Assessment of ARPA-E Energy Storage Program: Capability and Capacity to Solve Battery Waste Issues

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REVIEW PAPER

Assessment of ARPA-E Energy Storage Program: Capability and Capacity to Solve Battery Waste Issues

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Abstract

Society today relies on batteries to power our devices, electric vehicles, and at growing rates grid-scale energy. As the demand for batteries increases so does the amount of waste produced. The Advanced Research Projects Agency-Energy (ARPA-E) has tried to tackle the battery waste issue through its energy storage program with a project called Catalyzing Innovative Research for Circular Use of Long-Lived Advanced Rechargeable (CIRCULAR). The program intends to introduce Electric Vehicle (EV) battery technology with longer lifespans and driving ranges to a circular supply chain. They also want to integrate an EV battery health monitor into the circular supply chain practices. The program intends to determine the ability of the project to commercialize at scale through analytics. This article notes previous ARPA-E efforts to solve the battery waste issue through a circular supply chain and develops a proposed innovation policy framework for a circular battery economy. This framework is separated into five categories which identify emerging technologies and create a system of federally funded waste and recycling sites. We propose integrating support mechanisms and using neoclassical economic tools to induce innovation. Also, we recommend collaborating with the appropriate agencies for the creation, continuation, and oversight of facilities. Lastly, we will include technology transfer of emerging technology for testing and validation upon hand-off. The article utilizes the proposed framework to guide policy recommendations and contribute one possible solution for the battery waste issue through a national system of transport and collection for material recovery, reuse, and cascaded use.

Keywords ARPA-E · Circular economy · Battery · Innovation policy · DARPA model · Energy storage · Electric vehicle · Health monitor

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Introduction

Lithium-ion battery (LIB) development began in the 1970 s and has contributed to a wide range of applications that we rely on today in everyday life, such as the use of energy storage, electric vehicles (EVs), mobile devices, and laptops [1, 2]. With the rise of LIB supply and demand, there is also a rise in the amount of waste produced. With the transition toward carbon neutral goals and integration of renewable sources into the electric grid, LIBs are one cost and energy efficient solution to provide dispatchable power at higher demand and minimize intermittency that cannot meet requirements [3]. The United States (U.S.) faces a massive undertaking in the energy sector to develop a battery supply chain that advances technological innovation and manufacturing competitiveness. We must address strategies to tackle carbon-neutral goals and sustain national defense. ARPA-E is a critical agency working towards a circular battery supply chain.

The Advanced Research Projects Agency-Energy (ARPA-E) aims to be an enabler of revolutionary energy technology. Modeled after the Defense Advanced Research Projects Agency (DARPA) with its flat organization, flexibility, autonomy, and connected science model, ARPA-E seeks to create an ecosystem for breakthroughs with early developments that reach commercialization through their initial vision [4, 5]. The Department of Energy's energy storage program focuses on decarbonization of the transportation and energy sectors to enable the U.S. to secure economic growth and national security through the creation of a circular economy (CE) [6]. Thus far, ARPA-E has made strides in battery lifespans and driving ranges as well as stationary storage [7–9]. At ARPA-E, a CE starts with creating a circular supply chain through a recent program called Catalyzing Innovative Research for Circular Use of Long-Lived Advanced Rechargeable (CIRCULAR) which was allocated 30 million USD for the challenge of creating a self-sustaining supply chain within the legacy energy sector [10]. This assessment of ARPA-E focuses on the CE approach to battery waste and recycling that includes public-private partnerships at a nationwide scale to address the issues faced by the U.S. environment, community, economy, and workforce.

Lithium-ion Batteries Pose a Hazardous Risk to the Environment and Society

LIBs pose a threat to the environment and communities because of combustibility, physical degradation, and metal leachate. This is due to their underlying chemistry (see the main chemistries in Supplementary Information Table 1) [11, 12]. LIBs must be disposed of according to their toxicity. Recent studies [13] expose the threat they pose based on the metal concentrations and leachate [11, 14–19]. Under adverse conditions, they can corrode, combust, and leak toxic fumes and leachate [20]. At the LIB end-of-life they are transported to a landfill, waste-to-energy facility, recycling facility, or given reuse applications [13]. The EPA conducts an analysis on fires caused by LIBs in waste or recycling facilities with an investigation into the facility impact [21]. With 40% of landfills experiencing an emergency response and an estimated 95% of all global LIBs (portable consumer electronics and EV batteries) output into those landfills, there are clear safety issues with LIBs in the general waste stream [21, 22]. Between 2014 and 2020, manufacturers who manage end-of-life LIBs spent an average across all markets of 1540 USD/t for collection and transportation [23, 24]. North American landfill tipping fees continue to rise since the 1980 s and vary based on region, and were at an average of 45 USD/t in 2012 [24] with a recent 2023 price of 57.63 USD/t [25]. This brings the total collection and tipping cost to a market average of $\sim$ 1560 USD/t. We must address the current policies surrounding the LIB waste stream, acknowledging the worsening environmental threat, emergency hazard, and potential for recycling, reuse, and cascaded use to avoid landfill costs.

Current policies broadly address LIB waste but require specificity and can use lead-acid batteries as an example. The U.S. Environmental Protection Agency (EPA) does not explicitly deem all LIBs hazardous but instead deems their waste hazardous through the Toxicity Characteristic Leachate Procedure (TCLP) [13]. There are also updated standards from the California Waste Extraction Test (WET) [1, 13, 14]. The only batteries listed as hazardous waste are lead-acid and nickel-cadmium, which are now heavily recycled to prevent them from entering general waste [26]. The lead-acid battery recycling rate nears 100% and has stayed at or above 99% since the 2000 s [26]. This industry is strengthened by its common battery chemistry, material quality, long-term partnerships between collection and material recovery facilities, and existence since the 1980 s, giving it ample time to become cost-effective [22, 26]. More importantly, federal and state policies ban them from landfills and require recycling. General waste streams are not the solution for long-term LIB waste and policies should reflect the stringent ones set for lead-acid batteries to induce the transition to a LIB CE

A Circular Economy for Batteries

ARPA-E's CIRCULAR program [27] aims to develop and integrate a supply chain within a CE, a closed-loop system that reduces supply waste through recycling, reuse, cascaded use, and energy recovery to maximize its resources, energy, and economic growth [28–31]. Within a CE, an EV battery can be reused with its use cascaded into grid-scale energy storage and recycled for re-manufacture. Or in the worst case, non-recycled materials can undergo energy recovery [28]. ARPA-E is not creating a new economic system for EV batteries but instead is working within the established and predictable economic system to achieve a circular supply chain that can be commercialized and scaled up [5, 29, 32]. Therefore, ARPA-E is adopting new approaches to move innovations into existing systems and improve them, instead of solely forward-looking innovation [33]. The CIRCULAR program envisions the fruition of the program through four main elements, 1) regeneration, 2) repair, 3) reuse, and 4) re-manufacture [10]. The policy imperative behind it is for the U.S. to secure a domestic energy supply chain, minimize EV waste in landfills, and drive down the cost of recycling and reuse while simultaneously lowering battery cost so that both are competitive with current EV battery prices, internal combustion engine transportation costs, and grid-scale energy storage [10, 27, 28].

The ARPA-E energy storage program area often aligns with federal pushes. The Biden Administration promoted building a CE for resiliency and security. and had intentions to allocate funds from the Inflation Reduction Act to enable EV battery materials recycling in the U.S. to qualify for subsidies [34, 35]. The Federal Consortium of Advanced Batteries (FCAB) also plays a role. The FCAB blueprint asserts that a domestic CE for LIBs will eliminate the end-of-life battery cost with lower recycling costs, secondary applications, and a reliable and secure supply chain [36]. While ARPA-E is not the first to put forth the concept of a circular supply chain, they are on the frontier of its development and integration into the current and future economy. All actors involved want to protect the environment and our communities while growing the economy through an innovation system that guarantees a supply chain and national security [30]. We must close the supply chain gaps with viable, scaled systems through institutional change under an updated policy framework [29, 31] We emphasize that a circular supply chain is a prerequisite to transitioning to a CE.

Outlining Our Assessment of ARPA-E Energy Storage

This work focuses on implementable solutions to the battery waste issue. We approach solutions through the lens of ARPA-E's energy storage program and their efforts towards a CE. The study begins with a literature review in Section "Assessing Where Battery Technology Stands" regarding battery technology its past, progress, and future. This literature review ends with an introduction into the multi-generational technology thrust that has led to the CIRCULAR program. This literature is meant to provide a foundation in preparation for understanding how innovation models and circular economies relate to battery technology. Section "Redesigning Innovation Models for a Circular Battery Economy" aims to discuss the role of innovation theories, acknowledge the similarities and differences between ARPA-E's from DARPA's strategies, and emphasize the importance of neoclassical economic tools in successful innovation policy. Based on previous work from Weiss and Bonvillian [37], the section concludes with our proposed innovation framework retrofitted for the specific application of a circular battery economy. We move into Section "Applying our Policy Framework to Enter the Market" which applies the innovation policy framework to reach a policy package for each category of the CIRCULAR program and macro-level supply chain steps from upstream to downstream. This leads to Section "Institutional Gaps to Consider" which distinguishes front-end and back-end gaps that ARPA-E faces. These sections lead up to the policy recommendations in Section "Discussing Proposed Policies Toward Circularity" based on the proposed innovation policy framework. These recommendations span the value chain upstream to downstream and pursue suggestions that encompass environmental and social benefits. The takeaways are actionable recommendations that are not only applicable to this program, but future circular battery endeavors.

Assessing Where Battery Technology Stands

Where does battery technology stand and what is the predicted path of innovation? The first part of this literature review covers how a battery is constructed, where its critical minerals are sourced from, its application, cost, and previous and current work in the field by ARPA-E. It also reviews recommendations from the FCAB on policy packages that align with its vision for the future of batteries. The second part of the literature review focuses on future technological advances in solid-state batteries (SSB). Next, we look at battery recycling and evaluate its progress through existing literature. Finally, it reviews previous and current ARPA-E projects that relate to battery development.

Batteries on the Rise

We can break a LIB into four main components: cathode, anode, electrolyte separator, and outer casing. The cathode is 25–30% of its mass and defines the battery chemistry [11, 15].

Factors that contribute to the rise of LIBs and a corresponding paradigm shift towards technology "lock-in" are 1) an increase in lithium supply, 2) Research and Development (R&D) funding, 3) lower cost, and 4) decarbonization initiatives [12, 38, 39]. Lithium supply is found in Australia, Chile, and Argentina, but more recently national efforts have expanded to explore and test Thacker Pass in Humboldt County, Nevada, and the Salton Sea in the U.S. as plentiful sites [12, 39–42].

There has been federal R&D funding for both stationary and mobile energy storage. Stationary energy storage received federal support in 2010 with Department of Energy funding to test various battery chemistries for grid-scale applications [38]. In 2011, this was complemented by federal mandates for the legacy energy sector to accommodate and create opportunities for battery storage [38, 43]. Federal support is bolstered by ARPA-E setting an initial target cost of 250 USD per kW h for storing grid energy which was updated to 100 USD per kW h for the battery storage device [44]. For mobile energy storage, major funding has been allocated by ARPA-E through programs such as Batteries for Electrical Energy Storage in Transportation (BEEST) which focused on lowering the cost of EV batteries and increasing their energy density for longer ranges and lifespan [5, 7].

As the cost of batteries decreases, they become more accessible to apply to the energy grid and EVs. Early costs of LIB EV cells were around 1000 USD per kWh, but have fallen to 100 USD per kWh signaling that there is competition between emerging EVs and traditional combustion engines [12]. ARPA-E [10] predicts that in 2023 28% of passenger vehicles will be electric which rises to 58% for 2040. These prices will continue to drop and enable decarbonization of energy storage.

