Feasibility Study for Industrial Scale Submicronic Engineered Amorphous Silica Particle (SEASP) Manufacturing for Stratospheric Aerosol Injection (SAI)

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A feasibility study is presented for scaling up manufacturing of Submicronic Engineered Amorphous Silica Particles (SEASP) to industrial throughput required for Stratospheric Aerosol Injection (SAI), with properties meeting safety and functionality requirements [1, 2]. Manufacturing is based on wet-precipitation chemistry via a TEOS-based Stöber sol-gel route. The goal of this study is to evaluate the feasibility of large-scale manufacturing of engineered amorphous silica particles for SAI deployment, encompassing cost, timeline, and identification of key risks and mitigation strategies. Scale-up is assessed across the components necessary to establish feasibility: process scalability, material availability, infrastructure, operations, waste and by-products, timeline, and cost.

Based on relevant available data on SEASP manufacturing and precipitated-silica scale-up benchmarks, it is assessed that scaling up manufacturing from the current specialty chemical scale of 0.1 kt/yr to a single module of 250 kt/yr is expected to be completed within approximately five years. No fundamental technology or process show-stopper was identified, provided that demand, logistics, financing, industrial partnering, and regional manufacturing hubs are developed in parallel.

Plant replication of the 250 kt/yr module to regional hub manufacturing at a climate-relevant scale of 1 Mt/yr, sufficient to offset a significant fraction of decadal warming, is expected to be completed within two additional years. An outlook is provided for further expansion toward climate-scale 10 Mt/yr manufacturing capacity, required for approximately 1% solar-flux modification. This climate-scale capacity is expected to be based on replicating the regional 1 Mt/yr hubs.

TEOS precursor availability is identified as the principal scale-up risk, and an integrated SEASP-TEOS manufacturing concept is presented to address this risk. Unit economics of approximately USD 5/kg, dominated primarily by raw-material costs, appear plausible, with further reductions possible through process optimization, solvent recycling, continuous operation, and precursor-route improvements.

I. INTRODUCTION

As climate risks intensify and emissions reductions may not proceed quickly enough to limit near-term warming [3, 4], solar radiation modification (SRM) has received increasing attention as a potential supplementary climate-intervention approach [5, 6]. The most widely discussed SRM approach is stratospheric aerosol injection (SAI) [6, 7], in which aerosols or aerosol precursors are introduced into the stratosphere to increase the reflection of incoming solar radiation [8–11]. By increasing Earth's reflectivity, SAI could in principle reduce near-term warming and some associated climate impacts [5, 6].

A central technical question for SAI is whether candidate particles can satisfy both functionality requirements and safety-related constraints [12]. In this context, companion and prior studies have demonstrated design and lab-scale production of submicronic engineered amorphous silica particles (SEASP), with controlled size, near-spherical morphology, narrow particle-size distributions, and tunable surface properties using wet-precipitation chemistry via a TEOS-based Stöber sol-gel route [1, 13]. These properties are necessary in order to meet the main particle-level requirements for SAI, including efficient shortwave scattering, limited longwave absorption, human health safety requirements, limited heterogeneous chemical reactivity, compatibility with airborne dispersion, approximate year-scale stratospheric residence, and monitoring system requirements [1, 2].

Illustrative images of the produced particles and synthesis route are shown in figure 1. These images, alongside the companion studies, illustrate the fact that the present work is focused on scaling up a viable particle-production route, rather than a purely conceptual material system.

Beyond particle performance, a key question is whether SEASP can be manufactured at scale [12]. Here we present a feasibility study for scaling the demonstrated TEOS-based SEASP manufacturing route to annual manufacturing rates relevant for SAI research, validation, and potential future climate-scale deployment. The objective is not to introduce a new particle chemistry, but to assess how existing small-volume Stöber sol-gel silica manufacturing capability, currently on the order of 0.1 kt/yr [14], can be expanded to climate-relevant rates of 1 Mt/yr and ultimately to climate-scale manufacturing of 10 Mt/yr. The former corresponds to an annual deployment required to offset a significant fraction of decadal warming [2]. The latter corresponds approximately to the annual deployment required for 1% solar-flux modification, subject to particle efficacy, residence time, and deployment assumptions.

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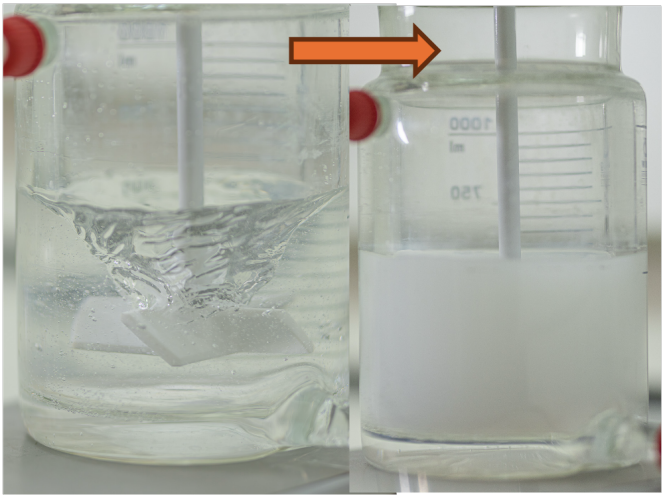

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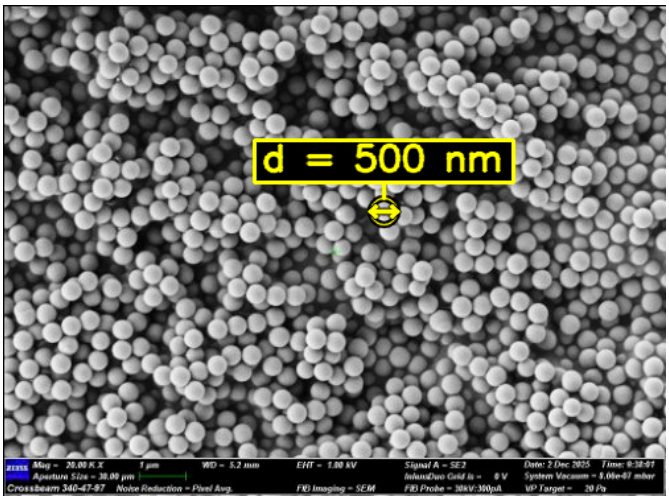

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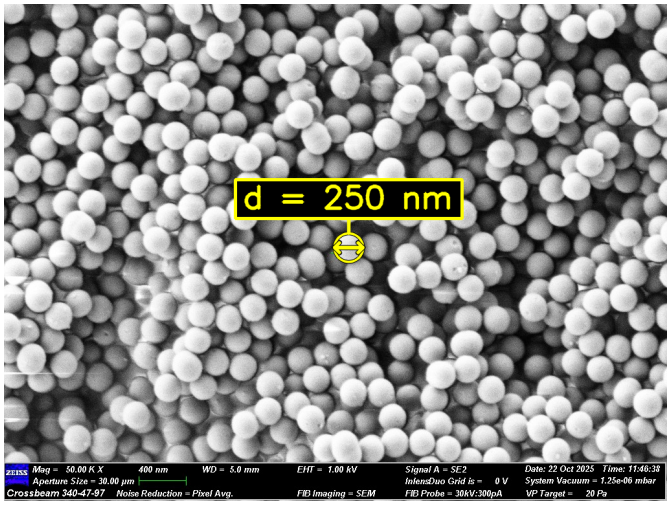

(d)

FIG. 1: Illustrative images of the current SEASP manufacturing process. (a) Laboratory wet-precipitation synthesis demonstrating the transition from a clear reaction medium to a SEASP suspension. (b) SEASP produced at the hundred-kilogram scale. (c,d) SEM images of near-spherical submicronic SEASP with representative diameters of approximately 500 nm and 250 nm, respectively.

We organize the industrialization pathway around four manufacturing levels: 0.1 kt/yr, 250 kt/yr, 1 Mt/yr, and 10 Mt/yr. In the first level ("existing manufacturing scale"), adaptation of existing small-volume specialty-particle fabrication capability is required, rather than building new manufacturing capacity. The main task at this level is to adapt and validate the process for SEASP-specific requirements, including surface treatment, quality assurance, packaging, handling, and process validation while retaining particle-size control, morphology, and composition; this level is assessed as achievable within approximately one year.

Based on relevant available data on SEASP manufacturing and precipitated-silica scale-up benchmarks, it is assessed that the 250 kt/yr level ("single-module scale") is achievable within approximately five years if process scale-up, equipment procurement, quality assurance, and integrated TEOS supply are developed in parallel. Although this level is below full climate-scale deployment, it could support assessment of global remote-sensing observability of the resulting stratospheric aerosol burden, as it is comparable in magnitude to the sulfate aerosol background during volcanically quiescent periods [15]. This single-module scale may be replicated to establish the 1 Mt/yr level ("climate-relevant scale"). Reaching this manufacturing capacity is expected within approximately two additional years, and a total of approximately seven years from launching the project. Once 1 Mt/yr manufacturing capability has been demonstrated, this research provides an outlook in which ramping manufacturing toward full climate-scale capability of approximately 10 Mt/yr would be primarily a matter of coordinated and gradual replication of 1 Mt/yr regional hubs. Construction of each of these additional 1 Mt/yr regional hubs is expected to take two or three years, and the limiting factors at this stage are expected to be capital deployment, project execution, infrastructure, precursor-supply coordination, and industrial partnering, rather than unresolved technical barriers in the SEASP manufacturing process.

