CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Low Rate Production Pilot Line for CO2 Electroreduction Membrane Electrode Assembly Fabrication

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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, energy transmission, and distribution and transportation.

In 2012, 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 utilities—Pacific Gas and Electric Company, San Diego Gas and 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 that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission 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), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

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

Twelve Benefit Corporation (doing business as Twelve) is a California-based startup developing a novel and scalable technology to convert carbon dioxide, a readily available waste gas, into valuable building blocks for chemicals and fuels. In this project, Twelve successfully installed, commissioned, and validated a low-rate initial production pilot line for manufacturing membrane electrode assemblies, the core functional component of Twelve's carbon dioxide electrolyzer. Consistent manufacturing yields more than 90 percent emission reduction and improved electrochemical performance were demonstrated following implementation of process improvements and quality management strategies. The success of this pilot line is critical to Twelve's demonstration-scale carbon dioxide transformation plant, which will produce sustainable aviation fuel with more than 90 percent emissions reduction on a well-to-wing basis compared to conventional Jet A. At scale, Twelve's carbon transformation technology platform is capable of addressing 2 to 3 billion tons of carbon dioxide per year across the $600+ billion petrochemicals industry.

Keywords: CO2 electrolysis, membrane electrode assembly (MEA), electrochemistry, manufacturing, carbon utilization

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Background

The atmospheric accumulation of greenhouse gases, including 80 percent carbon dioxide (CO_2), is the primary cause of climate irregularities across the globe. Over three trillion tons of greenhouse gases have been emitted since the industrial revolution, and occurrences of natural disasters such as heatwaves, wildfires, and hurricanes have only increased in regularity. Decarbonization has become an important strategic priority for nations and industries around the globe. A myriad of technologies have been developed to capture and store CO_2 from the atmosphere. However, most of these approaches do not address the ubiquitous demand for fossil fuels, nor are they capable of extracting value from the sequestered CO_2.

Twelve Benefit Corporation (doing business as Twelve) is a California-based startup developing a novel and scalable technology to convert CO_2, a readily available waste gas, into valuable building blocks for chemicals and fuels. To date, Twelve has demonstrated the utility of its electrolysis technology to create consumer chemicals (formates), polymer foams (polyurethane), sustainable aviation fuel, as defined by American Society for Testing and Material D7566 Annex A1, and polymers (polycarbonate) through partnerships with Procter & Gamble, Mercedes-Benz, the US Air Force, and Pangaia, respectively, as shown in Figure 1 in Chapter 1. Twelve is constructing a first-of-its-kind, demonstration-scale CO_2 transformation plant that will produce low-emission sustainable aviation fuel and naphtha. Naptha is a lighter cut of the synthetic crude oil generated by Twelve's process that cannot be used as jet fuel but can be used as a building block for green chemicals and materials. Operations are slated to begin in 2025 to fulfill offtake agreements with Alaska Airlines, Shopify, and International Airlines Group.

Twelve's core technology, the CO_2 electrolyzer, converts CO_2 into carbon monoxide. This system functions similarly to a water electrolyzer but has proprietary cathode catalysts to facilitate the electrochemical conversion of CO_2. At present, Twelve has developed, commissioned, and operated commercial electrolyzer prototypes at technology readiness level 7. At an industrial scale, Twelve's CO_2 electrolyzers can provide significant grid benefits. Twelve's CO_2 electrolyzers can load follow, ramping up or down in seconds to provide greater stability to the electric grid. This capability allows Twelve to use excess electricity during times of overgeneration to convert CO_2 into valuable chemical building blocks. This characteristic is particularly relevant to California, which curtails a significant amount of renewable energy every year. California curtailed 2.66 terawatt-hours of wind and solar in 2023, and 2.58 terawatt-hours of wind and solar in 2024.

In addition to grid benefits, Twelve's technology has significant emissions benefits. Twelve has already demonstrated pre-commercial sustainable aviation fuel production with significantly reduced emissions compared to conventional Jet A fuel. The emissions reductions at commercial-scale operation are projected to be more than 90 percent on a well-to-wing basis. Similarly, Twelve's E-Naphtha™ is cradle-to-gate carbon negative and can be a drop-in replacement for petroleum-based naphtha, which has an annual US production of over five million tons.

Widespread deployment of Twelve's technology would increase safety by reducing greenhouse gas emissions, improve grid stability, and provide a pathway to valorize emissions while displacing fossil fuels.

Project Purpose and Approach

The core functional component of Twelve's CO_2 electrolyzer is the membrane electrode assembly (MEA). The MEA is a sandwich structure composed of a cathode, anode, and polymer exchange membrane, as shown in the left half of Figure 2 in Chapter 1. During electrolyzer operation, an electric current is applied to a stack of MEAs, catalyzing the carbon transformation reaction in the cathode catalyst layer. The objective of this project is to support the scale-up of Twelve's MEA fabrication to the pilot scale, laying the foundation for demonstration-scale deployment of Twelve's CO_2 electrolysis technology.

Twelve's business strategy is based on the build-own-operate model, wherein Twelve will develop and manufacture CO_2 electrolyzers, and then deploy and operate them in its facilities, producing drop-in ready, value-added chemicals and fuels with high emissions reduction impacts. These products will be sold directly to off-takers such as Alaska Airlines and Shopify. The backbone of this approach is a robust MEA manufacturing process capable of producing high quality MEAs at volume, as hundreds of MEAs will be operated simultaneously at Twelve's demonstration-scale CO_2 transformation plant.

Seven tasks were defined for this project, broadly encompassing reporting and other administrative tasks, manufacturing infrastructure development, implementation and validation of new manufacturing capabilities, quality and throughput optimization, evaluation of project benefits, and knowledge transfer.

Key Results

In the first half of the project, Twelve successfully built the low rate initial production (LRIP) pilot line facility, encompassing 1,976 square feet of Twelve's facility in Alameda, California. The full interior building core was demolished, and a new floor plan was created to accommodate the needs of the LRIP pilot line. New electrical, heating, ventilation, and air-conditioning, and process piping systems were installed. Following infrastructure upgrades, the LRIP pilot line was installed and commissioned. Various optimization and validation workflows were then performed, and a quality management strategy was developed and implemented. Finally, knowledge transfer activities and evaluation of project benefits — including white papers, questionnaires, and a project case study — were completed.

Twelve successfully installed, commissioned, and validated the LRIP pilot line. Using optimized fabrication and process parameters, LRIP pilot line is able to consistently achieve MEA yields greater than 90 percent. Moreover, MEAs from the LRIP pilot line demonstrated superior electrochemical performance and decreased performance spread compared to Twelve's prior fabrication methods.

Knowledge Transfer and Next Steps

Twelve will continue optimizing and perfecting the LRIP pilot line installed and validated in this project, including further iterations on process conditions, characterization approaches, quality management strategy, and others. In particular, Twelve expects to exit production validation testing by the end of 2024 and enter sustaining mode, whereupon developmental work will cease. At that point, the focus will shift to maintenance and operations, and the LRIP pilot line will be exclusively used for MEA production for Twelve's demonstration-scale facility.

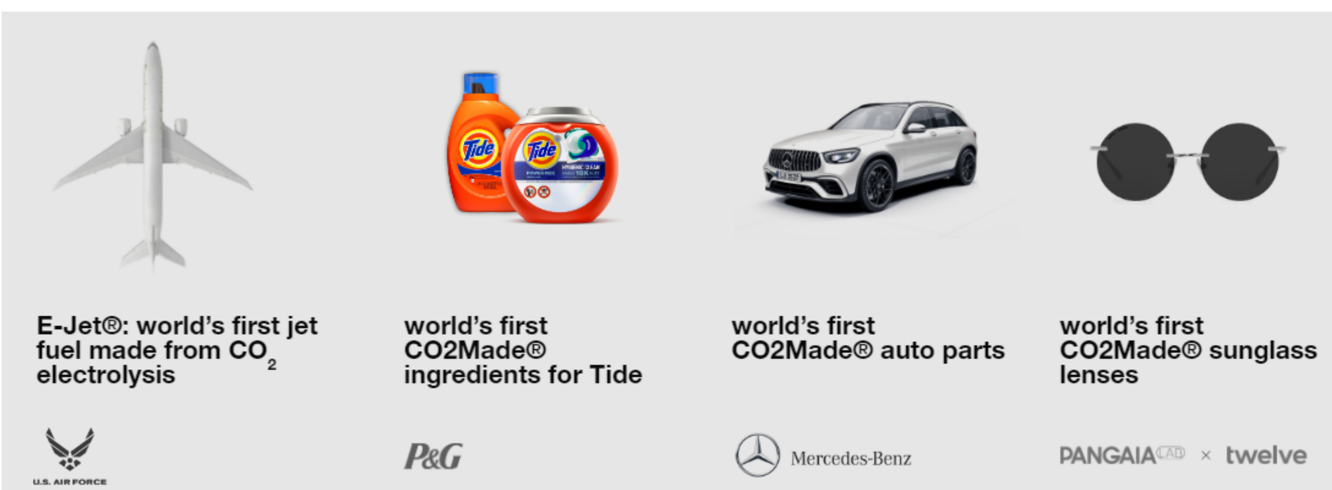
Additionally, Twelve plans to continue sharing information about its MEAs, manufacturing, and overall technology platform with industrial, academic, and governmental stakeholders. During the course of this project, Twelve participated in over eight workshops, conferences, and seminars, where it shared information about its MEAs, electrolyzer, commercial strategy, and other topics. Furthermore, Twelve published five peer-reviewed papers during this project, on topics ranging from catalyst stability to the technoeconomics of CO_2 electrolysis. Ongoing and future work will continue to be shared through such channels.

CHAPTER 1: Introduction

The atmospheric accumulation of greenhouse gases (GHG), including 80 percent carbon dioxide (CO_2), is the primary cause of climate irregularities across the globe. Over three trillion tons of GHGs have been emitted since the industrial revolution, and occurrences of natural disasters such as heatwaves, wildfires, and hurricanes have only increased in regularity. Decarbonization has become an important strategic priority for nations and industries around the globe. A myriad of technologies have been developed to capture and store carbon dioxide from the atmosphere. However, most of these approaches do not address the ubiquitous demand for fossil fuels, nor are they capable of extracting value from the sequestered CO_2.

Twelve Benefit Corporation (doing business as Twelve) is a California-based startup developing a novel and scalable technology to convert CO_2, a readily available waste gas, into valuable building blocks for chemicals and fuels. Using water, renewable electricity, and CO_2 as inputs, Twelve's carbon transformation technology platform is capable of mitigating 2 to 3 billion tons of CO_2 per year across the $600+ billion petrochemicals industry (Precedence Research, 2023). Twelve has worked with some of the world's biggest brands to demonstrate downstream applications for its technology. In all of these cases, Twelve's CO_2 electrolyzer produces chemical building blocks that are converted thermochemically to end products like jet fuel and polycarbonate. To date, Twelve has demonstrated the utility of its electrolysis technology to create sustainable aviation fuel (SAF), consumer chemicals (formates), polymer foams (polyurethane), and polymers (polycarbonate) through partnerships with the US Air Force, Procter & Gamble, Mercedes-Benz, and Pangaia, respectively (Figure 1).

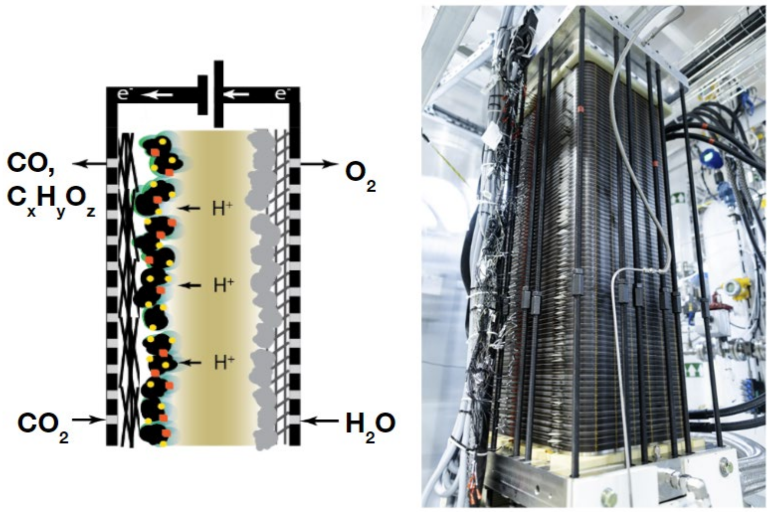
Figure 1. Commercial Demonstrations of Twelve's Technology



Source: Twelve

Twelve's core technology is the CO_2 electrolyzer, which converts CO_2 into carbon monoxide (CO). This system functions similarly to a water electrolyzer but has proprietary cathode catalysts to facilitate the electrochemical conversion of CO_2. The primary functional component of the CO_2 electrolyzer is the membrane electrode assembly (MEA). As shown in the left-hand side of Figure 2, the MEA is a sandwich structure composed of a cathode, anode, and polymer exchange membrane. During electrolyzer operation, a current is applied to a stack composed of many dozens of MEAs (right-hand side of Figure 2), catalyzing the carbon transformation reaction. At present, Twelve has developed, commissioned, and operated technology readiness level 7 commercial electrolyzer prototypes.