Battery storage facilities are critical to provide dispatchable power that meets electricity demand while permitting intermittent renewable sources to ramp up [3, 16, 18]. Braff et al. [16] propositions that a hybrid energy storage system permits the intermittent sources to integrate into the market share and removes the need for carbon intensive transmissions across long distances or back-up sources. Hybrid energy storage is less disruptive in comparison to an all-battery system making it more compatible with entering a legacy sector [45]. It is important for intermittent sources as wind and solar to reach higher market shares due to the benefits including, but not limited to installation speed, ability to scale rapidly, low water and energy usage, and lack of direct carbon. Under the proposition of an optimal hybrid system, the case study finds that in Massachusetts solar would be profitable in Spring and Summer, with wind profitable every season except the Summer. Overall, there is significant profitability for the whole year using a metric of a dimensionless ratio representing annual revenue annualized cost of a hybrid plant. This example is one of many and is pointed out to relay that the cost of storage is dependent on not just location and climate, but also capital cost. Recent studies [18] put forth that energy storage less than 20 USD per kW h can ease wind and solar into the grid to provide baseload demand for locations with consistently high supplies. They estimate the chemical cost of LIBs between $35 - 100$ USD per kW h by normalizing the cost of materials for 40 technologies. As the price of LIBs continues to decrease they expect this technology to meet the target cost.

Lastly, decarbonization initiatives from the federal level have been pulled forward by state efforts. ARPA-E's Strategic Vision Roadmap aims to decarbonize the transportation and electricity sector through its technological innovation system [6]. Complementary to this, the FCAB put forth a blueprint for batteries to decarbonize transportation and energy while reinvigorating domestic manufacturing [36]. States have been pulling these efforts forward in cases such as in California where large battery facility demonstrations were built quicker than expectations [38, 46]. These demonstrations began after the enactment of California Bill AB2514 in 2010 and have been followed by efforts in Massachusetts and New York which reviewed opportunities for state energy storage and set targets based on these results [46–50]. As of 2018, 20 states began the process to deploy state-level energy storage [51].

Solid-State Batteries and Beyond

Solid-state batteries are an emerging innovation, and it is often assumed they will replace LIBs because of improved safety. There are two types: SSBs which include a liquid electrolyte (LE) and an all-solid-state battery (ASSB). Thus, when we refer to solid-state batteries we refer to a LIB hybrid which still uses a liquid electrolyte, but in a smaller concentration [52]. One key improvement in battery innovation with an SSB is the lithium metal anode which increases the energy density of each cell. Between a higher energy density and the fast charging capability, this technology may be multifunctional across societal needs [53].

The mechanics of ASSBs are leading to current technical bottlenecks that the community must address to push towards commercialization. In the cathode there are mechanical issues causing fatigue, stress relaxation, and fracture [53]. These mechanical failures lead to short circuits and rapid capacity declines during the charging and discharging cycles [52, 53]. Kalnaus et al. [53] suggests a framework for how to overcome the common issues by identifying the strain sources to improve the design. One solution within this framework is to add a small amount of LE to the ASSB to create a SSB [52]. It is shown that SSBs also experience short-circuiting and hazardous temperatures. Despite these higher temperatures, the ASSB is at a higher risk for thermal runaway due to its high energy density at equal area capacity. With the suggested framework, these mechanical issues can be solved to overcome bottlenecks and achieve commercialization competitive with current markets.

ASSBs and SSBs appear viable for commercialization because of general safety improvements due to the lack of or minimal LE, and their higher energy density seems well suited for EVs and stationary grid-scale storage [38, 52, 54, 55]. In comparison to LIB technology, they can approximately double the energy storage capacity [53]. The increase in energy storage and density is related to the smaller volume which means future commercial packs and grid-scale storage require less footprint [54]. Their compact form enables commercialization, but its progress into the markets is slowed down by the balance between cost and consumption of energy and materials to create highly conductive cells. Current methods discussed in a 2024 case study [54] that produce highly conductive cells are energy and cost inefficient which shows in the price gap between an ASSB at 5.7 USD/W and commercial LIB at 0.45 USD/W. The difference is driven by volatile raw materials, new manufacturing techniques, and inputs needed for safety standards. In order to reach commercialization, mass manufacturing must be cost competitive with commercial LIBs which means researchers are looking at alternative anode materials as magnesium, sulfur, and sodium. Sung et al. [54] suggests a sulfur based solid electrolyte which would reduce the cell's cost to 0.46 USD/W. With alternative anode materials, mass production could be less material, time, and energy efficient which would result in lower production costs. Given this potential for cost competitiveness, it is important that we accommodate SSBs and ASSBs into consideration of the CE as well.

Fuel cells introduce a new market for clean energy sources. Proton exchange membrane fuel cells are high energy density, clean, and quiet energy converters which use hydrogen and water [56]. As manufactures aim to lighten EVs and increase driving ranges fuel cells can fulfill these requirements. The main issue is the short-term lifecycle. Declining reserves of platinum metals also poses an issue for the future of fuel cells [57]. As the innovation continues to progress health metrics can determine its progress towards longer lifespans. At this time, LIB lifecycles are longer and have the market advantage of time and regional and state pulls.

Whether we are considering solid-state batteries or beyond, we must briefly recognize thermal runaway risk and innovative monitoring systems. In Zhang et al. [58], researchers put forth a nondestructive monitoring technique that can be integrated into a battery management system to track the state of charge. Tracking the state of charge is important in early warning systems to identify batteries which are not discharging or charging within the normal bounds. Using a LFP battery as an example, the study explores the viability of implementing a joint estimation method and ultrasonic reflection waves to determine the difference between the actual state of charge and its prediction with varying temperature. Models as these can be retrofitted for other cathode chemistries and battery types. A standard model that manufacturers, refurbishers, and cascaded users can run to verify battery health.

Current Strides in Battery Recycling

Recycling is a main avenue toward achieving circularity for end-of-life EV batteries. LIB recycling is categorized into three types: 1. pyrometallurgical, 2. hydrometallurgical, and 3. direct cathode recycling [1, 59]. While pyrometallurgical and hydrometallurgical extract singular metals, direct cathode recycling preserves embodied energy in cathode material as ceramic powder. In the short term, both pyrometallurgical and hydrometallurgical processes are used to recover Co, Cu, Fe, and Al based on market value [1, 2, 59]. Recent reports [1, 59] share that Li and its compounds are not recovered in the U.S. from either pyrometallurgical and hydrometallurgical yields nor direct cathode recycling. With inconsistent perturbations in the lithium price, there is a lack of demand for recovered material which worsens its volatility [59]. Its volatility directly affects recycling costs and relithiation. Despite the lack of Li recovery in the U.S., Chinese and Korean companies yield Li as a product of pyrometallurgical activities for Lithium carbonate for cathode compounds as Li metal oxide/phosphate or Li carbonate/hydroxide [1]. Though current strides in recycling do not include all critical minerals, future scenarios may.

Battery recycling is not new. In fact, there are other commercialized battery types that are recycled. Figure 1 shows how LIB recycling is often cost inefficient in comparison to commercialized lead-acid batteries (LAB) and Nickel-metal hydride (NiMH) recycling processes. NiMH batteries are used in HEVs and are known for their safety, long lifecycles, and durability [60, 61]. Commercialized processes include hydrometallurgical, pyrometallurgical, and mechanical processes to extract rare earth minerals and critical minerals as Li and Co. While NiMH processes are more costly than for LABs, hydrometallurgy (includes collection and transport), pyrometallurgy (includes shipping), and mechanical (includes shipping) are less than the cost of reuse/repurposing, hydrometallurgy, and direct cathode recycling for LIBs. Given that those costs for LIBs are just for the singular process leaving out collections and transport, NiMH recycling appears cost efficient. Other cost efficient

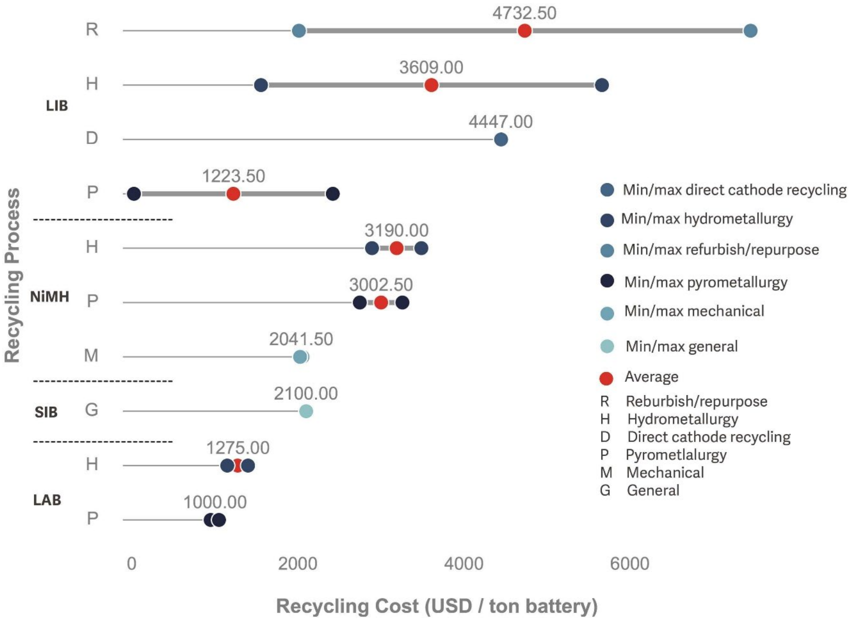


Fig. 1 Levelized recycling costs of various processes for four battery types including LIB, NiMH, SIB, and LAB. The minimum and maximum costs are shown along with the calculated average. All cost estimates are derived from the literature review in Section "Current Strides in Battery Recycling". The levelized costs are originate from case studies and analysis between 2015 and 2024

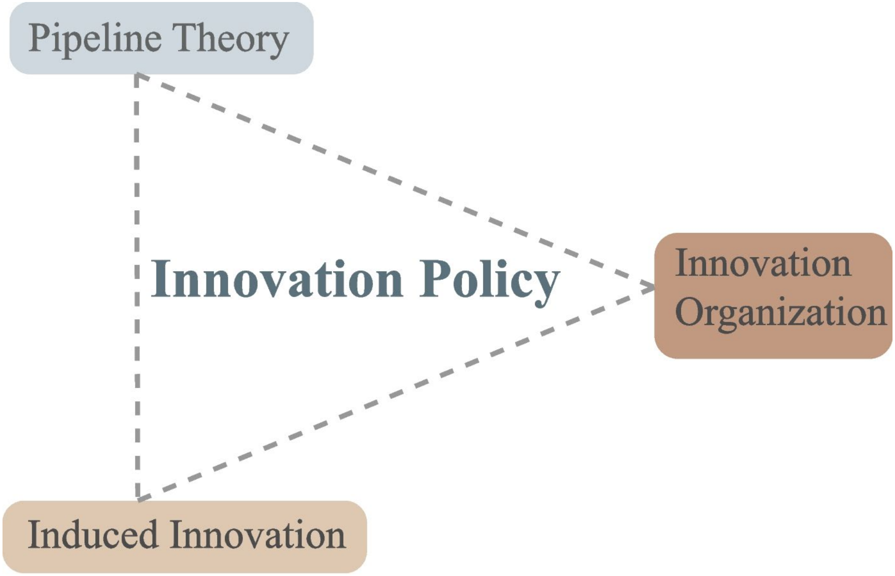


Fig. 2 The three innovation theories. All three are used in innovation policy to bring emerging technology to market while focusing on organizing around industrial and technology policy [37]

processes are LAB hydrometallurgy and pyrometallurgy techniques which are either one step, two steps, direct or indirect reductions, or a reduction using electrolysis [62]. A 2017 case study published an average of 1000 USD/t for pyrometallurgy and 1275 USD/t for hydrometallurgy [63]. Their narrow ranges indicate price stabilization in comparison to the differences in LIB processes. Despite these low, stable prices LAB recycling has a high global warming potential and produces metal hazardous air pollutants [62]. There are also markets for nascent processes. The sodium-ion battery (SIB) recycling processes are gaining commercial traction [64]. As such, few cost estimates exist, and fewer with specific estimates for each type of process. An early estimate from 2023 of 2100 USD/t gives a baseline, but with very low expected profits it is unclear how fast SIB recycling will be adopted. In addition, we add that although a cost estimate was not found for redox flow batteries (RFBs), we recognize that there is a market for their circularity [65].