The validation process aimed to assess that particle properties meet SAI requirements should be performed jointly with

the manufacturing feasibility study. A particle that performs well optically and chemically should also be produced reproducibly, at high purity, at acceptable cost, and at the required annual mass. Likewise, the manufacturing process should preserve the specified size distribution, morphology, surface chemistry, purity, and batch-to-batch consistency. For this reason, manufacturability is treated here as part of the particle-design requirement set rather than as a downstream engineering concern. We assess SEASP scale-up across the categories required for credible manufacturing: process scalability, precursor and raw-material availability, infrastructure, operations, quality assurance, waste streams and by-products, timeline, and cost, providing quantitative estimates where required. We identify key risks and bottlenecks and propose mitigation strategies.

The main conclusion of this assessment is that no fundamental process-technology barrier is identified for scaling SEASP manufacturing to climate-relevant and ultimately climate-scale annual production rates within the time frames mentioned above. This conclusion relies heavily on the fact that wet-chemical silica synthesis is already a well-established technology for manufacturing at industrial scale: precipitated silica is commercially manufactured at multi-million-ton-per-year scale with bulk prices of order USD ~$1/kg [14, 16–18]. It relies also on the fact that Stöber-type sol-gel synthesis at industrial scale provides the tight size, morphology, and surface-chemistry control critical to SEASP performance [19]. These anchors, and particularly the Stöber-type sol-gel particle manufacturing, serve as a solid starting point for the current feasibility study in terms of raw-material requirement, manufacturing equipment, waste capacity and so on. The major near-term bottleneck is TEOS precursor supply, which we address through an integrated SEASP-TEOS manufacturing concept in which precursor and particle manufacturing are scaled up jointly. Unit economics of ~$5/kg appears plausible, with further reductions possible through solvent recycling, improved reaction yield, transition toward continuous operation, and, if required, possible replacement of TEOS with lower-cost silica precursor routes.

Particle manufacturing at the relevant scale is only one aspect of SAI scale-up [20, 21]. Atmospheric testing and any potential future deployment would also require parallel scale-up of the aircraft fleet to the relevant capacity, as well as scale-up of dispersion hardware and operational logistics. The present work focuses solely on the SEASP particle manufacturing track. Future work will address the challenges related to other aspects of the operational chain, as well as potential adaptation of the wet-chemistry production lines to GEN2 Stardust particle production [22].

Scope and limitations: This paper assesses whether SEASP can be manufactured at climate-scale SAI quantities using known chemistry and available raw materials. The decisions about whether to deploy SAI sit with governments and the international community; this paper supplies one input they will need. Full validation of any SAI system towards potential deployment - particle performance, atmospheric behavior, and safety aspects - lies outside the scope of this work.

The structure of the paper follows the feasibility categories above. Section 2 describes the SEASP manufacturing process and analyzes process scale-up risks, including the integrated SEASP-TEOS manufacturing concept. Section 3 presents the scale-up strategy. Section 4 assesses feasibility across engineering, infrastructure, operations, and raw-material availability. Section 5 develops the production cost model and describes the main cost-reduction levers. Section 6 discusses alternative manufacturing pathways. Section 7 discusses energy use, waste streams and by-products. Section 8 concludes with the main implications for SEASP industrialization and for the broader feasibility of solid-particle SAI.

II. SEASP AND TEOS MANUFACTURING PROCESSES AND INTEGRATED SEASP-TEOS SYSTEM

A. Route Selection and Manufacturing Requirements

Several routes exist for manufacturing amorphous silica particles, including precipitated silica, fumed silica, ion-exchange-derived colloidal silica, and sol-gel synthesis. These routes differ in precursor chemistry, reaction medium, process cost, achievable particle-size control, porosity, morphology, purity, and surface tunability. Precipitated silica offers high-volume, low-cost manufacturing, but typically yields polydispersed, aggregated, high-surface-area particles. Fumed silica can be highly pure, but is usually low-density, high-surface-area, and relatively expensive. Sol-gel routes, and particularly the Stöber process, provide substantially greater control over particle size, morphology, porosity, and surface chemistry, but historically have been employed at smaller manufacturing volumes, primarily due to its higher cost.

The Stöber-type route was selected as the baseline manufacturing process for SEASP production, owing to its high process controllability, which enables the consistent particle quality required to meet SAI-relevant specifications – including narrow particle-size distribution, low surface area, near-spherical morphology, purity, and tunable surface chemistry — through precise control over size, morphology, and surface properties. These characteristics are essential for reproducible optical behavior, dispersion performance, stratospheric residence, and reduced heterogeneous reactivity. The bottom-up synthesis route also provides a platform for implementing future traceability approaches, through elemental or isotopic markers, required for monitoring and compliance systems.

Since the Stöber-type route for production of amorphous silica particles with the required properties is well-established, the main industrial challenge is to preserve tight product specifications while increasing throughput by several orders of magnitude. The process should retain particle size, size distribution, morphology, surface chemistry, impurities, and dispersibility under industrial processes like: mixing, separation, calcination, drying, surface-treatment, and storage conditions.

B. SEASP manufacturing using Stöber-type sol-gel chemistry

The Stöber process, first reported in 1968 [19], produces amorphous silica particles from tetraethyl orthosilicate (TEOS) in an alcohol-rich medium. TEOS hydrolyzes in the presence of water to form silicic acid and ethanol. The silicic acid then condenses to amorphous silica, releasing water. In simplified form, the reactions can be written as follows:

$$\mathrm{Si(OC_2H_5)_4 + 4\,H_2O \longrightarrow Si(OH)_4 + 4\,C_2H_5OH}$$
$$\mathrm{Si(OH)_4 \longrightarrow SiO_2 + 2\,H_2O}$$

$$\mathrm{Si(OC_2H_5)_4 + 2\,H_2O \longrightarrow SiO_2 + 4\,C_2H_5OH}$$

In practical terms, Stöber synthesis is performed in a controlled kinetic and colloidal regime. Water availability, ammonia concentration, solvent composition, temperature, mixing, and reactant-addition rates determine the balance between TEOS hydrolysis, silica condensation, nucleation, particle growth. The alcohol-rich water-limited environment suppresses uncontrolled polymerization and bulk gelation, while supporting a defined nucleation event followed by uniform growth. The concentration of ammonia is a central process parameter: it raises pH, catalyzes hydrolysis and condensation, influences nucleation timing, and affects colloidal stability through surface-charge and interparticle-interaction effects.

At laboratory scale particle size and surface properties can be controlled by adjusting solvent composition, water-to-TEOS ratio, ammonia concentration, temperature, and addition sequence. The main challenge at industrial scale is to maintain a similar level of control of these various process parameters across larger reactor volumes, mixing regime and higher flow rates, longer operating campaigns, and repeatability of batches during all production. The scale-up program therefore focuses on preserving the process parameters combined with finding the appropriate industrial equipment and facilities while increasing throughput to receive better uniformity of particle size distribution.

C. Industrial SEASP process design

The proposed SEASP manufacturing process is designed as a modular industrial sequence consisting of six main steps. The sequence combines batch steps for the chemical reactions with semi-continuous steps where throughput, recovery, and industrial operability are the dominant design requirements.

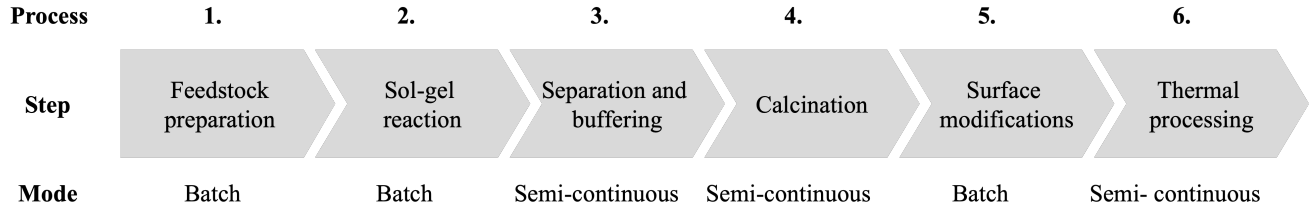

FIG. 2: Schematic overview of the SEASP industrial production sequence and operating mode.

Drying and calcination steps are designed to support large-scale handling, storage, and compatibility with high-altitude dispersion systems. Calcination additionally reduces residual silanol density, complementing the silane-based surface treatment.

The process configuration is underpinned by detailed process modeling, encompassing mass and energy balances, reaction yield estimation, process-duration and scheduling analysis, separation-efficiency assessment, and equipment sizing. These analyses support a consistent transition from laboratory-scale performance to industrial-scale implementation. The modeled balances indicate that the process is operable through a combination of batch and semi-continuous unit operations using appropriate industrial equipment, while maintaining tight control over particle-size distribution, process stability, and repeatability. Internal recycling of key raw materials, particularly ethanol, further enhances process efficiency and economic performance. Table I describes the purpose and design considerations for each process step.

