STEER: Scaling to TWh-Energy Endeavors from Research

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EXECUTIVE SUMMARY: STEER will provide quantitative thought-leadership on "What to build" for the energy transition, starting with long-duration energy storage (LDES) and vehicle electrification. STEER will perform systems and technoeconomic analyses to answer key questions that define system architectures, guide research directions, and inform strategic investments. Becoming a central repository for data, know-how, and other inputs from industry and government partners, STEER will publish and communicate regular "STEER Assessments" answering critical questions that chart a roadmap on the necessary technical developments to address climate change with Speed & Scale.

MISSION: STEER will quantitatively predict technoeconomic feasibility of future energy technologies by performing systems analysis and predicting learning curves, enabling direct comparisons between complex technology sets to guide investment decisions on the decadal timescale.

STRUCTURE & APPROACH: STEER will develop an integrated assessment tool that combines multi-level systems architecture analysis with a technoeconomic modeling framework. Critically, we will incorporate a sophisticated understanding of technology learning rates across the value chain. The foundation of STEER are five key technical pillars:

- ***Technology Learning***– Learning and experience rates are responsible for the dramatic cost reductions in energy-related technologies, including solar photovoltaics and Li-ion batteries. Yet, the factors affecting learning rates are not well-understood. We will develop deep expertise in technology learning rates, with the understanding that different components within a given system will learn at different rates. We will conduct extensive industry outreach to obtain valuable insights in addition to performing regression analysis on historical cost trends.
- ***Market Analysis***– Ultimately, the success of any technology is dictated by market growth, with demand driving further deployment, increased technology learnings, and innovative competition. Additionally, the presence or lack of complementary, parallel, or beachhead markets may greatly influence the success or failure of a certain technology. We will develop breadth across markets, including those unrelated to grid-scale storage or electric vehicles.
- ***Device & Systems Engineering***– Drawing from practical hands-on experience of our team members, we will develop detailed cell, pack and/or container models for each technology with a practical understanding of manufacturability and power/energy requirements at GWh scale. Manufacturing cost models, based upon a nominal starting annual production rate, will be developed to capture the true costs of labor, equipment, and yield. This approach ensures more accurate cost estimates, compared to traditional bill-of-materials analyses that often overestimate a technology's economic viability. Practical systems engineering considerations required for technology deployment, either in front-of-the-meter (FTM) or behind-the-meter (BTM) scenarios, will also be modeled. This includes the costs of containers, balance-of-system, converters, inverters, and substations. Additionally, engineering/procurement/construction (EPC), interconnection, augmentation, and developer costs will also be incorporated.
- ***Energy Markets***– This pillar will have expertise in the various energy markets across the United States and abroad, with deep understanding of current and future market operations, incentives, and policy. Starting with electricity grid markets, the group will expand to encompass all forms of energy accounting, including chemical and thermal. The group will model the operational regimes and identify recommendations for policy / market design to incentivize technology adoption.
- ***Minerals Supply***– Finally, this pillar will have deep expertise in the sourcing of minerals that span mining, refining, precursor synthesis, material production, and recycling. Each material, from copper current collectors to various cathode and anode candidates, will have defined minerals cost floors, detailed transformation process models, and accurate cost estimates for current and future volumes. Quantitative supply shortfall analyses will be performed upon a detailed understanding of current and future minerals reserve and extraction capabilities. We will also consider complementary or competitive minerals demand. Special attention will be given to geopolitically constrained critical minerals, and case studies will be performed to understand the supply

sensitivity to various regions. Additionally, other inputs beyond minerals, such as labor supply, will also be evaluated.

TEAM: STEER will be part of the Precourt Institute for Energy and will (1) remain technology agnostic, (2) present unbiased perspectives with deep scientific credibility, (3) leverage connections to industry, academia, government, and investors, and (4) become a central repository of information. Stanford's Precourt Institute is uniquely positioned to host such a team, taking advantage of the Precourt ecosystem which includes StorageX, Bits & Watts, and the Stanford Hydrogen Initiative, all while tapping into the industry-leading innovators within Silicon Valley. Finally, STEER will partner with external parties for data sources, supply chain and manufacturing insights. Leveraging the Silicon Valley startup ecosystem ensures STEER stays at the forefront of technology progress as it quantifies their future feasibility. The key investigators include:

- **William Chueh** – Stanford Associate Professor of Materials Science & Engineering; co-founder of Mitra Chem, a battery materials company
- **Sally Benson** – Stanford Precourt Family Professor of Energy Resources Engineering; former Deputy Director for Energy & Chief Strategist for the Energy Transition at the White House OSTP (2021-2023)
- **Adrian Yao** – Graduate researcher; co-founder & former CTO of EnPower, Inc (2014-2022), a Li-ion cell manufacturer

STATEMENT OF WORK: The output of STEER will be regular publications, tentatively named "STEER Assessments," each addressing a critical question to guide "What to build." Additionally, STEER will develop and make public software tools that allow others to evaluate technology learning curves for different scenarios.

The STEER team will be established in a phased approach, organically building upon STEER's initial core expertise while expanding to address key questions in wide-ranging areas of interest. The tentative Phases of STEER are presented below. STEER will hold industry workshops to chart the direction of the organization and identify key questions to answer (see Industry Engagement section below).