Figure 2. Illustration of Twelve's Core Technology



Source: Twelve

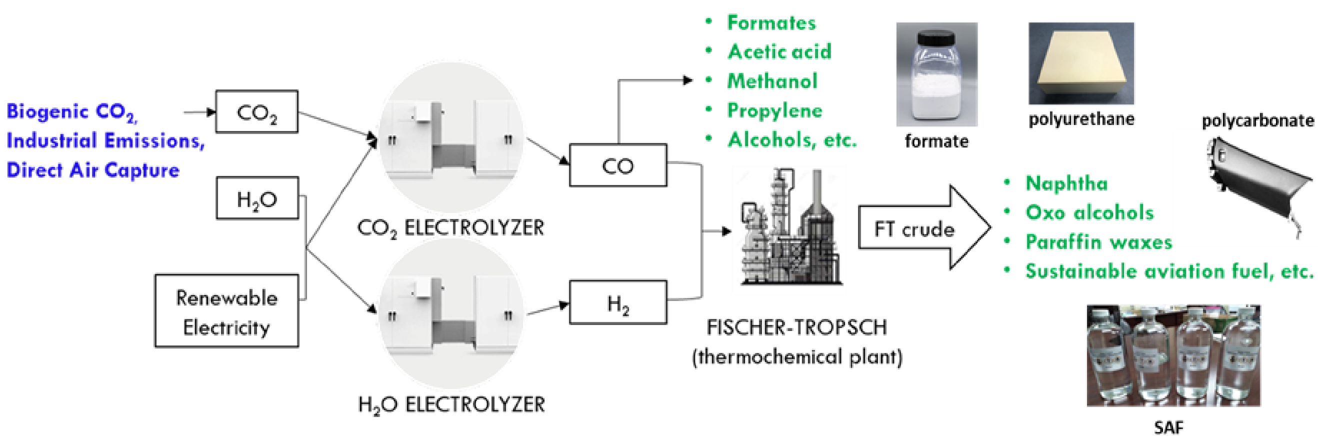
Twelve is presently constructing a first-of-its-kind, demonstration-scale CO_2 transformation plant that will produce low-emission SAF and naphtha (Figure 3). Operations are slated to begin in 2025 to fulfill offtake agreements with Alaska Airlines, Shopify, and International Airlines Group.

Figure 3. Twelve Began Construction of its CO_2 Transformation Demonstration Plant in July 2023

Source: Twelve

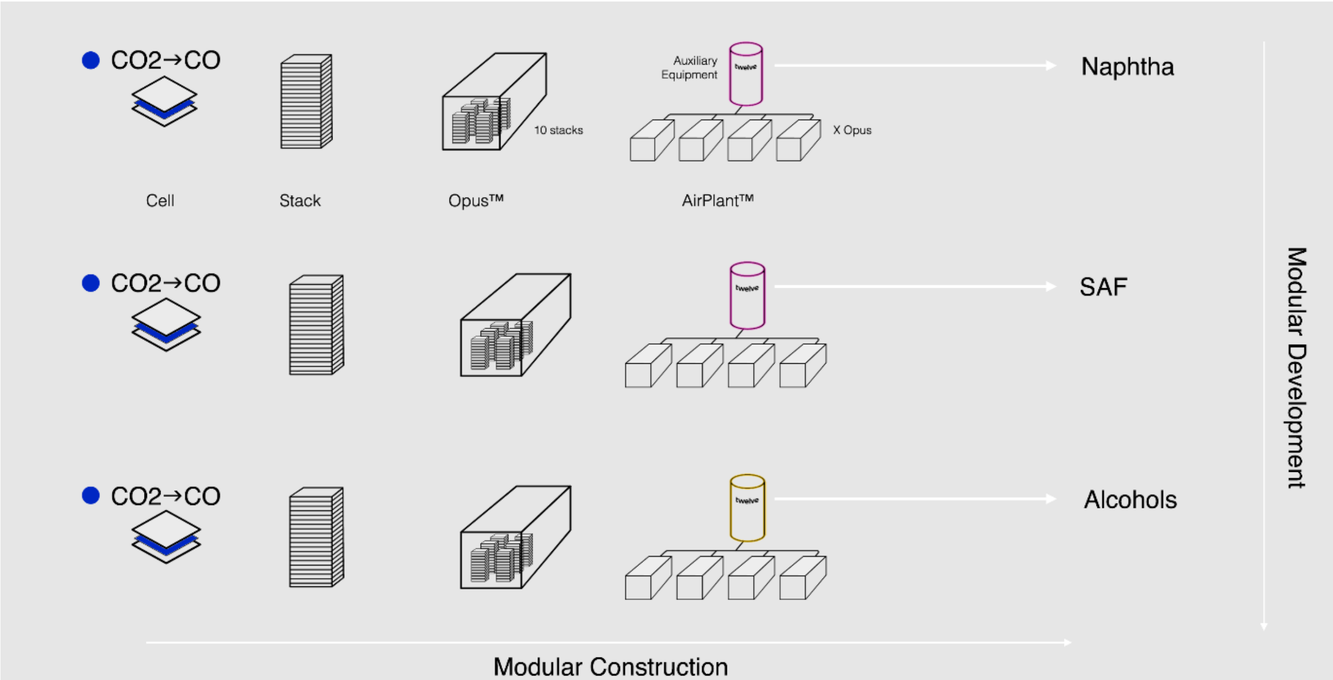
Twelve's demonstration plant has multiple touchpoints across the chemicals value chain (Figure 4). First, CO_2 and water are fed into Twelve's CO_2 electrolyzers and commercial water electrolyzers, producing CO and hydrogen gas, respectively. The CO is then enriched, combined with hydrogen gas to form syngas, and then fed into a Fischer-Tropsch reactor. The Fischer-Tropsch reaction results in synthetic crude, a mixture of hydrocarbons with a range of molecular weights. The subsequent fractionation step separates naphtha and SAF, both of which will be sold directly to off-takers. The intermediates and products formed during this process — CO, syngas, synthetic crude, and naphtha — connect to a broad range of chemicals with high life cycle GHG emissions. For example, naphtha can be used in existing pathways for primary chemicals as defined by the International Energy Agency (for example, ethylene, propylene, and benzene, toluene, xylene mixtures, which account for approximately two-thirds of the emissions from the chemicals industry as a whole (IEA, 2023). Similarly, CO is a critical feedstock for many carbon-based chemicals and can be sold directly to produce an array of chemicals including formates, acetic acid, methanol, propylene, or alcohols. Future Twelve plants can be configured for a myriad of chemical products by adding other downstream thermochemical processes (Figure 5). For example, electrolyzed CO can produce a wide range of products by leveraging different downstream processes.

Figure 4. General Schematic of Twelve's Demonstration CO_2 Transformation Plant



Source: Twelve

Figure 5. Diagram Illustrating the Modularity of Twelve's technology



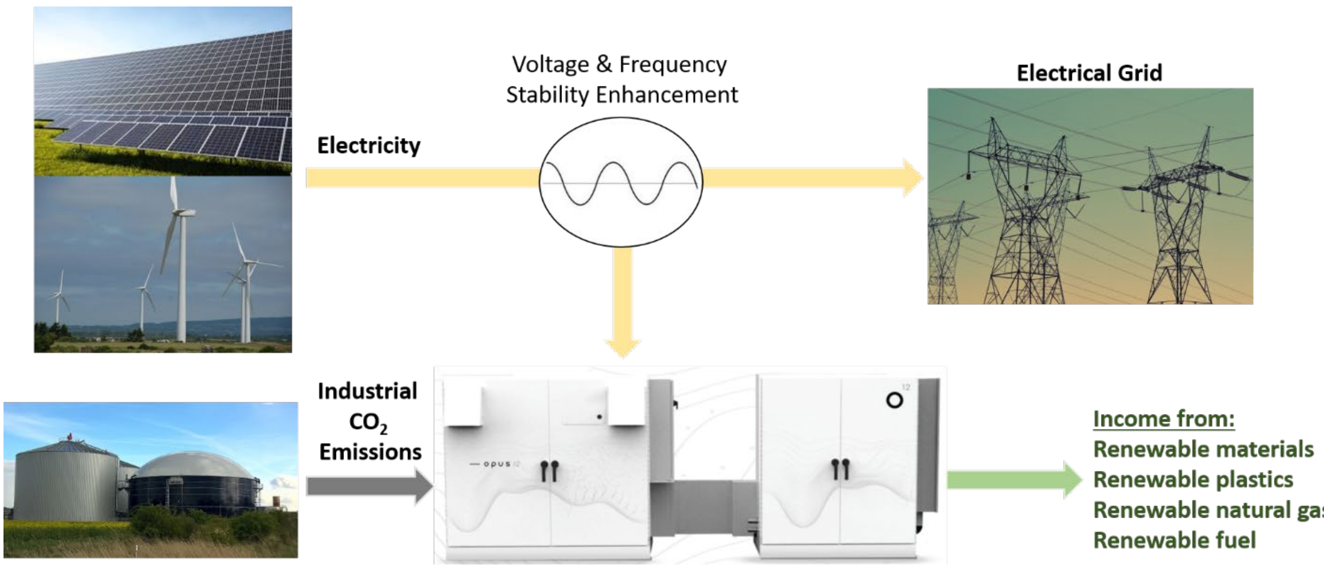
Source: Twelve

Twelve's process is powered by renewable electricity, enabling the production of chemicals with ultra-low carbon intensities. Twelve has already demonstrated pre-commercial SAF production with significantly reduced emissions compared to conventional jet fuel. The CO_2 emissions reductions at commercial-scale operation is projected to be greater than 90 percent on a well-to-wing basis. Similarly, Twelve's E-Naphtha™ is cradle-to-gate carbon negative and can be a drop-in replacement for petroleum-based naphtha, which has an annual domestic production of over five million tons (UN Data, 2024).

Twelve's emissions benefits are calculated by life cycle analysis. These analyses show significant potential emissions reductions for Twelve's SAF, as well as its chemical intermediate, CO. Twelve's core technology, CO_2 electrolysis, does not produce any direct CO_2 emissions. Some direct emissions of CO_2 can be attributed to fuel combustion for unavoidable process safety mechanisms in the fuel synthesis module. These contribute to less than 5 percent of the total well-to-wing GHG impact. Twelve's novel CO_2 electrolyzer and commercial water electrolyzers are similar in design and share a similar set of balance of plant equipment. As such, Twelve uses data from the water electrolysis industry to estimate lifecycle emissions related to stack construction and plant infrastructure. Based on prior life cycle analysis for water electrolyzers, the stack and balance of plant represent 5 percent of the overall carbon intensity score. Twelve estimates approximately 0.8 kilograms (kg) of CO_2 equivalent per gallon (CO_2e/gal) emissions from our E-Jet® (Twelve's registered trademark for E-Jet) while gasification averages 1.2 kg CO_2e/gal, hydro-processed esters and fatty acids averages 5 kg CO_2e/gal, and alcohol-to-jet averages 6 kg CO_2e/gal (Air Transport Action Group). All life cycle analyses were done in accordance with International Organization for Standardization 14040/14044 requirements.

In addition to emissions benefits, Twelve's CO_2 electrolyzers can provide significant grid benefits when deployed at an industrial scale. Twelve's CO_2 electrolyzers can load follow, ramping up or down in seconds to provide greater stability to the electric grid (Figure 6). This characteristic is particularly relevant to California, which curtails a significant amount of renewable energy per year. This capability allows Twelve to utilize excess electricity during times of overgeneration to convert CO_2 into valuable chemical building blocks. Economic production of chemicals and products from excess renewable electricity will further incentivize renewable deployment. Thus, Twelve's CO_2 electrolyzer enhances grid stability, reduces rates through income-generating utilization of excess renewables, and increases safety by reducing GHG emissions.

Figure 6. Grid Benefits of Twelve's CO_2 Electrolyzer



Source: Twelve

The scale of curtailment in California is increasing rapidly, with 2.58 terawatt-hours (TWh) of solar and wind already curtailed in 2024 from January through June (CAISO, 2024). In comparison, a total of 2.66 TWh of solar and wind was curtailed in all of 2023. This number will only increase as the state proceeds toward its renewable portfolio targets. Multiple approaches must be taken to manage this oversupply, from regional integration to large-scale batteries. CO_2 electrolysis could provide an effective lever that is virtually unlimited in scale. Based on expert interviews on approximate hours of overgeneration and seasonal variability, Twelve estimates 7 TWh of overgeneration by 2030. Using Twelve's technology, this excess energy could be used to convert 0.9 million tons of CO_2 into 1.2 million tons of CO for downstream conversion to a variety of chemicals. Twelve's CO_2 electrolysis technology can benefit California ratepayers by providing lower costs, greater reliability, and increased safety and decreased CO_2 emissions, as detailed below.