Process step	**Purpose and design considerations**
1. Feedstock preparation (batch)	The process begins with the preparation of two distinct feed streams: an organic phase comprising ethanol and TEOS, and an aqueous phase comprising water and ammonia. This separation enhances control over mixing conditions and supports a reproducible, well-defined reaction process. Feed preparation is carried out through controlled dosing of ethanol, TEOS, water, and ammonia, with solvent-recovery streams integrated to improve process efficiency and reduce material consumption.
2. Sol-gel reaction (batch)	Based on the current preliminary process model, the reaction is carried out by combining the organic and aqueous feed streams in a reactor of approximately 700 m^3 volume, with a reaction time of 4–5 hours. Key process parameters, including raw-material quantities, temperature, mixing method, addition rates, and flow regime are tightly controlled to achieve the target particle-size distribution. Under defined pH and mixing conditions, TEOS undergoes controlled hydrolysis and condensation via the Stöber route, yielding amorphous silica particles with a narrow size distribution centered around a tunable submicron diameter. This bottom-up synthesis approach is consistent with the morphology and size-control requirements established in the companion particle design paper [13].
3. Separation and buffering (semi-continuous)	Following the reaction, particles are separated from the solvent-rich phase – principally ethanol – by continuous multi-stage high-speed centrifugation at a representative flow rate of 10–30 L/s. Centrifugal separation is a slower process than the reaction itself; accordingly, the centrifuge array will be coupled with intermediate buffering to stabilize flow between the batch reaction stage and downstream semi-continuous operations, enabling smoother process control and improved continuity.
4. Calcination (semi-continuous)	The resulting semi-dried particles are subsequently transferred to a conveyor oven operating at 1000–1200°C for calcination. During this stage, the particles undergo approximately 15% volumetric shrinkage, yielding a tunable submicron average particle diameter.
5. Surface modification (batch)	The second production stage comprises surface functionalization, in which the particles are coated with a hydrophobic surface layer. This is accomplished by dispersing the particles in water and introducing a trimethylmethoxysilane (TMMS) solution, prepared in ethanol, into the reactor. The functionalization step has a duration of approximately 2–3 hours under mild heating conditions. Treatment with TMMS reduces accessible silanol density and introduces lower-polarity surface terminations, promoting hydrophobic behavior under stratospheric conditions. This step addresses the surface-engineering requirements identified in the companion particle design paper, including suppression of interparticle cohesion, regulation of atmospheric interactions, and enhanced dispersibility.
6. Curing, drying, and packaging (semi-continuous)	Following surface modification, the coated material undergoes liquid–solid separation and drying in a manner analogous to the preceding stage. Final drying is conducted in an oven at 120–200°C for 30–60 minutes, after which the dried particles are stabilized and packaged.

TABLE I: Industrial SEASP production sequence and operating mode.

In Figure 3 an integrated process design for SEASP production is presented. Note that the process diagram is schematic and conceptual and serves for illustrative purpose only. It shows one icon for each equipment type, but the actual plant design may include multiple parallel units. For example, a single centrifuge symbol may represent several centrifuge trains operating in parallel to satisfy the required flow rate and provide operational redundancy.

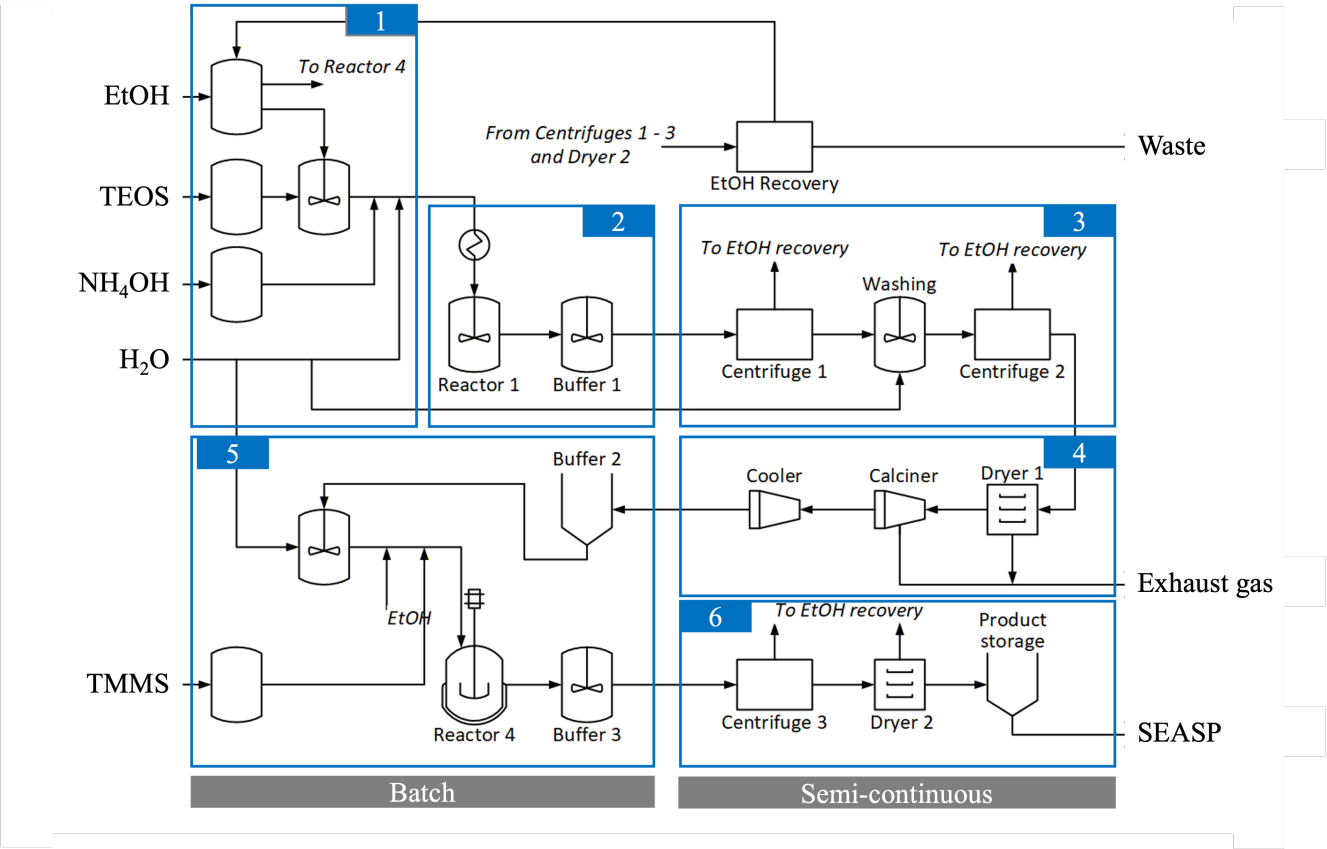

FIG. 3: Schematic overview of the integrated SEASP production process

D. System-level integration of TEOS and SEASP manufacturing processes

SEASP manufacturing could in principle be operated as a standalone process sourcing TEOS from external suppliers, an approach viable at small production scales. For climate-relevant production, however, a system-level integrated design is the recommended approach. In the integrated configuration, TEOS production and SEASP manufacturing are engineered, constructed, and operated jointly as a coordinated industrial system. The plants should be co-located or in close proximity, with shared planning for material flows, and a co-operated system for quality control, safety, operations, utilities, and supply-chain management.

The main advantage of integration is the closed-loop relationship between TEOS and SEASP (see Figure 4). TEOS is supplied directly to the SEASP plant as the silica precursor. During SEASP synthesis, ethanol is released and recovered — both to the SEASP plant itself and to the TEOS plant. This loop reduces external raw-material requirements, lowers transport burdens, improves supply resilience, and strengthens cost control. As production capacity increases, every small improvement in ethanol recovery has a large effect on total cost and feedstock demand.

The preliminary process model uses an approximate TEOS-to-SEASP mass ratio of 5:1. For manufacturing of 250 kt/yr SEASP, this implies consumption of roughly 1.25 Mt/yr of TEOS capacity. At 10 Mt/yr SEASP, the implied TEOS consumption requirement would be approximately 50 Mt/yr. This consumption requirement is far larger than the present specialty TEOS market and therefore shifts TEOS from a purchased reagent to an upstream industrial subsystem that should be scaled up together with SEASP production.

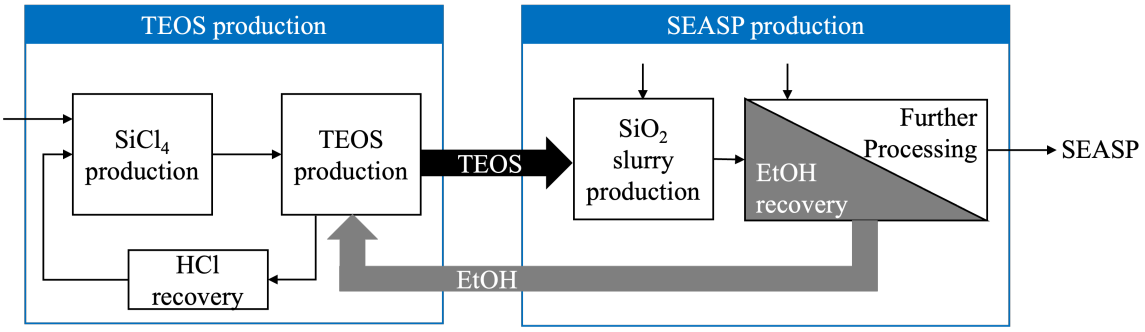

FIG. 4: Conceptual drawing of integrated TEOS and SEASP manufacturing with TEOS and Ethanol loop.

E. TEOS manufacturing route and upstream integration

First, it should be noted that in the chemical industry TEOS is used for a variety of use-cases. While semiconductor-grade TEOS requires extremely high purity, often 99.999% or above [14], preliminary analysis suggests that SEASP production requires TEOS with approximately 95% purity. Therefore, for SEASP production, a lower and cheaper purity specification of TEOS may be sufficient, compared to semiconductor-grade TEOS. However, the specification should be subject to impurity-control requirements established by product testing and safety assessment.

