ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Machine Learning-Enhanced Acoustic Inspection to Improve Battery Manufacturing

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Finally, this accomplishment would not have been possible without the dedication, resilience, and brilliance of the entire Feasible team. Through challenging periods and ambitious goals, their passion and commitment to Feasible's mission have been the driving force behind this achievement.

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency; renewable energy and advanced clean generation; energy-related environmental protection; transportation; and energy transmission and distribution.

In 2011, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned electric utilities — Pacific Gas and Electric Company, San Diego Gas & Electric Company, and Southern California Edison Company — were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs to promote greater reliability, affordability, and safety for California electric ratepayers. EPIC investments advance these values by:

- Providing societal benefits.
- Reducing greenhouse gas emissions in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs, first with energy efficiency and demand response, next with renewable energy (distributed generation and utility-scale projects), and finally with a clean electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Machine Learning-Enhanced Acoustic Inspection to Improve Battery Manufacturing is the final report for EPC-20-020 conducted by Feasible, Inc. The information from this project contributes to the CEC Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

Over the past decade, battery costs have declined significantly due to advancements in design, economies of scale, and automation. Yet, lithium-ion batteries remain too costly for widespread adoption of electric vehicles and renewable energy storage systems. As battery cells become larger and more energy-dense, traditional electrical inspection methods are increasingly limited — they struggle to detect the small manufacturing inconsistencies that can lead to major performance issues, reduced yields, and higher costs. These inefficiencies represent an estimated $6 billion annual challenge based on 2022 production volumes. There is an urgent need for next-generation inspection technologies that can be deployed effectively in modern gigafactories.

Feasible's EchoStat® platform is a breakthrough inspection technology that addresses this need by enabling real-time, nondestructive detection of process issues upstream — where they occur — rather than at the end of production. It leverages ultrasound and advanced data analytics to fill a critical gap left by today's leading quality-control methods. This innovation focuses on improving productivity, throughput, and yield in battery cell manufacturing — key factors in enabling the rapid scale-up of electrification. By providing earlier insights, EchoStat can accelerate yield ramps by up to two times and increase steady state production yields by 5 percent in high-volume manufacturing environments.

When the California Energy Commission BRIDGE project began, Feasible's technology was at Technology Readiness Level 4. Over the course of the project, the team designed, built, deployed, and demonstrated the technology across cell prototyping, pilot, and production-scale facilities to validate its techno-economic value. By the project's completion, EchoStat successfully reached Technology Readiness Level 7 — demonstrating commercial readiness.

As a result, Feasible secured multiple new customers, including a major European cell manufacturer, where EchoStat was successfully integrated in-line at a gigawatt-hour-scale production facility. The company has since raised follow-on investments from both financial and strategic investors, enabling continued expansion of Feasible's customer footprint and accelerating the impact of this transformative technology.

Keywords: ultrasound, acoustic, electrochemistry, quality control, batteries, electric vehicle, EchoStat, lithium-ion, sodium-ion, lithium-metal (Li-metal), zinc-based

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Background

Governor Newsom issued an Executive Order in September 2020 that required all new passenger vehicles sold to be zero-emission by 2035 and announced that the State of California will aggressively move away from reliance on climate-change-causing fossil fuels. The transportation sector is responsible for more than 50 percent of carbon pollution, 80 percent of smog, and 95 percent of toxic diesel emissions in California. As a result, disadvantaged and low-income communities in Los Angeles County and the Central Valley breathe some of the most toxic air in the country.

Moreover, California investor-owned utility electricity ratepayers are increasingly vulnerable to power outages due to electrical equipment and infrastructure failures, wildfires, earthquakes, and landslides. Currently, California is battling the twin threats of extensive wildfires and the corresponding power outages and shutoffs that result from such fires or attempts to reduce them. The most promising and effective California Public Utilities Commission strategies to counter these threats are: (a) expanded deployment of renewable distributed energy resources, especially microgrids, (b) policies and insurance to incentivize residential solar-plus-battery power to increase grid resilience, and (c) energy efficiency and demand management initiatives.

Lower-cost and more reliable batteries are a critical part of the solution to both the transportation and power grid problems, as they enable widespread adoption of electric vehicles and renewable energy storage. While there are many efforts to develop new battery materials, there is a significant opportunity for near-term impact by improving the cost, efficiency, and reliability of battery manufacturing — particularly as it relates to process inspection. As cells (the smallest individual units of batteries) have grown in size and energy density, standard inspection methods are less sensitive to physical variations that affect quality. There is a critical need for breakthrough inspection technologies that can be practically deployed for superior battery production.

Feasible, Inc. is commercializing a machine-learning-driven battery inspection platform, called EchoStat®, that uses ultrasound and data analytics to fill a gap in today's leading methods. This California Energy Commission project focused on demonstrating EchoStat's ability to detect manufacturing issues earlier and with more sensitivity than standard methods at cell prototyping, pilot, and production lines. EchoStat enabled reduction of battery production costs by detecting defects and process variations earlier in production and with greater sensitivity than state-of-the-art methods. Feasible, Inc. validated its techno-economic value proposition, first at a cell prototyping scale and then in pilot production. EchoStat products were also deployed in-line at a gigawatt-hour-scale factory in Europe. When scaled, EchoStat will improve the quality, safety, and performance of batteries and significantly decrease battery costs, all of which are crucial for broad adoption of electric vehicles and renewable energy storage systems.

Project Purpose and Approach

The goal of this project was to demonstrate EchoStat's capability and techno-economic value on battery pilot and production lines in detecting manufacturing issues earlier and with more sensitivity than state-of-the-art methods**.** The insertion point for EchoStat in cell manufacturing was and continues to be in cell (the smallest unit of a battery) finishing processes (specifically, electrolyte fill, formation, aging, and quality control) at cell prototyping, pilot, and production lines. The project team demonstrated how EchoStat creates significant value by quickly delivering actionable insights to improve yield and process time and lowering developmental iteration time.

Through pilot- and production-scale demonstrations on industry-relevant cells, the project team: 1) showed how EchoStat creates value in production environments, 2) clearly defined system requirements and a roadmap for commercial adoption, and 3) secured follow-on commitments to support deployment of EchoStat at multiple customer sites.

The technology's value proposition hinges on its ability to detect subtle process issues earlier and/or with greater sensitivity than state-of-the-art methods. Feasible, Inc. deployed EchoStat systems at cell prototyping lines and offline at the pilot facilities of cell- and auto-maker partners to collect large datasets on hundreds to thousands of cells as they go through cell finishing process steps. By comparing EchoStat results to standard electrical methods and computed tomography (CT) scans (collected alongside) and correlating to cell performance metrics, the team successfully demonstrated that EchoStat can improve yield and process time at a pilot production scale and beyond.

Below are a few key target metrics that were achieved in this project.

- It reduced battery manufacturing yield ramp by over 50 percent.
- It reduced production cycle time by over two weeks.
- It demonstrated yield for pilot production by 10 percent.
- It improved EchoStat system cost and cell scan time by greater than (>) $5 per kilowatt hour (kWh) and >15 seconds per scan, respectively.

Key Results

This project aimed to scale EchoStat technology to deploy and eventually sell products into cell manufacturing facilities. To do that, the team worked with cell manufacturers at different scales and validated value propositions. With feedback from customers, Feasible defined the product system requirements, built a business case, and refined the commercialization roadmap.

First, Feasible engaged partner customers to do an evaluation project. The goal was to validate that EchoStat technology could solve a key challenge for them. Then, based on the requirements of the measurement (for example, cell geometry, process conditions, correlation to performance, and throughput) the team designed and built the EchoStat ARRAY system, a highspeed battery inspection system that uses the EchoStat technology to inspect prismatic and pouch battery cells of varying dimensions, for both offline and in-line implementation.

Over the course of the project, four main value propositions were defined, tested, and validated at partner customer sites.

1) Decrease Process Time

Goal: Reduce electrolyte soaking time during cell finishing.

EchoStat enabled real-time monitoring of electrolyte saturation in pouch and prismatic cells at a leading electric vehicle original equipment manufacturer (OEM). Data from acoustic scans showed when saturation was complete, allowing operators to cut soak times by 50 percent — from 24 hours to 12 hours — without compromising quality.

2) Detect Process Errors Early

Goal: Identify underperforming or defective cells before formation.

EchoStat scans during soak stages were able to flag outlier cells by up to 95 percent earlier than conventional post-formation electrical testing. In a pilot project with a sodium-ion cell maker, the system achieved > 85 percent accuracy in identifying poorly soaked cells. These findings were verified by downstream performance and CT imaging.

3) Predict Cell Performance

Goal: Forecast cell performance (for example, cycle life) at the end of line (EoL) using EchoStat data post-formation.

At multiple customer sites, EchoStat's machine learning (ML) models predicted cycle life with 80 to 98 percent accuracy across various chemistries and form factors. For example, in Li-metal cells, the mean absolute error of prediction was just 14 percent. These insights enabled faster process tuning and yield ramp-up.

4) Accelerate Quality Assurance/Quality Control

Goal: Replace slow, costly Quality Assurance tests with high-speed in-line scans.

EchoStat replicated insights typically obtained through nine-day electrochemical testing in under 10 minutes. In cylindrical cells, high-speed scanning identified EoL anomalies and defects, with suspect cells routed for higher-resolution secondary scans. This enabled manufacturers to screen 100 percent of cells with confidence.

