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Article

Specification-driven feasibility and techno-economic assessment of recycling and valorization of HTV silicone rubber manufacturing scrap from composite insulator production

Kadir Aydin*

Department of Mechanical Engineering, Faculty of Engineering, OSTİM Technical University, Ahi Evran OSB Mahallesi, 100. Yıl Bulvarı No: 55/F, Yenimahalle, 06374 Ankara, Türkiye
* Corresponding Author: kadir.aydin@ostimteknik.edu.tr

ABSTRACT

Composite silicone insulators are rapidly displacing ceramic and glass units in high-voltage transmission, and their manufacture generates substantial cured high-temperature-vulcanized (HTV) silicone rubber scrap that is chemically inert and non-degradable. This study presents a specification-driven feasibility and techno-economic assessment of recycling and valorizing 24 t/year (2 t/month) of cured HTV scrap (grade MPC D010707) generated in the production of 170 A/B, 170 C and 420 A/B composite insulators. Using the manufacturer quality specification together with the stoichiometry of aluminum trihydroxide (ATH) dehydration, a compositional model of approximately 55 wt% ATH, 5 wt% reinforcing silica, and 40 wt% polydimethylsiloxane (PDMS) is inferred without new laboratory characterization. Three valorization routes are modeled: mechanical recycling by ambient and cryogenic grinding with reincorporation into virgin compound; oxidative pyrolysis to recover a silica-rich inorganic residue; and high-temperature mullite synthesis. A linear property-degradation model, anchored to a recent peer-reviewed high-consistency rubber recyclate dataset, shows that mechanical property loss is not the binding constraint. Instead, the particle-size specification of 10 µm median diameter and the tracking and erosion requirement of class 1A4.5 restrict reincorporation into insulator housings to roughly 10 to 15 parts per hundred rubber (phr) until qualified by testing, whereas downcycled products tolerate up to 60 phr. Stoichiometric mass balances give a 73% inorganic yield for oxidative pyrolysis, of which 375 kg/ton is a high-value silica fraction, and 500 kg/ton mullite for the ceramic route. Techno-economic modeling identifies ambient mechanical recycling as the most attractive first investment, with a capital expenditure near USD 21,000 and a payback below one year, contingent on internal absorption capacity, with recovered-silica pyrolysis as a strategic second phase. The work is presented explicitly as a modeling and techno-economic feasibility study based on manufacturer specification data and literature-derived property models.

Keywords: *HTV silicone rubber, Composite insulator, Circular economy, Pyrolysis, Techno-economic analysis, Recycling*

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1. INTRODUCTION

Electric Composite polymer insulators with silicone rubber housings have become the dominant technology for outdoor high-voltage insulation. Relative to porcelain, polymer units weigh 80–90% less, resist pollution flashover through surface hydrophobicity, and enable live-line maintenance. The market reflects this transition: the composite insulators market is estimated at USD 7.72 billion in 2025 and is projected to reach USD 11.29 billion by 2030, a compound annual growth rate of 7.90% [1]. This growth is mirrored by rising silicone rubber consumption and, inevitably, by increasing manufacturing scrap and end-of-life waste. The housing material is almost universally a high-temperature vulcanized (HTV) silicone

rubber, also called high-consistency rubber (HCR) or heat-cured rubber, highly filled with aluminum trihydroxide (ATH) for tracking and erosion resistance and with reinforcing, typically fumed, silica for mechanical strength. The very attributes that make cured HTV silicone rubber excellent in service, namely chemical inertness, thermal stability and a densely crosslinked network, also render it non-degradable and difficult to recycle. Manufacturing scrap in the form of flash, sprues, rejected parts and trimmings is generated continuously and, absent a recycling route, is landfilled or incinerated. The literature describes several recycling families: mechanical grinding, both ambient and cryogenic; chemical depolymerization to cyclic siloxanes and polydimethylsiloxane (PDMS) oils; thermal and oxidative pyrolysis to recover silica or ceramic phases; and biological degradation [2]. Several of these have been demonstrated specifically for composite-insulator silicone [3–5].

Abbreviations

ATH	Aluminum trihydroxide
CAPEX	Capital expenditure
HCR	High-consistency rubber
HTV	High-temperature vulcanized
IEC	International Electrotechnical Commission
LOI	Limiting oxygen index
PDMS	Polydimethylsiloxane
phr	Parts per hundred rubber
SME	Small-to-medium enterprise
TGA	Thermogravimetric analysis
TL	Turkish lira
USD	United States dollar

The contribution of this work is threefold. First, a specification-driven compositional inference method derives the filler and polymer split from routine quality-control thresholds and ATH dehydration stoichiometry, avoiding new laboratory characterization. Second, a dual-route pyrolysis yield comparison contrasts oxidative silica recovery with mullite synthesis using closed stoichiometric mass balances. Third, a techno-economic analysis at realistic industrial small-to-medium enterprise (SME) scale ranks the routes and isolates the binding constraints. The work is framed as a modeling and techno-economic feasibility study built on manufacturer specification data and literature-derived property models, not a new experimental campaign; no experimental results are claimed. Figure 1 summarizes the valorization routes assessed.