Future advancements in recycling technology could drive down cost and increase lifecycle greenhouse gas (GHG) offsets while increasing cost efficiency so that other critical minerals are economically viable [12]. In order for recycling to scale up, the cost of recycling must be less than that of a new EV or stationary grid-scale storage pack. Standardized cost estimations for LIB waste treatments (excluding transportation and collection) range from $26-5662$ USD/t shown in Fig. 1 [28, 66–71] with one extreme variant found of 8430 USD/t [70] from a study which includes transport and collection in this cost. This range of $26-5662$ USD/t is affected by a multitude of factors, including the single or mixed nature of the cathode types in the waste stream [24, 28]. Cost-effectiveness is not the only factor to consider. GHG emissions from recycling processes should also be taken into account. Ciez and Whitacre et al. [59] analyze the three process for NMC-622, NCA, and LFP cathode chemistries for pouch and cylindrical cells. Their examination reveals that hydrometallurgical and direct cathode recycling GHG net reductions exceed that of pyrometallurgical processes. Highest reductions are for NMC-622 and NCA versus LFP due to the inclusion of high market critical minerals. Net reductions are also affected by the GHG offsets from grid electricity. One route to increase cost efficiency of a recycling plant is to minimize the outside resources and raw materials. Battery Resources® and LithoRec® are two companies which use emerging technology to reduce their raw inputs and through a synergy with the Massachusetts EV grade manufacturer, 6k® [72], Battery Resources has increased their cost efficiency through partnership [1]. Later, we delve into how partnerships between recycling facilities and cell and pack manufacturers can be scaled upwards.

In 2024, advancements in the reuse of battery cells from Chen et al. [73] propose that the replacement of the cell's Li supply and charging results in extended lifetimes for LIBs and high specific capacity, cost-effective solutions, and stability for Li-deficient cells. During the experiment, the LFP cell was rejuvenated to 99.6% of its original capacity after $1,824$ cycles and still retained 96% after $11,818$ cycles. In comparison to the average 2000 cycles from full discharge, each cell's lifetimes could extend by almost six times the number of cycles. With a cost of 0.9 USD per kW h to replace the Li supply, this innovation brings expanded reuse options. As cost-effective reuse solutions arise, we consider the magnitude of Li supply injections to reduce unrecoverable waste.

Programs That Led to CIRCULAR

There were several predecessor programs at ARPA-E to CIRCULAR that sought to fill missing gaps in creating a clean-energy economy and a viable solution for a closed-loop economy [10]. ARPA-E has had a multi-generational technology thrust in its programs, recognizing that in a legacy economic sector like energy, advances can be disruptive even if they are incremental [5]. A series of these programs are noted below.

Batteries for Electrical Energy Storage in Transportation (BEEST) [7]: This ARPA-E program focused on developing disruptive EV/PHEV (Plug- in Hybrid Electric Vehicle) battery technology to transform battery longevity, cost, range, and performance.

Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS) [74]: This program's objective was to innovate advanced energy storage to be cost-competitive for current energy sector practices so that it could be implemented into the complex established legacy sector (CELS) for ubiquitous adoption and connect renewable energy to a dispatchable system [5].

Robust Affordable Next Generation Energy Storage Systems (RANGE) [9]: RANGE aimed to decrease the weight of EV battery cells while increasing the driving range. It also focused on functional designs that were customizable for the needs of various EV battery manufacturers.

Electric Vehicles for American Low-carbon Living (EVs4 ALL) [8]: The active program began in 2022 to develop EV battery cells that remove or minimize cobalt and nickel to reduce foreign dependency on these critical minerals while increasing EV adoption and reduce emissions and energy consumption.

Redesigning Innovation Models for a Circular Battery Economy

Roles of Existing Innovation Theories in Innovation Policy

Innovation policy aims at bringing emerging technology to market using a mixture of innovation theories and focuses on organizing industrial and technology policy around specific technology market goals. Existing theories include the pipeline, induced innovation, and innovation organization theories shown in Fig. 1. The three theories make up the foundation of how we model the process of technological progress and innovation [37].

The Pipeline Theory of innovation developed by Vannevar Bush [75] stems from the concept that scientific progress is based on fundamental research; it can lead to market commercialization by industry of emerging technology. The government's role is to support fundamental research; this is separate from the industry's role to commercialize it. This theory reflects one of Bush's concerns, that science itself should be protected from government bureaucracy and therefore tend towards basic research. Today, this model continues in agencies such as the DOE's Office of Science which focuses on early-stage technology grants with the idea that they could reach industry and therefore market introduction through the pipeline [32]. Unfortunately, there is a bottleneck effect where there are many emerging technologies with only a few reaching the market due to the "valley of death". This "valley" is the gap between the research, on the left side of the pipeline and later stage development on the right-hand side of the pipeline where most technology fails to transfer into the market

[76]. Despite the valley, the theory can generate energy innovation if it can be accepted by the energy sector and the industry is prepared to transfer it into the market.

Innovation policy also utilizes the second theory which is induced innovation. Vernon Ruttan [77] introduced this model for how industry typically innovates: a potential market demand induces the industry to sponsor a new technology, usually an incremental advance. Both these models remain viable strategies for technology adoption. The third model is the "innovation organization" theory which incorporates and integrates the other two models. This innovation organization model is meant to create an ecosystem that fosters technology breakthrough [4, 78]. It seeks connections between the industry actors - industry, universities, and government - to fill gaps in the innovation system, with support mechanisms available at each stage of technology development, from research through technology implementation.

Both ARPA-E and DARPA embody this third model. Elements in the DARPA model were used in the ARPA-E model. These include the technology "challenge" approach of pursuing breakthroughs not simply incremental gains [5]. ARPA-E, like DARPA, has a culture that hires highly skilled and experienced talent that works on a project for terms of 3 to 5 years. A program manager (PM) leads each project, aiming to form research teams with the elements of great groups [79]. The agency operates on a protected island for research development while retaining a bridge back to the DOE leadership to help spur implementation [4, 79]. These elements are complemented by the flat and simplified two-layer structure which catalyzes communication between the PMs and office directors for flexibility and the ability to pivot quickly. Not only can ARPA-E act quickly, but it can also hire and undertake contract procurement rapidly, outside normal government constraints.

In some ways, ARPA-E is different from DARPA, building a support community, and new approaches to commercialization pathways into CELS [5]. A major issue ARPA-E faces is transferring technology into commercialization because it has no access to procurement funding, such as DARPA obtains from DOD [5, 78]. However, its innovation organization approach tries to tackle this "valley of death" issue by forming close relationships with early-stage technology developers and only making awards to projects where there is a clear commercialization pathway. It is assisted in this step by a team of its own in-house technology transfer experts [5, 76]. Because DOD has a strong interest in certain new energy technologies, ARPA-E also tries to get them to implement new energy technologies relevant to DOD's mission. The DOD programs relevant to ARPA-E projects include the Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) [5]. ARPA-E can utilize SERDP for R&D while ESTCP can provide the testbed and demonstration for emerging technologies to help scale up its new technologies.

How ARPA-E can Adapt Neoclassical Economics with Innovation Policy

One of the pillars behind innovation policy is Growth Theory. In earlier neoclassical economics growth was assumed to be based on three factors, the national savings rate, capital supply, and labor supply. Robert Solow [80] changed this approach and developed the Growth Theory. He substituted technological innovation for savings rate and found it was the dominant cause of growth. However, his work saw technological advances as exogenous to the system because it was so hard to measure and put into the metrics of neoclassical economics. Paul Romer [81] found this problematic and put forth that technological change must be seen as endogenous to Solow's growth theory model. Romer agreed with Solow's premise that technological change drives economic growth and argued that humans innovate because of market incentives. But Romer's endogenous technological change approach continued to face issues with the number of variables in the complex systems for innovation [32]. Tools often used in neoclassical economics to incentivize technological change are tax incentives on R&D and technology development support [32]. Other tools that can alter the market and so drive innovation change include regulations.

Tax incentives and regulations range in their effectiveness. Mohnen and Lokshin [82] evaluate the effectiveness of R&D tax incentives and include an example case study using the Dutch system. They define the cost of R&D tax incentives as the sum of net compliance, opportunity, and administration costs. Their work overturns the previous standard that a R&D tax incentive is only effective if the cost-effectiveness ratio is greater than 1. Instead, they assert that if the 'net welfare gain' surpasses that of the aggregated cost then the policy is effective. We point out that welfare gain is complex to quantify and contains many endogenous variables, but we can think of this study in terms of its concept. The case study can be applied globally as a measure of general R&D tax incentive effectiveness. Another common measure is cap-and-trade which is newer than tax incentives yet influential.

Cap-and-trade is known to be an effective regulation. Empirical analysis since the 1980's smog case is an example of how allowing emissions trading can effectively lead to advanced innovation that coincides with environmentally conscious changes [83, 84]. Power plants produced sulfur dioxide, which entered the atmosphere through the exhaust, and the acid rain damaged human health, forests, water systems, and buildings [84]. After years of frustration and over 70 acid rain regulations by 1989, there had to be an alternative route that replaced controlling power plants by requiring scrubbers and instead allowing them to profit and 'internalize the externalities'. With the cap lowering each year, there is an added bonus of increased profit as the value of each credit rises in a limited market. The Clean Air Act of 1990 monitored power plant emissions and the cap-and-trade took effect in 1995. Not only did emissions fall by 3 million t in the first year, but it costs about 3 billion USD total across all domestic firms and halved acid rain events, reducing human and environmental health damages. Cap-and trade is known as a success and exemplifies that sustainable practices can return profit and reduce externalities.

Another effective regulation is planned obsolescence. This tool has been successfully applied to cases such as chlorofluorocarbons (CFCs) and stratospheric ozone [85, 86]. The development of CFCs for supersonic technology and more commonly known as a compound in aerosol cans, depletes ozone, with the most significant damage appearing as holes at polar and mid-latitude regions. This issue escalated from domestic to global from the 1970 s into the 1980 s. The 1987 Montreal Protocol called a planned obsolescence of CFC production and consumption. Successful cooperation of all United Nations members by 2009 resulted in above a 98 % reduction in chemicals related to ozone depletion, and has been regarded as the most successful global treaty. Its success is followed by hydrofluorocarbons (HFCs) joining the protocol's substance list for 85% phase out by 2036. Planned obsolescence is a success story that should be used today for situations where the human and environmental costs require immediate action. The three tools discussed each have their strengths which ARPA-E can use for successful technology transfer.

ARPA-E aims to spur innovation in the energy technology sector. It creates a technology transfer strategy for each of its projects. Despite former U.S. technology transfer failures into the energy sector, further isolating the energy sector and preventing growth, barriers that hinder innovation must be addressed and overcome. ARPA-E strategies account for the established firms' advantages, including subsidies and price incentives, entrenched regulation systems, public support, and technology dominance [45]. Experts [5] attribute ARPA-E's successes to market launches into the military, industry, and entrepreneur VC model which we will detail later on. For CIRCULAR, it is critical that the strategy develops from innovation policy and takes advantage of tools to secure hand-offs and technology transfer towards the end of the 3–5 years ARPA-E allocates for its projects [10]. The PMs and collaborators when organizing around a circular battery economy should ensure that the right support mechanisms and infrastructure are in place before a hand-off to industry or to other agencies to continue development. Policy packages can be prepared for a technology's market launch that stimulates the markets for commercialization at scale by incentivizing industry through tax benefits or other incentives, and through regulations forcing planned obsolescence of current waste methods which will hinder adopting a CE [31, 37]. Regulation will also play a key role in setting standards for recycling, landfills, and gathering state support for the federal regulatory approaches. Thus, we must support the battery technology that emerges from CIRCULAR by creating policy packages before hand-off which catalyze the beginnings of a CE.

