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ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Production Scale-up of Advanced Wafer Technology for Drastic Solar Photovoltaics Cost Reduction

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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; 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.

Production Scale-up of Advanced Wafer Technology for Drastic Solar Photovoltaics Cost Reduction is the final report for the Production Scale-up of Advanced Wafer Technology for Drastic Solar Photovoltaics Cost Reduction project (EPC-18-016) conducted by Halo Industries, 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](http://www.energy.ca.gov/research/) (www.energy.ca.gov/research/) or [contact](mailto:ERDD@energy.ca.gov) the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

This final report documents the development and production scale-up of novel, laser-based manufacturing technology for advanced silicon solar wafers at Halo Industries' Santa Clara, California facility. The project's core innovation focuses on replacing traditional mechanical, chemical, and thermal processes with proprietary laser-based equivalents, leading to significantly higher quality, lower cost, and dramatically reduced environmental impact. These improvements support the goals of drastically reducing the cost of solar photovoltaics and accelerating the deployment of renewable energy (Senate Bill 100) by enabling more cost-effective and large-scale deployment of solar photovoltaic resources. Furthermore, the innovative manufacturing process contributes to building a sustainable, resilient domestic supply chain within California.

The highest cost of most solar installations is the cost of the solar module itself. The silicon solar wafer, which is the base material from which individual solar cells are fabricated, currently accounts for 30 percent to 40 percent of the solar module cost. Due to the high technical complexity associated with developing a process to replace the entrenched, traditional methods used in existing wafer manufacturing, there have been no substantial, successful technological advances to reduce wafer cost, improve wafer quality, and enable next-generation solar cell/module architectures.

This project scaled up a novel solar wafer manufacturing technology that has been proven at the full-scale prototype level to provide significant benefits, including: a solar wafer cost reduction of 50 percent or more; solar wafer specifications, such as total thickness variation, bow, warp, surface roughness, number of defects/microcracks, etc., that are more than 20 times better than those achieved with current state-of-the-art fabrication techniques; a reduction of approximately 50 percent in greenhouse gas emissions associated with wafer manufacturing; and the enabling of next-generation solar cell/module architectures. By moving from one-off wafer production toward a pilot manufacturing system, Halo Industries demonstrated the ability of its wafer fabrication technology to scale to industrially relevant throughput and yield, while simultaneously reinvigorating California's solar manufacturing base with an efficient, revolutionary, automated process that will generate lasting, high-skilled solar jobs and be directly competitive with even the lowest-cost global competitors. The technology is ready for immediate low rate initial production and subsequent rapid evolution to full rate production to quickly bring its substantial benefits to the solar market.

Keywords: solar, silicon, wafer, fabrication

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EXECUTIVE SUMMARY

Background

This final report documents the successful development and production scale-up of novel, laser-based manufacturing technology for advanced silicon solar wafers at Halo Industries' Santa Clara, California facility. The project's core innovation focuses on replacing traditional mechanical, chemical, and thermal processes with proprietary laser-based equivalents, leading to significantly higher quality, lower cost, and dramatically reduced environmental impact. These improvements are critical to achieving the goals of drastically reducing the cost of solar photovoltaics and accelerating the deployment of renewable energy.

The escalating impacts of global climate change, including increased frequency of extreme weather and grid instability, pose a direct threat to the resilience and sustainability of California's communities and economy. In response to these threats, the State of California and its institutions have committed to transitioning the state to renewable energy generation through the passage of Senate Bill 350 (De León, Chapter 547, Statutes of 2015), which set a target of procuring 50 percent renewable energy by 2030, and Senate Bill 100 (De León, Chapter 312, Statutes of 2018), which increased the 2030 target to 60 percent and added a 100-percent target by 2045. Halo Industries expects solar photovoltaics to constitute the vast majority of the additional renewable generation capacity that California will add to meet these targets. Although the dramatic decrease in solar module pricing seen over the past 10 years has resulted in tremendous growth in solar electricity generation, this benefit has been primarily due to the scaling up of manufacturing in low-cost regions of the world, such as China. The take-away from most solar analysts has been that the world has now reaped the primary benefits of solar production capacity scaling and new innovations are needed to drive down costs and accelerate adoption.