2. ANALYSIS OF THE PROBLEM

The Silicone scrap arising in composite insulator manufacture is not a single material. It separates into two streams that differ fundamentally in recycling value. Uncured, so-called green, compound from mixing, milling and pre-forming has not yet crosslinked and can be returned directly to fresh compound on a two-roll mill at high substitution rates, at essentially zero processing cost. Cured scrap, comprising mold flash, sprues, rejected parts and deflashing fines, is the difficult fraction and is the subject of this study. Once the peroxide or platinum-catalyzed cure has formed the siloxane network, the material can no longer be remelted or reshaped, so the thermoplastic recycling paradigm does not apply. Three features make cured HTV insulator scrap harder to valorize than commodity rubber waste.

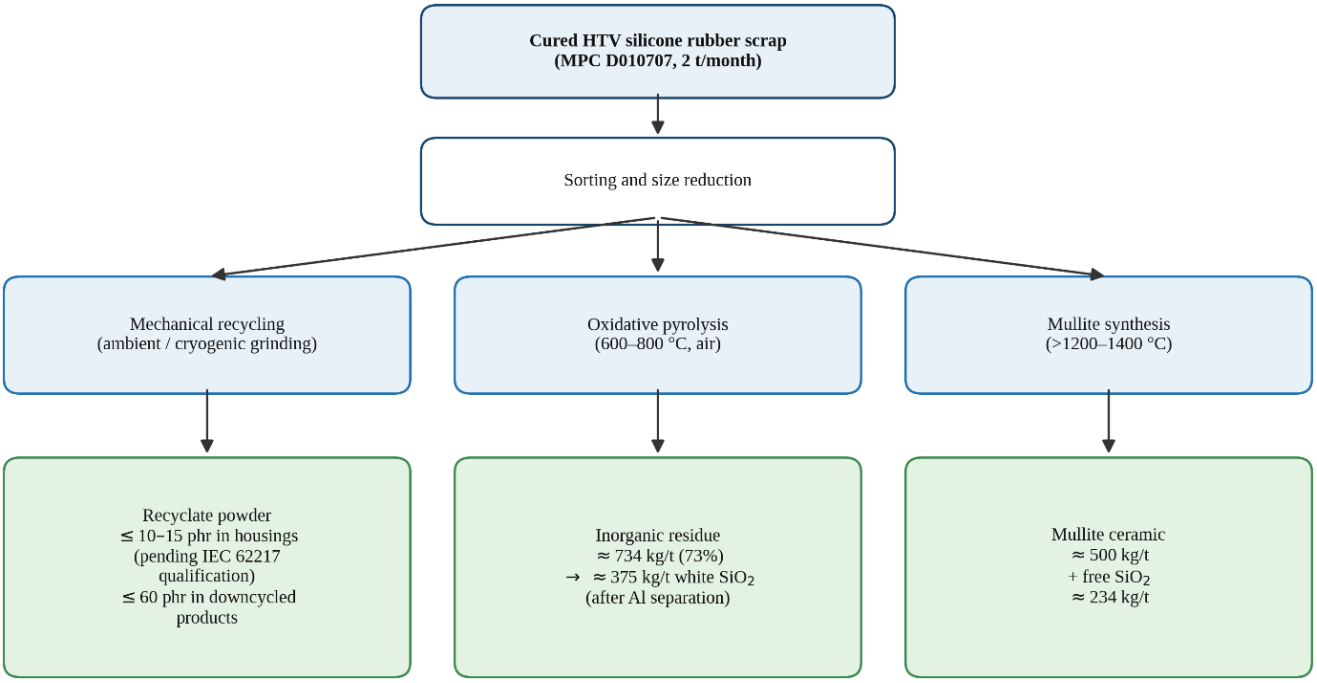

Figure 1. Valorization routes assessed for cured HTV silicone rubber scrap from composite insulator manufacturing

The polymer network is chemically inert, so simple solvent or thermal softening is ineffective. The inorganic loading is very high, approaching 60 wt%, so combustion for energy recovery is impractical because it liberates a large mass of fine silica ash rather than releasing useful calorific value. Finally, and most importantly for this application, the material performs a safety-critical electrical function. An insulator housing must retain hydrophobicity, resist surface tracking and erosion, and survive decades of multi-stress aging. Recycled content therefore cannot be judged on mechanical properties alone, as it might be in a gasket or a floor mat; it must be judged against the full acceptance specification that governs the product. The published work on this waste stream is informative but incomplete for an industrial decision. Studies on composite-insulator silicone demonstrate that monomer recovery, nano-silica separation and mullite formation are technically achievable [3,4], and recent work shows that silica microspheres recycled from silicone rubber perform comparably to commercial fillers in epoxy insulation [5]. Studies on HCR recyclate quantify the mechanical penalty of reincorporation [6], and industrial announcements report reincorporation rates above 50% in non-critical formulations [7]. What is missing is the connection between these results and the manufacturer's own acceptance specification: none of the available studies establishes how much recyclate a given insulator compound can absorb before a named specification clause is violated, nor which clause binds first, nor whether the economically rational route at the scale of a single plant is mechanical, thermal, or chemical.