Innovation wave theory from various theorists [76] suggests the timetable for technology to reach maturity. It predicts a period of roughly 10–5 years for the technology to improve followed by 10 years of rapid growth. This leads to 20 years or more of stable, incremental improvements until tech maturity is reached. Given this timetable, we can form the rough timeline of each tax incentive and regulation tool between 10–15 years to allow ample time for a technology to improve with the market push for the innovation to be adopted. For the energy legacy sector to adopt the technology it must fit within existing structures or have incremental, not disruptive changes. In the case of our disruptive recommendations, there must be support in place before technology can scale up.

Leverage Public-Private Partnerships to Sustain the ARPA-E Community

ARPA-E leverages the relationships grown from each project to create a community that supports commercialization and promotes innovation in the energy sector. The most recent ARPA-E annual report [6] announces a cumulative 129 firms founded, 268 inter-agency partnerships, and 829 issued patents since ARPA-E began. Many of the former PMs and contractors go on to establish firms in the energy sector with ARPA-E partnerships [5]. This serves as a positive feedback loop for programs to launch pathways into commercialization while also creating partners for future programs. ARPA-E is an enabler of national innovation systems through leveraging the community and university labs [87]. They conduct what Richard Nelson [87] described as a mutual relationship of science and technological innovation giving rise to one another. Past energy storage programs take full advantage of firms and universities for research, prototyping, and tech transfer (refer to "Programs That Led to CIRCULAR in Subsection Programs That Led to CIRCULAR").

ARPA-E utilizes the customer base it cultivates for gathering political support and venture capital (VC). While it cannot automatically launch into the DOD and military sector as DARPA can and without an equivalent technology transfer in the front-end heavy DOE, they rely on creating a surrounding energy community and unifying existing firms and university research to launch their technology innovation [5]. The fruition of a customer base is the root of its political support which lobbies for funding on behalf of ARPA-E. VC firms gravitate towards ARPA-E as well for its high-risk and high-reward model which leads to commercialization of groundbreaking technology. Therefore, the agency's innovation organization is self-sustaining, establishing a continual loop of growing public-private partnerships and venture capital support which directly extends into a political base from their substantive model. This model of public-private partnerships can be used to apply our innovation policy framework in the next section.

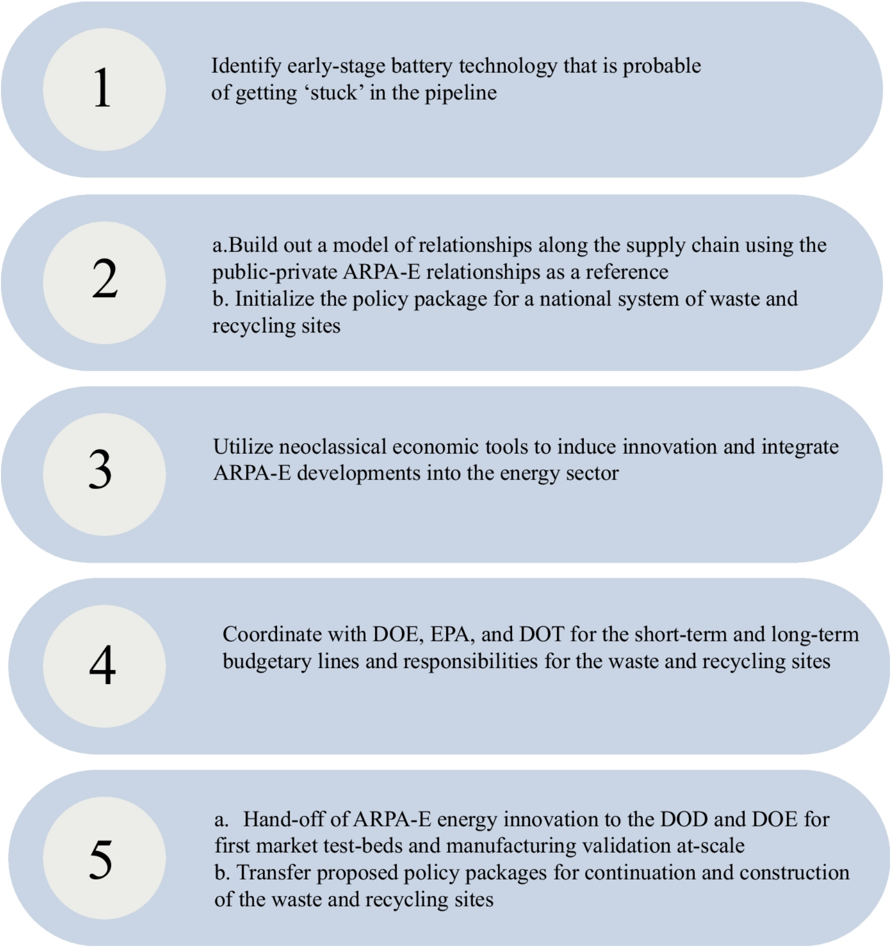
A Theory of Innovation Policy Framework for the Circular Battery Economy

Previous work from Weiss and Bonvillian [37] put forth a 'four-step analytic framework' to launch emerging energy technology into the markets using a combination of the pipeline, induced innovation, and innovation organization theory. It includes 1) identifying and classifying emerging energy technology most likely to bottleneck, 2) creating a technology-neutral policy package that pairs with each technology classification, 3) supporting the energy innovation using available mechanisms, and 4) identifying institutional gaps to find an agency which can fulfill the gaps in the commercialization process. While this framework is well-suited for the energy CELS because it creates a launch path for emerging technology due to technology-neutral policy and tackles gaps in supporting steps for the technology transfer, we must alter it to fit the needs of a circular battery economy. Specifically, a circular battery economy must be self-reliant and self-sustaining with strong public-private partnerships.

Figure 3 outlines the proposed innovation policy framework to catalyze a circular battery economy. These begin with ARPA-E identifying which early-stage, frontier battery technologies could get 'stuck' in the linear pipeline and are likely not to materialize into commercialization at scale [37]. Based on the DARPA model applied to energy, this first step is assured at ARPA-E.

Secondly, we propose that ARPA-E should maximize the public-private partnership model on a wider scale. Figure 3 demonstrates how they should build out a model of business relationships along the supply chain. The first set of relationships begins downstream for the EV, aviation, national defense, and stationary storage sectors. ARPA-E can initiate the matching process between these sectors to domestic battery pack manufacturers, refurbishers, and cascaded-use facilities. By modeling the matching process between downstream components, it can be translated into a policy package in which the companies that manufacture and sell battery technology must have contract agreements with reuse, refurbishment, and cascaded use facilities. The downstream supply chain must also have a direct relationship back to the midstream national materials processing and cell manufacturers at scale. Midstream firms will require a legal partnership for domestic raw materials production of critical minerals. For minerals not in abundance in the U.S. it is important to maintain international relations with foreign mineral sources.

After the first prong of the second step, we introduce the second prong which is a policy package that creates a national system for waste and recycling with transportation from pickup points. The sites would be within a certain radius of cities and/or regions and the



1 Identify early-stage battery technology that is probable of getting 'stuck' in the pipeline

2 a.Build out a model of relationships along the supply chain using the public-private ARPA-E relationships as a reference
b. Initialize the policy package for a national system of waste and recycling sites

3 Utilize neoclassical economic tools to induce innovation and integrate ARPA-E developments into the energy sector

4 Coordinate with DOE, EPA, and DOT for the short-term and long-term budgetary lines and responsibilities for the waste and recycling sites

5 a. Hand-off of ARPA-E energy innovation to the DOD and DOE for first market test-beds and manufacturing validation at-scale
b. Transfer proposed policy packages for continuation and construction of the waste and recycling sites

Fig. 3 We illustrate the five steps in our policy framework which we recommend for applying innovation policy towards a circular battery economy. Our steps are initially inspired by the policy framework from Weiss and Bonvillian [37] and adapted for specific support mechanisms and infrastructure

waste sites would be federally funded and controlled, while the recycling aspect would be contracted to private companies with subsidization from each state.

For the third step, federal mandates should utilize neoclassical tools using the induced innovation model to stimulate energy innovation in the private sector to adopt ARPA-E's output of longer lifespan batteries that are easy to disassemble and fit within a circular path. Not only should the firms respond to the market changes by adopting the new technology and starting the process to alter existing practices incrementally, but they should also build up improvements to the technology.

Fourth, ARPA-E is recommended to work with the DOE, EPA, and DOT to agree on splitting responsibilities and budget for continuing these waste and recycling sites with proper oversight and organization.

Lastly, ARPA-E is obliged to hand-off of the technology to DOD and DOE for first market testbeds and leading examples of manufacturing at scale. This step also involves transferring the proposed policy packages for the continuation and construction of the waste and recycling sites.

Applying our Policy Framework to Enter the Market

There are two main issues with the current infrastructure and policy packages at the federal and state level. The first is that there is no federal or state-mandated standards for LIB recycling. Specifically, there is no standard procedure or guidelines for the range of recycling processes that a plant must be able to complete. Nor is there any standard for the specific metals that the plant should aim to recover. There is no standard for battery technology and configuration. The FCAB national blueprint [36] calls for the ability for LIB technology to have transformable battery technology that serves the Department of Defense and military-industrial requirements. According to experts [30] eco-designs fit best in CEs. Combining these concepts, the FCAB concept of a "form-fit-function" standard battery design can be applied to grid-scale energy storage and EVs.

Another major issue is the lack of a national system for recycling. We have previously read of the micro-scale relationship between Battery Resources and 6k [1, 72]. This connected relationship must be done on a broader scale across the nation with partnerships between manufacturers, cascaded-use facilities, and refurbishers [28, 29]. Thus, when matching launch paths to policy packages we keep in mind the need for standards on recycling and a national system to recycle, reuse, and re-manufacture batteries through a CE. Without a standard for recycling or a system, the U.S. cannot establish or implement a CE even with ARPA-E CIRCULAR breakthroughs in a circular supply chain. There must be a system for the circular supply chain to fit into.

First, we assess the cost curve for LIB batteries for EV and grid-scale storage. This includes a brief cost analysis of past and current cost structures. Next, we assess each category (Category A, B, C, and D) of the CIRCULAR program to recommend ways to leverage economic tools to launch the circular supply chain into effective policy. The economic tools we put forth are supported by incentive packages [33].

Cost Structure of a Circular Supply Chain

LIB costs continue to drop and show promising cost-competitiveness with the market. The market cost of a stationary storage LIB battery pack was 953 USD/kWH in 2010 and reduced 85 % to an average of 143 USD/kWH in 2020 [36]. The FCAB national blueprint sets a goal of 60 USD/kWH for each LIB pack. This can be fulfilled by using recycled materials from LIB batteries that have reached their energy capacity or contain recoverable materials [28, 36].

Forecasting decreasing LIB cost is effective in predicting future EV market costs. In 2020, a LIB pack (across light-duty EVs, commercials EVs, and grid-scale storage) price was 100 USD/kWH at its lowest [88]. This price is forecasted to predict declining market costs for a 100-kWH storage capacity. With battery packs at 100 USD/kWH they can be cost-competitive upon entrance into the market against the internal combustion engine.

Under the other assumption that 10 million EVs will be produced and sold globally by 2040 then there is a 100 billion USD market for EV batteries priced at a consumer market cost of 10, 000 USD per EV owner [36]. We can conclude based on the estimated 90 % price drop that LIB battery pack costs will continue to decrease and that their cost-competitive market price will incentivize more global citizens to purchase an EV. Most importantly, a successful implementation of a CE will not only make EVs cost-competitive but cost-beneficial in comparison to internal combustion engines.