TEOS can be produced directly from silicon and ethanol or through chlorosilane chemistry. The current candidate route uses Silicon tetrachloride ($SiCl_4$), ethanol, and triethylamine (TEA) as an acid scavenger/catalytic base under dry, inert conditions. The simplified reaction is:

$$SiCl_4 + 4\,C_2H_5OH \longrightarrow Si(OC_2H_5)_4 + 4\,HCl$$

Stoichiometrically, four moles of ethanol are required per mole of TEOS. Without recycling, the ethanol consumption will be exceedingly high. In the integrated plant, ethanol recovered from SEASP synthesis is returned both to the SEASP plant and to the TEOS production plant. If an overall ethanol recovery rate of approximately 90% is achieved, annual fresh ethanol consumption is reduced substantially relative to gross process throughput. At large scale, further improvements in solvent recovery become a major economic lever.

Potential routes for manufacturing $SiCl_4$ include direct reaction of silicon with chlorine, reaction of silicon with HCl, and a ferrosilicon route in which ferrosilicon reacts with chlorine. The ferrosilicon route is currently preferred in the model because it can use a broader quartz feedstock base and may provide favorable processing characteristics at scale. This preference is driven mainly by feedstock flexibility and potential cost advantage: metallurgical-silicon routes generally require higher-purity quartz, whereas the ferrosilicon route can use a broader quartz-quality range at potential lower cost. Quartz feedstock must also satisfy physical requirements for furnace operation, including suitable particle size, mechanical stability, and thermal-shock resistance.

The simplified upstream reactions are:

$$SiO_2 + 2\,C + Fe \longrightarrow FeSi + 2\,CO$$
$$FeSi + 3.5\,Cl_2 \longrightarrow SiCl_4 + FeCl_3$$

This upstream chemistry is energy-intensive and generates carbon monoxide or carbon dioxide from carbothermal reduction. Access to low-cost, low-carbon electricity and heat is therefore important for both economics and lifecycle emissions. The TEOS process design is illustrated in Figure 5, comprising two primary stages: $SiCl_4$ production via carbothermal reduction and chlorination of ferrosilicon, followed by TEOS synthesis and purification. A third stage, HCl conversion to chlorine, is omitted from the figure as it relies on established commercial processes. Key equipment includes an electric arc furnace and a fluidized bed reactor in the first stage, and a TEOS reactor with distillation columns for Ethanol separation in the second. The design is supported by process modeling encompassing reaction yields, separation performance, distillation requirements, solvent recovery, chlorine recycling, and energy demand. The conceptual scheme shows one unit per equipment type; the actual model might include multiple units.

The proposed route also requires chlorine-loop management. Hydrogen chloride generated during TEOS production can be converted back to chlorine for $SiCl_4$ production, reducing net chlorine demand and closing the material loop. Chlorine handling at this scale is an established industrial capability, but it requires careful site selection, safety engineering, environmental permitting, and integration with chlor-alkali infrastructure. At scales above the first integrated-plant level, onsite or closely integrated base-chemical production, including chlorine-loop management, may become increasingly important.

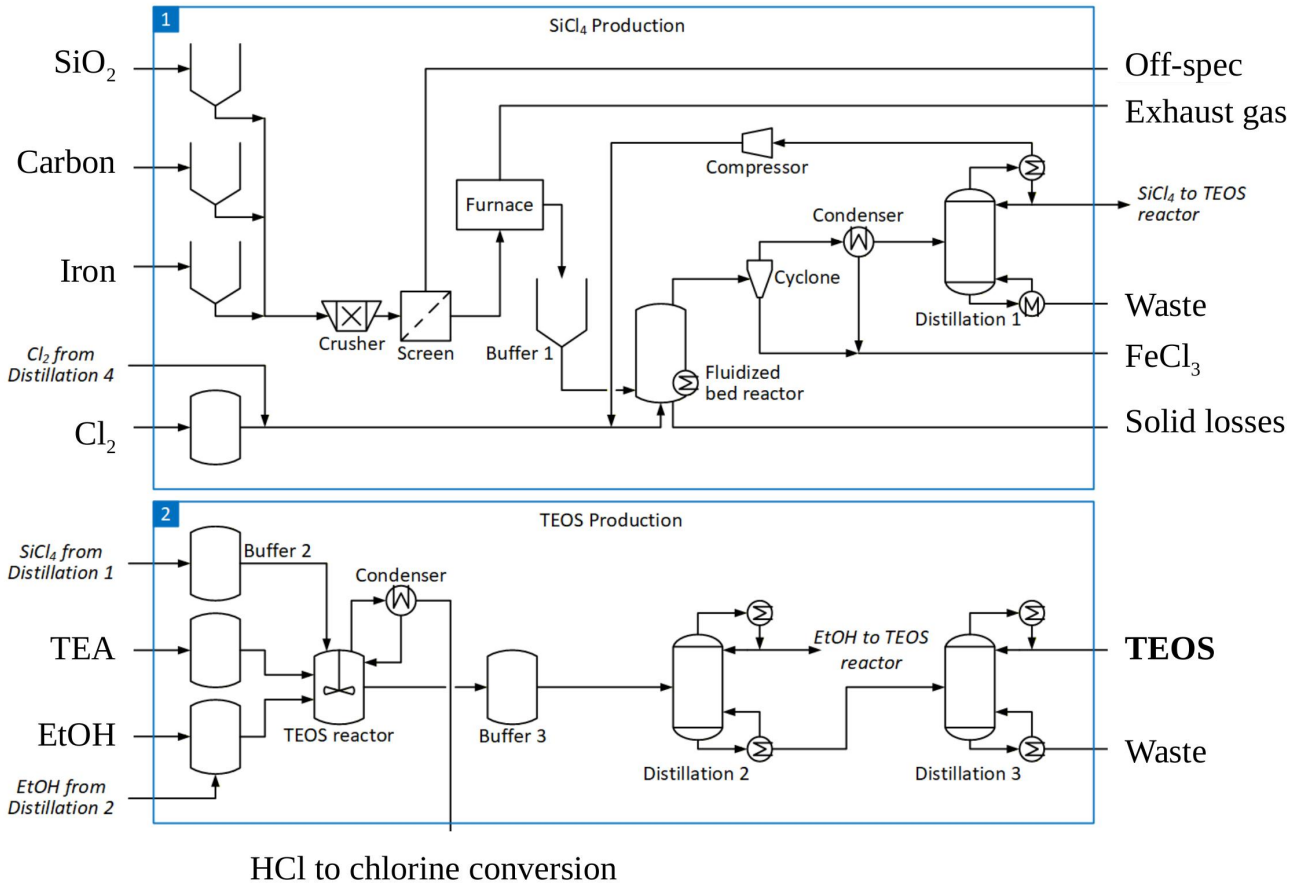

FIG. 5: Process design of TEOS manufacturing

III. SCALE-UP STRATEGY AND CAPACITY EXPANSION OUTLOOK

Figure 6 presents an overview of the scale-up trajectory to 250 kt/yr SEASP within five years and the longer-term outlook to 10 Mt/yr. The near-term plan is grounded in bottom-up engineering of an integrated SEASP–TEOS system with a 250 kt/yr SEASP capacity. The strategy is to design, validate, and scale the process, encompassing all required equipment and infrastructure, to a 50 kt/yr SEASP module that serves as both the foundation for scale-up and the first routine production line. Five such modules, operated as parallel production lines, are then combined to form a single integrated 250 kt/yr SEASP plant. The longer-term outlook to 1 Mt/yr and subsequently 10 Mt/yr follows a modular replication strategy, presented as a top-down scenario in which standardized 250 kt/yr integrated plants are replicated across multiple sites to ultimately achieve 10 Mt/yr SEASP capacity.

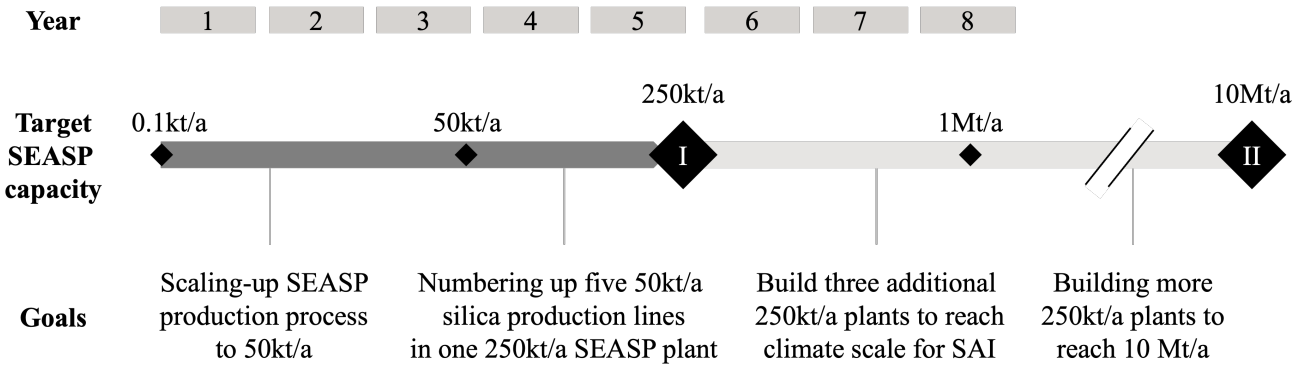

FIG. 6: Scale-up pathway from approximately 0.1 kt/yr to 250 kt/yr, followed by a capacity-expansion outlook to 1 Mt/yr and 10 Mt/yr.