Problem statement: For a defined cured HTV scrap stream of 24 t/year arising from a known compound whose acceptance specification is available, this study determines: (i) the composition of the scrap, inferred from the specification itself rather than from new measurement; (ii) the maximum recyclate loading that can be reincorporated into the insulator housing compound without violating that specification, and which specification clause constitutes the binding constraint; (iii) the recoverable product masses delivered by the two competing thermal routes; and (iv) which valorization route is economically rational as a first investment at this scale.

3. MATERIALS AND METHODS

3.1 Waste stream and specification data

The waste studied was cured HTV silicone rubber scrap of grade MPC D010707, arising from three insulator families, namely 170 A/B, 170 C and 420 A/B (Table 1, Figure 2), at a rate of 2 t/month, equivalent to 24 t/year. The manufacturer quality specification KORUCU QC-FO-17-00 was used as the sole source of material data. It defines the following controls and performance thresholds: total filler content of ATH plus silica not exceeding 60 wt%; thermogravimetric analysis (TGA) mass loss between 200 and 350 °C not exceeding 19 wt%; silicone content of at least 30 wt%; tensile strength of at least 4 MPa; elongation at break of at least 150%; tear strength of at least 13 kN/m; hardness of Shore A 60 to 70; specific gravity not exceeding 1.6; tracking and erosion class of at least 1A4.5 with erosion depth not exceeding 2.5 mm, determined per IEC 60587 [8]; hydrophobicity class HC1 per IEC/TS 62073 [9]; flammability class V-0 per IEC 60695-11-10; limiting oxygen index (LOI) of at least 40%; median particle size not exceeding 10 μm; volume resistivity of at least 1×10^{14} Ω·cm; and electric strength of at least 20 kV/mm.

Figure 2. HTV composite silicone insulator

Table 1. Technical specifications of KORUCU Makina Elektrik A.Ş. Ankara/Türkiye 170 A/B, 170 C and 420 A/B type HTV composite silicone insulators

Parameter	170 kV Type A/B	170 kV Type C	420 kV Type A/B	Unit
Dimensions (H x D)	568×Ø195	508×Ø195	622×Ø200	mm
Crepe Distance	757 ± 30	824 ± 20	690 ± 20	mm
Insulator Length	291 ± 10	235 ± 10	235 ± 10	mm
Number of Skirts	3	4	3	piece
Core Diameter	Ø25	Ø25	Ø36	mm
Large Skirt Diameter	Ø195	Ø195	Ø200	mm
Small Skirt Diameter	Ø165	Ø165	Ø167	mm
SML	120	120	210	kN
Weight	~3.7	~4.0	~5.5	kg
Connection Hardware	*Steel – Galvanized*	*Steel – Galvanized*	*Steel – Galvanized*	-

3.2 Specification-derived composition

The dominant filler ATH, $Al(OH)_3$, equivalently $Al_2O_3 \cdot 3H_2O$, releases chemically bound water on heating according to Eq. (1):

$$2\,Al(OH)_3 \rightarrow Al_2O_3 + 3\,H_2O \quad (1)$$

The mass fraction of water released is $3M(H_2O)$ divided by $2M(Al(OH)_3)$, that is 54.05/156.0 = 0.3465. ATH therefore loses 34.6 wt% as water on full dehydration between approximately 200 and 350 °C. Because the specification TGA window of 200 to 350 °C coincides with ATH dehydration, the 19 wt% mass-loss limit constrains the ATH content through Eq. (2):

$$w_{ATH} = \frac{\Delta m_{(200-350\,°C)}}{0.3465} \quad (2)$$

At the limit Δm = 19 wt%, $w_{ATH} \approx 0.19/0.3465 \approx 0.548$, that is approximately 55 wt% ATH. With total filler not exceeding 60 wt%, reinforcing silica is approximately 5 wt%, and the balance, comprising PDMS plus minor additives, is approximately 40 wt%, which is consistent with the specified silicone content of at least 30 wt%. The inferred baseline composition was therefore taken as 55 wt% ATH, 5 wt% silica, and 40 wt% PDMS.

3.3 Incorporation-ceiling model for mechanical recycling

Recyclate loading was expressed in parts per hundred rubber (phr) and converted to a weight fraction using Eq. (3):

$$w_{recyclate} = \frac{r}{100 + r} \quad (3)$$

A linear property-degradation model for tensile strength σ as a function of recyclate loading r was adopted, as given in Eq. (4):

$$\sigma(r) = \sigma_0(1 - k\,r) \quad (4)$$

where σ_o is the virgin baseline tensile strength. The degradation coefficient was anchored to a peer-reviewed HCR recyclate dataset in which 60 phr of recyclate reduced maximum stress by up to 45% and elongation by up to 25%, increased compression set by approximately 22%, and left hardness essentially unchanged [6]. This anchor gives $k \approx 0.45/60 = 0.0075$ per phr. The tensile-limited incorporation ceiling r_{max}, at which $\sigma(r)$ meets the specification floor σ_{spec} = 4 MPa, follows from Eq. (5):

$$r_{max} = \frac{1 - \frac{\sigma_{spec}}{\sigma_0}}{k} \quad (5)$$

The ceiling was evaluated for three plausible virgin baselines, σ_o = 5.0, 6.0 and 7.5 MPa, and was then compared against the two non-mechanical constraints that the specification also imposes, namely median particle size not exceeding 10 µm and tracking and erosion class of at least 1A4.5 per IEC 60587 [8].