<u>Lower costs</u>: Currently, overgeneration of electricity provides little or no income to utilities, and the volume of overgeneration is expected to increase substantially as a larger share of generation shifts to renewables. An income-generating use of excess electricity would reduce

the overall cost of electricity generation and could increase the economic viability of installing additional renewable generation capacity.

Greater reliability: Managing overgeneration in the future California grid would provide greater stability in the system. Twelve’s technology can be seen as a controllable load, since it can ramp capacity up or down in a matter of seconds. This could stabilize the grid by adding a reliable offtake for surplus electricity and a way to reduce the load in moments of high demand. CO_2 electrolyzers can also provide shorter timescale grid services, such as load following, and performing these services while using CO_2 emissions would provide a double benefit.

Increased safety and reduced CO_2 emissions: Deploying this technology at scale could reduce CO_2 emissions by 2 to 3 billion tons per year; thereby reducing the impact of climate change, which translates into lower risks of fire and flooding. Annual wildfires in California are clear demonstrations of the impact of climate change on California.

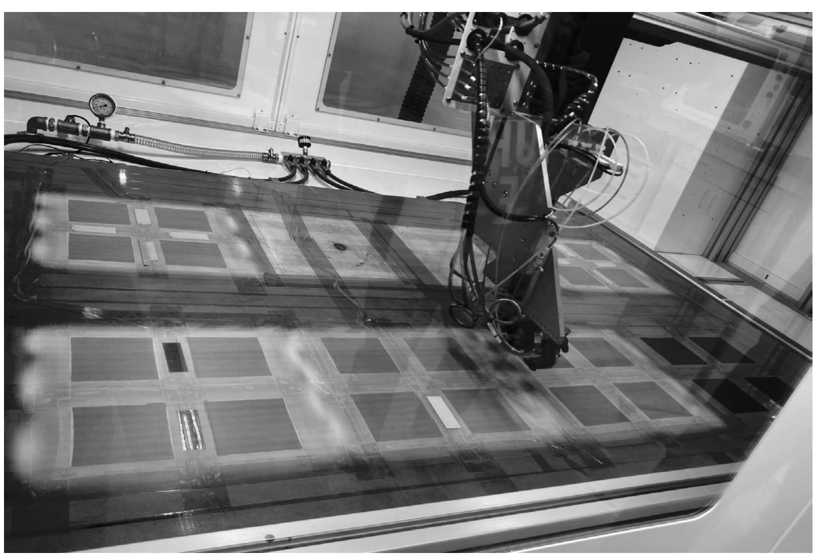
CHAPTER 2: Project Approach

The objective of this project is to support the scale-up of Twelve's MEA fabrication to the pilot scale, laying the foundation for demonstration-scale deployment of Twelve's CO_2 electrolysis technology. Twelve's demonstration-scale CO_2 transformation plant entails simultaneous operation of hundreds of MEAs; as such, Twelve requires a robust MEA manufacturing process capable of producing high quality MEAs at volume.

Twelve fabricates MEAs using layer-by-layer deposition of active materials from a liquid ink. This approach is widely used in adjacent electrochemical technologies such as water electrolyzers and fuel cells. However, this approach is underdeveloped for the specific materials and considerations relevant to CO_2 electrolyzers, presenting a barrier for commercialization. Thus, a key goal of this project is to develop fabrication process science knowledge at the pilot scale, enabling commercial-scale deployment of CO_2 electrolyzers.

Prior to project start, Twelve used a low throughput, batch-based approach to MEA manufacturing (Figure 7). While this approach was sufficient for lab-scale iteration and development, it is insufficient for Twelve's demonstration-scale plant, because it is not amenable to parallel workflows and requires significant operator time as well as manual alignment processes that introduce significant batch-to-batch variation. Building on the manufacturing and process knowledge gained working with those batch-based systems, Twelve scoped and designed a semicontinuous MEA manufacturing system using the same fabrication principles. The focus of this project is the installation, commissioning, and validation of Twelve's semicontinuous, low rate initial production (LRIP) pilot scale MEA fabrication system (Figure 8) capable of producing high quality MEAs at the requisite volumes for Twelve's demonstration plant.

Figure 7. Twelve's Previous, Batch-based Manufacturing Approach



Source: Twelve

Figure 8. Twelve's Semicontinuous, LRIP Pilot Scale MEA Fabrication System that was Installed, Commissioned, and Validated in this Project

Source: Twelve

Seven tasks were defined for this project, broadly encompassing reporting and other administrative tasks, manufacturing infrastructure development, implementation and validation of new manufacturing capabilities, quality and throughput optimization, evaluation of project benefits, and knowledge transfer. The project roadmap is described below:

Project roadmap:

1. General Project Tasks
2. Infrastructure and Facility Upgrade
3. MEA Fabrication Preliminary LRIP Tool Validation
4. MEA Fabrication LRIP Pilot Line Build and Performance & Throughput Assessment
5. Develop and Implement Quality Management Strategy
6. Evaluation of Project Benefits
7. Knowledge Transfer Activities

The overall flow of the project was envisioned as follows. First, Twelve would develop infrastructure at its facility in Alameda, California to prepare for installation of the LRIP pilot line system (Task 2). Following completion of construction, Twelve would install and commission the LRIP pilot line. After initial mechanical and electrical validation of the system were completed, Twelve would transfer the MEA fabrication process and associated quality checks from the batch-based system to the LRIP pilot line, including ink formulation, ink characterization, MEA fabrication, fabrication process monitoring, post-fabrication MEA characterization, and post-fabrication MEA performance evaluation (Task 3). These processes would be individually validated, and then integrated to confirm the functionality of the overall MEA fabrication process, including supporting workflows. Then, fabrication optimization to improve MEA yield and performance would begin in earnest, involving optimization of process parameters, reduction of cycle times, and so forth (Task 4). In parallel, statistical tools and quality management strategies would be developed to better quantify and guide the optimization process (Task 5). Evaluation of project benefits and knowledge transfer activities would occur throughout the project, ramping up towards the end as Tasks 4 and 5 approached completion. Thus, the project can be thought of as proceeding in three stages:

1. Construction and preparation for installation of the LRIP pilot line
2. Commissioning and initial validation of the LRIP pilot line
3. Optimization of LRIP pilot line yield and throughput and implementation of quality management strategies

Twelve's Process Development function served as the internal owner of the LRIP pilot line and led the bulk of this project. This team is headed by project Principal Investigator Dr. Daniel Hellebusch, Director of Materials & Electrochemical Engineering & Process Development, who is supported by Curtis Takagi, Senior Manager of Process Development. Administrative support, including award administration, meeting with the CEC, preparing reports and deliverables, budget tracking, and so on, was provided by Twelve's Grants team. Other Twelve teams and functions were also involved as needed, including Environmental Health & Safety, Facilities, Software, Characterization, Material Operations, Engineering Support, Program Management, Intellectual Property, Supply Chain, and others. Toward the end of the project, as the LRIP pilot line completed Engineering Validation Testing, and transitioned into Design Validation Testing, internal ownership of the LRIP pilot line was transferred to Twelve's Material Operations function, specifically Nik Kondov, Pilot Production Manager. The core team for this project was composed of approximately 10 individuals at project start, growing to a team of 20 individuals by project end. As of 2023, Twelve is among the 25 largest employers in the city of Berkeley, California, and is one of two startups to make the list alongside large private sector corporations such as Bayer and Meyer Sound and retailers such as Safeway, Whole Foods, and Target (Office of Economic Development, 2023). See Figure 9.

Figure 9. Twelve was One of the 25 Largest Employers in the City of Berkeley in 2023

Employment Activity
largest employers

Top 25 Berkeley Employers

Company	Sector
Backroads Inc.	Recreation
Bayer Corp.	Biotech
Berkeley Bowl Produce	Food & Beverage
Berkeley Cement Inc.	Construction
Berkeley City College	Education
Berkeley Unified School District	Education
City of Berkeley	Government
Fieldwork Brewing Co.	Food & Beverage
Foresight Mental Health	Healthcare
Information Systems and Accounting	Business Services
Kaiser Permanente Medical Group Inc.	Healthcare
Lawrence Berkeley National Lab	Laboratory
Lifelong Medical Care	Healthcare
Meyer Sound Laboratories	Manufacturing/ R&D
OC Jones & Sons	Construction
Twelve	Manufacturing/ R&D
Safeway Inc.	Food & Beverage
Siemens Corp.	Manufacturing/ R&D
Sutter Bay Hospital	Healthcare
Target Corp.	Retail
The Wright Institute	Education
University of California	Education
UPSIDE Foods	Biotech/R&D
Whole Foods Market	Food & Beverage
YMCA of the Central Bay Area	Recreation

*Source: State of California Employment Development Department (EDD), Q1 2023**

(Clockwise) Meyer Sound, Fieldwork Brewing, Upside Foods, Twelve *Credits:, Business Wire, Traveler Mag.*

Twelve's carbon transformation technology converts captured CO2 into products historically made from fossil fuels *Pictured at right:* The company's O12 reactor

Upside Food's meat is grown directly from animal cells

Berkeley's top 25 employers (by number of employees) is reflective of the city's diverse economy. Top employers include four in the healthcare sector and four in the education sector, including UC Berkeley, one of the city's main economic engines. There are also a few large private sector corporations in Berkeley, notably Bayer and Meyer Sound. Two startups also made it onto the 2023 list: Upside Foods and Twelve.

*Data from Q1 2023 excludes companies no longer in Berkeley by the end of 2023

CITY OF BERKELEY | OFFICE OF ECONOMIC DEVELOPMENT | 2023

Source: Office of Economic Development, 2023.

Additionally, a technical advisory committee was formed to advise on the project. The technical advisory committee was composed of:

1. Dr. Lihui Wang, Manager of Electrolyte Engineering at Form Energy
2. Dr. Christopher Hahn, Deputy Group Leader of Materials for Energy and Climate Security at Lawrence Livermore National Laboratory
3. Dr. Ethan Secor, Assistant Professor of Mechanical Engineering at Iowa State University

CHAPTER 3: Results

Results are provided for key development stages and technical tasks of the project, in accordance with the three stages defined in Chapter 2.

Infrastructure Expansion and Upgrade

The LRIP pilot line facility is a part of Twelve's facility in Alameda, California. This site serves as Twelve's manufacturing and demonstration facility, where the LRIP pilot line and demonstration-scale electrolyzers are located. Construction work for the LRIP pilot line facility occurred as part of a larger construction project.

The overall construction project built out 19,895 square feet of an existing building. The full project scope includes laboratories, pilot fabrication plant, office, and supporting systems. The full interior building core was demolished, and a new floor plan was created to accommodate these spaces. Work included new electrical, mechanical, plumbing, and process piping and equipment yard. Design began in May 2022, construction began in September 2022, and construction was completed in June 2023.