A. Bottom-up scale-up to 250 kt/yr

The starting point of the bottom-up scale-up plan is the current small-volume industrial SEASP capability of approximately 0.1 kt/yr. The first industrial milestone is a 50 kt/yr SEASP manufacturing module, targeted for deployment within approximately three years. This module serves as the foundational building block for capacity scaling through modular replication. Its primary engineering challenge lies in scaling process equipment to a level sufficient to resolve key uncertainties in mass and energy balances, reactor hydrodynamics, particle agglomeration, separation efficiency, calcination behavior, drying and packaging, product-quality control, by-product and waste management, and process repeatability. Specifically, the module is designed to close mass and energy balances, define process-control windows, confirm product-quality reproducibility, and establish equipment performance envelopes to guide subsequent replication stages.

The 50 kt/yr module also provides the basis for detailed equipment specifications, process-control envelopes, procurement planning, safety analysis, and commissioning protocols. The second milestone is a 250 kt/yr integrated plant constructed by modular replication of five parallel 50 kt/yr modules at one site. In this architecture, the first module provides the reference design, while subsequent modules benefit from the engineering learning curve and shared infrastructure. Where possible, shared infrastructure such as solvent recovery, utilities, quality-control laboratories, storage, and parts of the TEOS integration system should be designed from the beginning to support both the 50 kt/yr module and the later 250 kt/yr plant. Because the modeled TEOS-to-SEASP mass ratio is approximately 5:1, even the first 50 kt/yr SEASP module requires integration with approximately 250 kt/yr TEOS supply or equivalent precursor capacity.

A three-year timeline to establish a 50 kt/yr SEASP module and a five-year timeline to reach a 250 kt/yr integrated SEASP–TEOS plant are ambitious targets. The estimate for the SEASP manufacturing scope is supported by analogy to historical capacity expansions in the precipitated-silica industry. Although Stöber-type SEASP production and conventional precipitated-silica production employ distinct chemistries, the comparison provides a useful basis for assessing scale-up challenges, construction timelines, and approximate capital requirements for several post-reaction unit operations.

Precipitated silica is currently produced at a global capacity exceeding 2 Mt/yr, with reported prices ranging from approximately USD 800–2,700/t depending on grade, application, and market conditions [23]. It is widely used in applications where broad particle-size distribution, mesoporosity, aggregation, irregular morphology, and lower purity are acceptable. Typical plant capacities fall in the range of approximately 20–100 kt/yr. Industrial precipitated silica is generally produced from sodium silicate, commonly referred to as water glass, using sulfuric acid in an aqueous medium, with semi-batch operation as the dominant production mode. Temperature, pH, and reactant-addition control are the key process parameters governing particle formation. Post-reaction operations include filtration, washing, drying, milling of agglomerated material, dust control, wastewater treatment, and optional post-treatment. Raw materials are low-cost and the required equipment is standard industrial specification.

The analogy to SEASP production is therefore not predicated on identical particle chemistry, but on meaningful overlap in several downstream and solids-handling operations. Following particle growth, both processes require liquid–solid separation, washing or solvent removal, drying, dust containment, storage, packaging, and optional post-treatment. Precipitated-silica plant expansions accordingly provide a partial benchmark for the scale-up of SEASP post-reaction processing, while recognizing that SEASP demands tighter control of particle size, morphology, purity, surface chemistry, solvent recovery, and integrated TEOS supply.

Recent precipitated-silica expansion records indicate that capacity additions in the tens of kt/yr range can be executed on construction timelines of approximately one to two years. Evonik reported approximately 1.5 years from construction commencement to start of operations for a 40 kt/yr capacity expansion in Turkey in 2019, and a nine-month expansion project in Thailand in 2014, both involving lower-double-digit-million investment levels [24, 25]. Evonik has also announced a mid-double-digit-million-euro investment to expand its Charleston, South Carolina facility by 50%, with construction planned over approximately two years [26]. Tata Chemicals announced an expansion from 14 to 50 kt/yr over approximately 27 months, at an investment of ₹7.75 billion, equivalent to roughly USD 85 million [27]. Quechen Silicon is reported to be constructing two 50 kt/yr plants over approximately two years at a combined cost of approximately USD 100 million [28]. Across these examples, capacity additions of approximately 40–50 kt/yr are associated with capital intensities on the order of USD 0.5–1.5 million per kt/yr of installed annual capacity.

These precedents do not eliminate the specific risks associated with SEASP scale-up. SEASP production requires tighter particle control than conventional precipitated silica, employs a TEOS-based Stöber route rather than sodium-silicate precipitation, and must integrate solvent recovery, surface modification, high-purity product handling, and upstream TEOS supply. Nevertheless, the comparison indicates that the required SEASP plant sizes fall within the range of conventional chemical-industry project execution, provided that process development, engineering design, supplier engagement, procurement, and construction activities are advanced in parallel.

Strategic partnering is central to this plan. Relevant partners include companies with experience in silica production, TEOS or chlorosilane chemistry, chlor-alkali operations, high-volume solvent recovery, large-scale chemical construction, and process safety. Brownfield integration or co-location with existing chlor-alkali, chlorosilane, silicon-materials, or silica-production assets could reduce capital intensity, shorten timelines, and lower execution risk relative to fully greenfield deployment. Partnering can reduce execution risk dramatically by leveraging existing industrial platforms, experienced engineering teams, established supplier relationships, brownfield integration opportunities, and regional utility and logistics infrastructure. Experienced partners may also choose a different expansion strategy or technological routes, which may prove faster and introduce lower uncertainties and risks. The goal of this feasibility study is to establish preliminary estimates for timeline

and cost, to identify potential major bottlenecks and risks, and to offer potential mitigation strategies for these risks.

During scale-up, produced material may be accumulated for future testing or deployment-related research. This requires controlled storage, packaging, inventory rotation, batch traceability, humidity and temperature control, contamination prevention, and documented quality assurance. Product storage should be treated as part of the industrial process rather than as a downstream afterthought.

B. Outlook to 1 Mt/yr and 10 Mt/yr

At the Mt/yr scale, the dominant challenge shifts from individual equipment feasibility to system coordination, logistics, and operational integration. At this scale, capacity growth requires the synchronized expansion of TEOS production, chlor-alkali infrastructure, quartz and carbon supply chains, solvent recovery systems, energy supply, by-product handling, logistics networks, regulatory approvals, quality assurance frameworks, and deployment interfaces across multiple plants. Site selection should consider energy cost and carbon intensity, access to feedstocks, existing chemical infrastructure, transport routes, workforce availability, safety regulations, and proximity to any future deployment system. At this scale, standardized quality-assurance protocols, process-control systems, maintenance strategies, and regulatory compliance frameworks would be required to ensure uniform product performance across geographically distributed production hubs. Regulatory requirements for the processes, products, and related activities will be addressed in each location according to the applicable demands of the local authorities.

Several industrial precedents inform the scale-up analysis and provide the basis for the top-down time estimation presented below.

- The chlor-alkali industry [29, 30] represents one of the largest electrochemical manufacturing sectors globally, with individual plants reaching capacities of 500–800 kt/yr of chlorine. Capacity expansion in this industry has historically relied on modular replication of electrolyzer units, integration with downstream chlorine consumers, and co-location with energy infrastructure. Its relevance to the present system lies in the management and recycling of hydrochloric acid and chlorine-containing streams within TEOS production, as well as the requirement for coordinated upstream and downstream capacity expansion. This confirms that the key electrochemical infrastructure required for TEOS production is commercially available at the scales considered here.

- The polyethylene industry [31, 32] has expanded through the deployment of world-scale plants, typically 300–600 kt/yr per unit, enabled by standardized reactor designs and systematic replication across multiple sites. The principal lesson is that large-scale capacity growth is generally achieved not by scaling individual units beyond proven engineering limits, but by replicating standardized modules and leveraging accumulated learning curves across design, procurement, construction, and operations. This establishes that the 50 kt/yr module scale targeted here is well within the range of proven, replicable industrial units.

- Polysilicon and solar materials [33, 34]: The rapid expansion of polysilicon production for the photovoltaic industry, from approximately 8,000 tonnes/yr of solar-grade silicon in 2005 to approximately 1.6 million tonnes/yr by 2023, demonstrates the capacity to scale silicon-based chemical manufacturing under sustained demand growth. This expansion required substantial capital investment and supply-chain development, including chlorosilane-related infrastructure, as well as continued process optimization, yet it did not depend on fundamentally new chemistry.

IV. FEASIBILITY ASSESSMENT FOR A 250 KT/YR INTEGRATED PLANT

This section evaluates the feasibility of a 250 kt/yr SEASP manufacturing plant integrated with approximately 1.25 Mt/yr TEOS production. The assessment focuses on the feasibility of 250 kt/yr production, based on the scale-up of a 50 kt/yr production line. Four categories are considered: engineering and equipment, infrastructure and construction, plant operations, and supply chain and raw-material availability.

In table II the summary of the feasibility assessment for the 250 kt/yr integrated plant is presented. The assessment of each category is composed of two distinct scores: “critical” vs. “uncritical” and “high certainty” vs. “low certainty”. A “critical” score implies that unresolved problems could endanger the feasibility of the scale-up pathway. A score of “low uncertainty” implies that the current model is feasible but requires validation during engineering, supplier engagement, site selection, or the first 50 kt/yr module. Confidence across all assessment categories is expected to increase through realization and operation of the integrated 50 kt/yr SEASP plant, which serves as an intermediate validation milestone before scale-up to the 250 kt/yr SEASP plant.