3.4 Pyrolysis stoichiometric mass balance

Per 1000 kg of cured scrap, the inferred inputs were ATH 549 kg, reinforcing silica 51 kg, and PDMS 400 kg, where the rounding is relative to the 55/5/40 split accounts for minor additives. Two thermal routes were balanced.

Route 1, oxidative pyrolysis at 600 to 800 °C. In air, the PDMS repeat unit $[Si(CH_3)_2O]$, C_2H_6OSi, of molar mass 74.15 g/mol, oxidizes to leave one SiO_2 unit of molar mass 60.08 g/mol per repeat unit, while organic carbon and hydrogen leave as CO_2 and H_2O, as expressed in Eq. (6):

$$[Si(CH_3)_2O]_n + 4n\,O_2 \rightarrow n\,SiO_2 + 2n\,CO_2 + 3n\,H_2O \quad (6)$$

Silica derived from PDMS is 400 × (60.08/74.15) = 324 kg. Reinforcing silica is retained at 51 kg. ATH converts to alumina via Eq. (1), giving 549 × (101.96/156.0) = 359 kg Al_2O_3. The total inorganic residue is therefore 324 + 51 + 359 = 734 kg, a 73% yield. After aluminum separation, for example by acid or alkali leaching, the high-value white SiO_2 fraction is 324 + 51 = 375 kg.

Route 2, mullite synthesis above 1200 to 1400 °C. The mixed oxide residue was assumed to react according to Eq. (7):

$$3\,Al_2O_3 + 2\,SiO_2 \rightarrow 3Al_2O_3 \cdot 2SiO_2 \quad (7)$$

Mullite, $3Al_2O_3 \cdot 2SiO_2$, has a molar mass of 425.9 g/mol. The available Al_2O_3 is 359 kg, that is 3520 mol, while the available SiO_2 is 375 kg, that is 6240 mol. The 3:2 stoichiometry makes the reaction Al_2O_3-limited. The mullite formed is therefore (3520/3) × 425.9 ≈ 500 kg, the SiO_2 consumed is approximately 141 kg, and the free residual SiO_2 is approximately 234 kg.

3.5 Techno-economic model

Indicative unit values were adopted as follows: virgin HTV compound 6.5 USD/kg; recycled silicone powder 1.8 USD/kg; recovered SiO_2 2 to 8 USD/kg depending on application; mullite 1.2 USD/kg; and disposal cost 35 USD/t, equivalent to approximately 1500 TL/t at an exchange rate of 1 USD ≈ 43 TL as of June 2026. The annual mass was 24 t. For each scenario, the avoided disposal cost, the product revenue or avoided virgin purchase, the operating cost, the capital expenditure (CAPEX), and the simple payback period were estimated. A key operational constraint applies to mechanical recycling, namely downstream absorption capacity: at 15 phr reincorporation, absorbing the recycle powder requires a virgin throughput of the order of 13 t/month.

4. Results and Discussion

4.1 Inferred composition

The specification-derived composition, given in Table 2, is 55 wt% ATH, 5 wt% reinforcing silica and 40 wt% PDMS. It is internally consistent with all specification thresholds and with formulation practice for ATH-filled HTV insulator housing, in which ATH loadings of 50 to 60 wt% are typical in order to meet tracking, erosion and flammability requirements [3, 4]. The practical significance of this result is that a routinely available quality-control document, rather than a dedicated analytical campaign, is sufficient to fix the input composition for all subsequent mass balances.

4.2 Incorporation ceiling and binding constraints

Applying Eq. (5) with k = 0.0075 per phr and σ_{spec} = 4 MPa, as plotted in Figure 3, the tensile-limited incorporation ceiling ranges from approximately 27 phr for σ_o = 5.0 MPa to approximately 62 phr for σ_o = 7.5 MPa.

