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C2E2: Consortium for Circular Economy of Energy Storage

Precourt Institute for Energy, Stanford University

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1. Introduction

The energy storage revolution is intimately linked to three mega trends over the past quarter a century: the growth of information technology and telecommunications in the 1990s and 2000s, the electrification of transportation in the mid 2010s, and the decarbonization of the electricity grid which is taking shape today. By 2030, the annual market for electrochemical energy storage will reach US $1 trillion, exceeding that of the microelectronics industry today. The exponential growth of technology such as lithium-ion batteries (LIBs) requires a quantitative and systematic examination of the supply chain and sustainability. Indeed, *beginning-of-life* issues such as the responsible mining of raw materials has already received significant attention. Likewise, supply chain inelasticity has also highlighted the opportunity to use recycled materials as input for manufacturing new goods. Similarly, *end-of-life* issues have received attention, largely driven by market signals (with an anticipated 1 TWh of electric vehicle battery retiring in this decade).

Historically, battery technologies have benefited from a highly coordinated effort between technology development, manufacturing and regulatory policy. For example, the exceptional recycling rate of lead acid batteries, exceeding 95%, has enabled the sustainable use of a toxic material in over 1 billion vehicles worldwide. In the case of LIB, current battery disposal regulations are built around consumer electronics, e.g., waste electrical and electronics equipment, WEEE. Moving forward, the same opportunity exists for current and future energy storage technologies but at a far greater scale. The shear difference in the market size between consumer electronics and electric vehicles, approaching 100 times by 2030, calls for designing a new circular economy for energy storage.

2. A Crosscutting Consortium

Stanford University is forming an academic-industrial consortium to co-innovate a circular economy for energy storage that meet the needs of the rapidly growing electric vehicle and grid storage markets. The need for a consortium is rooted in the interdisciplinarity required to tackle this grand challenge, crosscutting **(1) technology for recycling, repurposing and remanufacturing, (2) decision-making tools informed by techno-economics and environmental footprint, (3) geographically- and market-specific business models, and (4) regulatory framework**. The consortium will involve Stanford faculty members working across these areas and industry partners engaged across the entire value chain of tomorrow's circular economy. As a whole, the consortium will be well-positioned to engage with policymakers internationally and to advocate for industry-wide actions.

3. People

Faculty, staff and students from Stanford's School of Engineering, School of Earth, Energy & Environment, and Graduate School of Business will work alongside industry partners and stakeholders.

Faculty

Ines Azevedo	Department of Energy Resources Engineering
Sally Benson	Department of Energy Resources Engineering
William Chueh	Department of Materials Science & Engineering
Yi Cui	Department of Materials Science & Engineering
Simona Onori	Department of Energy Resources Engineering
Stefan Reichelstein	Graduate School of Business
Alberto Salleo	Department of Materials Science & Engineering
William Tarpeh	Department of Chemical Engineering

Staff:

Jimmy Chen	Precourt Institute for Energy
Tracy Turner	Precourt Institute for Energy

4. Research Pillars

Below, we briefly describe research pillars for the first three years of C2E2, along with the need for industrial input and participation.

A. New Processing Technology for Recycling

Lithium demand for LIB will likely eclipse global lithium reserves by 2040. Although LIBs enable products like electric cars that reduce greenhouse gas emissions, their widespread adoption could pollute soil and water ecosystems. This paradox arises from historically separate design of water treatment and chemical production based on linear, extract-and-emit approaches to chemical manufacturing. Less than 1% of lithium is currently recycled from batteries;[3] as lithium becomes scarcer, lithium recycling will become increasingly vital and economically feasible. There is an urgent need to identify supplementary sources of lithium (Li) to sustain growing demand for LIBs. We overcome this barrier by reimagining obsolescent batteries as modern mines of raw materials; with this perspective, we reduce inputs and emissions for both chemical production and environmental remediation. Li recovery also enhances battery production and disposal by enabling distributed lithium sources, which reduces transport of produced and disposed batteries, as well as price volatility associated with local economic perturbations. Beyond lithium, our activities can also be leveraged to recover other valuable metals from batteries.

Replacing conventional extractive mines with battery recycling can reduce energy, chemical inputs, costs, and emissions of lithium management. We imagine a zero-discharge future in which every industrial waste stream (e.g., battery leachate) is mined for maximal value as influents to other processes (e.g., cathode materials). To achieve this ambitious vision, C2E2 will investigate novel membranes, adsorbents, materials intercalation, and electrodialysis with low capital costs, high recovery efficiency, and record-breaking selectivity. Another focus is developing technology suitable for distributed recycling, i.e., processes that are efficient and cost effective a small scales.

Together, these efforts will result in high-purity lithium products achieved with fewer separation steps.

Industrial input & participation: C2E2 to incorporate industry feedback on potential product formulations and purity, appropriate cost structures, and performance metrics such as selectivity and recovery efficiency.

B. Data-driven Technology for Repurposing

As an alternative to recycling, repurposing is a potentially attractive pathway for end-of-first-life LIBs. Selecting a pathway depends strongly on the residual performance of the battery, such as calendar life, cycle life and round-trip efficiency. Forecasting such residual performance is a formidable task due to the diverse use cases (e.g., different grid storage scenarios such as peak shaving, frequency regulations, and arbitrage) as well as the extent of extrapolation in forecasting (i.e., predicting battery performance ten years into the future). Matching performance among modules is also crucial for ensuring the performance of the whole battery system.