Category	Rating	Rationale
Engineering and equipment	Uncritical, low uncertainty	• Use of standard industrial equipment and well-established process steps. • Chemical handling at the required scale relies on existing industrial know-how. • Numbering-up strategy applied from the 50 kt/yr module onward. • **No novel engineering development is required; all unit operations are available off the shelf, resulting in low technical uncertainty.**
Infrastructure and construction	Uncritical, moderate uncertainty	• Existing precipitated-silica plants with capacities of up to 100 kt/yr, and documented 50 kt/yr capacity expansions completed within approximately two years. • Existing industrial examples of infrastructure development and material-flow handling at relevant production scales. • **Uncertainty is moderate rather than low because site-specific civil engineering, utility integration, and permitting timelines introduce variability that cannot be fully resolved at this stage.**
Plant operation	Uncritical, low uncertainty	• Operation of equipment within commercially proven performance ranges. • Use of state-of-the-art recycling technologies for ethanol and HCl/chlorine streams. • Regulatory requirements, energy availability, and workforce availability depend on regional site selection. • **Low uncertainty reflects the availability of operational analogues at comparable scales in the precipitated-silica and specialty-chemicals industries.**
Supply chain and raw materials availability	Uncritical at 250 kt/yr, moderate certainty	• Most raw materials are commodity products with large production volumes, and the estimated material requirements are expected to be readily met. • Uncertainty remains for specialty chemicals such as TEA and TMMS, for which market data are currently limited; however, demand is expected to be addressable through existing suppliers or supplier capacity expansion. • **The rating reflects confidence in commodity feedstock availability, tempered by limited market visibility for specialty chemicals at the required volumes.**

TABLE II: Summary of the feasibility assessment for a 250 kt/yr integrated SEASP–TEOS plant.

A. Engineering and equipment

The engineering effort involved is significant, but it is conventional. Detailed design should specify reactor volumes, mixing regimes, residence times, dosing rates, mass-transfer limits, heat-transfer loads, separation rates, drying capacity, calcination throughput, dust containment, explosion and fire safety, and quality-control sampling. Some specialized components, such as high-capacity centrifuges and precision-controlled calcination units, may have lead times exceeding 10–12 months. Early supplier engagement is therefore a critical execution requirement. Operation remains well within the commercially available performance ranges of standard equipment. Key unit operations, including mixed reactors, centrifugal separation, and thermal-processing units, are maintained within established industrial operating envelopes, avoiding reliance on novel or unproven equipment configurations. The chemical industry already has established experience handling TEOS, chlorine, and ethanol at the relevant production volumes. It is therefore reasonable to assume that the required particle properties can be achieved at the presented industrial production scale, provided that appropriate process-control and quality-assurance measures are implemented.

The process model indicates that the 50 kt/yr SEASP module can be implemented using known chemical reactions, conventional industrial equipment, and established unit operations. Required equipment includes mixed reactors, dosing systems, solvent-recovery units, continuous or semi-continuous centrifuges, calcination ovens, dryers, distillation units, storage systems, packaging systems, and process-control infrastructure.

Modular replication from 50 kt/yr to 250 kt/yr reduces scale-up risk because additional production lines are expected to mirror the validated module and implement lessons learned in its design. System engineering remains important because ethanol recovery, TEOS supply, utilities, and storage must be optimized across the full site rather than within isolated production lines.

B. Infrastructure and construction

Precipitated-silica plants and particularly their capacity expansions provide useful benchmarks for infrastructure and construction planning, in spite of some important differences that are mentioned below. Existing precipitated-silica plants reach capacities of approximately 100 kt/yr, and several reports have been published about capacity expansion in the 40–50 kt/yr range with construction periods around one to two years [24–28]. SEASP differs from precipitated silica because it requires tighter product control and a TEOS-based precursor system, but many downstream process steps–washing, separation, drying, dust handling, post-treatment, storage, and packaging–are common to both production processes. The initial 50 kt/yr SEASP capacity is consistent with the size of current precipitated-silica plants. Expanding this to 250 kt/yr through four additional modules of equal size is likewise well within demonstrated industrial capacity expansions.

In the proposed project planning much of the shared infrastructure will be constructed during the 50 kt/yr stage, enabling faster expansion to 250 kt/yr. Shared infrastructure may include solvent recovery, utilities, storage, quality-control laboratories, safety systems, packaging, waste treatment, and parts of the TEOS integration. This approach reduces schedule risk by commissioning critical systems early and identifying operational constraints well before the full 250 kt/yr capacity is installed. Experience gained during construction of the first 50 kt/yr plant is expected to accelerate delivery of subsequent units, reducing both capital cost and construction schedule.

The demanding part of the integrated plant is the installation of the TEOS infrastructure. A 1.25 Mt/yr TEOS facility is large relative to current specialty TEOS manufacturing plants and requires careful integration of chlorosilane chemistry, dry processing, distillation, chlorine management, HCl conversion, energy supply, and by-product handling. Partnering with existing TEOS, chlorosilane, chlor-alkali, or silicon-materials producers will therefore be essential in this process.

C. Plant operation

Plant operation is assessed as technically feasible at 250 kt/yr, assuming appropriate engineering validation and commissioning. Routine operation relies on continuous process monitoring of temperature, pressure, pH, flow rates, solvent composition, particle-size distribution, product moisture, calcination conditions, and surface-treatment performance. The plant also includes standard operating procedures for startup, shutdown, changeover, maintenance, deviation handling, and product release.

The most important operational controls are those that preserve product quality at high throughput. These include stable feedstock composition, precise dosing, controlled nucleation and growth conditions, reliable separation, efficient solvent recovery, repeatable thermal treatment, and consistent surface functionalization. Some equipment, such as continuous centrifuges, may operate near high-throughput limits and will be validated closely with equipment suppliers.

Safety, environmental compliance, and waste management should also be incorporated into the operating model. TEOS, ethanol, ammonia, chlorine, hydrogen chloride, and silane reagents all require appropriate handling procedures. Preventive maintenance, operator training, process-safety management, emergency response, environmental monitoring, and regulatory documentation are mandatory, and are integral components in the feasibility basis.

D. Supply chain and raw-material availability

The raw-material availability assessment is based on the quantities required for manufacturing of 250 kt/yr SEASP and approximately 1.25 Mt/yr TEOS. At this scale, most inputs appear to be available as commodity materials. The main uncertainties are with respect to specialty chemicals and the upstream feedstocks for TEOS expansion. Table III summarizes the preliminary assessment.

Process	Raw material	Quantity (kt/yr)	Type	Global capacity estimated share	Preliminary rating
SEASP	NH_4OH	215	Commodity	< 1%	Certain / Uncritical
SEASP	TEA	40	Specialty	~ 20%	Uncertain / Uncritical
SEASP	TMMS	TBD	Specialty	n.a.	Uncertain / Uncritical
Both	Ethanol	250	Commodity	< 1%	Certain / Uncritical
TEOS	Quartz (SiO_2)	940	Commodity	< 1%	Certain / Uncritical
TEOS	Carbon (coal)	380	Commodity	< 1%	Certain / Uncritical
TEOS	Iron	140	Commodity	< 1%	Certain / Uncritical
TEOS	Chlorine	430	Commodity	< 1%	Certain / Uncritical

TABLE III: Preliminary raw-material availability assessment for a 250 kt/yr integrated SEASP plant.

Ethanol, ammonium hydroxide, carbon, iron, and chlorine are assessed as uncritical at the 250 kt/yr SEASP manufacturing scale because the required quantities are small relative to global commodity flows. TEA and TMMS, on the other hand, are specialty chemicals. TEA, triethylamine, is produced from common upstream inputs. Therefore, its supply is not expected to be a fundamental raw-material availability constraint, but supplier capacity must be confirmed. TMMS is a specialty surface-treatment reagent, and available market data are currently limited; however, the required quantities are expected to be small relative to the main precursor and solvent streams, so TMMS is not anticipated to represent a fundamental scale-up bottleneck. All material quantities listed in the table represent global production volumes. The exact quantity varies according to the material purity required for each process. Its availability and pricing will nevertheless be verified directly with suppliers during the next engineering stage.

Extending beyond the 250 kt/yr manufacturing capacity toward the Mt/yr scale requires a dedicated raw-material and logistics assessment, including the quality and regional availability of high-purity quartz feedstock, carbon source, iron, chlorine, and energy. At the 10 Mt/yr scale, raw-material logistics may require regional supply-chain planning and, in some locations, co-location with or development of base-chemical production for inputs such as ammonia or ammonium hydroxide, ethanol, chlorine, and upstream silicon materials. Future market response, supplier expansion, and possible process changes may substantially alter these constraints.

The available data and precipitated-silica industry experience at comparable scale support the assessment that a single-module SEASP manufacturing capacity of 250 kt/yr is achievable within approximately five years. No critical show-stoppers were identified in this process.

V. PRODUCT COST MODEL

The preliminary cost model serves to establish the economic feasibility assessment for SEASP manufacturing at 250 kt/yr. The model combines process-level mass and energy balances, equipment sizing, operating-cost assumptions, capital-recovery assumptions, and internal TEOS production. It is not a final front-end engineering design cost estimate; rather, it is a structured model for identifying cost drivers, sensitivities, and scale-up priorities.

Because there is no direct commercial benchmark for SEASP used for SAI deployment, the model uses a provisional feasibility threshold: production costs materially above ~$10/kg are assumed to be challenging for large-scale application, while costs materially below that threshold are considered potentially feasible and a basis for further elaboration. This feasibility threshold was determined based on assumptions regarding the future total cost of deployment. Clearly, there is some level of arbitrariness in setting it at this early stage. Future work may refine this threshold as well.

