · VAT ESB24827511 · info@3Dresyns.com · www.3Dresyns.com

References - independent scientific evidence

- [1] D. Nguyen, M. Murialdo, K. Hornbostel, S. Pang, C. Ye, J.K. Stolaroff, “3D Printed Polymer Composites for CO₂ Capture,” *Industrial & Engineering Chemistry Research* 58(48) (2019) 22015-22020. DOI: <https://doi.org/10.1021/acs.iecr.9b04375>
- [2] K.B. JivraKh, A.M. Varghese, S. Ehrling, S. Kuppireddy, K. Polychronopoulou, R.K. Abu Al-Rub, N. Alamoodi, G.N. Karanikolos, “3D-printed zeolite 13X gyroid monolith adsorbents for CO₂ capture,” *Chemical Engineering Journal* 497 (2024) 154674. DOI: <https://doi.org/10.1016/j.cej.2024.154674>
- [3] L. Cai, G. Tan, X. Yang, H. Xue, Y. Lin, X. Hu, Z. Song, Y. Zhang, “Efficient carbon dioxide adsorption properties of cellular structure Li₄SiO₄ sorbents prepared by additive manufacturing based on polymer-derived ceramics strategy,” *Chemical Engineering Journal* 483 (2024) 149125. DOI: <https://doi.org/10.1016/j.cej.2024.149125>
- [4] L.F.A.S. Zafanelli, A. Henrique, H. Steldinger, J.L. Diaz de Tuesta, J. Gläsel, A.E. Rodrigues, H.T. Gomes, B.J.M. Etzold, J.A.C. Silva, “3D-printed activated carbon for post-combustion CO₂ capture,” *Microporous and Mesoporous Materials* 335 (2022) 111818. DOI: <https://doi.org/10.1016/j.micromeso.2022.111818>
- [5] K.B. JivraKh, S. Kuppireddy, L.F. Dumée, K. Polychronopoulou, R.K. Abu Al-Rub, N. Alamoodi, G.N. Karanikolos, “A critical review on 3D-printed adsorbents, membranes, and catalysts for carbon dioxide capture, separation, and conversion,” *Journal of Cleaner Production* 472 (2024) 143522. DOI: <https://doi.org/10.1016/j.jclepro.2024.143522>

Manufacturer implementation source

[M1] 3Dresyns by Resyner Technologies S.L., “3Dresyn CDC1, Carbon Dioxide Collector,” controlled public product/TDS page, TDS-3DRESYN-CDC1-EN, August 2026. <https://www.3dresyns.com/products/3dresyn-cdc1-carbon-dioxide-collector-our-3d-resin-which-captures-carbon-dioxide-co2-from-air-to-reduce-green-house-gas-pollutants>