Silicon solar wafers are the starting material pieces that are processed into solar cells, which are then combined and integrated into deployable solar modules. Wafers currently account for approximately one-third of the cost of a solar module. While small, evolutionary improvements have been occurring year by year with the traditional, 50-year-old solar wafer fabrication technique, Halo Industries' technology, with its unique new laser-based slicing technology, provides a revolutionary method to replace the wire saw for wafering solar-grade silicon ingots into solar wafers. At the full-scale prototype level, this technology has been proven to provide the following benefits:

- Solar wafer cost reduction of 50 percent or more
- Solar wafer specifications, such as total thickness variation, bow, warp, surface roughness, number of defects/microcracks, etc., that are more than 20 times better than those achieved with current state-of-the-art fabrication techniques
- A reduction of approximately 50 percent in greenhouse gas emissions associated with wafer manufacturing
- Enabling of next-generation solar cell/module architectures

Project Purpose and Approach

The goal of this project was to move from one-off wafer production toward a pilot manufacturing line to demonstrate the ability of Halo Industries' wafer fabrication technology to scale toward throughput of approximately 20 seconds per wafer and a yield greater than 95 percent. This project was accomplished in a regimented fashion by: first completing the engineering and design work to configure a pilot production line to achieve the target pilot production metrics using both in-house capabilities and outsourced expertise; then by developing a stable, scalable supply chain and constructing the pilot production system; and finally by validating the end-to-end pilot production process with an existing, committed first customer as an impartial third party.

Halo Industries' technology will play a crucial role in continuing the downward trend in solar pricing by initially reducing the cost of existing solar wafers by nearly 50 percent and then providing even more benefits as thin, flexible, next-generation solar architectures are enabled by the novel production process. This translates into an immediate solar module cost decrease of approximately 15 percent in the short term as the technology is adopted at scale, followed by a 30-percent or more decrease over the long term as solar cell and module technology adapts to the availability of thin, nearly zero-cost wafers that simply cannot be manufactured with traditional methods. Rapid commercialization is the next logical step, and Halo Industries is working hard to secure the resources necessary to bring these benefits to the market.

Key Results and Conclusions

Through the course of this project, Halo Industries successfully scaled up its initial proof of concept into a fully operating pilot production line capable of low rate initial production to demonstrate to customers the capabilities of its technology. The company has achieved excellent production metrics (see Table ES-1) that significantly improve upon the traditional manufacturing approach and have led to commercial traction.

Table ES-1: Target and Achieved Project Performance Metrics

Performance Metric	Target Performance	Achieved Performance	Significance of Metric
Wafer production throughput	20 sec/wafer	approximately 116 sec/wafer	Though the aggressive target was not met, achieved performance meets the bar for production scale.
Wafer production yield	95%	89% average	A yield greater than 80% is required for industrially relevant production.
Wafer total thickness variation	5 micrometers	less than 5 micrometers	Tighter total thickness variation leads to improved solar module performance.

Performance Metric	Target Performance	Achieved Performance	Significance of Metric
Wafer surface roughness	2 micrometers	1–2 micrometers	Lower wafer surface roughness reduces solar cell fabrication cost, increases cell fabrication yield, and improves cell efficiency.
Wafer manufacturing cost savings compared to wire saw	50%	49%, based on cost of operations model	Cost is the primary driver for the adoption of new solar technologies.

Source: Halo Industries

Execution of this project prompted a number of key lessons. The first is that laser technology is generally much more performant than the traditional wire saw but that the primary challenge to scaling it is achieving very high throughputs compared to a parallelized and automated mechanical process. This can be overcome with innovative approaches and technology, but the broader cost structure must remain attractive. A second lesson learned is that all complex technical projects take significantly longer than one expects, especially due to the unknowns when a project is started. Halo Industries encountered many unexpected technical issues that slowed development in certain areas. The team had to come up with a wide array of novel solutions to unblock the path forward. Finally, a third key lesson learned is that the ecosystem for solar manufacturing has been heavily degraded in the United States, such that domestic supply chains are very tenuous and downstream customers/partners that can take Halo Industries solar wafers and make solar cells and modules in meaningful volume are all currently located in Asia.

Benefits to California Ratepayers

The following benefits to California ratepayers are expected as a result of the commercialization of this technology.