The LRIP pilot line facility encompasses 1,976 square feet. This area contains the LRIP pilot line, a gowning room, and a MEA quality control room. Supporting systems for this facility include:

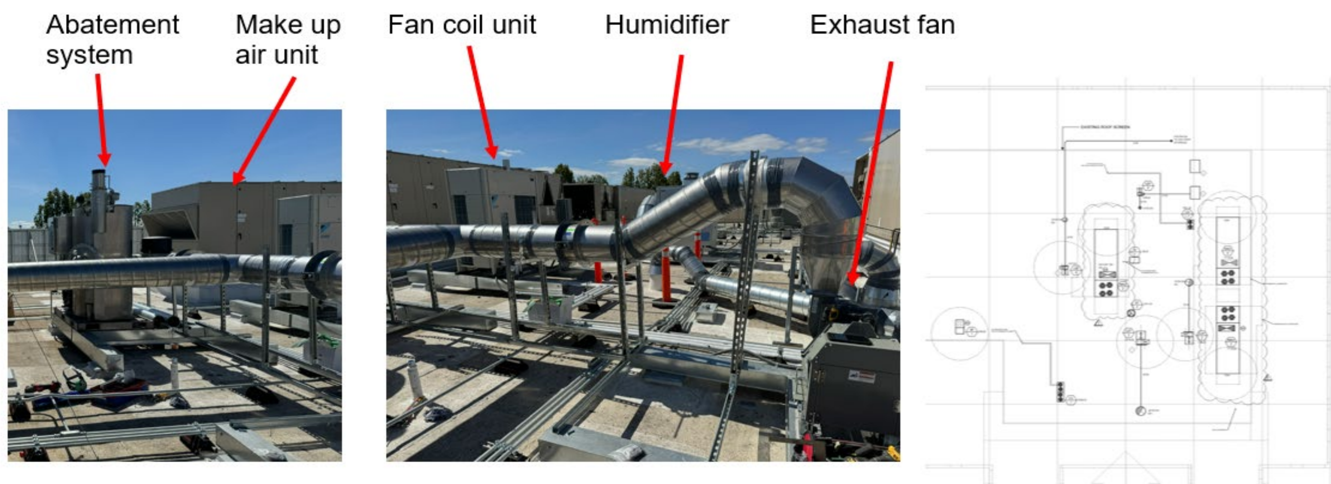
- Electrical support, including new panels, electrical room, and electrical upgrade from 1,600 amperes to 4,000 amperes
- Exhaust fans for LRIP pilot line and rooftop abatement system for solvents
- Heating, ventilation, and air conditioning systems, including:
    - Make up air unit to equalize room pressures
    - Fan coil unit for temperature and humidity support
    - Humidifier
    - Cleanroom fan filter units (HEPA) for class 10,000 cleanroom
- Compressed dry air piping
- Seismic bracing for LRIP pilot line

All construction items included in Twelve's proposal were completed, with the exception of a reinforced concrete floor to support the fabrication system. This was found to be unnecessary for the LRIP pilot line, thus, it was not pursued in this facility upgrade. Additionally, it was determined that stainless steel lines for pressurized air flow were not suitable for compressed air. Hence, the line for compressed air was made with copper, while the lines for all other gases were made with stainless steel. Pictures of the LRIP pilot line room are shown in Figure 10, while roof-top equipment is shown in Figure 11.

Figure 10. Images of the LRIP Pilot Line Facility

Source: Twelve

Figure 11. Roof-Top Equipment Installed for the LRIP Pilot Line Facility



Source: Twelve

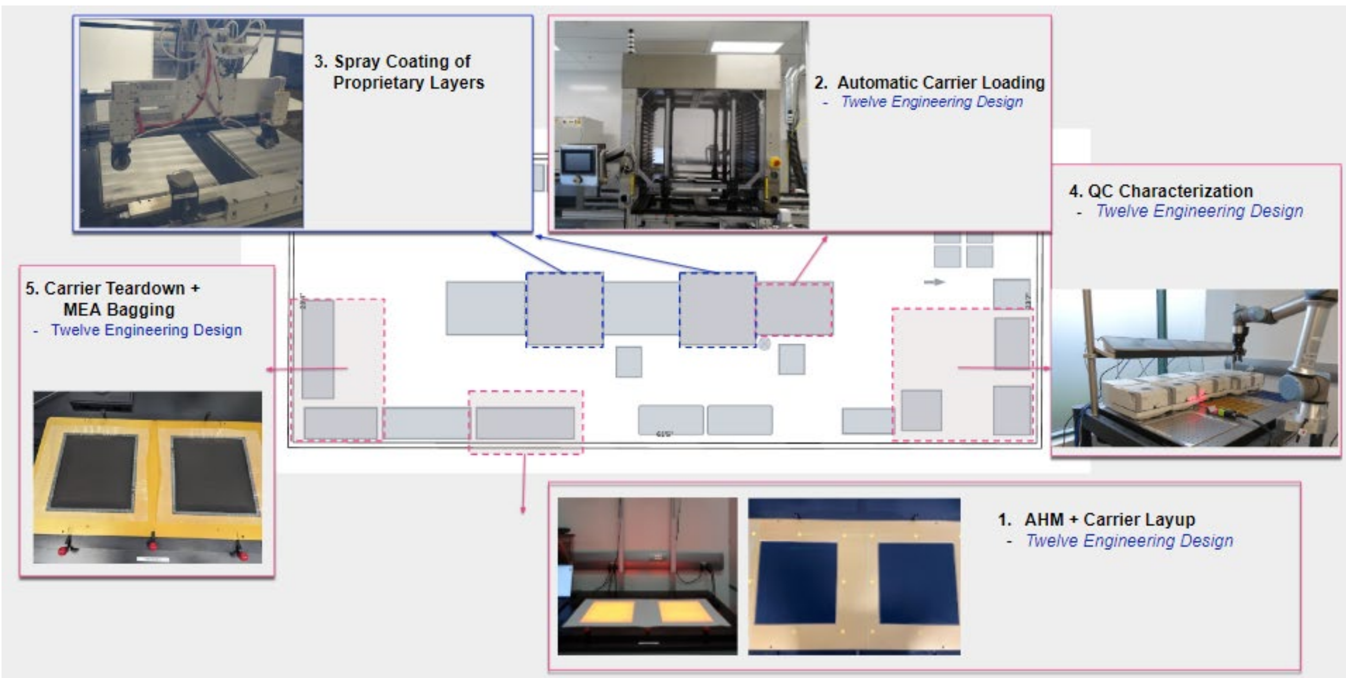
The contract method for this construction project was:

- Architectural contract follows American Institute of Architects (AIA) B101-2017 with DG Architects
- Construction contract follows AIA A104-2017 with SC Builders

LRIP Pilot Line Installation and Validation

Following completion of construction and successful factory acceptance testing of the LRIP pilot line at the manufacturer's facility, the LRIP pilot line was installed at Twelve's facility in Alameda. The LRIP pilot line is a coater/conveyor system, wherein treatments are performed sequentially onto MEAs loaded on a conveyor belt. A schematic of the system and its primary process steps is presented in Figure 12.

Figure 12. Schematic and Process Steps of the LRIP Pilot Line



Source: Twelve

Details regarding each step of this process are:

1. First, the MEA substrate is placed onto a carrier, which is designed to interface flawlessly with the conveyor belt, ensuring proper alignment during the MEA fabrication process.
2. Then, the carrier is placed into a carrier loading system, which automatically dispenses them onto the conveyor belt as programmed.
3. MEAs are fabricated during the third step, which involves two treatments in separate booths.
4. In the fourth step, MEAs are characterized in a semi-automated manner, involving both in-line and off-line methods.
5. In the fifth step, MEAs are removed from the carrier, and MEAs that pass quality control in the fourth step are bagged and transferred to storage, while MEAs that do not pass quality control are placed in quarantine for further analysis.

However, the steps listed here do not encompass the entire workflow of MEA fabrication. Twelve's workflow for MEA manufacturing also involves incoming quality control of supplies and components, as well as preparation of the inks that are used in the LRIP pilot line. Thus, for this project, Twelve developed a quality management strategy that guides the entire MEA fabrication workflow, from incoming quality control to ink preparation, to MEA fabrication. The following sections describe these stages and their corresponding quality management strategies, many of which were developed during this project.

Incoming Quality Control

First, Twelve performs incoming quality control on the materials that go into MEAs. This is performed each time a new lot of material is received. These materials include, but are not limited to, polymers, catalyst, MEA components, ink additives, and substrates. This step ensures that the procured materials meet desired specifications, which in turn ensures that MEAs can be successfully fabricated and that they will be able to achieve performance targets. High performing MEAs are critical to Twelve's business model.

For example, the molecular weight and polydispersity of purchased polymers are assessed by gel permeation chromatography, while the particle size, metal content, and purity of catalyst material is assessed by transmission electron microscopy, thermogravimetric analysis, and inductively coupled plasma, respectively. A representative image of a material specification sheet used by Twelve is shown in Figure 13. Twelve uses four different specification levels: certificate of analysis (COA), critical to quality (CTQ), monitor only (MO), and method qualification or understanding (MQU). The definitions and implications of these specifications are listed in Table 1.

Figure 13. Representative Material Specification Sheet

[Template] Document ID:	[redacted]	twelve

Material Specification Sheet

for internal use only

Product Name:	Catalyst		
Product Description:	Catalyst used to convert CO2		
Intermediate/Finished Product:	[redacted]	Doc ID:	
Internal Part Number:	[redacted]	Effective Date:	July 31, 2023

Description	QC Test	Test Method	Unit	Min.	Target	Max.	Data Link
Physical Characteristics							
[redacted]	CTQ	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	Link
[redacted]	MO	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	Link
Chemical Characteristics							
[redacted]	MO	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	Link
[redacted]	CTQ	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	Link

Source: Twelve

Table 1. Twelve Specification Levels.

Level	Description	Decision for Product
COA	For these attributes Twelve reviews the Certificate of Analysis to ensure that the reported value meets the required specifications	Pass/Fail decision based on the result of the review
CTQ	Twelve conducts internal measurements with an internally-defined test method to confirm that the product is within specifications.	Pass/Fail decision based on the result of the test
MO	Twelve conducts internal measurements with an internally-defined test method but only for data collecting purposes	No Pass/Fail decision
MQU	Twelve measures the attribute for process qualification or for supplemental understanding only (not a standard production event)	No Pass/Fail decision

Source: Twelve

The quantitative bounds for material specifications in the incoming quality control process are derived from historical data. The specification ranges are set by the following method:

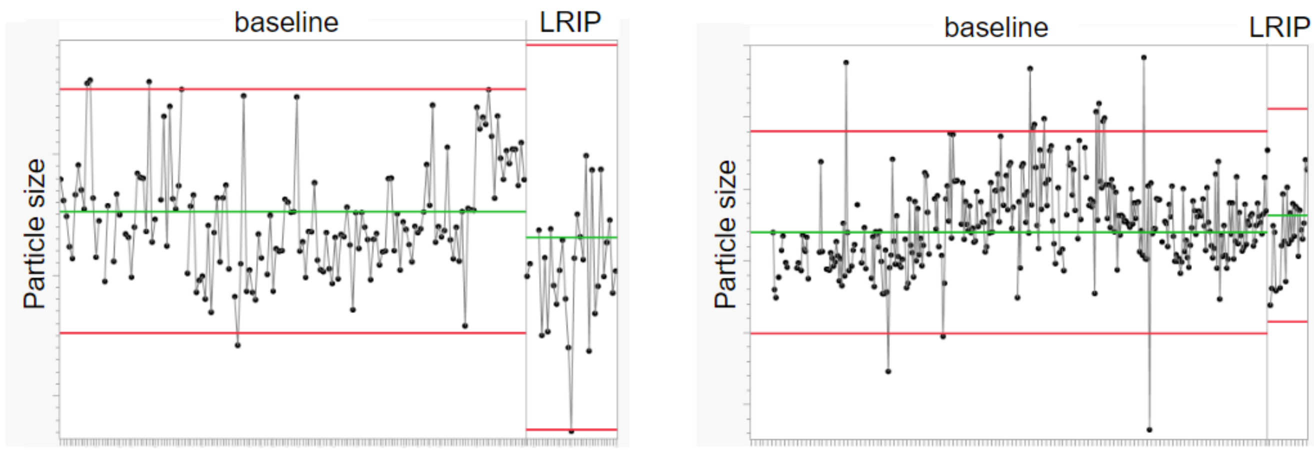
> Historical baseline data was correlated with electrolyzer performance to identify material attributes of interest. If the material characteristic proved to be a leading indicator of cell performance, baseline control limits (defined as three sigma [3**σ**] spread) for that particular property is defined as the material specifications.

Twelve works with vendors to address any material lots that do not pass incoming quality control. Based on the percentage of material lots that pass incoming quality control, Twelve assigns a status to the vendor. Vendors that have demonstrated the consistent ability to provide products that pass incoming quality control are considered validated suppliers. Twelve currently has several such validated suppliers. In the future, it will evaluate its vendors and determine if they meet the company's broader requirements including, but not limited to, product quality, quality control, production capacity, and regulatory conformance. At the moment Twelve does not impose such requirements onto its suppliers (such as an ISO 9001 standard), but it believes such an approach would ensure quality and timely production at scale.

Ink Preparation

The second step in MEA manufacturing is ink preparation. Twelve uses an ink-based MEA fabrication method that is amenable to scaling manufacturing volume. During the ink preparation process, ink is formulated; then dynamic light scattering, viscometer measurements, and moisture content analysis are used to verify its specifications. A key step in this project was to transfer the ink manufacturing process from Twelve's facility in Berkeley to the LRIP pilot line facility in Alameda, while also scaling the volume of ink production. This was performed in parallel with the installation of the LRIP system. After some iteration on ink processing conditions and identification of problematic material lots, alignment with the baseline process was established. Figure 14 shows ink particle sizes for baseline and LRIP inks as measured from dynamic light scattering (Left – ink 1, right – ink 2). The vast majority of inks falls within the control limit (red lines), which is defined as three standard deviations. This quality control step is performed for each batch of ink that is prepared. Twelve's baseline is defined by historical data correlated with measured electrolyzer performance.