A. Model inputs and assumptions

The model is employed for a plant manufacturing 250 kt/yr SEASP with an integrated TEOS capacity of approximately 1.25 Mt/yr. Levelized manufacturing cost is calculated as the sum of operating costs and capital recovery over a 10-year recovery period. Operating costs are derived from modeled material consumption and prices, utilities, labor, and process flows. Raw-material prices reflect the working assumptions used in the draft model and should be updated as supplier quotations become available. Here, we refer to Q1 2026 prices and list them as important reference values for evaluating the current cost results.

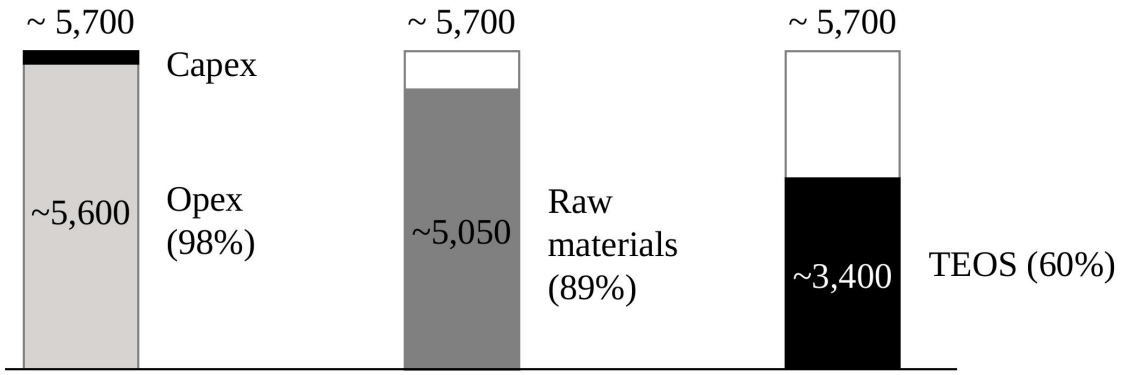

FIG. 7: Levelized SEASP manufacturing cost at 250 kt/yr scale under the preliminary model assumptions.

Plant/process parameter	Value	Material/utility	Value	Capital parameter	Value
SEASP plant capacity	250 kt/yr	Ethanol	USD 700/t	Capex recovery period	10 years
Silica reactor volume	710 m^3	NH_4OH	USD 200/t	Discount factor	10%
Ethanol recovery fraction	90 wt%	Chlorine	USD 146/t	Capex: 250 kt/yr SEASP plant	USD 163 million
TEOS plant capacity	1,250 kt/yr	Electricity	USD 0.09/kWh	Capex: 1,250 kt/yr TEOS plant	USD 730 million
TEOS reactor volume	960 m^3	Natural gas	USD 7.9/MMBtu		
HCl conversion yield	85%	Labor			

TABLE IV: Selected cost-model inputs and assumptions.

The levelized cost breakdown at 250 kt/yr is summarized in Figure 7. Under the current assumptions:

- The estimated levelized SEASP manufacturing cost is approximately USD 5–5.7/kg.
- Operational expenditures dominate the cost structure, with capital recovery representing a small share under the model assumptions.
- Assuming a 10-year lifetime, 98% of total costs are operational expenditures, while 2% are capital expenditures.
- Raw materials account for approximately 89% of total production cost.
- TEOS is the largest individual cost component, representing approximately 60% of total SEASP cost.
- Ethanol recovery is a major cost lever because fresh ethanol demand decreases sharply as recovery improves. Increasing the recovery rate significantly reduces product costs.
- TEOS production costs, assuming ethanol recovery from SEASP production, are estimated at less than USD 1,000/t. This is below current market prices and can be explained by ethanol-recovery synergies, lower TEOS purity requirements, and improved process efficiency due to economies of scale.

Additional cost model parameters are provided in Table IV.

B. Detailed cost results

Under the model assumptions, raw materials dominate the cost structure; see Figure 8. TEOS cost alone accounts for about 60% of the total cost at approximately USD 3.4/kg. Other raw materials account for approximately 29%, utilities for approximately 6%, labor for approximately 1%, other costs for approximately 2%, and capex recovery for approximately 2%.

The integrated plant design enables internal TEOS production at a transfer cost of approximately 730 USD/t, significantly below current Q1 2026 market spot prices of $900–1,700 per metric ton [14]. This advantage is driven primarily by process integration, economies of scale, ethanol-recovery synergies, and the elimination of external supplier margins.

With respect to the TEOS production cost structure, raw materials account for roughly 62% of total cost, with ethanol and chlorine as the major inputs. Sale of by-products, including ferric chloride, reduces the modeled TEOS cost by approximately 6%. The detailed TEOS cost breakdown is shown in Figure 9.

The low apparent contribution of capital recovery should be treated carefully. The contribution of capital recovery to the overall levelized cost remains relatively limited, accounting for approximately 2% for SEASP production and 13% for TEOS

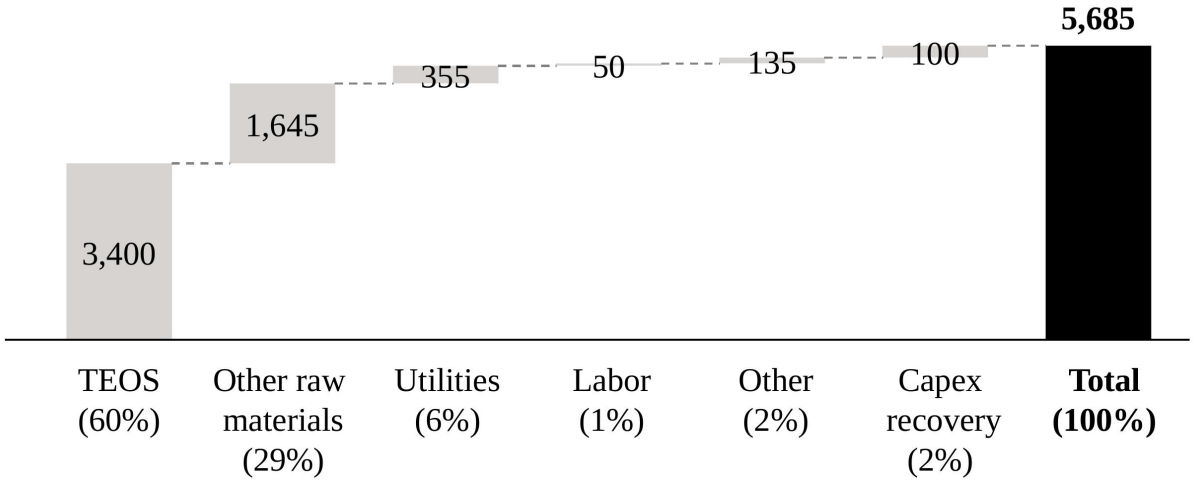

FIG. 8: Detailed breakdown of levelized SEASP manufacturing costs under the preliminary model assumptions.

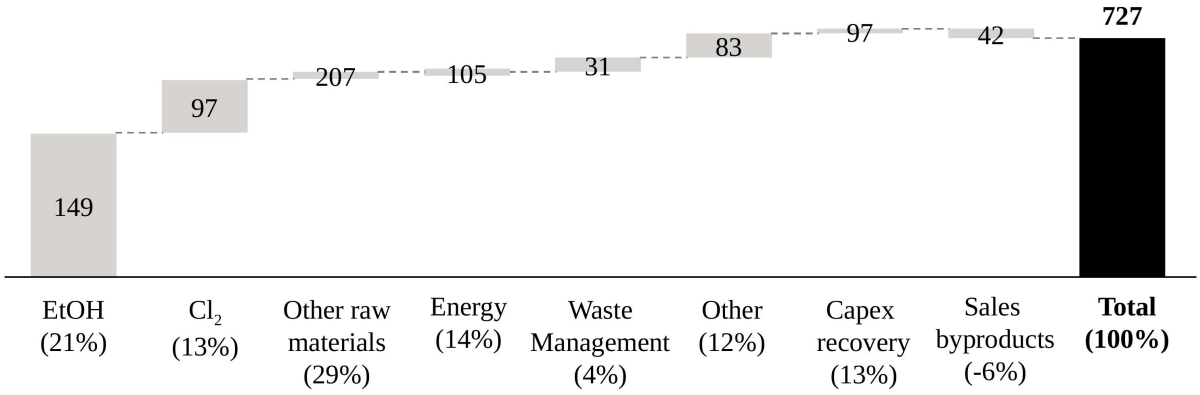

FIG. 9: Detailed breakdown of levelized TEOS manufacturing costs under the preliminary model assumptions.

production. It reflects the large modeled contribution of raw-material costs and the specific capital and recovery assumptions used here. As engineering design matures, capex, contingency, financing cost, construction schedule, utilization rate, and maintenance assumptions should be updated and sensitivity-tested.

C. Cost-reduction opportunities

Optimizing unit economics is critical for minimizing both production cost and scale-up investment. Engineering analysis identifies several avenues for improving process efficiency and reducing overall operating costs. These opportunities are organized across the two main production plants, SEASP and TEOS, reflecting the structure of the integrated manufacturing system.