Assessment of Category A

Category A focuses on elongating EV battery cell life through its materials and design (Table 1) [10]. Improved materials and design can allow for easier refurbishment of batteries for use. A case where a battery can be refurbished is when an EV is no longer in use (failure, early replacement, etc), but the battery has storage capacity [28]. An EV cell pack is considered viable for reuse with refurbishment if it has not reached 80 % of its capacity [89]. It is designed to not reach capacity until $\sim$ 9 years. The storage capacity decline is not linear. In fact, after its first EV vehicle with a “life span mismatch” can be expected to have half of its design life left. We summarize the goal of category A as advancing battery design and materials for maintenance, reuse, and reuse with refurbishment.

To implement a longer battery lifespans we suggest two parts. The first is ARPA-E early-stage investment matching with venture capitalists into EV batteries with increased storage capacity and safety measures [5, 90]. An EV battery is expected to have a longer lifespan if the storage capacity, energy density, and safety measures improve. The SSBs and ASSBs are a great option for commercialized batteries with a higher energy density and lower risk of failure apart from short circuits [52]. We assert it is optimal for ARPA-E to match investments simultaneously in LIBs, SSBs, and ASSBs with longer lifespans. Investment matching will draw attention from VCs due to the lower risk of a longer-term project with the burden of entering the CELS [33].

We can complement investment matching with a tax incentive on a sliding scale. For 10 years, each EV battery pack reused or refurbished is counted and there is a tax break in which the percentage is dependent on the annual sum. The percentage is highest for reuse and lower for refurbishment. After 10 years this tax incentive turns into a tax. For each EV battery a manufacturer has not attempted to reuse or refurbish there is a tax based on the total count of packs untested. Recent assessments [28] suggest implementing economic incentives, but we expanded upon a specific case. By doing these steps, vehicle manufacturers will drive down the cost of reusing and refurbishing EV batteries as they gain more knowledge and scale up. Thus, matching government investments with VCs will attract more capital into the early development of EV batteries which will have improved safety and longer lifespans. With a sliding scale for tax incentives, manufacturers and their refurbishment counterparts (if not done in-house) are promoted to reuse batteries whose storage capacity is not exceeded and after 10 years are expected to test for the ability to reuse a battery.

Table 1 Summary of policy recommendations for each CIRCULAR category goal

	Goal	Policy Recommendation
Category A	Elongating EV battery cell life through its materials and design[a]	• ARPA-E early-stage investment matching with venture capitalist into EV batteries with increased storage capacity and safety measures[b] • Sliding scale 10-year tax incentive for EV manufacturers to reuse and refurbish batteries in-house or contracted • After 10-year tax incentive, a tax applies for batteries not evaluated for reuse or refurbishment
Category B	Advance battery pack innovation for easier disassembly through its materials and design[a]	• ARPA-E designs a standard battery pack design for LIBs, SSBs, and ASSBs • Federal mandate for planned obsolescence of non-standard LIBs, SSBs, and ASSBs within 10 years from the approval date • Utilize the Chinese innovation model of manufacturer specialization for private partnerships to become experts in niche aspects of the design and function as energy density, capacity, and performance etc...[c] • Eliminate Co and Ni from the standard design for less reliance on foreign imports[d]
Category C	Apply and develop sensing technology to track the health status of EV batteries[a]	• Temporary tax incentive for 15 years as a placeholder to set federal regulations requiring EV manufacturers to adopt this health monitor • Launch the monitor to SERDP/ESTFP as a first market for DOD and military application testing and validation before reaching civilian markets[e] • Alter the health monitor based on arisen issues from the DOD testbed
Category D	Produce a set of analytical tools to measure program impact and inspire growth and creation of small and large firms[a]	• Measure the growth of U.S. manufacturing through each step of the circular EV battery supply chain • Collaborate with DOE to create educational incentives for university and vocational students to enter the energy sector [f] • Create a specialization rank for firms which specifies their level of expertise in niche manufacturing practices [c] • Secure political backing for a innovate here/produce domestically culture[g]

The policy recommendation is based on our innovation policy framework keeping in mind the need for a system of battery waste and recycling and federal recycling regulations

Source:

[a] [10]

[b] [5, 90]

[c] [90]

[d] [12, 36]

[e] [5]

[f] [91]

[f] [35]

Assessment of Category B

Category B aims to advance battery pack innovation for easier disassembly through its materials and design (Table 1) [10]. Pack manufacturing is a part of the downstream circular supply chain. For easier disassembly of a battery, ARPA-E can pair this with easier pack manufacturing using a "fit-form-function" design as suggested by the FCAB [36]. This design would set a standard for different LIB cathode chemistries, SSBs, and ASSBs that fit more seamlessly into a national system of recycling, reuse, and cascaded use [30].

For a "fit-form-function" design it is imperative to eliminate cobalt and nickel. The Co supply chain is a cause for concern due to political instability in the Democratic Republic of Congo and high eco-toxicity [12, 19]. As a byproduct of Ni, Co demand would decrease if Ni was eliminated from the battery materials which incentivizes manufacturers to decrease the cost of each pack through reducing material cost. Also, there is concern about a drop in Ni demand which would create a loss of Co supply. Without Co and Ni, current and future U.S. battery manufacturers can have increased economic security and national defense by not relying on foreign critical minerals.

ARPA-E can develop a standard design for the three battery types for EVs which can be disassembled and cascaded into grid-scale energy storage. There must be a public-private partnership with small and large EV and grid storage battery manufacturers who can agree on a standard design in which each company can still implement slight changes to differentiate them. By no means do we want to eliminate the differentiation of energy density, capacity, and performance of each manufacturer, but instead grow each of their businesses through a standard design that can be implemented into the legacy energy sector. This takes the niche specialization aspect of Chinese innovation and applies it to the battery circular supply chain [90]. ARPA-E can utilize its strength of organization around a common interest for their public-private partnerships [5]. With agreement on a standard design, the federal level can apply planned obsolescence of non-standard LIBs, SSBs, and ASSBs within 10 years of the start date. For SSBs and ASSBs this will be much easier since they are more nascent in their development. Hence, a "fit-form-function" design will allow for differentiation of firms, while establishing a standard that will decrease reliance on foreign mining and refinement, but also drive down the cost and optimize efficiency of assembly and disassembly.

Assessment of Category C

ARPA-E aims to apply and develop sensing technology to track the health status of EV batteries through Category C (Table 1) [10]. Sensing technology can be placed under "hard" technology which may be more difficult to find VC investors for. It may be best suited for the agency to first launch into the military sector. The SERDP/ESTF model would benefit the agency in achieving this goal [5]. The ESTF can use the DOD as a first market for EV battery sensors that are designed not just for EVs but also for battery-powered electronics, drones, and combat equipment. As a first market, ARPA-E can validate and demonstrate the range of use of a battery health sensor, while also fixing any issues before reaching the civilian market. VCs and capital investors will gain interest in the DOD as the first market and support technology transfer into the civilian world for vehicle and EV battery manufacturers.

Next, we recommend a tax incentive to empower EV battery manufacturers, refurbishers, and automobile firms to use the breakthrough technology. This tax incentive set at 15 years serves as a placeholder to set federal regulations requiring manufacturers to adopt this health monitor. Thus, sensing technology benefits both national security and the civilian markets for consumer use.

Assessment of Category D

Lastly, Category D intends to produce a set of analytical tools to measure program impact and creation of firms (Table 1) [10]. We recommend the development of an analytic tool to measure the growth of U.S. manufacturing through a circular EV battery supply chain. In order to meet the needs of a fully functional circular supply chain, there will have to be scale-up and growth of U.S. manufacturing. Manufacturing growth puts positive pressure on the vocational system as well as the university system to empower students into energy sector fields and attract a new audience of students who are interested in tackling the climate challenge [91].

ARPA-E's proposed analytical tool is key to quantifying manufacturer specialization progress. Similar to the Chinese innovation model from Nahm and Steinfeld [90], the analytical tool can measure the specialization of each manufacturing firm and quantify their expertise in separate areas such as EV battery manufacturing, refurbishing, and cascaded use into grid-scale energy storage for just a few examples. Through inter-manufacturing firm partnerships, the manufacturing sector can develop advanced technology and collaboration to find cohesiveness between the separate niches. The domestic manufacturing sector can grow exponentially from achieving expertise in all aspects of the CE for battery waste and recycling. There must be an industrial shift of an innovate domestically, produce nationally mindset [35]. Through a re-imagined mindset, the U.S. can cultivate a self-sustaining ecosystem of a strong technical, manufacturing workforce in the energy sector.

Institutional Gaps to Consider

Front End Gaps

A major front-end institutional gap in the ARPA-E model is the juxtaposition between their disruptive, emerging energy technology which challenges the entry CELS and dominant technology lock-ins. The energy sector is a longstanding sector that prefers incremental changes [5]. Incremental changes have benefited the energy sector because new technology often fits into the existing system and software. While early scientists [92] would argue that the nation can solve climate issues by scaling up existing technology and capabilities, we argue that the current climate status requires more drastic measures [93]. We also assert that the contradiction with innovation policy is a front-end issue because ARPA-E requires bipartisan Congressional support [31]. The current Congressional culture does not have complete bipartisan prioritization of the energy technology challenge [5]. Many are not aware of the drawbacks of a technology lock-in in hindering revolutionary innovation that can benefit the national economy, community, and security [38]. For these reasons, there is a clash of vision outside of ARPA-E forcing leadership and PM’s to defend the agency’s vision.

The ERFCs, energy innovation ’Hubs’, and advanced manufacturing institutes are not at the necessary scale to tackle systematic initiatives. The ERFCs conduct key early-stage development of new technology [75]. The issue lies in the funding. With an annual 3–5 million USD to awarded laboratories and universities, the size of funding is minimal in comparison to the scale of the climate challenge [32]. There needs to be a scale-up of university and laboratory partnerships in addition to funding. We identify that the Hubs that scale up early-stage technology are great partners for the ERFCs. The issue is the proportion of funding for each Hub. Each Hub receives an annual $\sim$ 4 million USD [32]. Similarly, to the ERFC this is not adequate funding to perform validation and demonstration of emerging technology on the desired scale. Lastly, another major front-end problem is the advanced manufacturing institute appropriations. These are funded through the Clean Energy Manufacturing Initiative to create cost-competitive revolutionary technology ready to enter the market on its first day [32]. These institutes are expected to split 70 million USD with other public-private partnerships over a period of 5 years. Overall, we observe that on the front end there is an allocation of funds and scaling issue with the partnerships that cover the “right-left” model from advanced manufacturing, testbeds, and R&D. Without adequate funding, these strong initiatives and institutes will not be able to meet the demands to commercialize ARPA-E breakthroughs at the scale required.

Back End Gaps

After five decades of failed national energy independence through energy technology, ARPA-E takes a new approach to tackle the climate issue, but with current back-end problems facing large hurdles. The first back-end institutional gap is emerging technology acquiring VC support and testbeds. Revolutionary technology has to be not only cost competitive once launched onto the market for it to be adopted and profitable, but the technology also has to be validated and tested before market launch [5, 33]. Despite the need to decarbonize existing infrastructure, many VCs might avoid ARPA-E technology because of the high risk involved in launching technology into a sector that prefers to fit innovation into existing software and platforms. To make matters worse, ARPA-E multi-generational energy breakthroughs are on a longer timescale. They have to find opportunities in an existing market and sometimes accommodate public policy in requiring the energy sector to create flexibility in grid-scale and transportation storage [38]. Thus, traditional VC investments are less common in comparison to the path to launch into a new or growing market.

Solidifying testbeds for prototypes and commercial scale testing and validation is another gap. Since the DOE Office of Science focuses on the front end of basic research funding, they inherently have technology transfer gaps [5]. The valley between basic research and commercialization is being addressed through the ERFCs, Hubs, and advanced manufacturing institutes, but is not at the scale to close this gap [32]. Unlike DARPA, ARPA-E does not have the DOD built into its innovation organization to test and validate developments. Instead, they attempt to amend this gap by utilizing the DOD environmental research program SERDP and ESTCP for R&D and testbeds which strengthen their innovations [5]. The DOD took an interest in energy storage for its military installations, zones, and off-grid activity providing initial markets. Efforts to close the back-end gaps focus on investment matching to lower risk for VCs and using the DOD and military for testbeds and initial markets.