Knowledge Transfer and Next Steps

Feasible published technical white papers and conference talks/papers based on the work performed during this project. As this is a new and innovative technology, the battery community is not very familiar with Feasible's ultrasound and data-analytics-based cell inspection platform. As such, one goal of the project was to educate the industry and stakeholder community through outreach at relevant conferences (technical, industrial, and policy-related meetings) and through one-on-one discussions with essential stakeholders (customers, potential licensees, and strategic partners). Specifically, the technology/knowledge transfer activities included: (1) white paper and case studies based on process insights and improvements facilitated by EchoStat during electrolyte fill/soak as well as EoL anomaly detection, (2) presentation materials to share at various conferences like the International Battery Seminar & Exhibit and the Battery Show North America on the knowledge gained and anonymized deployment results, and (3) high-quality digital photographs of EchoStat being used at a battery pilot production facility that were shared on LinkedIn, YouTube, and other social media. Feasible also shared key components of the project and lessons learned, customer validation of industry pain points, and EchoStat's techno-economic value proposition.

Additionally, Feasible developed business cases for early product offerings: offline systems for either cell prototyping or process development settings. The team also performed strategic analyses of the outcomes of engagements with key partners, customers, and partnership plans to facilitate commercialization. By the end of the project, Feasible sold and integrated its first in-line fully automated EchoStat ARRAY system into a major European cell manufacturer's first cell production facility in Sweden.

Feasible's intellectual property portfolio was expanded during the course of the project and currently has a total of 24 patent families, with 11 issued in the U.S. and various other global jurisdictions.

With the BRIDGE project research and demonstrations, Feasible is positioned to have a major impact on the cell quality and yield improvement of battery cell manufacturers and electric vehicles and energy storage systems original equipment manufacturers worldwide. By implementing EchoStat technology in major pilot lines, next-generation cell development can be accelerated to create higher-capacity, lower-cost, longer-lasting, and more reliable battery cells. Furthermore, this technology can speed up the ramp-up phase for new gigafactories and rapidly improve cell yields on existing production lines. The results of these processes and reliability improvements will result in safer, higher-capacity, and lower-cost batteries, making greater adoption of electric vehicles and battery-based energy storage for renewable energy sources more likely, thus contributing to California meeting its statutory energy goals.

CHAPTER 1: Introduction

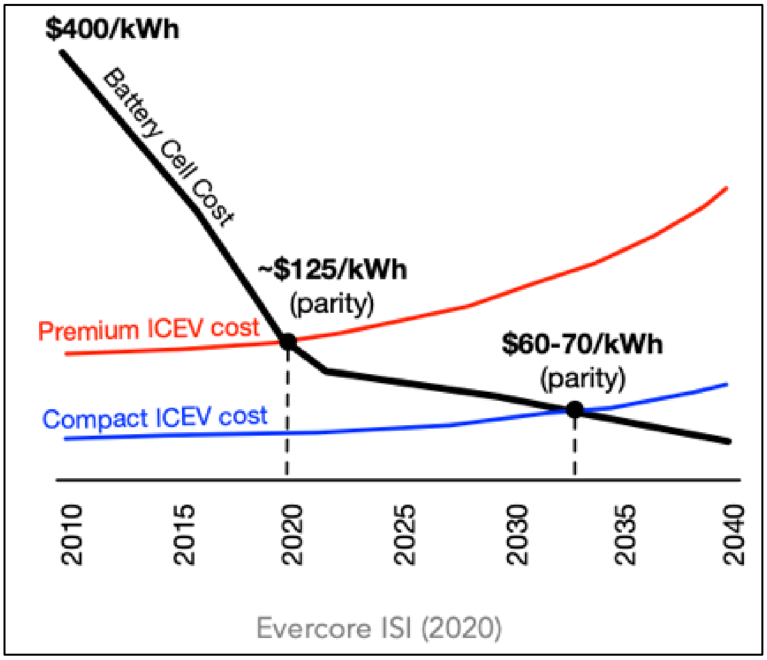
Governor Newsom issued an Executive Order in September 2020 that required all new passenger vehicles sold to be zero-emission by 2035 and announced that the State of California will aggressively move away from reliance on climate-change-causing fossil fuels. The transportation sector is responsible for more than 50 percent of carbon pollution, 80 percent of smog, and 95 percent of toxic diesel emissions in California. As a result, disadvantaged and low-income communities in Los Angeles County and the Central Valley breathe some of the most toxic air in the country.

Moreover, California investor-owned utility electricity ratepayers are increasingly vulnerable to power outages due to electrical equipment and infrastructure failures, wildfires, earthquakes, and landslides. Currently, California is battling the twin threats of extensive wildfires and the corresponding power outages and shutoffs that result from such fires or attempts to reduce them. The most promising and effective California Public Utilities Commission strategies to counter these threats are: (a) expanded deployment of renewable distributed energy resources, especially microgrids, (b) policies and insurance to incentivize residential solar-plus-battery power to increase grid resilience, and (c) energy efficiency and demand management initiatives.

Lower-cost and more reliable batteries are a critical part of the solution to both the transportation and power grid problems, as they enable widespread adoption of electric vehicles and renewable energy storage. While there are many efforts to develop new battery materials, there is a significant opportunity for near-term impact by improving the cost, efficiency, and reliability of battery manufacturing — particularly as it relates to process inspection. As cells (the smallest individual units of batteries) have grown in size and energy density, standard inspection methods are less sensitive to physical variations that affect quality. There is a critical need for breakthrough inspection technologies that can be practically deployed for superior battery production.

Despite a greater than 85-percent decrease in cost in the past decade (Lee 2020; Moore and Bullard 2020), lithium-ion (Li-ion) batteries (LIB) are still too expensive for broad adoption of electric vehicles (EVs) and energy storage systems (ESS) (Pacific Gas and Electric Company 2021; Howell et al. 2016; Paoli and Bennett 2019). Currently, the EV battery cost is at approximately (~) $125 per kWh (Pillot 2019), which is barely enough to compete with internal combustion engine vehicles on cost in premium vehicles. For compact EVs to reach cost parity, the Li-ion cell cost must drop by more than (>) 40 percent, to less than (<) $70 per kWh (Figure 1) (Baik et al. 2019). Similarly, the 2020 median cost for a 4-hour grid storage battery pack is $330 per kWh, dropping to $248 per kWh by 2025 (Küpper et al. 2018), but it needs to drop to < $150 per kWh to be cost-effective (Ziegler et al. 2019). Cost-effective ESS are required to meet California's statutory energy goals, particularly Assembly Bill (AB) 2514 (Skinner, Statutes of 2010, Chapter 469) — Energy Storage Systems, whether it is Li-ion or other battery technologies (Cole and Frazier 2019). Battery production is also a notoriously low-margin business, and demand for increased production and lower prices strains manufacturers' ability to scale profitably (Küpper et al. 2018). For this reason, battery cost is a major focus for battery companies, and it impacts the market adoption economics of EVs and ESS.

Figure 1. Influence of Cell $/kWh on EV/Internal Combustion Engine Vehicle Cost Parity



ICEV = internal combustion engine vehicle cost
Source: Evercore ISI, 2020.

Incumbent electrical inspection and diagnostic methods are ineffective and a major source of excess cost. The industry relies heavily on electrical methods, which offer only battery-averaged insights and are often blind to local defects and internal variations in physical condition. It can take weeks of electrical tests to detect small inconsistencies that have a big impact on cell performance. These limitations are especially prominent for large EVs and ESS cells, as the sensitivity of electrical methods decreases as cell size and energy density grow. As tight process control requires high-fidelity data, ineffective inspection creates long feedback loops that make development and scale-up slow; this makes it difficult to rapidly scale manufacturing readiness of new battery chemistries (for example, those for non-Li-ion batteries, including zinc-based and lithium metal batteries), to ramp yield for new production lines, and to improve steady state productivity of Li-ion batteries. For example, currently, the equivalent of approximately one in six cells is scrapped during production11 (~ $4 billion per year lost based on 2019 volumes). With demand growing 10 times (x) by 2030 (Baik et al 2019; Curry 2017), and the benefits of localized supply chains (Kumar 2020), there is a critical need for breakthrough inspection technologies to be commercially deployed within three to five years.

Feasible, Inc. has developed a machine-learning-driven battery inspection platform, called EchoStat®, that uses ultrasound and data analytics to bridge the gap in electrical measurements and X-ray methods. EchoStat scans batteries rapidly and non-invasively and processes data to deliver spatially resolved insights about internal structure, enabling users to quickly understand how batteries differ from each other in terms of their physical properties. With this unique and scalable capability, EchoStat could bring step-change improvement across the development, manufacturing, and management of EV- and ESS-relevant batteries. In the near term, Feasible is focused on improving battery manufacturing yield and consistency, thereby reducing costs and inefficiencies in utilization. EchoStat can detect production issues at their source and could reduce LIB costs by ~ $14 per kWh at scale.

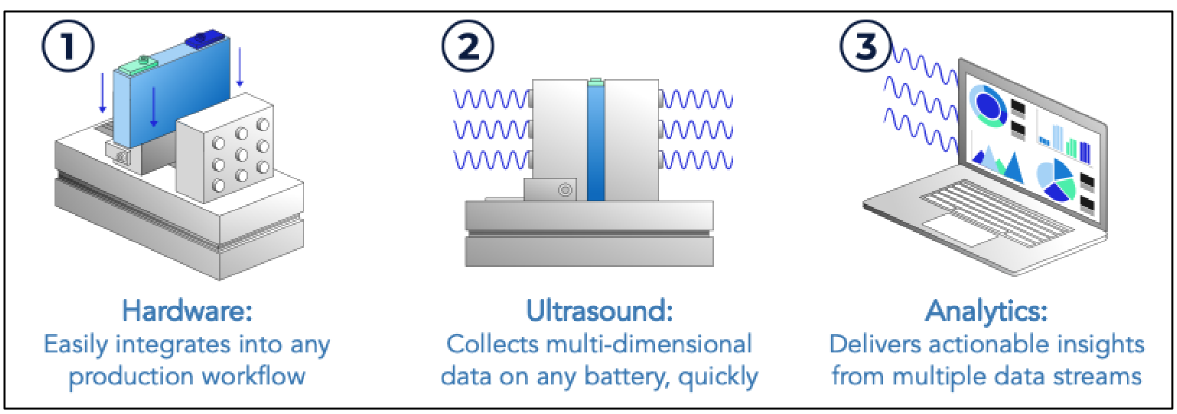
The goal of this project was to demonstrate EchoStat's capability and techno-economic value on battery pilot and production lines in detecting manufacturing issues earlier and with more sensitivity than state-of-the art (SoA) methods, focusing on cell finishing processes (specifically, electrolyte fill, formation, aging, and EoL quality control).