Phase-I: Li-ion Adjacent Technologies
Topic areas: Li-ion, Na-ion, solid-state batteries, other jellyroll/stacked enclosed cell architectures, etc.

Phase-II: Next-generation Battery Architectures
Topic areas: Flow batteries, air-breathing batteries, high-temperature liquid batteries, aqueous, etc.

Phase-III: Beyond Electrochemical Storage
Topic areas: Thermal (sensible, latent, thermochemical) storage, chemical storage, mechanical storage, etc.

INDUSTRY ENGAGEMENT: The success of STEER depends on the ability to consistently provide value by systematically and quantitatively answering complex, challenging questions that will define technical roadmaps on the decadal timescale. To ensure relevance, STEER must be highly engaged with industry stakeholders, including:

- **Startups** – Companies at the forefront of technology development and commercialization—many of which are Stanford-affiliated or within Silicon Valley—who can provide critical insights and leverage learnings
- **Large Corporations** – Corporations with existing assets, know-how, R&D capabilities, and capital that have strategic interest in participating in the energy transition and maximizing their impact
- **Investors** – VC firms or research analyst groups within investment banks that place a premium on insights for medium- to long-term investment opportunities
- **Market Intelligence / Data Collaborators** – Firms that can provide best-in-class datasets and market analysis while also highly interested in scientifically-driven, quantitative, and novel insights around deep-tech movements

To properly engage with the above stakeholders and build a Stanford-centric community, STEER will host industry workshops on a semi-annual basis inviting current and prospective affiliates of the STEER program. At these events, STEER will present in-depth findings and conclusions, host panel discussions, and workshop relevant questions regarding "What to build" for the subsequent phases of STEER. Each phase of STEER is likely to attract different corporate entities, creating a dynamic and evolving industry community. Example corporations most relevant to each phase is presented in Figure 1, showing significant opportunity to expand beyond existing Stanford-affiliated entities.

OUTCOMES: By establishing STEER as a novel, technology-agnostic, and deeply quantitative research organization providing critically needed thought-leadership, the STEER program effort will establish Stanford, the

Precourt Institute for Energy, and the Doerr School for Sustainability as credible leaders in the energy transition. The impact of STEER will be reflected by the investment decisions and resource allocation of its audience and will have far-reaching implications. Leveraging the unique capabilities and ecosystem of Stanford, the STEER program will drive significantly increased industry engagement, relevance, and funding toward the University.

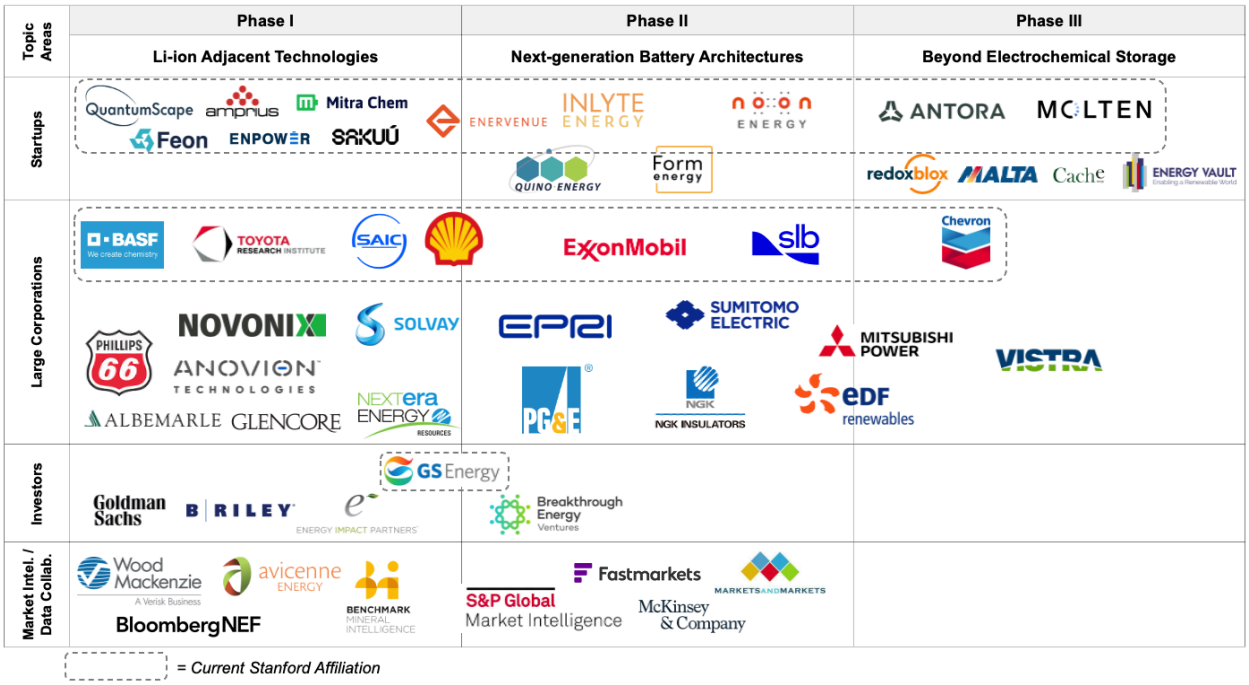

Figure 1: Example corporate entities most relevant to each STEER Phase organized by category