Table 2. Specification-derived composition of cured HTV scrap, per 1000 kg

Component	wt%	Mass (kg)	Basis
ATH, $Al(OH)_3$	≈55	549	TGA 200–350 °C ≤ 19 wt% ÷ 0.3465
Reinforcing silica	≈5	51	Total filler ≤ 60 wt% minus ATH
PDMS + additives	≈40	400	Balance; silicone content ≥ 30 wt%

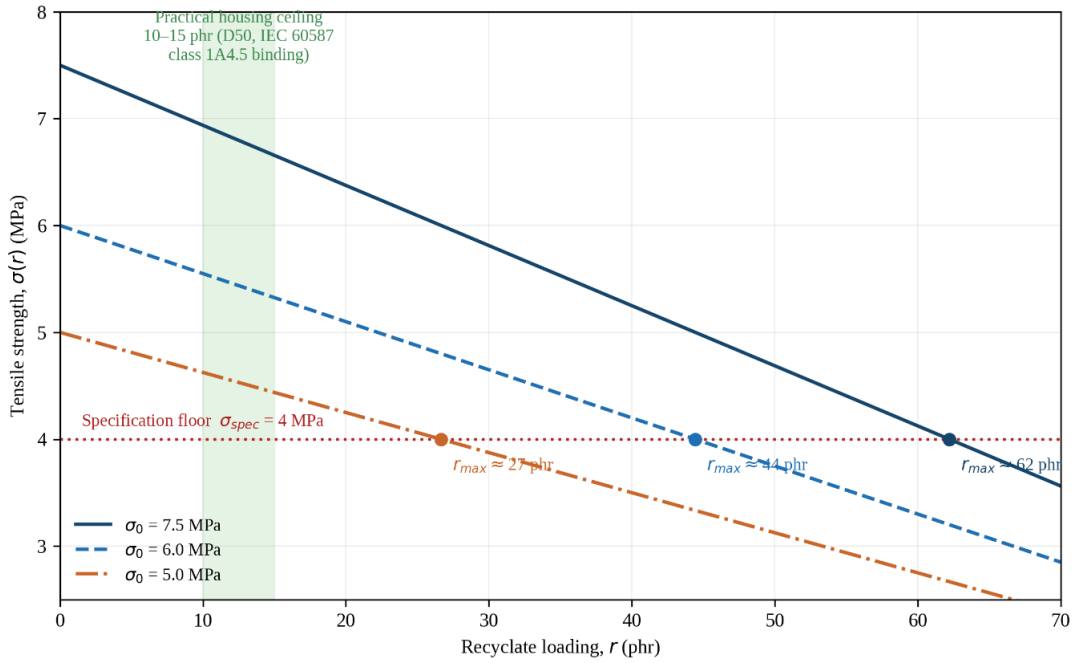

Figure 3. Linear property-degradation model of Eq. (4) with k = 0.0075 per phr: tensile strength versus recyclate loading for three virgin baselines. The shaded band marks the practical housing ceiling of 10 to 15 phr imposed by the median particle size and IEC 60587 class 1A4.5 constraints

If tensile strength were the sole criterion, meaningful reincorporation in the range of 25 to 60 phr would appear feasible, and the recycling problem would be largely solved by grinding alone. The binding constraints, however, are not mechanical. First, the specified median particle size of 10 µm cannot be met by grinding cured rubber: ambient grinding yields approximately 150 to 830 µm and cryogenic grinding approximately 75 to 355 µm [3], which is one to two orders of magnitude coarser than the 10 µm ceiling. Coarse recyclate particles act as stress concentrators and, more importantly, as defects that degrade the tracking and erosion performance that is safety-critical for housings. Consequently, for reincorporation into insulator-housing compound, the practical ceiling is approximately 10 to 15 phr pending qualification by full IEC 62217 testing [10], which incorporates the class 1A4.5 tracking and erosion protocol together with the 1000 h multi-stress and salt-fog aging test. For downcycled, non-housing products such as gaskets, mats, low-voltage accessories and spacers, loadings up to approximately 60 phr are defensible because tracking and erosion are not design-limiting. This tiered outcome is consistent with recent literature.

Hofmann et al. [6] reports that, for peroxide-curing HCR, the recyclate has no influence on crosslinking and that only a slight decrease in mechanical properties occurs at small recyclate contents below 10 phr. Cryo-milled silicone waste has likewise been reused directly as a soft and elastic filler in silicone formulations without compatibilizers [11]. Independently, the RENOV consortium comprising Elkem, Hutchinson, Nexans and CNRS laboratories announced in September 2025 the validation of a mechanical-recycling proof of concept for HCR with reincorporation rates exceeding 50% and retained mechanical properties [7]. That result, however, applies to non-safety-critical formulations rather than tracking-rated housing, which supports the distinction drawn here between housing-grade and downcycled loadings.

4.3 Comparison of pyrolysis Route 1 and Route 2

Table 3 and Table 4, together with Figure 4, present the stoichiometric mass balances of the two thermal routes. Both routes convert the same input into the same total solid mass of 734 kg per ton, but they distribute that mass between products of very different unit value.