During this BRIDGE (Bringing Rapid Innovation Development to Green Energy) project, Feasible secured EchoStat system sales and deployments at customer pilot and production environments. Through cell prototyping-, pilot-, and production-scale evaluations on EV and ESS relevant cells, Feasible accomplished the following objectives by the end of the project.

1. It scaled EchoStat technology and products for deployment in Li-ion and non-Li-ion battery research and development (R&D) and pilot production to help diversify the state's energy storage solutions.
2. It defined system requirements, the business case, and the roadmap for commercial adoption.
3. It established manufacturing systems and an initial supply chain to enter low-rate production.

The EchoStat platform consists of: 1) hardware that can integrate into any production workflow, electronics, and sensors for quickly collecting ultrasound data on any battery type, and 2) software analytics that deliver valuable insights to customers (Figure 2).

Figure 2. High-Level EchoStat Hardware/Software Platform

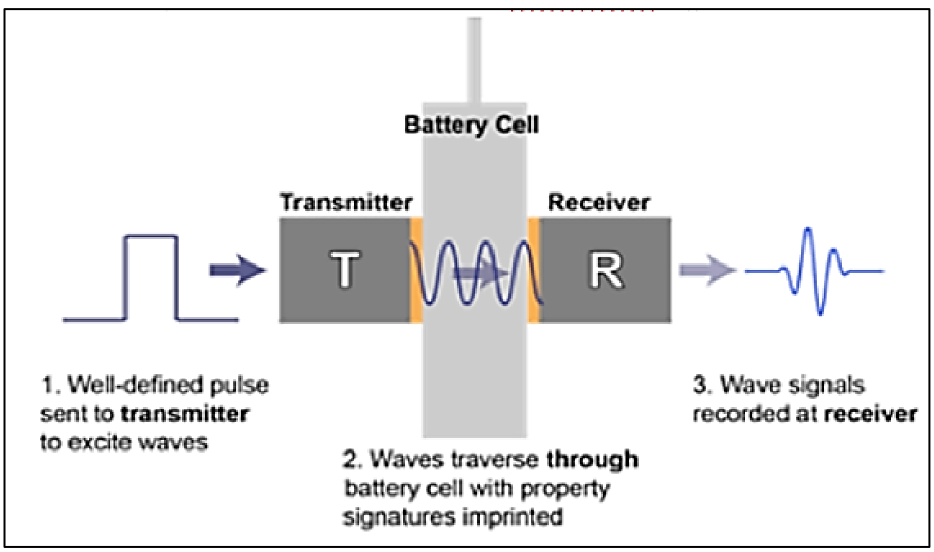


Source: Feasible, Inc.

EchoStat works with batteries of any chemistry and form factor; just as vocal systems transform airflow to give voices their unique character, batteries transform ultrasonic pulses into signatures of their internal structure. This is due to the influence of density and modulus (specifically, acoustic impedance) on the behavior of sound traveling through a material (Hsieh et al. 2015). As sound waves travel between two materials, their behavior is influenced by the mismatch in acoustic impedances. Since EchoStat is sensitive to subtle changes in a battery's physical integrity, construction quality, and state of degradation, it directly probes the internal condition of any battery type. Each individual acoustic measurement takes < 1 millisecond and does not interrupt operation or require current to be drawn from the cell, and the hardware is easily scalable.

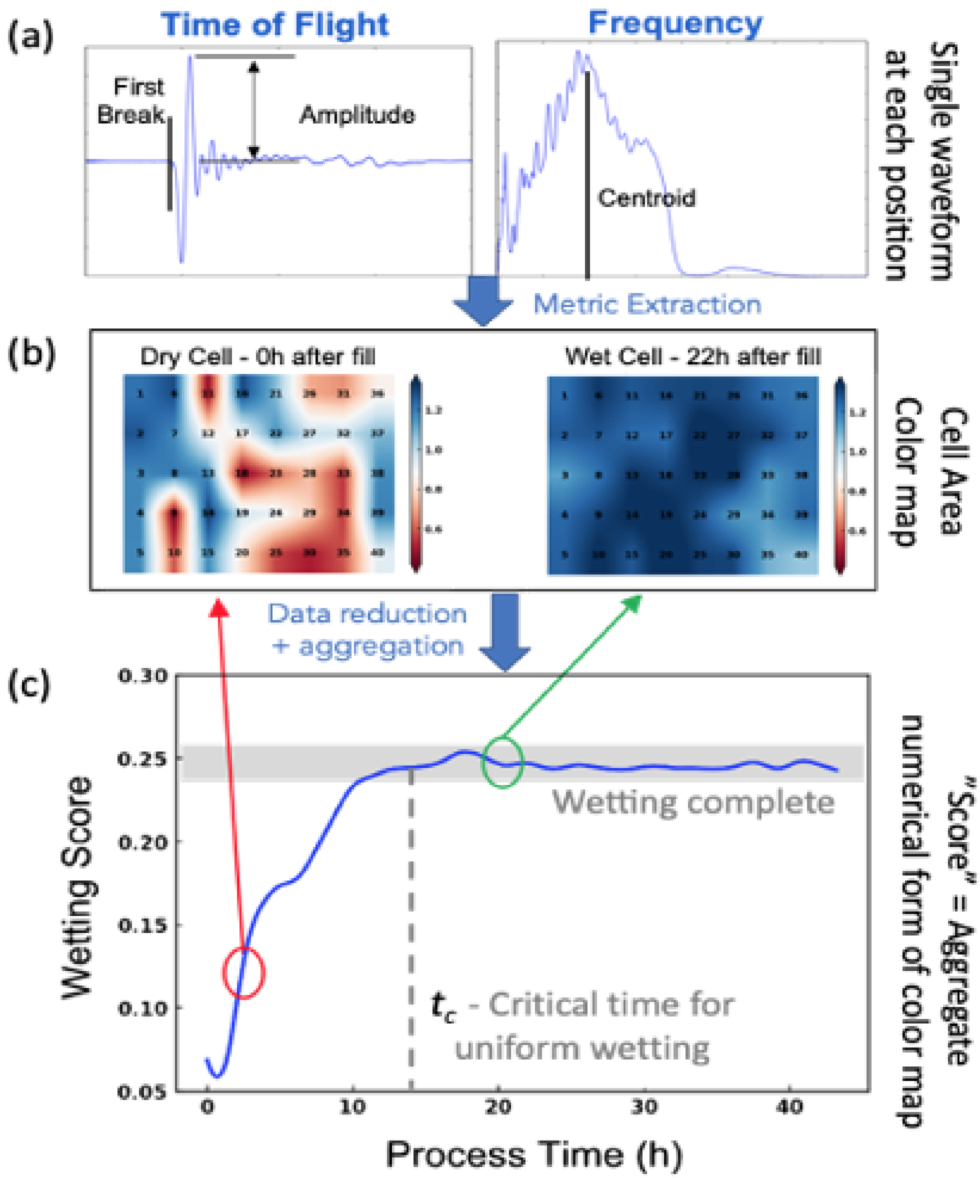
In a simple schematic (Figure 3), a well-defined acoustic pulse is transmitted into a battery sample, and the echo response signal is received and recorded into the EchoStat database. To obtain meaningful results from the raw waveforms, EchoStat analytics use time- and frequency-domain signal processing to generate a family of acoustic metrics from each sensor position. Key acoustic metrics include centroid frequency, signal amplitude, and sound speed, but also empirically-derived metrics and aggregate metrics (Figure 4a). When acoustic data is collected at multiple sensor positions across the cell area, signal metrics can be compiled into colormaps for easy visualization (Figure 4b). An EchoStat "score" is then calculated by aggregating a combination of metrics across all measurement positions (Figure 4c). These colormaps and numerical scores can be used for comparing cells, in-line process control and development, EoL quality control (QC), and state of charge and state-of-health monitoring.

Figure 3. High-level EchoStat Operations



Source: Feasible, Inc.

Figure 4. Response Waveform in Time and Frequency Domain, Metrics, and EchoStat Score



(a) A response waveform in time and frequency domain, and the key metric extracted. (b) Metrics from multiple positions give spatially resolved colormaps. (c) These are aggregated into a 'score.'

Source: Feasible, Inc.

The charts in Figure 4 are an example of process optimization by determining the critical wetting time for electrolyte filling. Shorter process time and complete filling both result in lower cell assembly cost. The goal of the project was to validate Feasible's technology, transitioning from Technology Readiness Level (TRL) 4 to TRL 6. Table 1 lists some key targets metrics for the project.

Table 1. Minimum and Stretch Targets During BRIDGE Project

Objective	Baseline	Minimum Target	Stretch Target
Yield ramp time	1x	0.5x	0.25x
Pilot production cycle time	3-7 wks	2-4 wks	< 2 wks
Steady state yield (pilot line)	70%	> 80%	> 88%
Overall cost of capacity (decrease from baseline)	$0/kWh decrease ($125/kWh)	> $5/kWh decrease (< $120/kWh)	> $15/kWh decrease (< $110/kWh)
EchoStat system cost	$15/kWh	< $5/kWh	< $1.50/kWh
EchoStat test time	30 seconds/cell	< 15 seconds/cell	< 5 seconds/cell

Source: Feasible, Inc.