Figure 14. Ink Mixing and Characterization Workflow

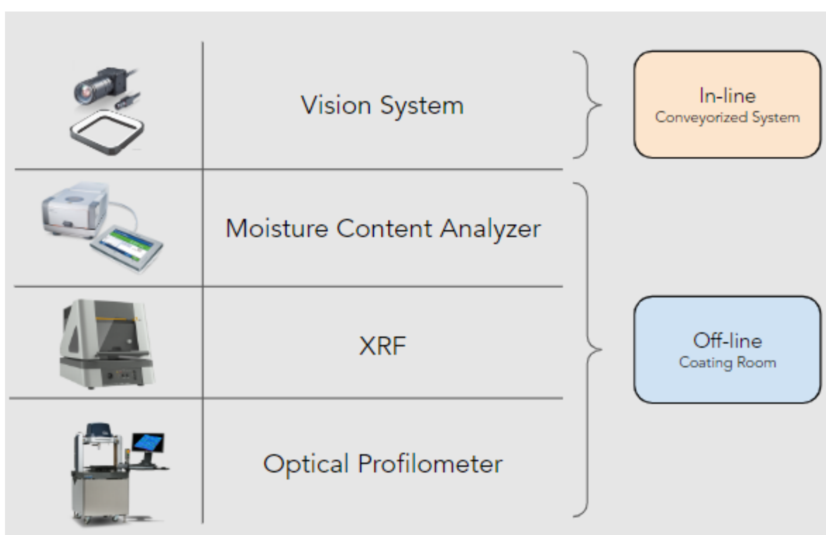


Source: Twelve

MEA Fabrication

After the ink is prepared, the MEA is manufactured on the LRIP pilot system. A number of in-line and off-line characterization methods are used to assess the quality of the resulting MEA. Figure 15 shows in- and off-line characterization methods used to assess process and quality control on the LRIP pilot system. In-line methods are integrated into the LRIP pilot system itself, while off-line methods are used after MEA fabrication.

Figure 15. Characterization Method to Assess Process and Quality Control



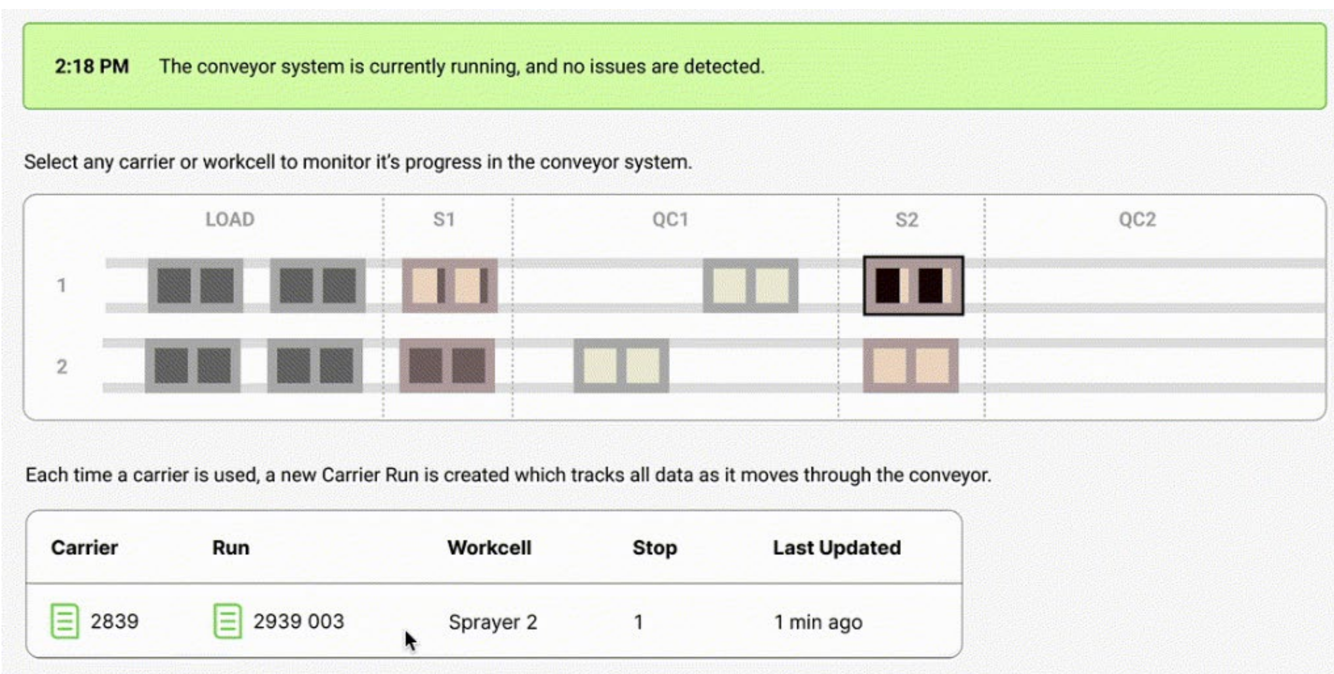
Source: Twelve

The vision system provides a first check, allowing for visual identification of issues such as tears, wrinkles, sputtering, and so forth. Visual checks are performed on each manufactured MEA. The off-line methods are used to ensure adherence to technical specifications and are performed on selected MEAs. MEAs are randomly selected from each manufacturing run for off-line testing.

During initial validation of the LRIP pilot line, extensive ink deposition and characterization was performed to calibrate and optimize all process parameters. The ideal behavior of the LRIP pilot line involves uniform ink deposition across the entire deposition area, enabling uniform and high-performing MEAs, though in reality, deposition can be uneven. Typically, this optimization and calibration would be performed by depositing ink onto MEA substrates, which represent the intended deposition substrate, followed by characterization. However, to reduce developmental costs and material waste, an optimization process using test coupons (non-functional substrates) was developed. Twelve determined that glass slides are an appropriate proxy for the MEA substrate and can offer valuable insight such as deposition uniformity and loading. These coupon tests allow for quantification of layer characteristics such as thickness, area variation, and so forth, without wasting costly MEA substrates. A significant amount of the early optimization in this project was done using coupons.

Additionally, Twelve has built a number of software tools to control and automate the MEA fabrication process, including a dashboard for visualizing the current status of the system (Figure 16).

Figure 16. Dashboard Visualizing the Current Status of the LRIP MEA Fabrication System



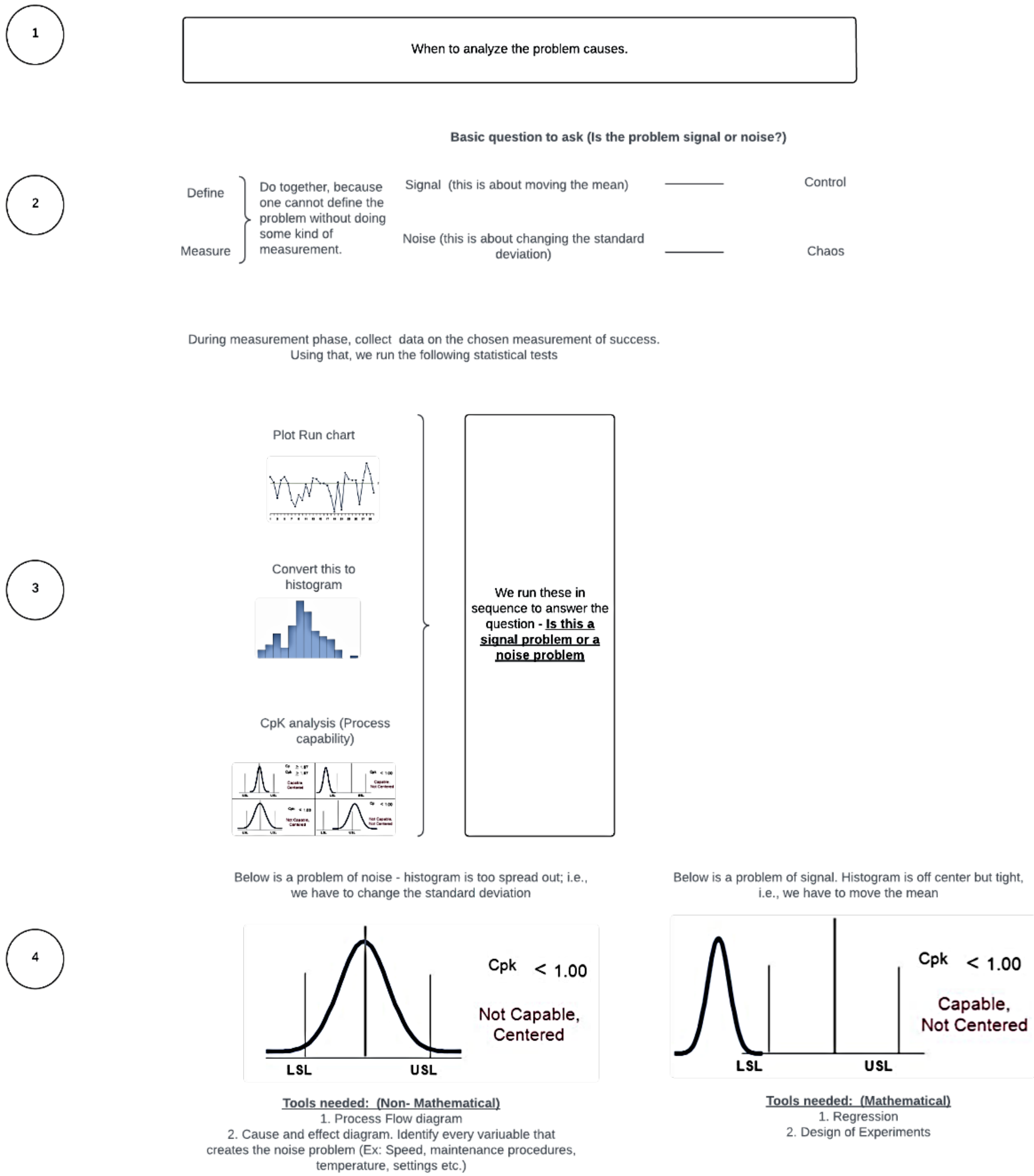
Source: Twelve

While Twelve had already established a MEA manufacturing workflow prior to this project, many specifications, such as incoming quality control specifications, and post-fabrication specifications, were further developed or optimized in this project. Other specifications that were optimized include: thickness, surface roughness, catalyst loading, and MEA dimensions.

LRIP Pilot Line Optimization and Implementation of Quality Management Strategy

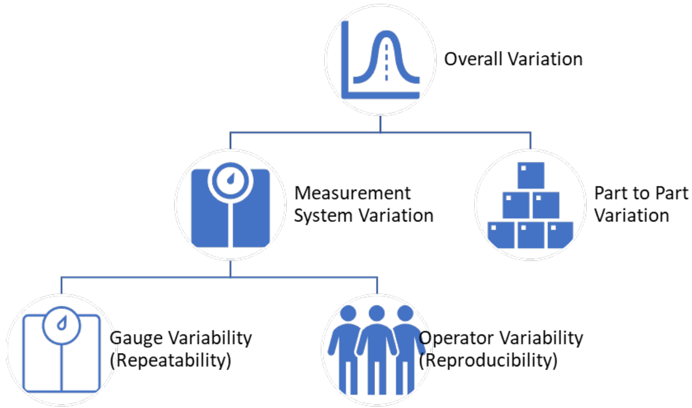
Initial quality, performance, and yield validation took place over three months, concluding in November 2023, which marked the beginning of regular operation and Engineering Validation Tests (EVT). Around this time, Twelve also began the process of transferring operation of the LRIP pilot line from the Process Development team to the Material Operations team. Manufacturing yields during this period were low, prompting further optimization of the LRIP pilot line. Three recurring issues were identified at this stage in the project. These issues were identified with approaches such as root cause analysis, measurement system analysis, gage repeatability and reproducibility, and others. See Figures 17 and 18.

Figure 17. Root Cause Analysis Workflow



Source: Twelve

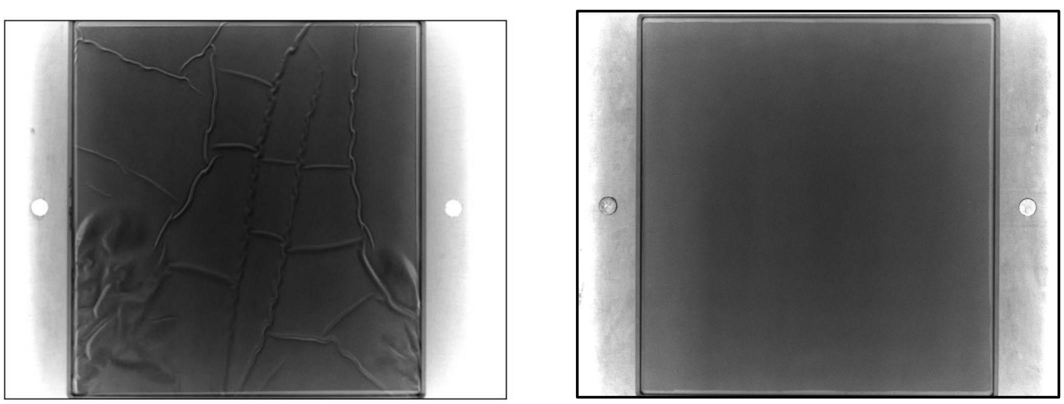
Figure 18. Examples of Inaccuracies Investigated During Measurement Systems Analysis



Source: Twelve

The specific issues unearthed by these quality control approaches, along with their resolutions, are shown in Figure 19 (reduction in MEA wrinkling), Figure 20 (removal of MEA sputtering), and Figure 21 (reduction in MEA warping) below. Figure 19 shows a wrinkled MEA on the left-hand side and reduction of MEA wrinkling on the right-hand side after process improvements and implementation of new MEA carriers.