C2E2 will develop data-driven and model-driven technology to rapidly evaluate residual battery performance at the point of disposal. Emphasis is placed on evaluating residual battery performance without disassembling the battery pack, since the labor cost for disassembly can be prohibitive. Likewise, the use of inexpensive hardware, combined with advanced software, will be key focus to lower the capital expenditure. Enabling rapid diagnostic at the point of disposal (rather than at centralized recycling or repurposing facility) will reduce the cost of transportation, which is another major consideration. To achieve these goals, we will combine physics-based modeling of battery health with data-driven forecasting to predict future battery performance. The ultimate goal is to develop a performance evaluation tool that rapidly predicts the residual performance for a wide range of use cases, providing operators at the point of disposal quantitative assessments.

Industrial input & participation: C2E2 will establish a data sharing platform with its partners to curate training data spanning a wide range of first-life and second-life uses cases. C2E2 will also provide training on using residual performance forecasting tools.

C. Fair Market Value & Decision-Making Tool

Residual value comes hand-in-hand with residual performance. C2E2 will advance the understanding of the economic value of batteries that have completed the first stage of their useful lives in a mobile application. To that end, we seek to develop a life cycle valuation tool that includes repurposing and recycling as decision variables. In order to evaluate these decisions, and the timing thereof, from a business perspective, our model framework will take advantage of the recently advanced levelized cost of energy storage (LCOES) concept. This requires an assessment of the fair market value (FMV) of a battery pack that has experienced a particular usage history and at that stage could now be repurposed for a specific second-life application or recycles. To address this question, we posit that an investing party seeking a particular energy storage capability should be indifferent between the repurposed battery pack and the acquisition of a new battery pack purchased in the marketplace. The notion of indifference here is that the LCOES of the two systems should be the same.

The research conducted by this consortium seeks to project the salvage value of EV batteries that will emerge for a competitive recycling industry that has the capacity to process a large volume of batteries at its facilities. Beyond creating an economic valuation methodology for second-life and end-of-life batteries, this project seeks to explore the incentives for the players at the different stages of the entire supply chain to coordinate their activities, specifically with regard to the design of the battery cells and the reliance on particular raw materials. Such coordination might have a significant effect on the value that can be captured by the value chain in total and the distribution of this value across the chain.

Industrial input & participation: C2E2 will work with its partner to analyze existing and potential business models across the circular economy value chain.

D. Environmental Impact Assessment Tool

Beyond costs, environmental implications of the disposition of EV batteries are also significant. Life-cycle analysis of energy, greenhouse gases (GHGs), water, and material flows is a well-established approach for quantifying the environmental benefits of alternative disposition pathways. Manufacturing batteries is material, energy, and water intensive. Both repurposing and recycling can reduce life-cycle environmental impacts. For example, replacing Li sourced from raw materials with used LIBs results in 10-fold to 30-fold reduction in the mass of material required to supply Li for new batteries. Recycling battery components such as cobalt are of even greater concern due to their limited reserves and geographically concentrated supply. From an energy perspective, extending the use of a battery by repurposing can greatly increase the energy-return-on-investment and carbon intensity two or three-fold, depending on how much more energy is delivered from the battery over its life-time. Likewise, the GHG intensity associated with battery manufacturing can be reduced by extending the useful cycles delivered from the battery. Additionally, the location where manufacturing and recycle takes place has a significant impact on GHG intensity, varying nearly two-fold, depending in part on the GHG intensity of the electricity used for manufacturing. Finally, battery technology is improving quickly, therefore, one can ask whether it is a better use of natural resources to recycle them to make a much more efficient battery as compared to delaying recycle until the second-use is complete. Our goal is to develop a life-cycle framework to quantify the environmental benefits of 2^{nd} use batteries, in comparison to, immediate recycle of all or parts of the battery or disposal. Use this framework in conjunction with the 2^{nd} use diagnostic assessment tool for assessing the environmental benefits of alternative disposition pathways for EV batteries.

Industrial input & participation: C2E2 will analyze existing manufacturing and recycling processes for their environmental impact in order to create accurate benchmark to understand that of emergent processes.

5. Governance Structure

Consortium General Information & Membership

1. The consortium will consist of the core faculty, associated students and researchers, and StorageX industry members who commit to contribute one or more tokens ($100k) per year to the consortium pool for 3 years. The industry members will be referred to as the consortium industry members.
2. Funds from the pool will be used to support one or more of the following: consortium seed projects, consortium research projects and associated researchers and students, consortium management, and consortium student internships

Industry Advisory Member

1. Only StorageX Sponsored members or Foundational members can become an Industry Advisory Member of a consortium.
2. Industry Advisory Members will make a three year commitment at a minimum of $250k of affiliate funds/year to the consortium.

Governance

1. The **Consortium Executive Committee** will consist of the core faculty of the consortium and the Managing Director of the StorageX Initiative, and the **Industry Advisory Board** for the consortium will consists of the Industry Advisory Members of the consortium.
2. The Industry Advisory Board of the consortium will propose the scope of research topics for the consortium.
3. The Consortium Executive Committee will create research proposals for the consortium, taking into account the scope of research topics proposed by the Industry Advisory Board.
4. All consortium industry members are invited to provide input to the consortium research proposals.
5. The Consortium Executive Committee will make the final decision on consortium project funding, taking into consideration the input of the industry members.
6. The Consortium Executive Committee and the Industry Advisory Board members will meet twice/year during the StorageX research forum to address consortium business. The Industry Advisory Board members will also be invited to the monthly working meetings.
7. Management: Consortium administration, operations and management of the research are performed by the management team including the Consortium Executive Committee, and the Co-Directors and the Managing Director of the StorageX Initiative.