Discussing Proposed Policies Toward Circularity

Raw Materials Production

Raw materials production is at the core of a circular battery economy. California mandates the classification of LIB materials as hazardous based on the concentrations of Co, Cu, and Ni (Table 2) [28]. With the aim to phase out Ni and Co in LIBs, we can focus attention to other critical minerals. We recommend a policy package of regulations on the environmental impact of lithium mining.

As lithium mining companies test and validate less invasive methods to extract lithium it is important that not only the environment is protected, but more critically the communities at risk [29, 39, 40]. There is increasing awareness that lithium mining depletes groundwater sources and alters ecosystems [57]. The Atacama Desert in Chile is one location where lithium mining reshapes diverse ecosystems into salt flats. Depletion of water resources and the destruction of ecosystems displaces communities and drives cycles of poverty. On top of this, there are occupational hazards involved in mining, including tailing pond failures and local water contamination. The many artisanal mining operations involved not just for lithium, but other critical and rare earth minerals, also experience oversight and environmental issues along with legalization and registration hindrances. Communities are directly impacted by water contamination and occupational hazards that harm their health and quality of life, also driving cycles of poverty. The lack of formalization around artisanal mines only amplifies the worsening issues around not only lithium mining, but the general critical and rare earth mineral mining. Considering these issues, we suggest recommendations to plan for a circular economy with communities and environmental mitigation in mind.

Regulations should require lithium mining practices to be accountable for upholding ethics in regard to the community and environment. These regulations can set the standard for a network of inter-firm relationships between domestic critical mineral firms to advance best practices. ARPA-E can initiate relationships between the lithium firms to other critical mineral mining firms so that they can collaborate to improve practices and reduce environmental and community impacts. Sovacool et al. [57] puts forth a few recommendations that align with this study. They recommend that artisanal mines be granted legal access to dormant mines and non-discrimination policies would allow them to support both local and national economies through meeting minerals demands and better governance and safety from legalization. They also suggest acknowledging that transparency and accountability are limited by politics. Even mapping mineral supply chains is affected by policies that govern data access. Their proposals are taken into account when analyzing the path forward.

Combining the suggestions from Sovacool et al. [57] with our proposal for ARPA-E to kick-start inter-firm relationships, a framework that focuses on regional best practices can be key. By focusing on firms cooperating within a region, this may avoid some political issues and refocus on how safety, environmental, and ethical improvements are improved based on geographical differences. We can extend these regional relationships from mining to recycling, reuse/refurbishment, and cascaded use firms. Since raw materials are needed

Table 2 The first column denotes the part of the circular supply chain the initiative falls under

Supply Chain Steps	Initiative	U.S. Current Policy	Policy Recommendations
Upstream	Raw materials production	CA: LIB materials are classified as hazardous based on concentration of Co, Cu, and Ni metals[a]	• Regulations on the environmental impact of lithium mining, promoting less invasive methods and protecting communities at risk • deleted (Tax incentives for domestic companies to extract lithium from domestic sources) • Network of inter-firm collaboration between • added (regional) domestic critical mineral replace(mining firms) (miners) to advance best practices added(Implementation of blockchain to map supply chains[b]
Midstream	Materials Processing	CA, MN: Labeling of battery type based on cathode chemistry and additional notes on safety and recycling status of battery type[a]	• Federal standards for safety labels for each battery type based on hazard to the environment and risk of corrosion, ignition, and combustion • Federal mandate to label the source of materials Planned obsolescence within 10 years of Ni and Co battery materials[c]
	Cell Manufacturing	US: Federal mandate for disassembly ease for non-LIBs with the Federal Mercury- Containing and Rechargeable Battery Management Act of 1996 [d]	• Regulations on the minimum storage capacity, energy density, and lifespan of each cell with updates every 10 years • Update federal mandates for ease of disassembly of LIBs, SSBs, and ASSBs

The second column describes the initiative we aim for through the policy recommendations. The current policy is based on the literature review that was conducted and the policy recommendations are put forth based on the methods in Section "Redesigning Innovation Models for a Circular Battery Economy" to fit into a CE. This first table covers the Upstream and Midstream supply chain steps. CA stands for California, MN represents, Minnesota, NY for New York State, and the US for the United States.

Source:

[a] [28]

[b] [57]

[c] [12, 34, 36]

[d] [94]

for recycling processes and often to repair packs or prepare them for cascaded use, it is important to have contractual relationships between them as well [1]. As far as transparency limited by politics, blockchain could be a great workaround for firms across the nation to record, access, and map their output in the context and scale of other critical mineral mines [57]. In light of these proposals, inter-firm relationships improving practices for the better of communities and the environment on a regional basis while tracking supply chains through blockchains on a national basis may benefit the circular economy.

Materials Processing

Materials processing is an important step in the circular process to label safety hazards, track the source of minerals, and monitor the phase-out of Ni and Co. California and Minnesota mandate that battery types must be labeled based on cathode chemistry (Table 2) [28]. In addition, notes on safety and recycling for each type are added. While this is a step towards standardization of materials processing there are missing pieces. Our recommendation is to set federal standards for safety labels for each battery type based on the hazard to the environment and risk of combustibility, corrosion, and ignition. Having a standardization of safety labels will make disassembly, reuse, cascaded use, recycling, and waste site processing efficient.

To incentivize the growth of domestic critical mineral mining, especially for lithium, there should be mineral source labels on the materials for the batteries so that the domestic mineral production levels can be tracked. This point relates to Category D of assessing the effectiveness of CIRCULAR [10]. A major source of raw materials in the circular supply chain will be the recycling facilities. As seen in Fig. 4, the recycling facilities must have a delivery system to the material processing plants. Finally, with these standards in place and the ability to analyze mining production Co and Ni should be made obsolete within 10 years (Table 2) [12, 34, 36]. This step is an important use of neoclassical tools for induced innovation because it will reduce reliance on Ni and Co from foreign countries and reduce the risk of reliance on minerals from zones of instability.

Cell Manufacturing

Cell manufacturing must have standards for disassembly and updated regulations for specification. The U.S. has set a federal mandate for the disassembly ease of non-LIBs in the Federal Mercury Containing and Rechargeable Battery Management Act of 1996 (Table 2) [94]. There must be an updated mandate for ease of disassembly of LIBs, SSBs, and ASSBs [30]. The updated mandate will create the necessary support for a circular battery economy to integrate the disassembly of battery cells into their recycling, reuse, cascaded use, and waste site processes we observe in Fig. 4. This sets the stage for regulations on the minimum storage capacity, energy density, and lifespan of each battery cell. There must be minimum regulations updated every 10 years for the LIB, SSB, and ASSB which signal to the cell manufacturers that energy innovation must continue to improve. Regulations after standards allow updates to all manufacturing within an existing design framework.

Pack Manufacturing

It is critical for pack manufacturing to have a standard design for assembly and disassembly. The U.S. FCAB intends to develop a federal policy package for domestic pack manufacturing at scale and has set expectations to expedite manufacturing firm expertise (Table 3) [30, 36]. These two steps are important to create a circular system that relies mostly on domestic manufacturing capabilities and continues to deepen its expertise as well as improve manu-

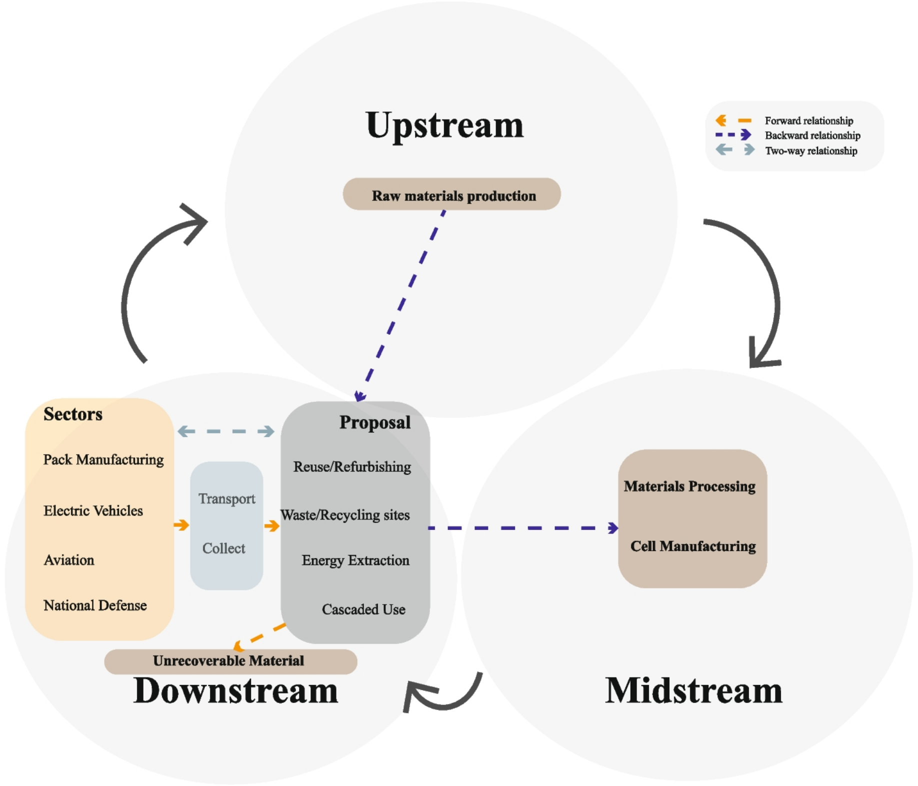


Fig. 4 The figure demonstrates the proposed relationships between components that generate a circular supply chain. We specifically highlight a relationship model between downstream applications of batteries to reuse and refurbishment, cascaded use, and collection for the waste and recycling site system. Another relationship model is between downstream and upstream components which completes the circular supply chain. The orange arrows refer to forward relationships and the navy blue arrows represent the backward relationships in the upstream direction. The gray-blue represents the two-way feedback between components. The light brown color denotes areas of the battery supply chain which are already established and we are not recommending structural changes to. These components are recommended for standardization and regulations, but their placement is not altered

facturing technology. We recommend that the policy package for domestic pack manufacturing set standardization for LIB, SSB, and ASSB pack design that can be assembled and disassembled easily [36].

A regulation that sets a standard battery pack design does not have to be limiting, but in fact, can provide a ’whiteboard’ space for pack manufacturers to develop specificity niche expertise and become valuable assets to the CE through their specialization [90]. The goal of the standard design is not to take away firm autonomy, but to create an ability for packs to be used, reused, cascaded, and recycled from different applications with ease and seamlessly transition between those options (Fig. 4). The ARPA-E improvements in battery design can be utilized to create a standard design ready for hand-off at the end of CIRCULAR.

Table 3 Downstream (1/2): The first column denotes the part of the circular supply chain and the second column describes the initiative we aim for through the policy recommendations

Supply Chain Steps	Initiative	U.S. Current Policy	Policy Recommendations
Downstream	Pack Manufacturing	• U.S.: FCAB intends on developing a federal policy package for domestic pack manufacturing at scale[a] • Intentions to expedite domestic pack manufacturing expertise[a]	• Standard LIB, SSB, and ASSB battery design that is easy to assemble and disassemble • Ability to customize the standard battery design for companies to have specific niche expertise
	Electric Vehicles	US: No current mandate only a classification for battery lifespan and range (DOE Office of Energy Efficiency and Renewable Energy classifies the current range of BEV as 100–400 miles per single charge and up to 60 miles per single charge for PHEV for a lifespan of 12–15 years with manufacture warranty an average of 8 years/100,000 miles[b]), but intentions to continue to drive down EV battery pack cost while increasing range, capacity, and durability[c]	• Government matching of investments into early-stage technology to reuse and refurbish EV battery packs • Mandate for EV manufacturers to have contracts with an EV reuse/refurbisher and cascaded use facility • Sliding-scale tax incentives for 10 years with follow up 10-year tax fee for EV battery reuse or refurbishment • Implement the EV health monitor with a 15-year tax incentive for manufacturers which implement this safety measure
	Stationary Storage	CA: Intentions to cascade battery packs from EVs to stationary grid storage at scale[d]	• Federal mandate for each EV battery manufacturer to have a cascaded use partner • Standard design for battery cells and packs optimal for cascaded use

The current policy is based on the literature review that was conducted and the policy recommendations are put forth based on the methods in Section "Redesigning Innovation Models for a Circular Battery Economy" to fit into a CE. CA stands for California, MN represents, Minnesota, NY for New York State, and the US for the United States.