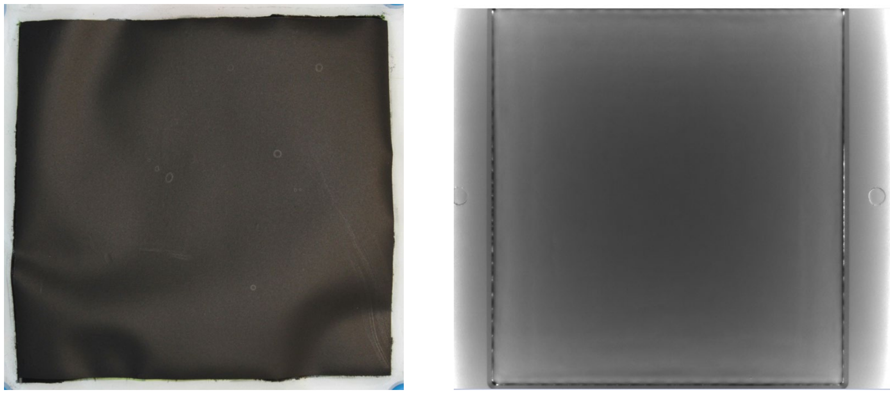
Figure 19. Reduction in MEA Wrinkling



Source: Twelve

Figure 20 shows a MEA with sputtering on the left-hand side and the MEA without sputtering on the right-hand side after process modifications and improvements to system cleaning protocols.

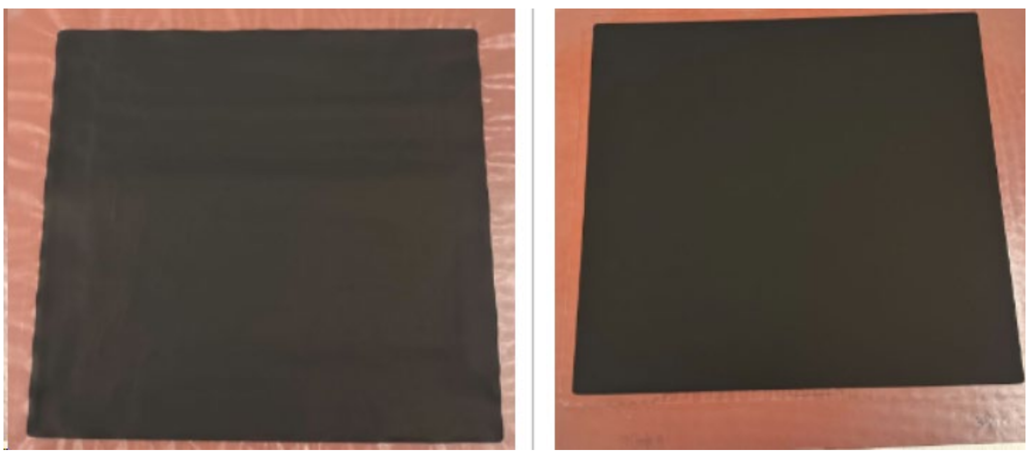
Figure 20. Removal of MEA Sputtering



Source: Twelve

Figure 21 shows a warped MEA on the left-hand side and the MEA with reduced warping on the right-hand side after a post-fabrication process step.

Figure 21. Reduction in MEA Warping

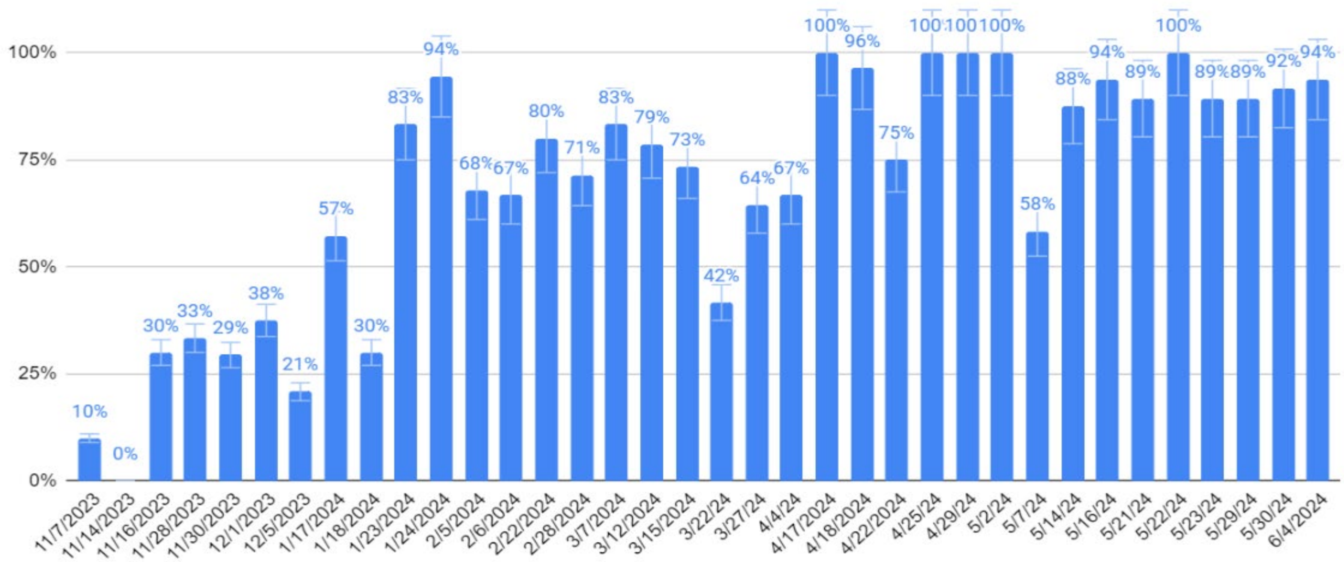


Source: Twelve

Extensive characterization and process modifications were undertaken to address each of these issues. Conversations with the LRIP pilot line manufacturer and suppliers also proved fruitful for resolving these problems.

Having resolved these MEA quality issues in the first half of 2024, Twelve was able to increase the MEA yield from approximately20 to 30 percent to over 90 percent. This is illustrated in Figure 22, which shows the MEA yield from commissioning of the LRIP pilot line to submission of this report. The improvement in yield was achieved through continual optimization of process parameters and implementation of quality management strategies. Moreover, detailed evaluation criteria were developed to accurately evaluate MEA pass rate. Currently, Twelve uses nine different evaluation criteria to evaluate MEA pass rate; only MEAs that pass all nine criteria are counted towards yield.

Figure 22. MEA Yield Over Time for the LRIP Pilot Line indicating increase in the MEA yield from 20% to 30%, to over 90%



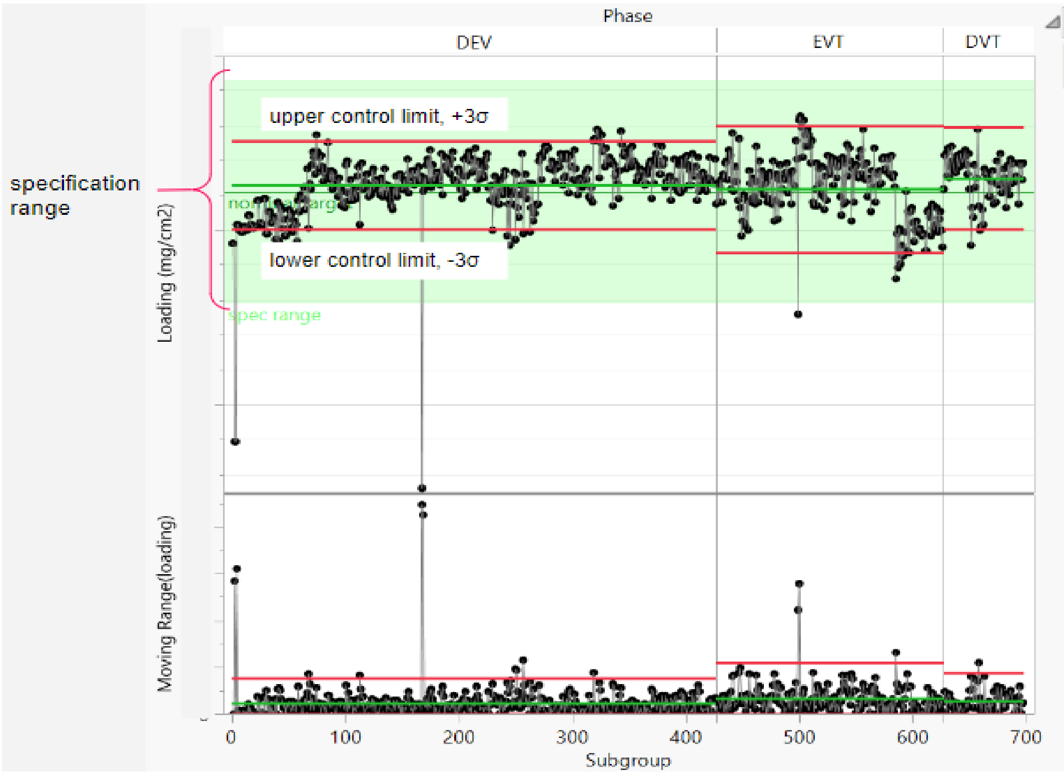
Source: Twelve

Twelve also uses statistical tools such as control charts and statistical measures to benchmark and analyze individual steps in the MEA fabrication process. The most important steps are the ink deposition processes that form the active layers of the MEA. During these steps, also called treatments, inks containing the functional elements of a MEA (for example, catalyst) are dispensed onto the MEA substrate in a controlled manner, resulting in the fabrication of a MEA. Twelve uses two treatment steps; a significant amount of data has been collected on both treatments. These treatments are critical to MEA performance, as various characteristics of the deposited layers – including morphology, thickness, and so on – dictate electrochemical performance. Twelve put a significant amount of effort into optimizing these treatment steps.

At time of writing, treatment 1 of 2 has been consistently in-spec, proving the scalability and robustness of the coating process, which was originally developed at the lab scale, and transferred to the LRIP pilot line in this project.

Figure 23 illustrates data from performing treatment 1 on the LRIP pilot line. Figure 23 shows that the loading of MEAs consistently falls within the specification range, denoted by the green area. The vast majority of MEAs were found to fall within the control limit (red lines), which is defined as three standard deviations (3σ). The nominal target, denoted by the green line, represents Twelve's baseline capabilities. Additionally, no changes were observed when manufacturing operations were transitioned from Twelve's Process Development team to Twelve's Materials Operations team, demonstrating the operator-independent robustness of this process. This is denoted in the figure by the transition from EVT, performed by Twelve's Process Development Team, to design validation testing (DVT), performed by the Materials Operations team.