- **Lower costs:** This benefit is the most direct and visible, as it will entail reductions in ratepayer monthly energy bills and \$0.13/watt to \$0.63/watt reductions in residential, commercial, and utility-scale solar installation costs.
- **Greater reliability:** This benefit is primarily due to the overall increase in affordability of residential/commercial installations. By empowering all ratepayers, regardless of income class, to affordably choose solar on their properties, this project will reduce their dependence on electrical grid infrastructure, which could be affected by various adverse events, thus helping ensure greater electricity reliability.
- **Increased safety:** The significant increase in solar photovoltaics' share of California electricity generation, driven by the overall benefits of this project, will result in increased safety. Decentralized solar generation will alleviate the burdens on the state's complex electrical transmission grid and help prevent tragic accidents such as the devastating fires that are caused by this aging infrastructure.

- Economic development: The creation of lasting, high-skilled solar manufacturing jobs in the state will be enabled by the revolutionary technology's inherently low cost, process efficiency, and high degree of automation, which ensure that it will be directly competitive even with global jurisdictions having the lowest labor costs.
- Environmental benefits: Solar wafers fabricated with existing methods take approximately 1.3 kilowatt-hours to produce, while those made with Halo Industries' technology require only 0.6 kilowatt-hours. Since 20 billion to 30 billion of these wafers are made annually, substantial waste and emissions can be avoided.

CHAPTER 1:

Introduction

This project entails the successful development and production scale-up of novel, laser-based manufacturing technology for advanced silicon solar wafers at Halo Industries' Santa Clara, California facility. The project's core innovation focuses on replacing traditional mechanical, chemical, and thermal processes with proprietary laser-based equivalents, leading to significantly higher quality, lower cost, and dramatically reduced environmental impact. This is a critical factor for achieving the goals of drastically reducing the cost of solar photovoltaics (PV) and accelerating the deployment of renewable energy. This effort directly supports California's commitment to a 100 percent clean electricity grid, aligning with mandates like Senate Bill 100 (SB 100) by enabling the more cost-effective and large-scale deployment of solar PV resources. Furthermore, the innovative manufacturing process contributes to building a sustainable, resilient domestic supply chain within California, supporting the state's broader economic and climate goals, including those outlined in the Climate Change Scoping Plan. This project achievement demonstrates the value of the California Energy Commission's support in accelerating innovative, clean-technology businesses and scaling up the manufacturing capacity necessary to meet California's clean energy objectives.

The escalating impacts of global climate change, including increased frequency of extreme weather and grid instability, pose a direct threat to the resilience and sustainability of California's communities and economy. To mitigate these risks, the State has established ambitious targets, notably the goal to achieve a 100-percent clean energy future by 2045. This project directly addresses this mandate by focusing on greenhouse gas (GHG) reduction and enhancing system resilience. By contributing an innovative, grid-supporting solution, the project helps California lead in demonstrating global climate leadership and securing a sustainable, equitable energy future.

To understand the impact of Halo Industries' technology, one must first understand the traditional solar wafer manufacturing process. More than 90 percent of solar cells are built on silicon, a common periodic table element that is abundant in the earth's crust, and that percentage will only increase over the next 10 years based on current trends. The silicon solar wafer is the base material on which solar cells are built. To produce modern high-efficiency cells, the wafers must have a certain minimum purity as well as meet a relatively stringent set of geometric and material quality specifications. To achieve the wafer purity requirements, the wafer must be fabricated from a high-quality feedstock material called solar grade polysilicon. This material is made by a chemical purification process called the Siemens process that is costly in every respect, especially in terms of energy use, chemical use, and labor. Current polysilicon prices range from \$10 to \$20 per kilogram (kg). The polysilicon is melted in a large crucible in a controlled environment, and a silicon seed crystal is partially dipped into the melt. As the seed crystal is very slowly raised out of the melt, it grows into a large, cylindrical, single crystal ingot due to the associated cooling of the molten material. This process is very expensive and energy intensive and requires between 24 to 36 hours to complete. Thus, final ingot costs are on the order of \$50/kg to \$150/kg, depending on quality and manufacturer.