Source:

[a] [36]

[b] [89]

[c] [6, 36]

[d] [28, 38]

Electric Vehicles

There is a critical need for EV battery packs to be reused, refurbished, or cascaded for stationary storage in addition to health monitoring. Currently, there is no mandate for EV battery lifespan and range, but the DOE Office of Energy Efficiency and Renewable Energy sets classifications for BEV and PHEV ranges and lifespan (Table 3) [89]. Both BEVs and PHEVs are expected to have energy capacity for 12–15 years, though manufacturer warranties only guarantee 8 years. A BEV can last 100–400 miles per single charge while a PHEV drives up to 60 miles on a single charge. Through the CIRCULAR program, ARPA-E aims to increase the range and lifespan of the EV battery [10]. To fulfill longer EV battery lifespans and increase range while integrating into a circular battery economy, we recommend that the government match investments into early-stage technology for reuse and refurbishing of EV battery packs. Government matching of investments creates the support necessary for venture capitalists to flock to early-stage technology while also providing a pathway to commercialization through DOD testbeds and DOE Hubs [90]. This support allows commercialized scale-up of reuse and refurbishment technology before a 10-year tax incentive for vehicle manufacturers applied to the attempted reuse and refurbishment of EV batteries. It will work on a sliding scale based on reuse or refurbishment. The tax incentive will prompt EV manufacturers to test each battery for the possibility of reuse or refurbishment. After the 10-year tax incentive there will be a 10-year tax penalty for EV manufacturers who do not evaluate EV batteries for reuse or refurbishment. These pair of tools are meant to induce the creation of an evaluation system for EV batteries for reuse and refurbishment.

Battery health monitoring of EVs continue to pose cost and consistency issues which can be diminished through emerging rapid tests and classifications. Current issues vary from untimely and financially consuming tests which are a factor into reuse, refurbishing, and cascaded use costs [95]. Secondly, the main characteristics tested for are capacity and internal resistance, but these do not provide a complete analyses on the continued battery performance and often misses risk factors. It is imperative that there is consistency of high-performance batteries for reuse, refurbishment, and cascaded use and that monitoring systems are reliable. Experts [95] identified four main characteristics to test EV batteries for including charging capacity, electrolyte concentration, and two diffusion capabilities that monitor charging and discharging rates. Given that ARPA-E aims to create an EV battery health monitor it is important to prioritize these characteristics in a rapid test. This rapid test must include value ranges, standard for each cathode chemistry for an LIB and across other battery types as fuel cells, NiMH, SIBs, and RFBs [3, 56, 60, 64, 95]. When the test is run and a value is outside this range, there should be automatic warnings and pending on the severity of the difference some batteries may automatically head towards the three main recycling processes. A 15-year tax incentive applied to manufacturers to adopt the monitoring system and implement it as a safety measure through the lifespan and to gauge them for reuse and refurbishment allows integration into a CE [10]. Potential issues with integration include oversight. There must be a governing body within the DOT that approves and oversees the health characteristic ranges and enforces these standards amongst companies engaging in manufacturing, reuse, refurbishment, and cascaded use. With these steps, EV batteries can be placed into the CE with support and induce innovation for health monitoring.

Stationary Storage

The cascaded use of EV batteries for stationary storage is integral for a circular battery economy. No federal mandates or regulations exist to cascade EV battery packs to grid-scale energy storage (Table 3). In Fig. 4, we suggest that ARPA-E creates a relationship model between EV manufacturers and cascaded-use facilities that manufacture stationary storage for grid-scale energy. A model of this relationship can be created using the existing support mechanism of ARPA-E partners and firms that emerge from previous projects. The relationship model can be handed off to the DOT for a federal mandate to require EV manufacturers to have a cascaded use facility partner. Before hand-off to the DOT for regulation the agency must identify institutional gaps in the DOT that would prevent a cascaded use requirement and utilize time before hand-off to collaborate on strategies to overcome those.

Another piece to achieving cascaded use of EV batteries is having the standard design for battery packs. California has demonstrated the use of stationary storage at scale with success at rapid construction and setup [38]. California bill AB2514 prompted grid-scale energy storage at 84.5 MW which has been mandated to increase another 500 MW [38]. We mention this specific case because having a standard design could increase the speed of completing storage facilities. A standard design also removes complexities when integrating into a CELS and creating mandates that the Federal Energy Regulatory Commission (FERC) can agree to [30, 43]. The standard design will allow for ease into a transition for grid-scale energy storage built rapidly and integrated into a CE.

There are arguments that the future of other battery types may reach large enough production volumes based on demand to be cost-effective despite the LIB market dominance. Previous [44] and recent [3] publications inform that grid-scale battery packs can withstand low energy density. Based on these findings, other battery solutions such as RFB, sodium-ion, or lead-acid batteries could be applied to energy storage systems. Of these, aqueous and nonaqueous RFBs have high risk and cost, while the all-vanadium RFB, lead-acid, and sodium-ion are lower risk. Particularly with the RFB, the ability to design the energy density and capacity separate is an advantage [3]. Despite some RFB deployments in Austrailia, U.S. and China, the high power and high efficiency of the LIB along with the key federal push and state pull supporting its integration into grid-scale energy lend itself for more rapid adoption.

Cascaded use of EV batteries can become cost-effective and more sustainable with extended lifetimes of the grid-scale packs. By externally adding Li salt using a common electrolyte to existing cells to produce extended lifetimes, the battery station requires less pack replacements [73]. At less than one US dollar to inject Li supply for the example LFP cell, annual operational and maintenance costs are heavily reduced. In the present battery storage market, reducing manufacturing costs and overheads while increasing production volume and introducing more competitors into the market are known to result in cost efficiency and lower fixed material cost [44]. Thus, externally re-supplying Li salts to the grid-scale battery cells can directly minimize variable costs of pack replacements and refurbishments associated with overhead costs. Annual operational costs become cost-efficient as well with less purchases of grid-scale packs. This innovation may stir increased production of Li salt and introduce market competitors which can drive down the cost from less than one US dollar to a value closer to zero based on Theodore Wright's hypothesis [96] of the power law decline of cost versus cumulative production.

National Defense

A standard design for LIBs, ASSBs, and SSBs improves battery applications for national defense. We disclose in Table 4 how the FCAB sets goals to apply a ’fit-form-function’ battery design for DOD and military markets [36]. While we realize that the standard design goes beyond DOD and military use cases, this provides an opportunity for first-market testbeds and validation. Using the SERDP/ESTCP model we can provide the standard design with on-site testbeds for the ARPA-E technology before hand-off to a DOE manufacturing institute for further development and adjustments based on military feedback [5]. The ’fit-form-function’ design catalyzes future development for defense applications and as certain elements are eliminated can reduce geopolitical risks associated with supply chains.

Table 4 Downstream (2/2): CA stands for California, MN represents, Minnesota, NY for New York State, and the US for the United States

Supply Chain Steps	Initiative	U.S. Current Policy	Policy Recommendations
Downstream	National Defense	US: FCAB intentions to apply a "fit-form-function" design for DOD and military markets[a]	• Use the SERDP/ESTCP model for initial testbeds and validation for the standard design • Design must meet off-grid requirements • added (Reduce geopolitical risk by eliminating Co and Ni in the standard design) [b] • add (Learn and improve upon Li recycling techniques from China and Korea) [c]
	Aviation	US: FCAB mentions agenda to implement LIBs into the aviation sector starting in 2028[a]	• Safety standards for aviation powered by a LIB, SSB, and ASSB • ARPA-E developed battery health sensors used to monitor lifespan and health status
	Collection	• CA, NY, MN: Manufacturer is responsible for collection of spent batteries[d] • Call2Recycle: US and Canada based program which battery manufacturers fund to collect at no cost to the consumer and recycle in South Korea[e] • Big Green Box: Collection company at a cost to the consumer who must ship their personal rechargeable product[e]	• Federal system to collect batteries at no cost to consumers for portable electronics • No cost pickup for the EV, aviation, and stationary storage sector
	End-of-Life Recycling	US: 97 % of lead-acid batteries recycled and high recycling rate for nickel-cadmium and lithium-sulfur packs, target to create circular supply chain by ARPA-E and executive initiative to create a CE[f]	• Federal system of recycling sites based on the population in a region, city, or state. Each site should be contracted to private firms with a multi-directional approach to obtain expertise on recycling of all current and future battery types • Cap-and-trade of raw materials into recovery systems to obtain low-intensity processes.

Source:

[a][10]

[b][12, 57]

[c][59]

[d][13, 97, 98]

[e][13]

[f][6, 26, 34]

Elimination of Co and Ni will minimize geopolitical risk in the global supply chain. The Democratic Republic of the Congo continues to face the aftershocks of lengthy conflict [57]. Compounded with unsafe and illegal working conditions, high human health damages, and inequitable treatment of women and children, moving away from reliance on cobalt and nickel may signal that domestic supply chains will not continue to support ill treatment of workers [12, 57]. Currently, the region produces about 64 % of global Co [57]. Moving away from these critical minerals also provides security for the supply chain and removes reliance on instable flows. Another aspect to geopolitical risk is assessing international competitors and partners.

The U.S. will never be 100 % removed from global trade of critical and rare earth minerals. For this reason, it is key to understand current international competitors and partners. China produces a significant fraction of many of the world's critical minerals including Mn, Co, and C [12] and Korea locates many successful recycling facilities [59]. This is not expected to change in the near future. While there are increased lithium mining efforts in the U.S. in areas such as Thacker Pass, Nevada and the Satlon Sea, it may not meet all of future demand [39–42]. Something that the U.S. can learn from China and Korea, are cost-efficient methods to yield Li from recycling processes for cathode compounds [59]. We propose that recycling facilities begin to learn and improve Li recycling methods from these competitors and partners in order to scale-up Li reycling across the U.S. and reduce reliance on Li supply. Although, the U.S. must always continue strong ties to foreign partners for supply, we can reduce this reliance and even scale-up manufacturing within the states.

The institutional gaps the manufacturing institutes face must be addressed before technology transfer of a standard battery design. In Section "Institutional Gaps to Consider" we cover how funds and scaling pose a front-end issue [32]. While funding is often an issue with many initiatives, scaling does not have to be. We propose that regional coalitions of private partnerships could advance the scale of manufacturing institutes without burdening individual firms. Regional coalitions enable cooperation and promote transparency and data accessibility needed for the complex issue of a CE.

Aviation

A future prospect of LIB, ASSB, and SSB is the aviation sector which should prioritize safety regulation. Figure 4 illustrates how in the long-term, the FCAB intends for LIBs to be integrated into the aviation sector with the beginnings of its implementation in 2028 (Table 4) [36]. We put forth a few recommendations to help this transition. The first is to set safety standards for aviation powered by a LIB, SSB, or ASSB. These safety standards are a policy package that will set the stage for DOT regulation of passenger and industrial electric-powered aviation. As a part of the safety standards, ARPA-E can collaborate with future all-electric or hybrid aviation firms to test and validate the battery health sensor for aviation application [10]. Based on the results of the testing and validation, improvements can be made to the technology before commercialization at scale across all passenger and industrial aviation firms.