Table 2 shows a select few customers, deployment duration, applications in cell manufacturing, and quantitative key results achieved.

Table 2. EchoStat Deployment at Customer Sites With Key Applications and Results

Partner/Location	Duration & Dates	Application	Key Results
EV OEM R&D, Michigan	12 months 2020-21	Electrolyte Fill + Soak, EoL QC	• Reduced electrolyte soak time by > 12 hrs. • Outlier detection during soak. • Predicted long-term cell performance for EoL quality analysis.
Solid State Manufacturing, California	9 months 2021-22	Electrolyte Fill + Soak	• Identified process control issues in the cell production process.
Cuberg, California	36 months 2021-22, 2023-24	Electrolyte Soak, Formation, QC	• Reduced electrolyte soak time by > 50%. • Removed defective cells before formation. • Predicted cell performance for EoL quality analysis.
Sodium-ion cell maker, California	9 months 2022-23	Electrolyte Soak, QC	• > 85% accuracy in determining poorly soaked cells during process development and QC testing.
EV Manufacturing, California	5+ months 2021-22	Fill + Soak, Formation	• Process development of customer's electrolyte formulation and formation protocol.
Northvolt, Sweden	18+ months 2022-2024	QC	• Deployed in-line EchoStat ARRAY system fully integrated physically and digitally with line-conveyance, manufacturing execution system, and data-cloud infrastructure. • Tested over 300,000 cells produced in line with automated scanning system and provided real-time results to flag defective cells and drift in process. • Predicted cycle life performance for EoL quality analysis.
Cylindrical Cell Manuf., NV	6+ months 2022-2023	QC	• Matched the performance of the company's standard 9-day electrochemical test in under 5 minutes/cell with EchoStat.

Source: Feasible, Inc.

CHAPTER 2: Project Approach

This project focused on validating EchoStat's value during cell finishing and QC. At cell prototyping and pilot scales, engineers rely on destructive post-formation teardown imaging or electrical performance cycling of the cells to evaluate new cell materials, designs, or fabrication processes. Each parameter change requires an iterative process that can take months to implement. The use of EchoStat in process development to non-invasively monitor the influence of upstream design or process parameter variations on cell quality can significantly accelerate process development and shorten time-to-market for new batteries. As ultrasound is well-suited to detect the distribution of fluids in porous media (specifically, active material and separator layers in a LIB cell), this presents a unique opportunity for value creation to quickly assess variation of cell internal properties. In mass production, during cell manufacturing line ramp-up as well as steady state production, engineers focus on improving yield, flagging defective cells, and ensuring quality and performance of the cells produced. EchoStat's in-line implementation provides cell production teams with additional data streams to screen out poor quality cells early and on 100 percent of the cells produced. Feasible demonstrated this capability and value during the BRIDGE project.

Ultrasound inspection has unique advantages compared to the incumbent electrical and radiographic inspection methods commonly used to monitor process quality during cell production (Figure 5). Ultrasound inspection will not replace these techniques but will complement and address their shortcomings.

Figure 5. Ultrasound-Based EchoStat Inspection Method Comparison to Current SoA Methods

	Innovation	Current State-of-Art Methods					
	Ultrasound	X-Ray	CT Scan	Voltage/ Resistance	Single Cycle test	Self-discharge	Long-term Cycling
Test in < 10 sec	✓	✓	✗	✓	✗	✗	✗
Multi-dimensional data	✓	✓	✓	✗	✗	✗	✗
Non-degrading	✓	✓	✓	✓	✗	✓	✗
In-line inspection	✓	✓	✗	✓	✗	✗	✗
Works on all geometries	✓	✓	✗	✓	✓	✓	✓
Sensitive to all components	✓	✗	✗	✗	✗	✗	✗
Accurate SOH estimation	✓	✗	✗	✗	✗	✗	n/a

Source: Feasible, Inc.

Electrical tests are standard in battery production; however, they are fundamentally limited: (1) faster tests (for example, open circuit voltage, alternating current resistance) take < 1 second but detect only major issues; longer tests (for example, self-discharge, cycle life) can uncover subtle quality issues but take days to weeks; (2) information is inherently an average of the battery's electrode area and thus cannot deliver position-specific insight; and

(3) they measure only the impact of process variation on performance and not underlying physical issues. This is sufficient for devices with small cells, but EV and ESS applications generally use 10x to 100x larger cells, making it nearly impossible for electrical tests to detect the subtle physical variations that have a big impact on performance.

Two-dimensional X-ray inspection can be used to confirm electrode alignment, but it is limited by numerous false positives. Also, X-rays have difficulty detecting low molecular-weight materials, such as separator membranes, Lithium metal, and electrolytes. The integrity of these components has a major effect on long-term performance and safety. CT scan inspection is widely used to detect defects in cells at EoL but is limited to low throughput and can be used only to scan 1 to 5 percent of cells produced in-line.

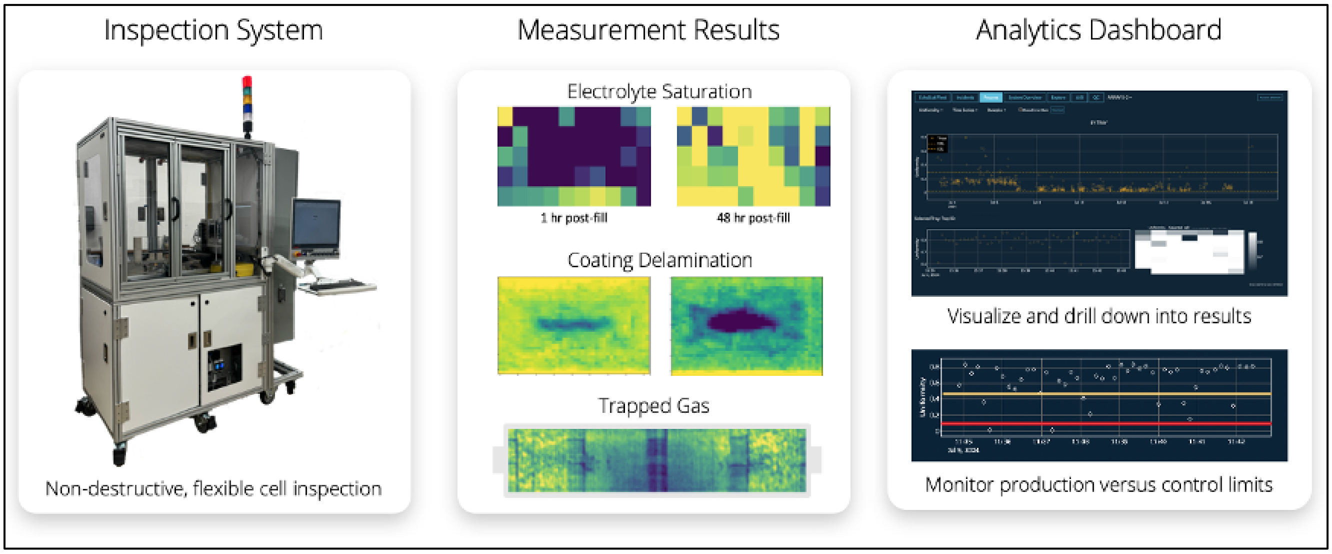
In this BRIDGE project, Feasible aimed to demonstrate that EchoStat fills the gap between X-ray, CT, and electrical inspection methods, by combining the speed and scalability of electrical methods like open circuit voltage and direct current resistance with the dimensional information of X-rays. As measurements can take 6 seconds per battery cell at scale, can directly probe physical structure, and are not limited by material type, Feasible's products enable valuable physical insights in battery development, manufacturing, and management life cycle that were previously impossible to obtain. Additionally, EchoStat scans can deliver position-specific data with high lateral resolution, can adapt to any size or geometry (pouch, prismatic, or cylindrical), and are agnostic to cell chemistry. EchoStat gives customers the ability to quickly uncover internal anomalies that standard electrical and X-ray methods are unable to detect and can monitor dynamic processes that are critical to production quality but are typically black boxes at scale (Figure 6).

Figure 6. EchoStat Systems: ARRAY, RASTER, and THETA

Source: Feasible, Inc.

Feasible has three EchoStat product platforms that have been developed over the years. These products use the same underlying technology of ultrasound sensing and ML to detect subtle spatial variations in battery cells during production. EchoStat ARRAY and EchoStat RASTER are product lines for flat (pouch and prismatic) cells for high throughput and high-resolution applications, respectively. EchoStat THETA is used for scanning cylindrical cells like 18650, 2170, and 46xx formats. These product platforms can be configured for offline and in-line implementation. These systems were deployed at customer sites during the BRIDGE project to scan cells in production environments and demonstrate value. As shown in Figure 7, EchoStat is a complete solution, which includes system hardware, measurement analytics, and a user-interface dashboard to provide value to customers in their cell and battery manufacturing facilities.

Figure 7. Different Components of EchoStat Complete Solution



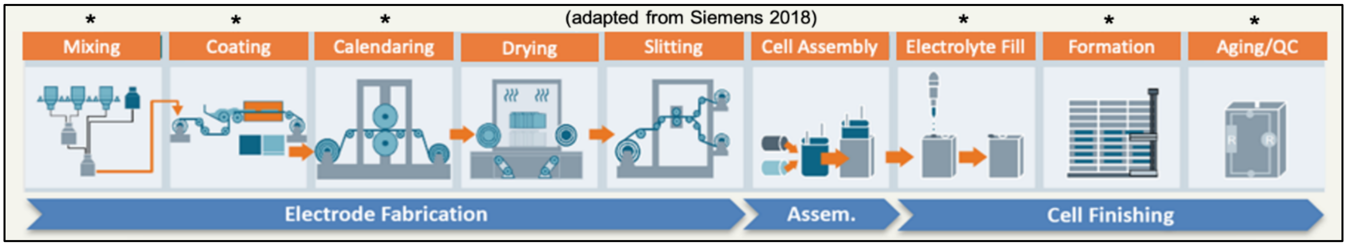
Source: Feasible, Inc.