To complete the traditional wafer manufacturing process, the cylindrical ingots are segmented, cropped, and shaped into a pseudo-square silicon block. These blocks are then cut into pseudo-square wafers that are approximately 150 micrometers (μm) thick with a diamond-coated steel wire and copious amounts of process water using a tool called a wire saw. The effective thickness of the diamond-coated steel wire is almost as large as the 150- μm -thick wafers that it is used to make. This leads to an immediate, nearly 50-percent loss of ingot material as silicon sawdust. Since this dust is impregnated with diamond and steel, it is not cost-effectively recycled. Moreover, the mechanical sawing process produces significant amounts of damage to the wafer faces that must be chemically removed and can also introduce micro-cracks into the wafer edges that lead to significant yield losses during subsequent solar cell production. In addition to these substantial drawbacks, the geometry of the wafers produced using this sawing process is mediocre at best, with significant 10- μm to 20- μm variations in wafer thickness on top of overall wafer bow and warp that can be as large as 40 μm . This is a very inefficient wafer manufacturing technique, especially when dealing with such high-quality and high-cost starting material.

Over the course of four years at Stanford University and subsequently another six years as a private enterprise, the founders of Halo Industries successfully built an entirely novel solar wafer fabrication process from essentially fundamental physical principles. The single crystal silicon ingot growth process had to remain mostly unchanged to preserve the high quality of the material, since this single crystal growth process enables all modern solar cell architectures and performance. However, the ingot slicing process was reinvented from the ground up. The as-grown, cylindrical silicon ingot is pre-processed with a single, simple, low-cost shaping step. The material is then processed with a proprietary laser process. This laser process enables the precise cleaving of individual silicon wafers from the ingot with no material loss and no significant damage to either the wafer surfaces or edges, and the geometric properties of the wafers are at least 20 times better than those routinely achieved with a wire saw.

This innovation drastically simplifies the wafer fabrication process and results in a wide array of benefits across the entire value chain. The 50-percent wafer cost reduction primarily comes from the material savings associated with converting the entire ingot into wafers, plus the overall process simplification and the elimination of consumables such as cutting wire and water. The 50-percent reduction in GHG emissions of wafer manufacturing is also most directly tied to the material savings associated with converting the entire ingot into wafers. GHG emissions are thought of as linearly proportional to the total energy cost of a product. For wafers produced with a wire saw, this energy cost is approximately 1.3 kilowatt-hours (kWh), while the same wafers produced with Halo Industries' technology have been calculated to have a total energy cost of only 0.6 kWh.

The lack of surface or edge damage in Halo Industries wafers leads to significantly improved solar cell production yields and performance. Moreover, the highly enhanced geometric properties of the Halo Industries wafers mean that each wafer is basically identical to the next, which results in very tight distributions in the outputs (current/voltage) and efficiency of manufactured solar cells. Some of the biggest performance losses in manufacturing solar modules are associated with having to use solar cells with different output properties. Halo Industries' wafers almost completely eliminate this problem and not only simplify the module

manufacturing process but also maximize final module efficiencies across the board. Finally, Halo Industries' revolutionary technology enables the fabrication of solar wafers as thin as 30 μm to 50 μm (compared to the current industry standard of approximately 150 μm). This would be impossible to accomplish with a wire saw because of the rough, mechanical nature of the cutting process, as well as the significant amount of material that would be lost when trying to produce such thin pieces. All envisioned next-generation solar cell architectures are relying on having access to these types of thin silicon wafers to make flexible, ultra-low-cost devices with improved performance characteristics. Halo Industries' technology is the only proven method capable of manufacturing these critical, future-enabling products at the appropriate cost, throughput, and yield.

The goal of this project was to move from one-off wafer production toward a pilot manufacturing line to demonstrate the ability of Halo Industries' wafer fabrication technology to scale toward an industrially relevant throughput of approximately 60 seconds per wafer and a yield greater than 80 percent. Laser technology is generally much more performant than the traditional wire saw but the primary challenge to scaling it is achieving very high throughputs compared to a parallelized and automated mechanical process. This throughput bottleneck can be overcome with innovative approaches and technology, but the broader cost structure must remain attractive. The core target market is high-volume solar manufacturers that are willing to adopt a novel wafer manufacturing process to improve existing solar cell architectures or potentially move aggressively toward next-generation flexible solar cell form factors. Successful demonstration by Halo Industries of the project metrics would clearly demonstrate technical feasibility of this unique laser-based manufacturing approach and incentivize the industry to move to the next stages of volume adoption.