Table 3. Oxidative pyrolysis, Route 1, mass balance per 1000 kg scrap

Stream	Mass (kg)	Notes
SiO_2 from PDMS	324	Eq. (6); 74.15 → 60.08 g/mol
Retained reinforcing silica	51	—
Al_2O_3 from ATH	359	Eq. (1); 156.0 → 101.96 g/mol
Total inorganic residue	**734**	**73% yield**
White SiO_2 after Al separation	375	High-value fraction

Table 4. Mullite synthesis, Route 2, mass balance per 1000 kg scrap

Stream	Mass (kg)	Notes
Mullite ($3Al_2O_3{\cdot}2SiO_2$)	≈500	Al_2O_3-limited; Eq. (7)
Free residual SiO_2	≈234	Excess silica phase

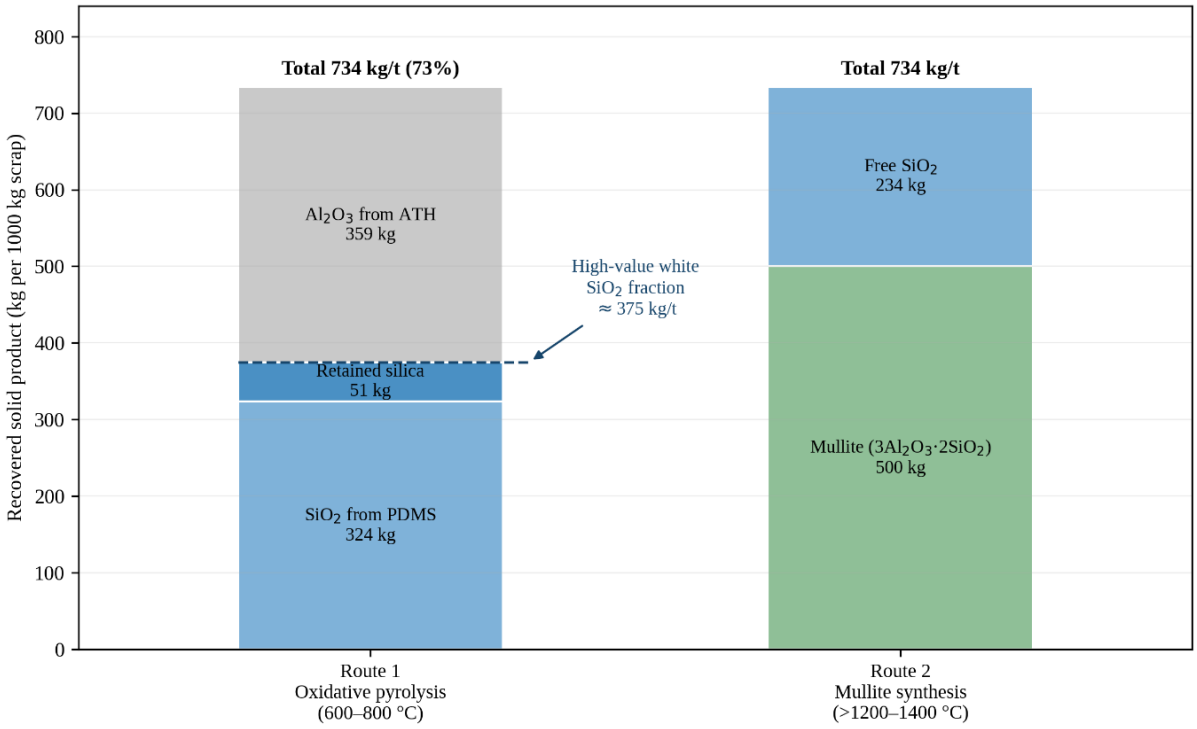

Figure 4. Linear property-degradation model of Eq. (4) with k = 0.0075 per phr: tensile strength versus recyclate loading for three virgin baselines. The shaded band marks the practical housing ceiling of 10 to 15 phr imposed by the median particle size and IEC 60587 class 1A4.5 constraints

Route 1 maximizes recovery of a high-value product, namely recycled SiO_2 suitable as a filler for epoxy insulation or as a fumed-silica substitute. Recent work on stepwise pyrolysis with post-fractionation shows that silica microspheres recycled from waste silicone rubber achieve dielectric enhancement in epoxy comparable to commercial fillers [5], and mechanochemical milling has been shown to substantially improve the pyrolysis efficiency of waste HTV silicone rubber [12]. Route 2 converts the mixed Al_2O_3 and SiO_2 residue into a single high-purity refractory ceramic, as demonstrated for composite-insulator silicone by Shang et al. [4].

ATH is a favorable in-situ alumina source because the transitional alumina it forms has a small diameter and dissolves readily into the silica phase, and residual Fe_2O_3 colorant lowers the mullitization temperature [4]. Mullite is nevertheless a low-unit-value commodity at approximately 1.2 USD/kg, so Route 2 is marginal on its own economics and is best regarded as a residue-valorization or co-product step rather than a primary revenue driver. A practical corollary is that the alumina-limited stoichiometry of Eq. (7) leaves 234 kg of free silica per ton, so the two routes are not mutually exclusive: a plant operating Route 2 still produces a silica stream that can be directed to the Route 1 product market.