The technology's value proposition hinges on its ability to detect subtle process issues earlier and/or with greater sensitivity than SoA methods. If this ability is successfully demonstrated during cell finishing, the team estimates that EchoStat will halve the ramp times, decrease production cycle time by 30 percent, and increase steady state yield by 2 percent. As shown in Table 1, located in Chapter 1, EchoStat inspection during cell finishing could decrease cost by at least $5 per kWh. For an industry with razor thin margins, this represents a more than doubling in profitability for cell manufacturers.

As EchoStat systems are scaled up and the company works with partners to validate the technology at increasing rates of production, Feasible will need to ensure that its solutions can deliver this value at a cost per kWh that is viable at the production scale of interest. Tracking system cost in terms of $ per kWh enables accounting for the increases in bill of materials and engineering costs needed to enable high-fidelity inspection at higher throughputs (kWh). During this project, the aim was, at a minimum, to develop systems that can take low-resolution EchoStat scans in < 15 seconds per cell and < 1 minute per cell at high resolution (regardless of cell format) for a system cost of < $5 per kWh. It is critical that test times are shorter than production rates so that multiple EchoStat systems are not required for any one assembly/pilot line. Based on Feasible's current roadmap, the team is on track to meet these cost metrics at scale, which would be sufficient for commercial deployment in pilot production and would be on track for a full-scale production system cost of $0.30 per kWh.

This project focused on validating EchoStat's value during cell finishing and QC. While there are several process steps during battery cell production where the technology can deliver valuable insights (Figure 8), currently Feasible's focus is on cell finishing (specifically, electrolyte fill, formation, and aging) and EoL QC inspection. To date, the team has shown, with bench-scale systems, that EchoStat can detect physical variations during electrolyte filling and can identify anomalous cells more effectively than standard electrical methods. The aim is to verify that EchoStat's technical advantage persists when scaled up to commercially relevant pilot settings.

Figure 8. Common Process Steps in Cell Production and, as Indicated by *, Where EchoStat Can Add Value



Source: Siemens 2016.

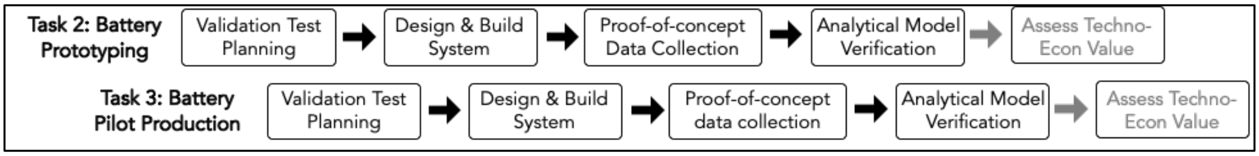
Cell manufacturers and EV original equipment manufacturers (OEMs) support EchoStat evaluations at cell prototyping- and pilot-scales. Several companies, including Daimler, Farasis, EnPower, Cuberg, and Anzode, provided letters of support for EchoStat evaluations on their pilot-production cells as part of the BRIDGE project. Feasible worked closely with these industry partners to validate the techno-economic value proposition, first at a cell prototyping scale and then in pilot production.

This project had two technical tasks:

- Task 2: Concept Evaluation at Cell Prototyping Scale — Generate proof data to showcase the platform's capabilities at a cell prototyping scale.
- Task 3: Capability Demonstration Offline at Cell Pilot Scale — offline (audit-style) validation testing during cell finishing at customers' pilot production facilities.

Feasible used validation test planning, design-of-experiment, and analytical model validation techniques and standards utilized in the digital products industry to carry out the tasks in the Scope of Work for this BRIDGE project. Planning included defining the test plan and success criteria (with customers); system design and build included assembly of EchoStat hardware and software for testing battery cells; proof-of-concept run involved collection of acoustic data, along with standard SoA data collected during cell finishing and battery manufacturing; advanced ML and statistical models then needed to be trained, validated, and tested with the collected data; and, finally, the techno-economic value of EchoStat was modelled based on comparison to SoA and customer feedback. These stages are similar in cell prototyping- and offline pilot-production scales (Figure 9).

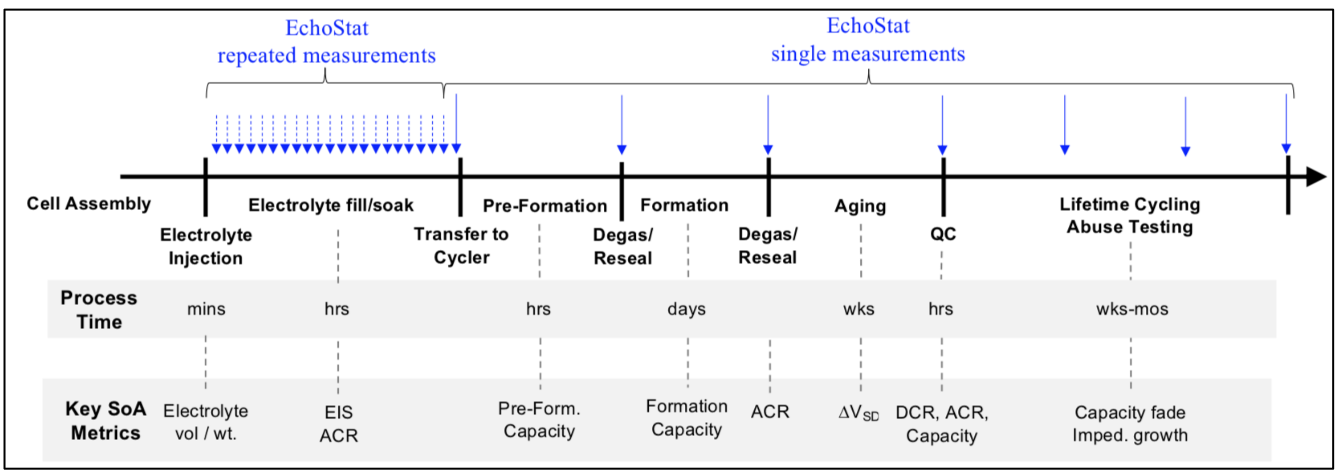
Figure 9. Stages of Data-Driven Product Engineering Stages



Source: Feasible, Inc.

The general workflow for Li-ion cell finishing is similar, regardless of battery type or production scale (Figure 10). Uniform electrolyte distribution throughout the cell is important for good performance. Electrode fabrication and cell assembly processes influence electrolyte distribution behavior. In turn, electrolyte saturation and formation protocols affect solid electrolyte interphase quality, which is also needed for good performance. Currently, SoA methods for determining the influence of process parameters on electrolyte distribution and solid electrolyte interphase quality are: formation capacity, self-discharge voltage fade during aging, long-term cycling, and/or destructive analysis at any point of the process. These are expensive, labor intensive, and can take between two weeks to four months to gather meaningful insights on the impact of process variation.

Figure 10. Manufacturing Workflow Shows the Cell Finishing and Performance Test Processes With EchoStat Measurements



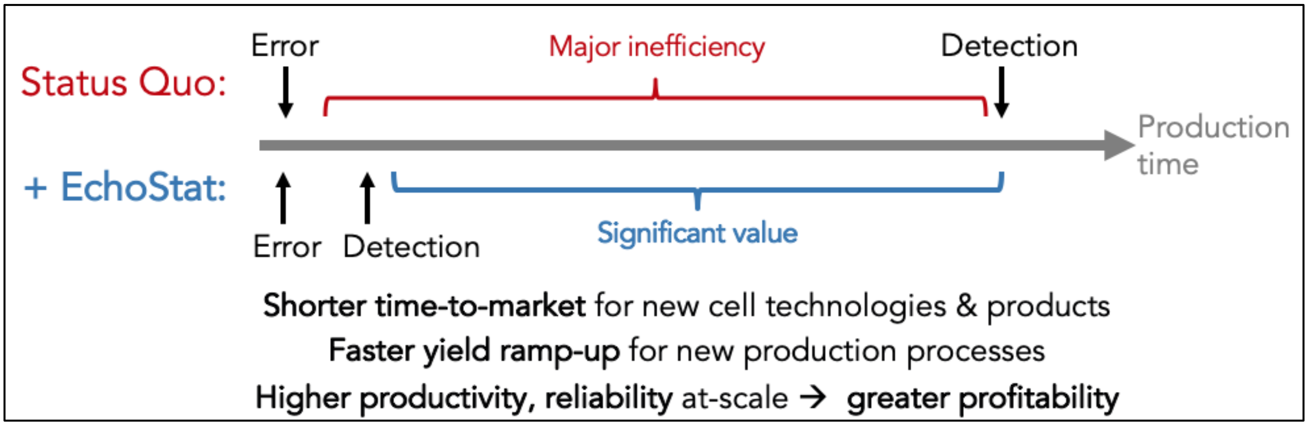
Source: Feasible, Inc.

Goals, Objectives, and Deliverables

Feasible's ML-driven battery inspection platform uses ultrasound and data analytics to detect production issues at their source and could reduce LIB costs by ~ $14 per kWh. This would improve profitability for battery companies and is a big step toward the < $70-per-kWh cell cost needed for widespread EV and ESS adoption to meet California's statutory energy goals.