Figure 23. Treatment 1 Results on the LRIP Pilot Line

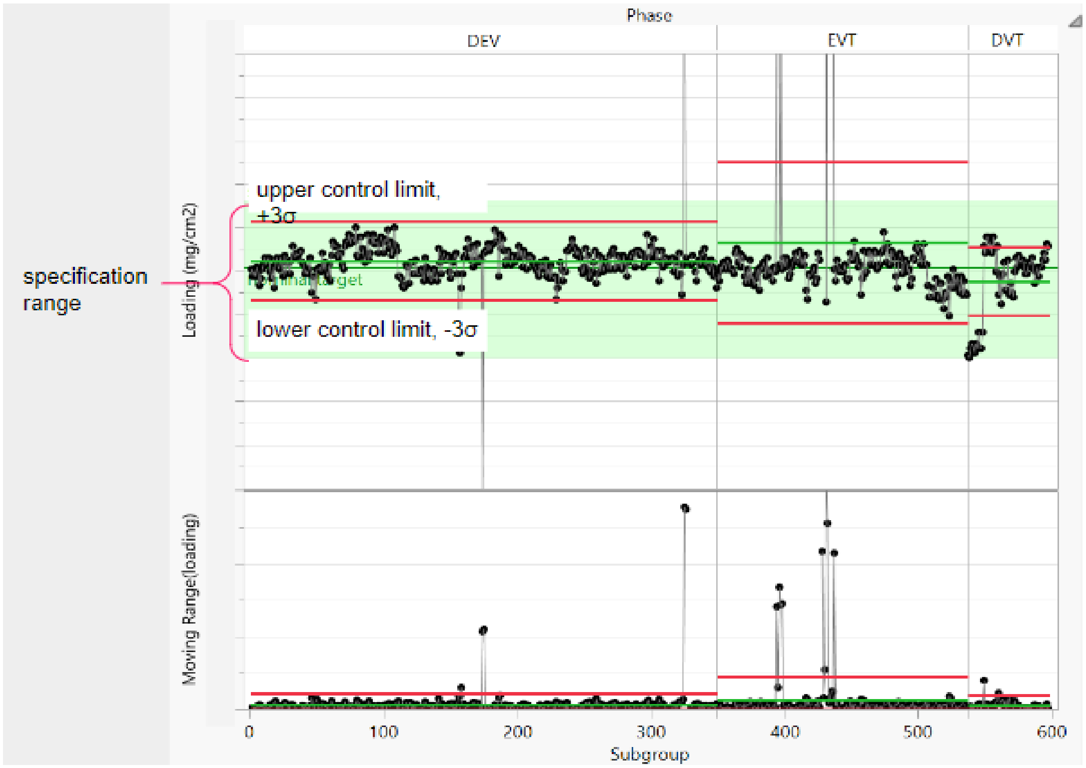


N is more than [>] 600, non-random sampling; DEV = development; EVT = engineering validation testing; DVT = design validation testing

Source: Twelve

Similar data was collected for treatment 2. Figure 24 illustrates data from performing treatment 2 on the LRIP pilot line (N > 600, non-random sampling). Like treatment 1, treatment 2 is also consistently in-spec, demonstrating the scalability and robustness of the coating process. No changes were observed when manufacturing operations were transitioned from Twelve's Process Development team to Twelve's Materials Operations team, demonstrating the operator-independent robustness of this process. The loading of MEAs consistently falls within the specification range, denoted by the green area. The majority of MEAs fall within the control limit (red lines), which is defined as three standard deviations (3σ). The nominal target, denoted by the green line, represents Twelve's baseline capabilities. However, unlike treatment 1, there are a small but noticeable number of outliers across all developmental phases (DEV, EVT, DVT). Twelve plans to continue monitoring these anomalies.

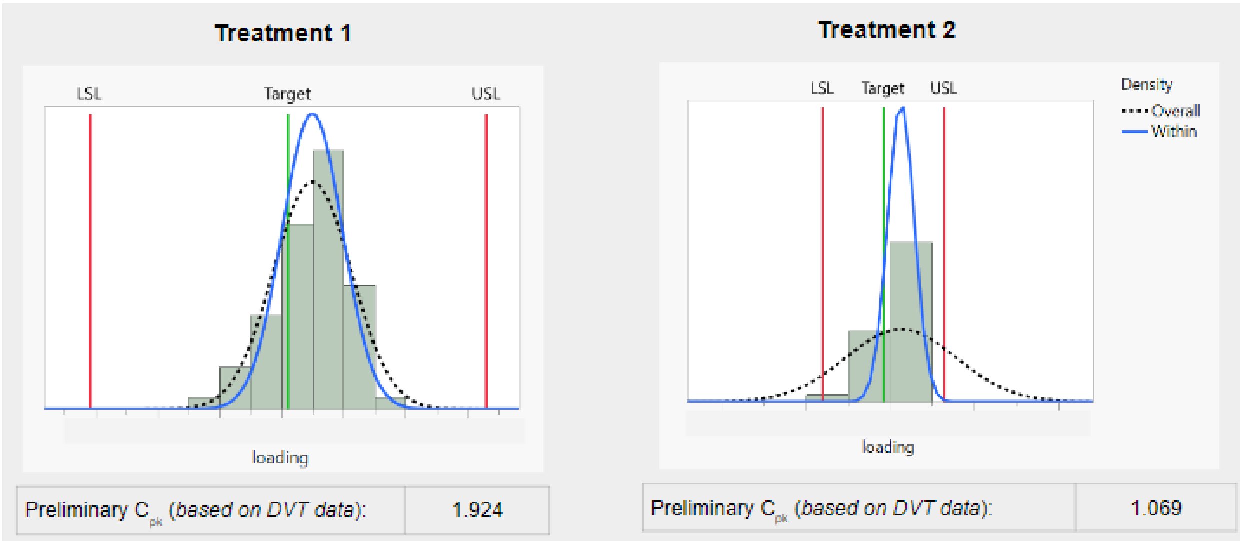
Figure 24. Treatment 2 Results on the LRIP Pilot Line



Source: Twelve

Further analysis indicates that treatment 1 is already highly capable, possessing a narrow distribution that is safely within the specification limits. As illustrated in Figure 25, measured specification data generally aligns with the target, which is denoted by the green line. The blue line represents the distribution of data points within the lower specification limits (LSL) and upper specification limits (USL), denoted by the red lines, while the black dotted line represents the overall distribution of data points (specifically, including data that falls beyond the LSL and USL). There is good agreement between the blue and black dotted lines, indicating that the majority of data points fall within the LSL and USL. In particular, treatment 1 demonstrates a process quality index (C_{pk}) of 1.92, close to the six sigma recommendation of 2.00. Treatment 2 needs additional refinement, as loadings are typically within the specification limits, but the variability is greater than desired, which would lead to low yields at larger manufacturing scales.

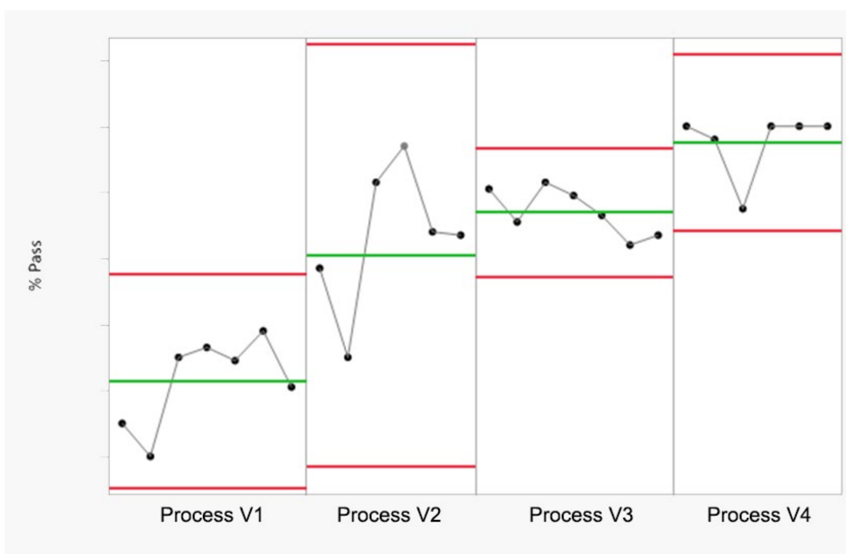
Figure 25. Process Capability of Treatments 1 and 2



Source: Twelve

During this project, Twelve used the tools shown in Figures 17 and 18 as well as other data to identify manufacturing steps and parameters that can be tweaked for improved quality. Figure 26 shows the comparison of four iterative processes developed for the LRIP pilot line. With each successive iteration, the average MEA pass rate was significantly increased. The average is denoted by the green line, while the control limits (3σ) are denoted by the red lines.

Figure 26. Pass Rate of MEAs for Different Iterations of the MEA Fabrication Process on the LRIP Pilot Line

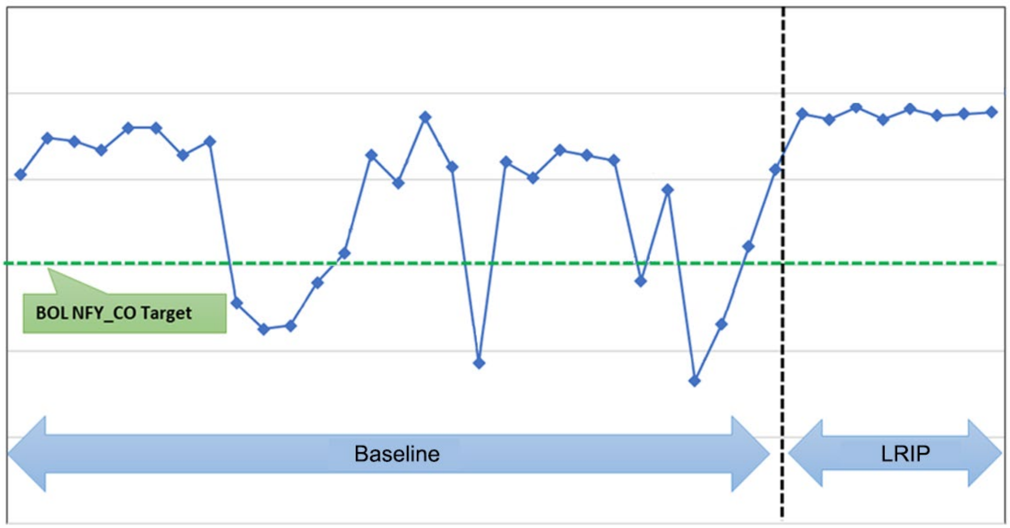


Source: Twelve

To validate that these MEAs are able to achieve the same electrochemical performance as Twelve's prior manufacturing methods, MEAs from the LRIP pilot line were assembled into electrolyzer cells and tested. Figure 27 compares the beginning of life (BOL) normalized

Faradaic yield for carbon monoxide (NFY CO), one of the most important performance metrics for MEAs, across Twelve's baseline and LRIP MEAs. As shown in Figure 27, MEAs fabricated on the LRIP pilot line (right of the black vertical dotted line) show consistently high BOL NFY CO, well above Twelve's target (green horizontal dotted line). NFY CO is a measure of the selectivity of the carbon conversion reaction – a high NFY CO indicates that the majority of renewable electricity put into the electrolyzer is being used to convert CO_2 into the target product CO. NFY is widely used as a performance metric in electrochemical technologies. Twelve compares NFY CO at BOL to ensure a fair comparison between distinct electrolyzers.

Figure 27. Comparison of the Electrochemical Performance Metric BOL NFY CO for Twelve's Baseline Process and the LRIP Pilot Line



Source: Twelve

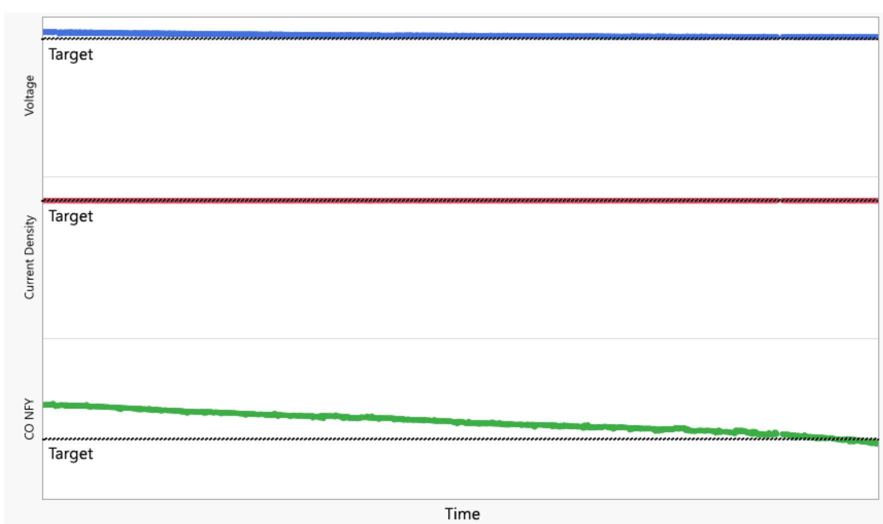
More in-depth electrochemical data for MEAs made from the LRIP pilot line is shown in Figure 28, showing fairly consistent results. All MEAs shown in the figure are close to the voltage target (lower is desired), and all MEAs are above the normalized Faradaic yield target (higher is desired). At time of writing, Twelve tested 12 stacks of MEAs from the LRIP pilot line (stack size ranging from one MEA to several dozen MEAs). Over 120 MEAs from the LRIP pilot line were tested, and over 700 MEAs were fabricated. At this point in time, Twelve is confident in the LRIP pilot line's ability to manufacture high quality MEAs for Twelve's demonstration-scale CO_2 transformation plant.