CHAPTER 2:

Project Approach

The proposed project was designed to achieve three critical goals and was phased by splitting the project period into three sequential stages. Each stage primarily focused on one objective and also included preparatory work for subsequent objectives:

1. Complete design and engineering work to configure and build a pilot production system that meets a set of industrially relevant process metrics that have been determined in conjunction with an existing, committed first customer.
2. Develop a stable, scalable supply chain for the necessary components and complete construction of the pilot production system based on the final, validated configuration developed as the end product of the first objective.
3. Bring the pilot production system online, demonstrating that it can achieve or exceed the target process metrics, and produce a quantity of solar wafers that both meet industry standard specifications and are validated as such by the existing, committed first customer.

Meeting these three objectives would enable the technology to be demonstrably ready for immediate low rate initial production (LRIP) with the first customer and subsequent scaling to full rate production (FRP).

The first objective, which involved the engineering and design work to configure the pilot production system, was achieved through leveraging the unique expertise of the existing project team, which had successfully completed the prototype development of this technology over five years, while bolstering the team with full-time industry veterans as well as contractors with directly relevant system scaling experience. An industry-standard approach was taken that involved staged reviews and third-party validation for critical elements. Success was quantified based on whether the target process metrics were met or exceeded in the final system configuration.

The goal of this first major task, which effectively encompassed the first third of the project's scope of work, was to complete the engineering and design work needed to determine and achieve target pilot production metrics using both in-house capabilities and outsourced expertise. As part of this task, Halo Industries engaged stakeholders, determined baseline performance metrics, and developed an end-to-end design of a production line incorporating its novel, laser-based solar wafer manufacturing technology.

Halo Industries developed its technology in-house over the course of several years and demonstrated its feasibility for commercial manufacturing with unit economics validated by a third-party customer, which was a large manufacturer of high-quality solar wafers. Although this customer preferred to remain anonymous due to the advantages that its partnership with Halo Industries provides in the market, it has been working with the company for five years and has provided invaluable guidance as the technology was spun out of Stanford University and optimized for production. The expertise of the customer's team was heavily leveraged

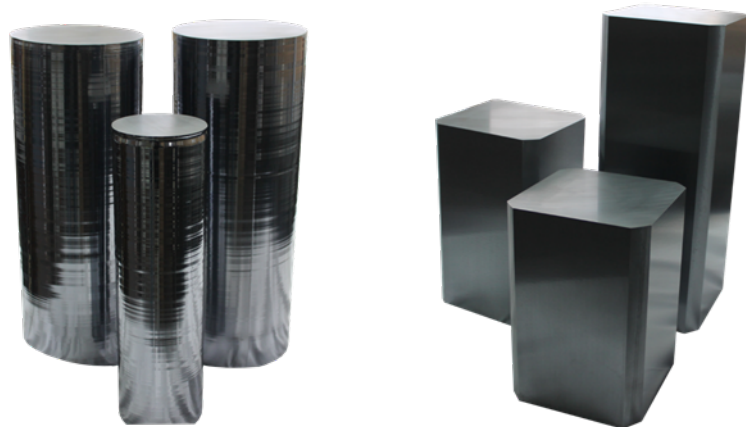
over the course of this project to provide the direct feedback necessary to ensure that the pilot system would meet all of the requirements for the eventual ramp-up to FRP. Additional technical and industry advisors were brought on board under confidentiality agreements to provide guidance on specific aspects of system engineering and design in the areas of industrial engineering, mechanical engineering, electrical engineering, and laser/optics engineering.

The first challenge associated with this effort was the determination of baseline performance metrics for the pilot production system. The goal with the pilot system was to achieve LRIP as a stepping stone to FRP. The key objective was setting metrics for what LRIP entails in a way that was commercially relevant and that demonstrated substantial progress of the technology toward FRP. Halo Industries engaged with its dedicated solar partner/customer extensively to this end due to the customer's intimate knowledge of the solar wafer manufacturing industry. After two deep dives into existing wire saw roadmaps and the current capabilities of Halo Industries' technology, the target metrics for a pilot LRIP system were agreed upon. Although the full details cannot be shared in this report since it is a public document, the top-level metrics were:

1. The capability to produce industry-standard geometry solar wafers.
2. Standard solar wafer specifications with a target thickness of 150 μm .
3. Throughput of less than 120 seconds per wafer.
4. A wafer fabrication yield greater than 80 percent.