The goal of this project was to demonstrate EchoStat's capability and techno-economic value to detect manufacturing issues earlier and with more sensitivity than SoA methods at customer cell prototyping and pilot production lines (Figure 11). Feasible focused on evaluating EchoStat's sensitivity to physical variations during cell finishing and its ability to detect poor-quality cells. The team showed how EchoStat creates significant value by quickly delivering actionable insights that go beyond SoA methods in improving yield and process times. For example, improving yield at electrolyte fill by 2 percent leads to an ~ $2.50-per-kWh benefit, while decreasing formation and aging times by 25 percent would lead to an ~ $2.90-per-kWh benefit. Feasible worked with customers to validate the techno-economic value of shorter feedback loops in accelerating yield ramp for new production processes (~ $5 per kWh), improving steady state yield and process times (specifically, productivity, ~ $9 per kWh) and increasing profitability for battery companies.

Figure 11. Location of Battery Cell Error Detection With EchoStat Technology Versus Status Quo Production



Source: Feasible, Inc.

Through cell prototyping — and pilot-scale evaluations on industry — relevant cells, the team:

1. Showed how EchoStat creates value in cell R&D and pilot production on different cell types.
2. Clearly defined system requirements and a roadmap for commercial adoption.
3. Secured follow-on commitments to support deployment of EchoStat at pilot and production scales.

During this project, Feasible's goal was to design, build, and demonstrate its technology platform with a commercial deployment offline at pilot cell production facilities to validate its techno-economic value. The team aimed to reach TRL 6, but it ultimately achieved TRL 7 by the end of the project. Feasible secured customer commitments to deploy EchoStat systems in production facilities. From the analysis of these datasets, the team used supervised ML algorithms and empirical analysis to generate a set of functions that will be used to interpret future test results.

CHAPTER 3: Results

This chapter summarizes the outcomes of Feasible's BRIDGE project, with a focus on quantifiable results that align with the project goals: to demonstrate that EchoStat, an ultrasound and ML-based inspection platform, can detect battery cell manufacturing issues earlier and with greater sensitivity than conventional methods. The project successfully transitioned EchoStat from TRL 4 to TRL 7, validated its technical and economic impact at multiple partner sites, and laid the foundation for widespread commercial adoption.

Overview of Technology and Research Outcomes

The core innovation demonstrated in this project is EchoStat's ability to generate spatially resolved acoustic data across battery cell surfaces and to analyze these signals using proprietary ML algorithms. The technology delivers predictive insights about cell uniformity, electrolyte fill quality, and expected performance — areas where incumbent electrical or X-ray methods fall short. During the project, the research team:

- Designed and deployed EchoStat systems across cell prototyping, pilot, and early-stage production lines.
- Developed analytical models to correlate acoustic data with battery performance and quality outcomes.
- Validated EchoStat's technical performance across various chemistries (for example, Li-ion, solid-state, and sodium-ion).
- Demonstrated over $5 per kWh in economic value creation through improved yield, reduced cycle time, and enhanced QC.

These outcomes support Feasible/Liminal's mission to lower battery manufacturing costs and enable broader adoption of EVs and ESS, aligning directly with California's clean energy goals.

Demonstration of Key Value Propositions

Over the course of the project, four main value propositions were defined, tested, and validated at partner customer sites. The results are summarized below, and in Table 3.

1) Decrease Process Time

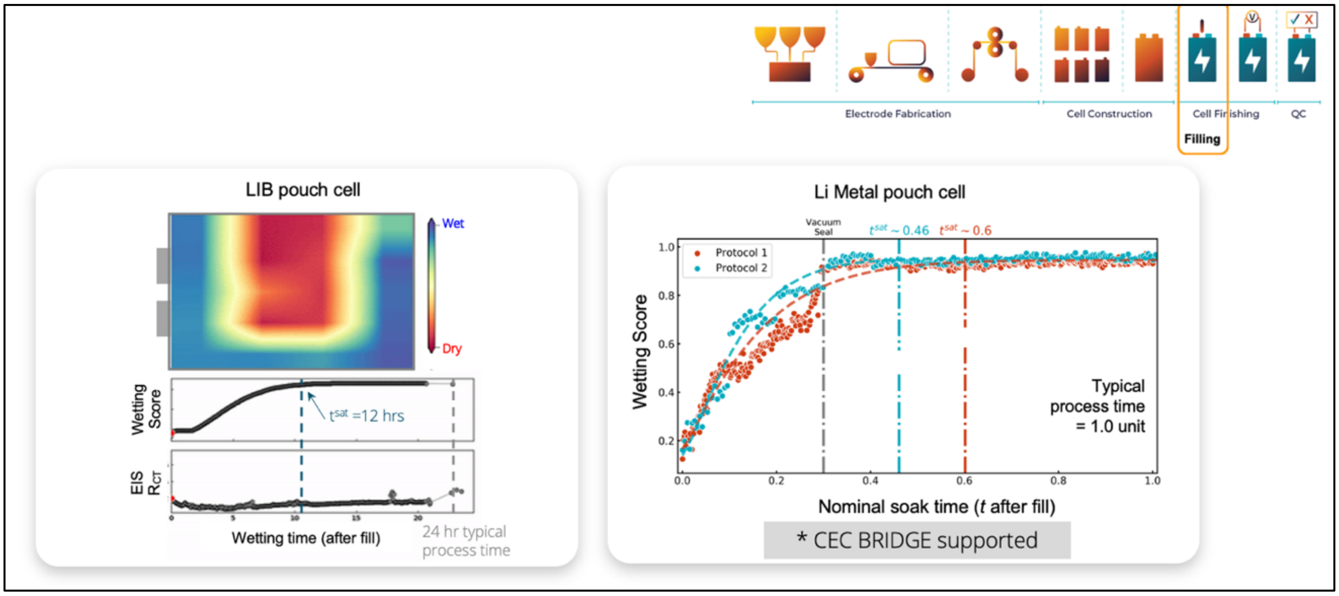
Goal: Reduce electrolyte soaking time during cell finishing.

At a leading EV OEM, EchoStat enabled real-time monitoring of electrolyte saturation in pouch and prismatic cells. Data from acoustic scans showed when saturation was complete, allowing operators to cut soak times by 50 percent — from 24 hours to 12 hours — without compromising quality.

Impact:

- Reduced soak time → higher throughput
- Lower process cost: ~ $1.83-per-kWh value created
- Saturation trends demonstrating a < 50 percent process time reduction (Figure 12)

Figure 12. EchoStat Monitors Electrolyte Saturation During Soaking for Optimizing Soak Time



Source: Feasible, Inc.

2) Detect Process Errors Early

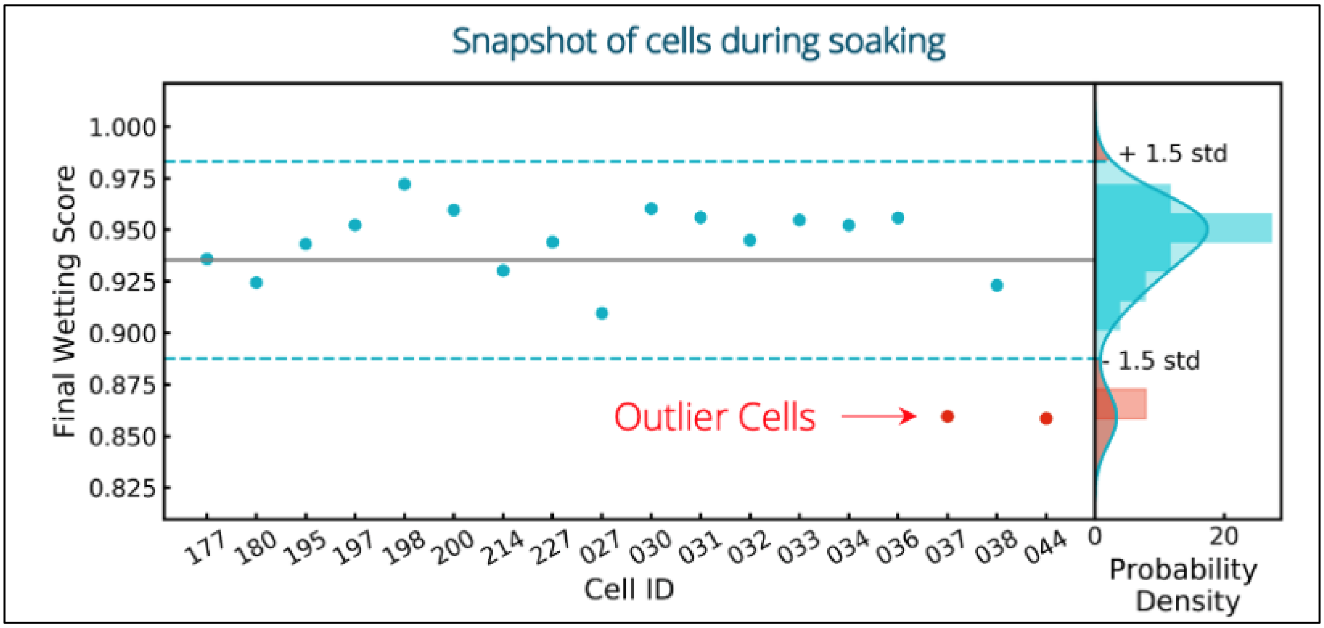
Goal: Identify underperforming or defective cells before formation.

EchoStat scans during soak stages were able to flag outlier cells up to 95 percent earlier than conventional post-formation electrical testing; see Figure 13. In a pilot project with a sodium-ion cell maker, the system achieved > 85-percent accuracy in identifying poorly soaked cells. These findings were verified by downstream performance and CT imaging. See Table 2 in Chapter 1 for partner details.

Impact:

- Early rejection → reduced scrap, higher equipment utilization
- Value created: ~ $0.43 per kWh

Figure 13. Example of Where EchoStat Was Able to Identify Outlier Cells During Soaking Process



Source: Feasible, Inc.