4.4 Techno-economic comparison

The three principal valorization scenarios were compared on a common basis of 24 t/year of cured scrap, using the indicative prices and model assumptions of Section 3.5. Table 5 summarizes the capital expenditure, the net annual benefit, the simple payback period and the key contingency governing each scenario, while Figure 5 visualizes the CAPEX values against the net annual benefit ranges together with the corresponding payback periods. Two features are immediately apparent from Table 5 and Figure 5. First, the ambient-grinding scenario exhibits the widest net-benefit range, because its return is dominated by the avoided purchase of virgin compound and therefore scales directly with the fraction of recyclate powder that can be absorbed internally. Second, the pyrolysis scenario combines the highest capital requirement with the largest relative uncertainty, since its revenue depends on the purity, and hence the realized selling price, of the recovered SiO_2. These observations frame the scenario-specific discussion that follows.

The economics favor mechanical recycling as the first investment: low CAPEX, sub-year payback, immediate avoided disposal of approximately 0.84 kUSD/year for 24 t, plus avoided virgin purchase at 6.5 USD/kg against a recyclate value of 1.8 USD/kg. The decisive caveat is absorption. The plant must consume the powder internally at 15 phr or less in qualified products, which requires sufficient virgin throughput of approximately 13 t/month, or else an external buyer for downcycled powder must be secured. Cryogenic grinding produces finer and cleaner powder, and therefore better reincorporation quality, at higher CAPEX and energy cost; it becomes attractive where powder quality or higher permissible loadings materially raise the qualified reincorporation rate.

4.5 Sensitivity and qualification pathway

The mechanical-recycling business case is most sensitive to the qualified reincorporation rate in phr and to recyclate price and absorption.

Table 5. Techno-economic scenario comparison at 24 t/year; indicative values, 1 USD ≈ 43 TL, June 2026

Scenario	CAPEX (kUSD)	Net benefit (kUSD/year)	Simple payback	Key contingency
Ambient grinding + reincorporation	≈21	≈35–128	< 1 yr	Absorption capacity, ≈13 t/month virgin at 15 phr
Cryogenic grinding + reincorporation	≈60	≈72	≈0.8 yr	Higher energy and operating cost; finer powder
Oxidative pyrolysis → SiO_2	≈105	0–53	≈2 yr (high-value case)	SiO_2 purity and price realization
Mullite route	—	Marginal alone	—	Low product unit value

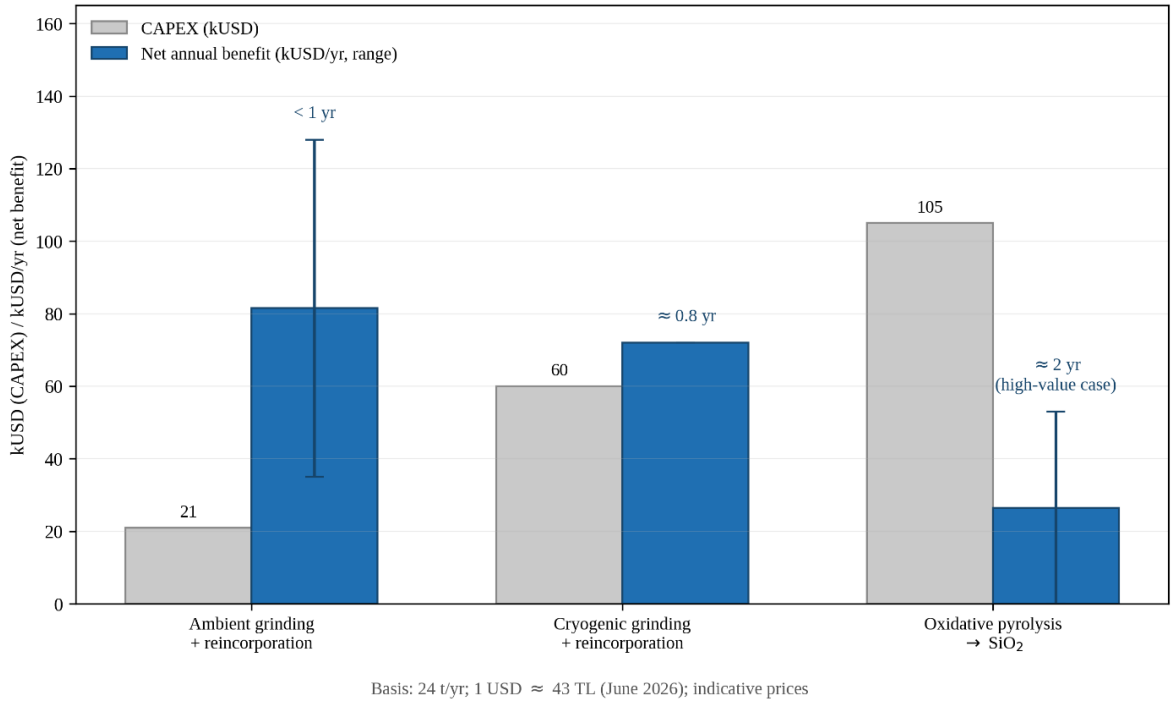

Figure 5. Techno-economic comparison of the three principal scenarios at 24 t/year, showing CAPEX bars and net annual benefit bars with ranges, with payback periods annotated