For SEASP production, the primary cost-reduction opportunities target ethanol-related costs through increased ethanol recycling efficiency and reduced solvent consumption. For many of these avenues, the potential cost reduction can be estimated quantitatively. Some improvements are partially interdependent, and their combined effect depends on implementation sequence and system-level integration. Taken together, however, these pathways indicate that production costs can be systematically and substantially reduced. The identified improvement avenues indicate a combined cost-reduction potential of up to approximately 40%, based on the techno-economic model. A structured implementation plan will evaluate each opportunity according to its expected impact and implementation complexity, enabling prioritization and phased deployment across the integrated production system.

The following cost-reduction avenues for the SEASP production process have been identified:

a. Basic improvement of ethanol recycling efficiency. Increasing ethanol recycling yield from 90% to 95% is estimated to reduce product cost by approximately 12%. This reduction is primarily driven by greater internal reuse of ethanol, which decreases demand for fresh solvent input. Given that ethanol represents a major cost component, even moderate gains in recycling efficiency have an outsized impact on overall cost.

b. Further improvement of ethanol recycling efficiency. A further increase in ethanol recovery from 95% to 98% could be achieved through specialized separation equipment adapted to process-specific conditions. This would further reduce ethanol losses and external supply requirements, yielding an additional estimated cost reduction of approximately 5%, and underscores the sensitivity of product cost to solvent recovery performance.

c. Optimization of raw-material ratios in the reaction. Ethanol functions primarily as a solvent and does not directly participate in the chemical reaction. Reducing its relative proportion in the reaction mixture therefore represents a meaningful cost-reduction opportunity. This can be achieved through advanced mixing technologies that maintain adequate reagent interaction at lower solvent concentrations. Preserving chemical yield under these conditions is essential, and appropriate mixing equipment enables this balance. The expected impact of this optimization is an approximately 10% reduction in product cost.

d. Reduction of separation time. The separation stage is a time-intensive step in the production process. Optimizing the separation process parameters reduces process duration and increases daily throughput, effectively improving plant productivity without requiring a proportional increase in installed equipment. This improvement translates into an estimated cost reduction of approximately 5%, driven by enhanced utilization of existing assets.

e. Transition to continuous processing. Transitioning the manufacturing plant from batch to continuous operation, including the reaction stage, represents one of the most significant opportunities for cost reduction. Continuous operation reduces downtime associated with batch cycling, improves equipment utilization, and enables more stable and controlled process conditions. Eliminating repeated start-up and shutdown cycles further reduces material losses and improves process consistency. Although precise quantification is complex due to interactions across multiple process stages, this transition is expected to be among the most impactful cost-reduction levers available.

Additional cost-reduction opportunities have been identified within the TEOS production plant:

f. Improvement of TEOS reaction yield and throughput. The baseline TEOS reaction yield of approximately 70% is relatively low compared with many established chemical processes, and is likely attributable to several process limitations. One contributing factor is inefficient gas–liquid mixing between silicon tetrachloride and ethanol. Improving mixing conditions through optimized reactor design and flow regimes could increase yield to approximately 85%, reducing raw-material losses and improving conversion efficiency, with an estimated cost reduction of approximately 12%.

A second improvement pathway relates to reaction time. Identifying operating parameters that accelerate conversion within the reactor could reduce TEOS reaction time from 4 hours to 3 hours, or potentially to 2.5 hours, thereby increasing overall plant throughput. As this reaction represents a critical process bottleneck, reducing its duration has a direct impact on total production capacity. Other process stages can be scaled independently if required, making reaction-time reduction a key lever for improving overall system efficiency.

A third improvement pathway involves optimizing the molar ratio of reactants. Enhanced process control, particularly with respect to feed rates, dosing precision, and reaction conditions, can enable operation closer to optimal stoichiometric conditions, allowing an estimated reduction of approximately 10% in ethanol consumption without compromising yield or product quality.

g. Optimization of TEOS/ethanol separation. The product stream exiting the TEOS reactor contains both TEOS and ethanol due to incomplete conversion. Efficient separation is achievable through distillation, given the substantial difference in boiling points between ethanol, approximately 78C, and TEOS, approximately 168C. Optimizing the distillation process is expected to improve separation efficiency, reduce energy consumption, and minimize material losses, resulting in an estimated cost reduction of approximately 6%.

h. Chlorine conversion optimization. Chlorine conversion optimization is also targeted; however, no specific cost-reduction estimate is provided at this stage, as this component is expected to be sourced as a commercial turnkey solution.

VI. ALTERNATIVE PRODUCTION PATHWAYS

The baseline route that was chosen in this article is TEOS-based Stöber-type synthesis. It was selected because prior work demonstrated its capability to yield particles with the required size-control, density, morphology and surface chemistry properties [1, 13]. However, additional potential technological routes should be explored. The scale and cost structure identified in this study justify continued evaluation of alternative precursors, modified wet-precipitation routes, and process-intensification strategies.

Near-term alternatives include changes within the TEOS route, such as using HCl instead of chlorine in $SiCl_4$ production, modifying chlorosilane integration, improving solvent recovery, or optimizing the TEOS reaction and distillation sequence. Another set of alternatives involve precursor substitution, to raw materials such as tetramethyl orthosilicate (TMOS) or other silicon sources. This set of alternatives will require extensive validation that the resulting particles meet the same specifications for size, morphology, surface chemistry, purity, reactivity, optical performance, storage stability, and dispersibility.

Any alternative route should be assessed against the same set of requirements used for the baseline TEOS route: particle performance, chemical safety, environmental profile, scalability, raw-material availability, process controllability, cost, waste streams, energy intensity, and compatibility with monitoring and quality assurance. The baseline TEOS route therefore serves both as an industrialization pathway by itself and as a benchmark against which future route improvements can be evaluated.

In this context, it is worth mentioning that Stardust is currently developing a novel alternative SEASP manufacturing route

based on sodium silicate as the silica precursor instead of TEOS. Sodium silicate is a lower-cost and more widely available industrial feedstock than TEOS, with costs potentially below USD 1/kg SEASP depending on grade, purity, and supply configuration. Preliminary synthesis processes yield promising results. If this route can successfully replicate the required SEASP specifications, it could substantially reduce manufacturing costs, lessen or eliminate the need to build dedicated TEOS manufacturing capacity alongside SEASP manufacturing, and significantly lower the process economics closer to those of conventional precipitated silica manufacturing.

VII. ENERGY USE, WASTE STREAMS, BY-PRODUCTS, AND CLIMATE-SCALE RELEVANCE

Energy use and waste-stream management are primary considerations in this scale-up process. Significant energy consumption rates are expected in upstream silicon or ferrosilicon production, chlorosilane production, solvent recovery, distillation, drying, and calcination. In spite of the fact that these processes are conventional in the chemical industry, their cumulative energy demand will be substantial at 1–10 Mt/yr SEASP manufacturing scales. Site selection should therefore prioritize reliable low-carbon electricity, heat integration, access to industrial utilities, and opportunities for co-location with existing chlor-alkali or silicon-materials infrastructure.

The integrated SEASP-TEOS design reduces raw-material consumption by closing the ethanol loop and by recovering chlorine through HCl-to-chlorine conversion. In the TEOS route considered here, ferric chloride is generated as a by-product and may have value in water-treatment markets, although the scale and market absorption of this by-product require further verification before final investment decisions. A full environmental assessment should quantify energy demand, lifecycle CO_2 emissions, solvent losses, waste-water treatment, acid-gas handling, solid residues, and by-product disposition for each candidate site.

A full climate-impact assessment should compare the lifecycle emissions and environmental burdens of SEASP manufacturing, transport, storage, and lofting against the modeled radiative-forcing and climate-risk-reduction benefits of the SAI scenario. It should be noted, however, that the negative radiative forcing that may result from any potential future SAI deployment based on SEASP particles is expected to be orders of magnitude higher in absolute value than the total greenhouse-gas impact associated with the lifecycle of the particles, including manufacturing, storage, transport, and lofting [2].

VIII. CONCLUSIONS

This article presents a feasibility assessment for scaling SEASP manufacturing from current small-volume capacity to climate-relevant and ultimately climate-scale annual manufacturing rates. The assessment treats manufacturability as part of the particle-design set of requirements: size distribution, morphology, surface chemistry, purity, and batch-to-batch consistency should be maintained tightly controlled while scaling by several orders of magnitude is performed.

The main conclusion is that no fundamental technology or process-related barrier has been identified for scaling TEOS-based SEASP manufacturing to 1 Mt/yr capacity and, with modular replication and coordinated upstream precursor supply, also to 10 Mt/yr capacity. It is established that the required unit operations are conventional in the chemical industry. Therefore, the main risks are not related to basic chemistry challenges, but rather to process validation at throughput, TEOS supply, project execution, energy supply, quality assurance, and industrial partnering.

The major scale-up bottleneck is TEOS precursor supply at acceptable cost and rate. A 250 kt/yr SEASP plant will require approximately 1.25 Mt/yr TEOS under the existing mass ratio between SEASP and TEOS. This scale strongly motivates an integrated SEASP-TEOS manufacturing architecture with ethanol recycling, chlorine-loop management, and captive or partnered precursor manufacturing.

The preliminary cost model indicates unit economics of approximately USD 5/kg SEASP, dominated by raw-material costs. Cost reduction should focus on Ethanol recovery, higher TEOS yield, optimized raw-material ratios, improved separation and drying efficiency, transition toward continuous operation, and potential lower-cost precursor routes that preserve particle specifications.

Overall, the findings support the view that SEASP manufacturing at climate-relevant scale is plausible within a conventional industrial framework. The next critical step is to retire scale-up risk through a validated industrial module, including product-quality validation, mass and energy balance closure, operational reliability, environmental assessment, and integrated TEOS supply at the relevant scale.

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