3) Predict Cell Performance

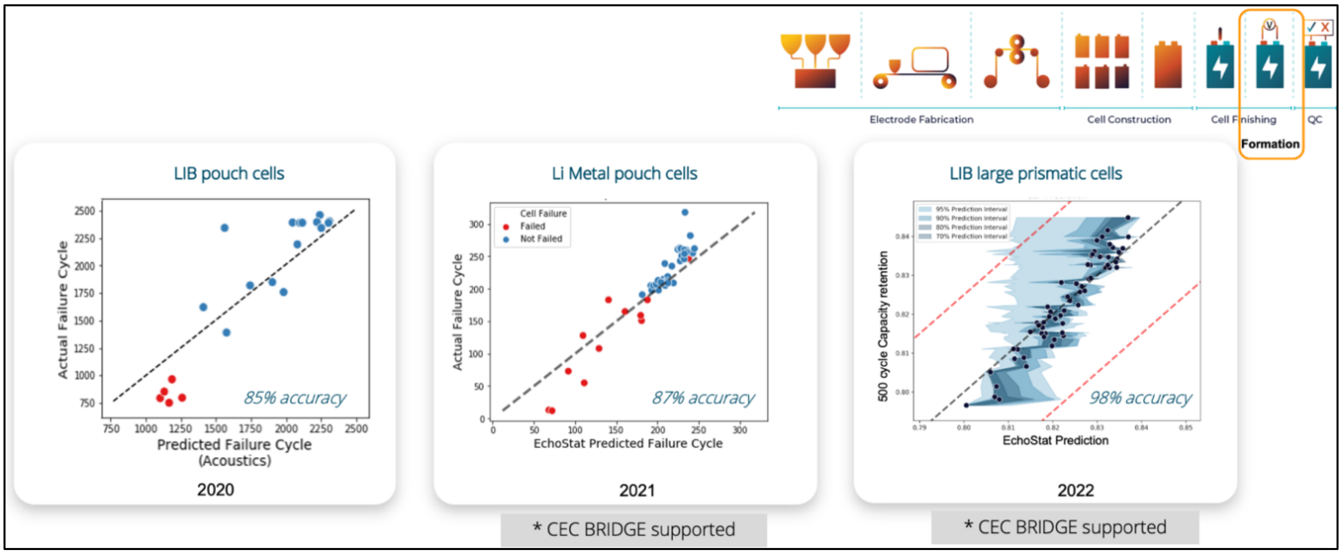
Goal: Forecast cell performance (for example, cycle life) at EoL using EchoStat data post-formation.

At multiple customer sites, EchoStat's ML models predicted cycle life with 80 to 98 percent accuracy across various chemistries and form factors. For example, in Li-metal cells, the mean absolute error of prediction was just 14 percent. These insights enabled faster process tuning and yield ramp-up.

Impact:

- Shortened cell qualification timelines as battery manufacturers increase yield and prepare cells for delivery to their customers; this allows for evaluating cell quality at EoL instead of after extended cycling.
- Faster yield ramp: ~ $1.42-per-kWh value
- Cycle life prediction workflow and model accuracy. With this predictive ability, cell makers and EV OEMs can avoid long-term cycling, thereby shortening yield ramp time for new lines or process iterations. Figure 14 shows examples of cycle life (performance) prediction using EchoStat for LIB pouch, Li-metal pouch, and LIB prismatic cells at EoL.

Figure 14. Cycle Life (Performance) Prediction Using EchoStat



Source: Feasible, Inc.

4) Accelerate Quality Assurance/Quality Control (QA/QC)

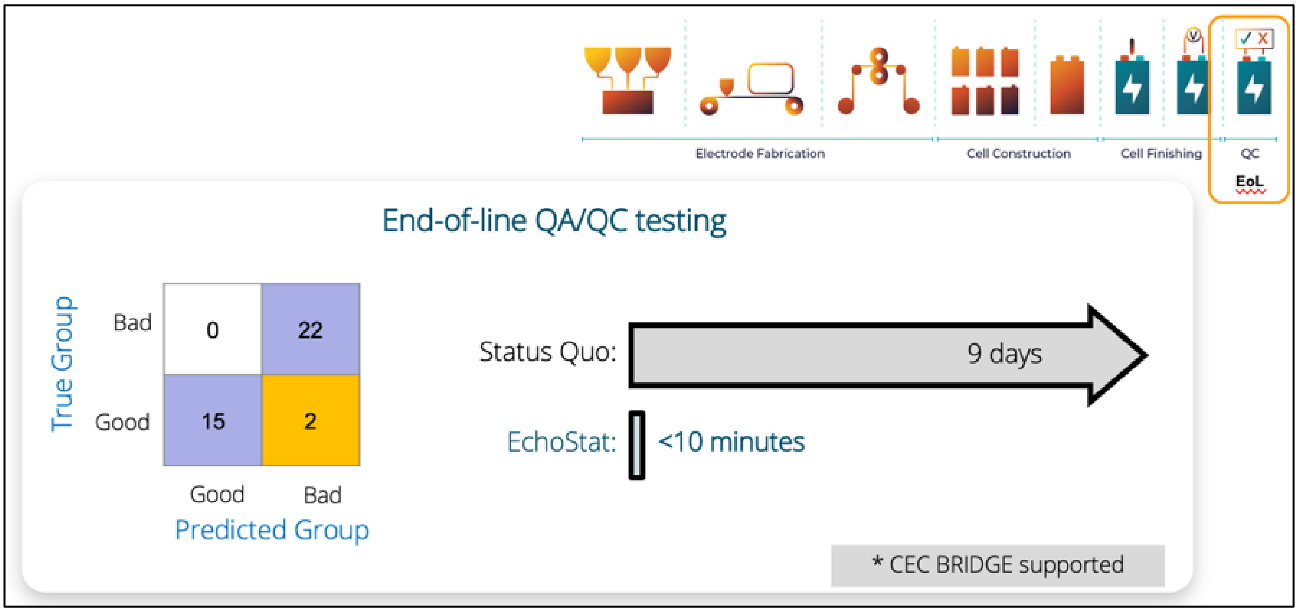
Goal: Replace slow, costly QA tests with high-speed in-line scans.

EchoStat replicated insights typically obtained through 9-day electrochemical testing in under 10 minutes. In cylindrical cells, high-speed scanning identified EoL anomalies and defects, with suspect cells routed for higher-resolution secondary scans. This enabled manufacturers to screen 100 percent of cells with confidence.

Impact:

- Increased throughput and QA coverage
- Value created: ~ $1.33 per kWh
- EoL inspection flow and results: to determine cell quality instead of using long and resource-intensive electrical, CT, and teardown analysis. See Figure 15 for an example.

Figure 15. QC Testing With EchoStat



Source: Feasible, Inc.

The total value created by this project was over $5 per kWh, as detailed in Table 3.

Table 3. Summary of Value Propositions Validated

Value Proposition	Technical Validation	Estimated Value
Decrease process time	50% shorter soak time at major OEM	$1.83/kWh
Detect errors early	95% earlier outlier detection during soak	$0.43/kWh
Predict cell performance	80%–98% accuracy in cycle life prediction	$1.42/kWh
Accelerate QA/QC	95% faster testing, 100% batch screening	$1.33/kWh

Source: Feasible, Inc.

Lessons Learned and Informative "Negative" Results

Not all hypotheses yielded expected results. In line with the spirit of R&D, these outcomes offered valuable learning opportunities.

- **Model portability challenges:** Early ML models trained on one chemistry or form factor often performed poorly when applied to another. This highlighted the importance of context-specific training data and led to the development of more robust, physics-informed ML frameworks.
- **Sensor calibration drift:** In a few early deployments, temperature fluctuations and mechanical misalignments caused minor shifts in sensor calibration, leading to noisy data. The team addressed this by integrating automated calibration checks and improved mechanical fixtures.
- **Limitations of acoustic signal in very thin cells:** For ultra-thin pouch cells (<3 millimeters), acoustic signal resolution was limited due to signal overlap. The team

adapted the scan protocol and signal processing algorithms to better isolate meaningful features, but performance remained less robust compared to that for thicker cells.

These findings were incorporated into subsequent product versions, contributing to improved accuracy and system reliability.

Technical Barriers and Solutions

Barrier: Achieving Production-Scale Throughput

Early prototypes lacked the throughput needed for high-volume lines. The team redesigned the EchoStat ARRAY platform (Figure 16) to include automation, parallel scanning heads, and manufacturing execution systems integration. Final in-line systems now achieve scan times of < 6 seconds per cell (10 parts per million).

Figure 16. EchoStat ARRAY 5 System Fully Automated and Integrated In-line at NorthVolt Meeting the Line Throughput Requirements (10 parts per million) and Detecting Six Defect Types with >95 Percent Accuracy.

Source: Feasible, Inc.

Barrier: Data Interpretation at Scale

As EchoStat generates high-dimensional acoustic data, extracting insights requires scalable and interpretable analytics. The team developed dimensionality reduction techniques and visual dashboards (Figure 7) that present actionable insights for operators.

Barrier: Versatility Across Formats and Chemistries

To serve multiple customers, EchoStat had to adapt to different cell geometries and materials. Modular hardware and universal acoustic data processing pipelines were developed, enabling broad applicability.

Market and Policy Barriers

Market Barrier: Industry Caution Toward New Technologies

Battery manufacturers are conservative adopters, given the high cost of downtime. To overcome this, Feasible/Liminal pursued a phased engagement strategy:

- Begin with offline testing.
- Validate with customer-specific data.
- Transition to in-line implementations once trust is established.

Market Barrier: Limited Familiarity With Acoustic Methods

Ultrasound is well-known in medical and nondestructive testing contexts but less familiar with battery manufacturing. Feasible/Liminal addressed this through educational efforts, including:

- Customer training and workshops.
- Visual dashboards that contextualize acoustic metrics.
- Physics-based explanations that build confidence in the science.

Policy Barrier: Lack of Standards

Current battery QA standards do not include acoustic inspection. While this did not prevent deployment, it highlighted the need for future collaboration with regulators and standards bodies. Feasible/Liminal intends to contribute to standards development as the technology matures.