Collection

The circular battery economy would not be possible without the collection of used consumer and firm batteries. California, New York, and Minnesota mandate that the manufacturer is responsible for the collection of spent batteries (Table 4) [13, 97, 98]. This system has not been met with the level of success required to collect used consumer batteries at a scale necessary to complete a CE. Call2Recycle is a U.S. and Canada-based program funded by battery manufacturers to collect at no cost to the consumer, but recycling is outsourced to South Korea [13]. The foundation of battery manufacturers funding a collection company is a strong initiation, but the outsourcing of recycling draws critical minerals away from the U.S. and Canada which could be used for domestic manufacturing. In addition, the Big Green Box is a collection company that charges the consumer to pay for shipment of the personal rechargeable product [13]. Despite the scalability of the private Call2Recycle with adjustments for domestic recycling, we suggest a complete rethinking of the collection system. We offer a recommendation for a federally managed collection system (Fig. 4). The program would be free for consumers to dispose of portable electronics. Vehicle manufacturers and dealerships, DOD testbeds and military bases, battery refurbishers, reuse facilities, aviation manufacturers, and stationary storage facilities would have a collection bin with free pickup of materials. All collections are scalable for consumers and firms with coordination of the DOT and states.

End-of-life Recycling

A circular battery economy would not be possible without recycling and a national system of sites that uphold standards and continue to innovate recycling practices. Presently, almost 100% of lead-acid batteries are recycled in the U.S. which is complemented by a high recycling rate of other hazardous batteries including nickel-cadmium and lithium-sulfur (Table 4) [26]. The ARPA-E agency as a whole aims to create a circular supply chain for recycled batteries to fuel the manufacturing of new batteries for EVs, stationary storage, and more [6]. We can analyze policies abroad to assess various strategies. The European Union (EU) battery passport mandates a 70% minimum recycling rate of lithium-based batteries by 2030 and gradually introduces more stringent minimums for critical mineral recovery and emission [99]. This initiative sets the standard for all EV and industrial batteries with a capacity above 2 kWh with the creation of a digital passport, data transparency, and required technical documentation. The battery passport model will feature a unique code along with information about the model, durability, performance, type, GHG emissions, and hazardous substances, among other critical factors. Thus, a national infrastructure built upon standards and continual innovation are key to a successful CE, but we must look to what a recycling system can look like.

In order to fulfill these goals, we must have a federal system of recycling sites based on the population in a region, city, or state (Fig. 4). Each recycling site should be contracted to at least one private recycling company with support for both small and large firms. These firms must sustain inter-firm relationships for a multi-directional approach to gain expertise in systematic battery recycling for all current battery types and frontier types as well. A federal regulation package across the DOE, EPA, and DOT will achieve a system of federally managed recycling sites using existing mechanisms to manage hazardous waste in the U.S.

These sites should conduct energy extraction before recovering materials that can be used to supply an extra source of power to the facility [28]. Firms can collaborate to automate specific processes of the recycling steps and to target areas of improvement for quality and efficiency. This federal system with private partnerships and multi-directional approach to continuously advance recycling technology to include newly commercialized battery markets can achieve success more rapidly through unpredictable markets.

To ensure progress, we address areas of improvement for recycling facilities as a whole. We underline one area of improvement for the contracted recycling firms which is reducing the amount of raw materials needed for the process. After the recycling system is in place, a cap-and-trade will limit the amount of raw materials used in the recycling process and induce innovation of less intensive recovery processes. By using the cap-and-trade system the federal mandates can decrease the cap every 10 years to incite more innovation. Another area of improvement is recycling capacity and system scale. Tankyou and Hall [100] illustrates the locations of LIB recycling plants, material production, and EV production plants in the U.S. with 8 operational recycling facilities and 10 announced for future operation. Their forecast of recycling capacity versus the end-of-life EV batteries (only accounting BEVs and PHEVs, excluding HEVs) imparts that the installed capacity of 101, 150 t as of September 2023 will sustain the spent batteries till 2036. As for the installed and announced capacity of 652, 293 t, it can withstand the expected feedstock until 2044. Recycling capacity will need to exceed that of the year 2044 which entails scaling up the existing and announced plants as well as the construction of new ones. Decentralization of the new plants is also key to minimize long-hault transport (Section "Transportation of Waste"). Overall, we suggest that recycling capabilities should minimize the need for raw material input and scale-up existing, announced, and future recycling facilities in all regions of the U.S. for a decentralized system.

Landfill

We propose policy recommendations to eliminate battery waste in landfills and minimize risk to the groundwater, soil, and surrounding communities. California instated the WET procedure for LIBs to deem them as hazardous based on the exceeded concentration of critical metals as Ni, Co, Cu, Pb, Al, and Li (Table 5) [13, 14, 101]. This WET procedure is much more stringent than the previous federal TCLP test set by the EPA [13, 14, 102]. The TCLP test was originally based on 1986 water standards but has not been updated since 1992 [102]. The TCLP organizes waste by hazard characteristics and does not outright deem LIB waste as hazardous, but instead deems it hazardous on a case-by-case basis. The EPA announced a planned amendment to the Codes of Federal Regulation (CFR) to create a new category for LIB waste based on cathode chemistry and safety risk [102]. Alongside these procedures, California, New York, and Minnesota banned LIBs from entering the landfills without any penalty for non-compliant actors [13, 97, 98]. Thus, there needs to be a system of waste sites to which states are compliant.

We recommend a system of federally regulated waste sites paired with the recycling sites to properly dispose of battery waste in a secure, underground structure (Fig. 3). These decentralized locations overcome issues with centralized waste storage and transportation for case studies such as Yucca Mountain Nuclear Waste Repository [103–106]. When energy or materials cannot be recovered further from battery cells and packs they should

Table 5 The first column denotes the part of the circular supply chain the initiative falls under

Supply Chain Steps	Initiative	U.S. Current Policy	Policy Recommendations
Landfill	Eliminate	• CA: Uses the WET procedure to deem LIB waste as hazardous based on the exceeded concentration of critical metals such as Ni, Co, Cu, Pb, Al, and Li[a] • US: EPA conducts the TCLP test for characteristically hazardous waste and is in the process of altering the CFR to create a new category for LIB waste based on cathode chemistry and safety risk[b] • CA, NY, MN: Bans on LIB entering the landfill without penalty for noncompliant actors[c]	• Federal ban of LIBs in landfills • State level tax penalty based on concentration of LIBs in landfills • Update TCLP limits according to new drinking water standards and toxic soil limits • Federally regulated underground mixed waste site paired with the recycling facility[d]
Transportation	Standards and Regulation	DOT Pipeline and Hazardous Materials Safety Administration bans LIBs on passenger rail and aviation[e]	• Federal regulations of heavy-duty vehicles and commercial rail to transport hazardous material to the federally managed recycling and waste sites • Packaging standard for battery waste to reduce fire hazard and fumes[f]

The second column describes the initiative we aim for through the policy recommendations. The current policy is based on the literature review that was conducted and the policy recommendations are put forth based on the methods in Section "Redesigning Innovation Models for a Circular Battery Economy" to fit into a CE. CA stands for California, MN represents, Minnesota, NY for New York State, and the US for the United States.

Source:

[a] [13, 14, 101]

[b] [13, 14, 102]

[c] [13]

[d] [19]

[e] [110–113]

[f] [21]

be disposed of under a controlled process to ensure environmental integrity [29]. Having this system run by DOE, EPA, and DOT has not been contributed as an idea in the literature review conducted due to the complexity of clearly defined budgetary lines, resolving institutional gaps, and overcoming the lack of collaboration between agencies. These barriers to initiating and continuing a system of waste and recycling sites led to a reluctance for the initiative.

The system of federal waste sites would create a system that allows for conventional policy packages that regulate current and future battery-type waste. An important regulation is the federal ban on LIBs in landfills. Next, is an update to the EPA's TCLP based on the most recent drinking water standards and toxic soil limits. There also should be state-level tax penalties based on the battery material in landfills instated once the federal ban is enacted. The tax penalty will be a sliding scale based on the concentration of battery material.

Transportation of Waste

Transportation of end-of-life LIBs to the waste and recycling sites is a valuable piece of circularity where there are near future actionable strategies to reduce cost, emissions, and health impact while adhering to federal safety regulations. A major consideration when transporting end-of-life batteries is the cost. The estimated cost of end-of-life LIB transportation is between 0.24 USD/kg [107] and 5.51 USD/kg [108] across 13 publications from $2014--2020$ [23]. Wtih an average cost of 1.54 USD/kg [23], transportation consumes about 41% of recycling cost. This high percent of associated recycling costs indicates that alternative, lower emissions modes of transport are required to integrate LIBs into a CE.

Emmissions and related health impacts of current modes of transport cause pause when preparing for scaled future infrastructure. Ciez and Whitacre [59] performed an assessment on the impact of transportation on the on GHG emissions during a study which yielded that collection and transportation of spent batteries, by mode of heavy-duty vehicles, produces 0.23 kg of CO_2e per kg battery. Transportation accounts for $\sim 2.45\%$ of total emissions that go into the LIB lifecycle for pyrometallurgical processes and $\sim 2.8\%$ for hydrometallurgical and direct cathode recycling. They assumed a distance of $2,500$ miles and some recycling facilities are located near EV manufacturing plants and when adjusting inputs distance and emission inputs there was only a minor effect on the yield. Moreover, with truck transport as a root cause of 99% of particulate matter, 54% of SO_2, and 62% of volatile organic compound human health damages we must find alternate, lower emissions transport modes [109]. It is possible to find alternate modes within regulation.

We adhere to the DOT Pipeline and Hazardous Materials Safety Administration bans LIBs on passenger rail and aviation (Table 5) [110–113]. With these regulations in mind, the DOT can mandate a mix of heavy-duty vehicles and commercial rail to transport hazardous battery waste to the recycling and waste sites. A California study [109] approximated a 23–45 reduction in GHG emissions pending on the mix of rail and heavy-duty modes. This is an actionable change which can still have coordination with consumer collection points, private firms, EV manufactures, and grid-scale storage (Fig. 3). When transporting, safety regulations and packaging standards must be met to prevent fire hazards and fumes as the ones investigating by the EPA at landfills and material recovery facilities [21]

Conclusions

ARPA-E contains the capability and capacity to achieve a circular battery supply chain as a prerequisite to a CE. At its core, the applied DARPA model to energy gives substantive grounds for a successful technology transfer and commercialization scale-up for each program [5]. Here, we propose how the agency has the capacity to implement a circular supply chain at scale through its community of small and large firms, dedicated VCs, growing relationships with DOE front-end programs, and relationship to DOD testbeds for validation and demonstration. Despite the challenge of implementing a new approach to battery technology lifecycles into a CELS, ARPA-E has the tools to gain capital investments into early-stage technology and public-private partnerships to launch into commercialization. We submit strategies to close the front-end and back-end gaps with more outside advocacy for a unified Congressional prioritization of the clean energy challenge, funding to the front-end DOE programs, non-traditional VC investments, and use of the DOD testbeds [32]. These possible solutions can propel the agency projects into commercialization. Simultaneously, the community and its partners can lobby for a standard Congressional package that includes policy recommendations proposed in this paper to force the existing energy sector to allow opportunities for disruptive, systematic battery technology.

We introduce linking the battery supply chain from upstream to downstream into a national system with federal regulations and standardization for battery recycling, reuse, and cascaded use to implement a CE system. The elements of the national system are linked by public-private partnerships and state-level pulls to have national recycling and waste locations for each city and region which are connected to battery manufacturers, reuse and refurbishing facilities, cascaded stationary storage, and energy recovery. Our proposed system closes gaps in the supply chain with infrastructure backed by the necessary neoclassical tools and support mechanisms to transition the U.S. to a CE. The U.S. can fulfill a self-sufficient system that provides a strengthened workforce, economic security, independence from foreign critical minerals, and a clean-energy grid through a national waste and recycling system.

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Supplementary Tables 1 and 2 are in the supplementary information file. Our first table clarifies the main cathode chemistries that define a lithium-ion battery. The second table contains the acronym and phrase descriptions referred to in the main text.