The pyrolysis case is most sensitive to the realized SiO_2 selling price, since 2 against 8 USD/kg swings the outcome from break-even to strongly positive. The adopted degradation coefficient k is a single-point linearization of the 45% at 60 phr anchor [6]; a sensitivity band on k of plus or minus 30% shifts the tensile-limited ceilings by a comparable proportion in the opposite sense but does not alter the ranking of constraints, because the particle-size and tracking and erosion gates bind first in every case examined. Any housing-grade reincorporation must pass the IEC 62217 design tests [10], including IEC 60587 inclined-plane tracking and erosion at class 1A4.5 [8] and the 1000 h multi-stress salt-fog and ultraviolet ageing test, together with verification of hydrophobicity class HC1 per IEC/TS 62073 [9], flammability class V-0, LOI of at least 40%, volume resistivity of at least 1×10^{14} Ω·cm and electric strength of at least 20 kV/mm. Until such qualification is complete, recyclate should be confined to non-housing and downcycled products.

4.6 Positioning within the recycling landscape

Chemical depolymerization offers the highest-value and most nearly circular outcome, regenerating cyclic monomers or PDMS oils. Krug, Asuncion and Laine demonstrated ambient-condition recycling of highly crosslinked thermoset silicones [13]; Vu et al. [14] advanced a polydentate ligand and potassium silanolate complex for back-to-cyclic-monomer recycling; and a gallium-catalyzed route converting silicone waste to key chlorosilanes has recently been reported [15, 16]. Wolf and Stammer estimate that only 35 000 to 45 000 t of silicone was chemically recycled worldwide in 2024, which indicates an immature sector [2]. Given an SME scale of 24 t/year and the capital and chemical intensity of depolymerization, chemical routes are not recommended as a first step in the present case; they remain a longer-term option should a regional consortium or a toll-processing partner emerge.

5. Conclusion

This study assessed the technical and economic feasibility of recycling 24 t/year of cured HTV silicone rubber scrap generated in composite insulator manufacturing, using only the manufacturer quality specification, published property data and closed stoichiometric mass balances, without recourse to new laboratory characterization. Three valorization routes, namely mechanical recycling with reincorporation, oxidative pyrolysis to recover silica, and high-temperature mullite synthesis, were quantified and ranked against the binding specification constraints and against each other on a common techno-economic basis. The principal conclusions are as follows.

- From routine quality-control specification thresholds and ATH dehydration stoichiometry, the cured HTV scrap composition is inferred as 55 wt% ATH, 5 wt% silica, and 40 wt% PDMS, obtained without new laboratory characterization.
- Mechanical property loss is not the binding constraint for reincorporation. The 10 µm median particle-size specification and the class 1A4.5 tracking and erosion requirement are binding instead. Housing reincorporation is therefore limited to approximately 10 to 15 phr pending qualification, whereas downcycled products tolerate up to approximately 60 phr.
- Oxidative pyrolysis recovers 73% of the input as inorganic residue, of which 375 kg per ton is a high-value silica fraction, while mullite synthesis yields approximately 500 kg per ton at low unit value.
- Ambient mechanical recycling is the recommended first investment, with a CAPEX near 21 kUSD and a payback below one year, contingent on internal absorption capacity. Recovered-silica oxidative pyrolysis is a strategic second phase if silica price and purity can be realized.
- The methodology, which derives composition and valorization ceilings from routine specification data, is transferable to other highly filled elastomer waste streams.

The uniqueness of this work lies in binding the recycling decision directly to the acceptance specification that governs the product, which converts a general materials question into a decision that a manufacturer can act upon. Its limitations should be stated plainly. The analysis is a model, not an experimental campaign; the compositional split is inferred rather than measured; the property-degradation law is a single-point linearization of one published dataset and has not been verified for this particular compound; and the economic figures are indicative unit values subject to exchange-rate and market volatility rather than firm quotations. Future work should therefore proceed along four lines: experimental verification of the inferred composition by independent thermogravimetric and ash analysis; measurement of the degradation law for this compound across a range of loadings; evaluation of jet or ultra-fine milling as a means of approaching the specified median particle size, followed by a formal qualification campaign against the full design-test suite; and a pilot-scale demonstration of oxidative pyrolysis with characterization of the purity and dielectric performance of the recovered silica.

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Ethical issue
The author is aware of and complies with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement
The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest
The author declares no potential conflict of interest.

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Nomenclature

Symbol	Quantity	Unit
k	Property-degradation coefficient	1/phr
M	Molar mass	g/mol
n	Number of PDMS repeat units	–
r	Recyclate loading	phr
r_{max}	Tensile-limited incorporation ceiling	phr
w_{ATH}	Mass fraction of ATH in the scrap	–
$w_{recyclate}$	Mass fraction of recyclate in the compound	–
Δm	Mass loss in the TGA window 200–350 °C	wt%
σ	Tensile strength	MPa
σ_o	Virgin baseline tensile strength	MPa
σ_{spec}	Specification floor for tensile strength	MPa