Knowledge Transfer and Public Awareness

Throughout the project, Feasible prioritized outreach to educate stakeholders and accelerate industry adoption. Key activities included:

- **Conference Presentations:** Delivered talks at the Battery Show North America, the International Battery Seminar & Exhibit (Cambridge EnerTech 2021), and others.
- **Publications:** Authored technical white papers (Dulaney et al. 2022) and case studies detailing deployment results and insights.
- **Social Media and Video Content:** Shared videos, deployment photos, and animations on LinkedIn, YouTube, and the company website (Liminal Insights, Inc. 2023a, 2023b, and News n.d.; Activate 2023).
- **Customer Engagements:** Held technical workshops with potential adopters, OEMs, and investors to build awareness and gather feedback.

- **Patent Portfolio:** Increased Feasible's intellectual property portfolio during the course of the project. The company currently has a total of 24 patent families, with 11 issued in the U.S. and various other global jurisdictions.

These efforts expanded visibility, built credibility, and supported the company's commercialization goals while sharing lessons learned with the broader clean energy community.

CHAPTER 4: Conclusion

The results of this project demonstrate that EchoStat, Feasible's ML-driven acoustic inspection platform, offers a viable, high-impact solution to some of the most pressing challenges in battery manufacturing. By enabling early-stage detection of quality issues, improving process efficiency, and enhancing EoL QC, EchoStat helps reduce the cost, time, and energy intensity of battery cell production. These capabilities are essential to accelerating the transition to EVs and renewable energy systems — two foundational pillars of California's clean energy and climate resilience strategy.

Supporting California's Clean Energy and Climate Goals

Battery technologies are crucial to California's decarbonization roadmap. In transportation, batteries power the growing fleet of zero-emission vehicles; in the power sector, they enable widespread adoption of renewable energy by supporting grid flexibility and reliability. However, battery affordability and reliability remain major hurdles to scale.

EchoStat addresses these challenges by enabling manufacturers to:

- Decrease production cycle times.
- Increase manufacturing yield.
- Improve product quality and safety.

These benefits lead directly to reduced battery cost per kWh, making zero-emission vehicles and energy ESS more economically viable. The adoption of tools like EchoStat thus play a critical role in reaching targets such as Governor Newsom's 2035 zero-emission vehicles mandate and the California Public Utilities Commission's energy storage goals under AB 2514 (Skinner, Statutes of 2010, Chapter 469).

Implications for Industry, Utilities, and Policy

The outcomes of this project have broad implications for the future of battery manufacturing in California and beyond.

- **Commercial Markets:** EchoStat significantly reduces the cost and risk associated with battery cell production, enhancing competitiveness for California-based manufacturers. This improves the economic feasibility of building and scaling local supply chains.
- **Utilities and Energy Storage Developers:** More reliable, lower-cost batteries support greater deployment of distributed energy resources and microgrids. EchoStat can help ensure that long-duration ESS meet performance and safety standards, enhancing grid resilience.
- **Consumers and Ratepayers:** As manufacturers pass cost savings down the value chain, consumers benefit from more affordable EVs and battery-backed home energy

systems. Ratepayers indirectly benefit from improved grid performance, reduced peak demand costs, and enhanced resilience to outages.

- **State Policymakers:** EchoStat contributes to meeting legislative and regulatory mandates by accelerating clean energy adoption without compromising safety or cost efficiency. The technology aligns with the priorities of the California Energy Commission (CEC), the California Air Resources Board, and the California Public Utilities Commission.

Lessons Learned and Opportunities for Future Development

Several lessons emerged from this project that will guide future development and deployment of EchoStat.

- **Scalability and System Cost:** The project validated that the system can scale to pilot and production environments. Continued R&D will focus on reducing per-unit system cost and enhancing integration with high-throughput lines.
- **Model Generalization Across Chemistries:** Variations in acoustic signal response across different cell chemistries highlighted the need for robust, adaptive models. Future work will continue to refine Feasible's physics-informed ML framework.
- **Inspection of Thin-Format Cells:** Signal interpretation challenges in ultra-thin pouch cells remain an open area for innovation. Refining scan protocols and sensor geometries may unlock broader applicability.
- **Operator Training and Analytics Visualization:** Adoption is accelerated when users can intuitively understand and act on inspection data. Continued investment in user-centric design and training will maximize impact.

Market Opportunities

The global battery market is expected to grow tenfold by 2030. EchoStat is well-positioned to serve several high-growth segments.

- **EV Battery Manufacturers:** With stricter yield and cost targets, manufacturers need better inspection tools to scale production of Li-ion, Li-metal, and next-generation chemistries.
- **Energy Storage Developers:** Long-duration and high-capacity storage systems require rigorous QC. EchoStat offers a pathway to ensure reliability and safety at a lower cost.
- **New Entrants and Startups:** As new cell technologies emerge, EchoStat supports rapid prototyping and faster time-to-market.
- **Advanced Manufacturing Initiatives:** EchoStat aligns with U.S. Department of Energy and state-level goals to strengthen domestic battery manufacturing capacity.

Recommendations and Next Steps

The following recommendations will help maximize the impact of EchoStat and similar technologies.

1. **Foster Policy Recognition of Acoustic Inspection**
   Include advanced inspection technologies in public incentive programs (for example, California Energy Storage Alliance programs, battery ESS incentives, and federal tax credits) to support first deployments and derisk adoption.

2. **Encourage Standards Development**
   Engage with the National Institute of Standards and Technology, SAE International (formerly the Society of Automotive Engineers), and Underwriters Laboratory to help define standards for acoustic battery inspection and integrate them into quality management systems.

3. **Expand Demonstration Projects**
   Leverage public-private partnerships to deploy EchoStat in additional use cases, including grid-scale ESS and solid-state battery manufacturing.

4. **Fund Continued Innovation**
   Support ongoing R&D through the EPIC program and other state mechanisms to improve system cost, throughput, and cross-chemistry applicability.

5. **Promote Workforce Training**
   Develop training materials and certification programs to ensure that California's clean tech workforce can effectively implement and benefit from acoustic inspection.

Conclusion

Feasible's EchoStat platform has proven to be a transformative tool in battery manufacturing. By reducing cost, accelerating time-to-market, and improving product quality, it directly supports California's broader climate and energy policy goals. The lessons learned through this CEC-funded project have already shaped commercial deployments, and the potential for continued impact is significant. With further support from public and private stakeholders, technologies like EchoStat can play a central role in building the next generation of clean energy infrastructure — one that is cost-effective, reliable, and equitable for all Californians and the global marketplace.

Glossary and List of Acronyms

Term	Definition
ARRAY	EchoStat ARRAY — a high-throughput scanning platform for flat cells
BRIDGE	Bringing Rapid Innovation Development to Green Energy — a CEC funding program
CEC	California Energy Commission
CT	computed tomography
EoL	end of line (quality control stage)
EPIC	Electric Program Investment Charge
ESS	energy storage system(s)
EV	electric vehicle
kWh	kilowatt hour
LIB	lithium-ion battery
Li-ion	lithium-ion
Li-metal	lithium metal
ML	machine learning
OEM	original equipment manufacturer
QC/QA	quality control/quality assurance
RASTER	EchoStat RASTER — a high-resolution scanning platform for flat cells
R&D	research and development
SoA	state of the art
TRL	technology readiness level

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Project Deliverables

The following is a summary of the project deliverables produced during the course of the CEC BRIDGE project (EPC-20-020), as outlined in the Scope of Work. These deliverables were critical to achieving the project objectives of demonstrating EchoStat®'s technical feasibility, commercial readiness, and value proposition in cell prototyping and pilot production environments.

All project deliverables, including interim reports and technical documents, are available upon request by submitting an email to pubs@energy.ca.gov with the agreement number EPC-20-020 included in the subject line. Where appropriate, additional materials and summaries are also available on the Feasible, Inc./Liminal Insights Inc. website at http://www.liminalinsights.com/.

- **Proof-of-Concept Evaluation Reports**
  Summarized outcomes of Task 2 activities, including test protocols, comparative analysis with SoA methods, and key findings from acoustic data collected during cell prototyping.
- **Pilot-Scale Demonstration Reports**
  Documentation of Task 3 validation testing, including EchoStat deployment procedures, integration with customer workflows, and quantifiable improvements in process time, yield, and QC.
- **Techno-Economic Impact Analyses**
  Analytical models and economic evaluations demonstrating EchoStat's ability to reduce battery production costs, including per-kWh savings and system return on investment.
- **Cycle Life Prediction Model Summary**
  Description of the ML-based cycle life prediction model developed during the project, with performance benchmarks, accuracy metrics, and cross-chemistry applicability.
- **Public-Facing White Papers and Case Studies**
  Shareable technical documents highlighting customer engagements, process optimization results, and insights into ultrasound inspection techniques.
- **Conference and Workshop Materials**
  Presentation slide decks and abstracts delivered at industry events, including the Battery Show North America and the International Battery Seminar & Exhibit.
- **Digital Media and Outreach Assets**
  High-resolution photos, explainer videos, and animated workflows used to promote public understanding and stakeholder engagement.
- **Workforce Development Report**
  Documentation of job creation aligned with project goals, including the creation of four full-time roles in California and the development of associated training materials.

- **Commercialization Roadmap**
  A strategic outline for scaling production of EchoStat systems, building supply chain capacity, and aligning with market needs.
- **Quarterly and Final Technical Progress Reports**
  Regular updates submitted to the Commission Agreement Manager summarizing milestones, risks, lessons learned, and progress toward TRL advancement.

These deliverables support the broader adoption of EchoStat and serve as a foundation for further innovation in battery inspection and quality control. Public-facing materials and highlights from the project can be found at: www.liminalinsights.com.