Figure 28. Electrochemical Data from MEAs made with the LRIP Pilot Line Showing Fairly Consistent Voltages and NFY CO

Source: Twelve

A particularly high performing stack with MEAs from the LRIP pilot line is highlighted in Figure 29. At the target current density (middle trace), voltage (top trace) was found to be close to the target value, while the NFY CO (bottom trace) was found to be well above the target for the majority of the stack's lifetime, which is especially significant because this stack achieved the highest lifetime of any stack built by Twelve. This test demonstrates the exceptional performance and durability of MEAs from the LRIP pilot line.

Figure 29. Illustration of a High Performing MEA Stack from the LRIP Pilot Line



Source: Twelve

Project Summary of Results

Tables 2 and 3 provide a summary of achieved results for the agreement goals and agreement objectives, respectively. In brief, Twelve successfully achieved all agreement goals and objectives, including aims related to LRIP pilot line fabrication area, deposition variation, manufacturing throughput, manufacturing workforce, and knowledge transfer. The primary challenges encountered in this project were related to MEA yield, which were resolved by implementation of quality management strategies. At time of writing, the LRIP pilot line has been fully transferred from Twelve's Process Development function to Twelve's Materials Operations team. Twelve will continue to tweak process parameters to maximize yield, reduce cycle times, and improve electrochemical performance, with the aim of exiting production validation testing and entering sustaining mode by the end of 2024. At that point, Twelve's focus will shift to maintenance and operations, and the LRIP pilot line will be exclusively used for MEA production for Twelve's demonstration-scale facility.

Table 2. Agreement Goals

Agreement Goals	Result Statement
Design and build an LRIP pilot line capable of making 2 to 5 times the current capacity of the producing electrode active area. This is equivalent to building a production line capable of fabricating 17,000 to 40,000 square centimeters (cm^2) of total MEA area per day.	Twelve successfully designed and built a LRIP pilot line capable of fabricating 17,000 cm^2 of total MEA area. Process improvements were implemented to increase throughput, allowing for the fabrication of 34,000 cm^2 of MEA area per day.
Validate manufacturability of the new LRIP line by fabricating MEAs in an equivalent deposition procedure and assessing deposition characteristics are within +/- 5% of the current fabrication tools.	Twelve successfully transferred and validated the deposition process of its previous fabrication tools on the LRIP pilot line, achieving ± 2% to 5% variation relative to target specifications with more than 600 samples.
Build a manufacturing workforce with the identified skillsets necessary to operate the new pilot line, manage production schedules and characterize product at various stages with analytical tools.	During the course of this project, Twelve assembled a workforce of 20 individuals to operate and manage the new pilot line, as well as characterize MEAs in- and off-line.
Fine tune the pilot line operating procedures for high throughput and good process quality control.	Twelve iterated on operation and process parameters, achieving over 90% MEA yield and enabling the fabrication of 34,000 cm^2 of MEA area per day.

Table 3. Agreement Objectives

Agreement Objectives	Result Statement
Validate an entry level LRIP fabrication prototype for capability within +/- 5% of lab/small scale fabrication tools as measured by deposition uniformity in thickness, mass loading, morphology characteristics, as well as Faradaic efficiency, voltage, and lifetime.	Twelve successfully validated the LRIP pilot line, achieving ± 2% variation in thickness and mass loading, ± 3% variation in Faradaic efficiency, and ± 5% in voltage and lifetime with more than 600 samples.
Design a deposition protocol that improves throughput by at least two times the current production rate of 115 square centimeters per hour (cm^2/hr) while maintaining +/- 5% to 15% of low throughput process as measured by deposition uniformity in thickness, mass loading, morphology characteristics, as well as Faradaic efficiency (>90%), voltage and stability of these metrics.	Twelve designed and optimized the deposition process to enable the fabrication of 34,000 cm^2 of MEA area per eight-hour shift, representing a production rate of 4,250 cm^2/hr.
Demonstrate the production of CO_2 electroreduction MEAs within an LRIP pilot line with consistent product quality. The fabrication line will have a combination of surface area and deposition protocol advantages to reach 17,000 to 40,000 cm^2/day throughput.	Twelve successfully validated the LRIP pilot line and implemented process improvements to improve throughput, allowing for the fabrication of 34,000 cm^2 of MEA area per day.
Summarize detail benefits of the technological advancements and breakthroughs to the ratepayer and to environment in general.	During the course of this project, Twelve participated in over eight workshops, conferences, and seminars, where it shared information about its MEAs, electrolyzer, commercial strategy, and other topics. Furthermore, Twelve published five peer-reviewed papers during this project, on topics ranging from catalyst stability to the technoeconomics of CO_2 electrolysis.
Produce regular knowledge sharing communications to keep stakeholders updated and identify opportunities for case study of technology application.	To inform stakeholders and enhance the impact of this project, Twelve produced a project case study to publicize the results of this project. The project case study includes key insights from the project, including Twelve's reflections on automation and project management strategy. Additionally, Twelve published several white papers about the technology and commercialization

Agreement Objectives	Result Statement
	pathway during the course of this project. Moreover, a large amount of information about the project was shared with the vendor during the design, commissioning, and validation of the LRIP pilot system, which will help the vendor design similar systems in the future.

Table 4 shows the project performance metrics. Twelve successfully achieved all minimum target performances and exceeded goal target performances in three metrics related to variation. The strong performance in variation control demonstrates the efficacy of the quality management strategies developed and implemented in this project. Twelve will continue to iterate on its quality management strategies to ensure a robust supply of high-performing MEAs for Twelve's demonstration-scale facility.

Table 4. Project Performance Metrics

Performance Metric	Minimum Target Performance	Goal Target Performance	Final Measured Project Performance
1) Membrane-electrode assembly (MEA) catalyst layer area fabrication capacity per day	17,000 cm^2	40,000 cm^2	34,000 cm^2
2) MEA quality control: Catalyst layer uniformity	+/- 10%	+/- 5%	+/- 2%
3) MEA quality control: voltage efficiency consistency	+/- 20%	+/- 5%	+/- 5%
4) MEA quality control: current efficiency consistency	+/- 15%	+/- 5%	+/- 3%
5) MEA quality control: durability consistency	+/- 20%	+/- 5%	+/- 5%

CHAPTER 4: Conclusion

In this project, Twelve successfully installed, commissioned, and validated the LRIP pilot line for fabricating MEAs, the key functional component of Twelve's electrolyzer that converts CO_2 emissions into valuable carbon compounds using renewable electricity. A skilled workforce of 20 individuals was assembled to operate and manage the LRIP pilot line. Consistent MEA yields greater than 90 percent and improved electrochemical performance were demonstrated, as well as a production capability of 34,000 cm^2 of MEA area per shift.

All four goals defined for this project were successfully completed:

1. Designing and building a LRIP pilot line with a production capacity of 17,000 to 40,000 cm^2 of total MEA area per day;
2. Using the LRIP pilot line to demonstrate deposition characteristics within ±5 percent of baseline fabrication tools;
3. Building a manufacturing workforce that can operate the new pilot line, manage production schedules, and characterize MEAs at varying stages of production, and
4. Optimizing the LRIP pilot line for yield and throughput.

Specifically, Twelve built a LRIP pilot line capable of fabricating 17,000 cm^2 of total MEA area and implemented throughput improvements to enable the fabrication of 34,000 cm^2 of MEA area per day, satisfying goals 1 and 4. Twelve also successfully transferred its baseline deposition process to the LRIP pilot line, achieving ± 2 to 5 percent variation in deposition characteristics ($N > 600$) relative to Twelve's target specifications, satisfying goal 2. Additionally, Twelve built a workforce of 20 individuals to operate and manage the new pilot line, as well as characterize MEAs in- and off-line. As of 2023, Twelve is among the 25 largest employers in the city of Berkeley, California, and is one of two startups to make the list alongside large private sector corporations such as Bayer and Meyer Sound and retailers such as Safeway, Whole Foods, and Target (Office of Economic Development, 2023).

The success of this pilot line is critical to supplying MEAs for Twelve's demonstration-scale CO_2 transformation plant, which will produce SAF with >90 percent emissions reduction on a well-to-wing basis compared to conventional Jet A. Experts forecast that SAF from CO_2 in particular is expected to be one of the largest alternatives to fossil aviation by 2050, as the global supply cap for waste oils is projected to be reached in the late 2020s, supplying only 5 percent of aviation fuel demand, and edible oils and sugar feedstocks face land and water constraints and must be carefully balanced with food consumption (Air Transport Action Group, 2021; and Lash, 2022). Twelve's E-Jet® also burns more cleanly due to a reduced concentration of aromatic hydrocarbons, reducing non-CO_2 climate impacts and particulate matter.

In addition to emissions benefits, Twelve's CO_2 electrolyzers can provide significant grid benefits when deployed at an industrial scale. Twelve's CO_2 electrolyzers can load follow, ramping up or down in seconds to provide greater stability to the electric grid. This capability allows Twelve to use excess electricity during times of overgeneration to convert CO_2 into valuable chemical building blocks. This characteristic is particularly relevant to California, which curtails a significant amount of renewable energy per year. In 2023, California curtailed 2.66 TWh of wind and solar. In 2024, 2.58 TWh of wind and solar had been curtailed as of June 3rd.

In conclusion, Twelve successfully built and validated a LRIP pilot line for MEA fabrication, marking a significant stride towards commercial-scale deployment of Twelve's carbon transformation technology as well as California's energy efficiency goals. Widespread deployment of Twelve's technology would increase safety by reducing GHG emissions, improving grid stability, and providing a pathway to valorize emissions while displacing fossil fuels. Twelve is currently constructing a first-of-its-kind, demonstration-scale CO_2 transformation plant that would produce low-emission SAF and naphtha. Operations are slated to begin in 2025 to fulfill offtake agreements with Alaska Airlines, Shopify, and International Airlines Group. Other offtake agreements are under negotiations (see Appendix A). At scale, Twelve's carbon transformation technology platform is capable of addressing 2 to 3 billion tons of CO_2 per year across the $600+ billion petrochemicals industry.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
>	more than, or greater than
3σ	three sigma, or three standard deviations
BOL	beginning of life
cm^2	square centimeter
cm^2/hr	square centimeter per hour
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e/gal	CO_2 equivalent per gallon
COA	certificate of analysis
C_{pk}	process quality index
CTQ	critical to quality
DEV	developmental phase
DLS	dynamic light scattering
DVT	design validation test
EVT	engineering validation test
GHG	greenhouse gas
kg	kilograms
LCA	life cycle analysis
LRIP	low rate initial production
MEA	membrane electrode assembly
MO	monitoring only
MQU	method quantification and understanding
NFY	normalized Faradaic yield
SAF	sustainable aviation fuel

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Project Deliverables

The following deliverables were completed in this project in accordance with the Scope of Work which can be found on CEC's website.

- Infrastructure Expansion and Upgrade Summary Report
- Sampling and Testing Plan
- Prototype MEA Fabrication Tool Sampling and Testing Results Summary Report
- Critical Project Review Report #1
- LRIP Pilot Line Sampling and Testing Results Summary Report
- Quality Management Report
- Verification Report
- Critical Project Review Report #2
- Initial Project Benefits Questionnaire
- Annual Surveys
- Final Project Benefits Questionnaire
- Draft Project Case Study Plan
- Final Project Case Study Plan
- Draft Project Case Study
- Final Project Case Study
- High Quality Digital Photographs
- Draft Final Report Outline
- Summary of Technical Advisory Committee Comments
- Draft Final Report
- Final Report

Project deliverables are available upon request by submitting an email to pubs@energy.ca.gov.

CALIFORNIA ENERGY COMMISSION

ENERGY RESEARCH AND DEVELOPMENT DIVISION

APPENDIX A: Commercial Offtake Agreements

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APPENDIX A: Commercial Offtake Agreements

The list below shows Twelve's signed offtake agreements with major airlines and corporate customers for the beachhead SAF market, demonstrating our ability to secure follow-on funding. Most recently, Twelve and International Airlines Group signed the largest E-SAF purchase to date, providing strong support for Twelve's future SAF plant development.

E-Jet® Offtaker:

- International Airlines Group
- Shopify
- Alaska Airlines / Microsoft

Twelve has targeted the high-volume, rapidly growing SAF market to ensure its demonstration plant will achieve long-term financial and operational sustainability. This market represents large green premiums, aggressive emissions reduction goals, and has few other options for deep decarbonization.

Twelve anticipates three interplaying forces to bolster revenue. First, a strong pipeline of customers for the SAF cut of our synthetic crude. Second, SAF production and use is being increasingly incentivized by the United States federal government through credits for the SAF industry and buyers, as well as through state level incentives like California's low carbon fuel standard credit, which allows Twelve to provide highly competitive pricing for both long-term offtakes of SAF and naphtha. Third, as Twelve reaches cost parity with petroleum sources, government incentives become less important, and it expects to market expansion beyond companies interested in reducing their carbon footprint to companies seeking a low-carbon, cost equivalent replacement.