With the target metrics in place, the detailed engineering and design work could begin. The most difficult challenge involved determining the form factor of the silicon ingots that would serve as input to the pilot system, because that would drive a significant number of other engineering and design decisions. There were two feasible options: cylindrical ingots and pseudo-square ingots. The traditional wire saw can process both of these form factors with some modifications, and it was important for Halo Industries to determine which path it would pursue first, with the solar industry as the target application. A thorough trade-off study was conducted with significant third-party feedback into the process. The top-level outcome of that study is displayed in Figure 1. Although it was technically feasible for Halo Industries to design and build a pilot system capable of processing both ingot types, it was determined that this would be overly complex and introduce significant timeline risk into the project. Taking into account the pros and cons of both options, the clear choice ultimately ended up being the use of cylindrical silicon ingot inputs to the Halo Industries process. This would have a number of benefits from an operations standpoint and allow the system to be tailored to achieve cost and performance improvements compared to a system that could process only pseudo-square ingots or both types.

Figure 1: Trade-off Between Cylindrical and Pseudo-Square Ingots as Pilot System Inputs

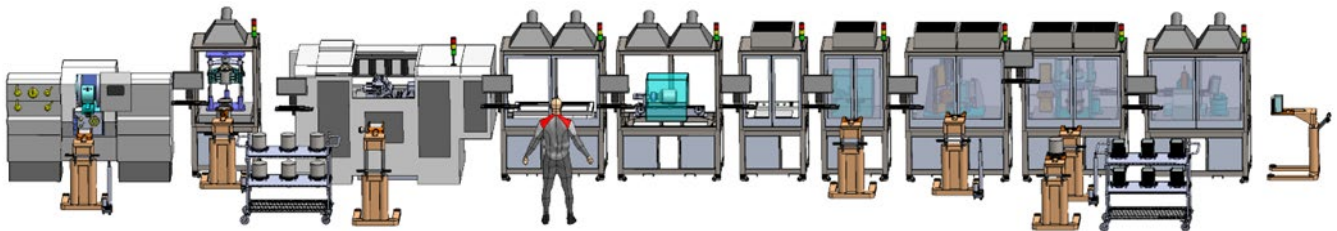


Pre-processing	Simple	Complex
Optics design	Complex	Complex
Laser process mechanics	Simple	Complex
Post-cleave wafer cropping	Needed	Not Needed

Source: Halo Industries

Having completed the critical trade-off study, the remaining engineering and design work had a clear path forward and a well-defined goal. With the assistance of third-party domain experts, the associated work progressed quickly and efficiently. Although the Covid-19 pandemic caused significant chaos and substantial delays, the company was able to successfully complete the effort and achieve initial validation from its solar customer/partner that the technology could meet the agreed-upon LRIP metrics. The associated details cannot be shared in a public document such as this, due to intellectual property concerns, but a basic diagram of the proposed pilot system design that does not reveal sensitive information is provided in Figure 2.

Figure 2: Halo Industries LRIP Pilot Production System Design



Source: Halo Industries

The next step was the development of a stable, scalable supply chain to source the various components of the aforementioned design, followed by the construction of the pilot system. Although some modifications may have been necessary during this second major phase of the project as unknown issues arose, it was expected that the majority of the design would remain

unchanged. Particular attention was paid to thoroughly vetting suppliers and their capabilities as well as their ability to scale with Halo Industries as it ultimately moved into FRP.

The second objective, which involved the development of a stable, scalable supply chain and the construction of the pilot production system, was achieved using the same experienced team that completed the engineering/design work. Trusted suppliers, with a strong preference for California-based businesses, were validated and engaged to provide the various elements of the pilot system. These elements were individually tested, integrated, and modified as necessary. Success was quantified by the ability to complete the work on schedule and within budget.

The third objective, which involved the validation of the end-to-end pilot production process, was also achieved with the core, experienced team that completed the earlier objectives but with additional support from an existing, committed first customer whose deep solar expertise and impartiality provided the requisite perspective to accurately assess the results. As the first step, the pilot system was brought online and end-to-end operation was verified. Modifications to the equipment and the process were necessary, and they were carried out to minimize overall impact. With the pilot system in working order, a validation run was completed to manufacture a statistically meaningful number of solar wafers. These wafers were thoroughly characterized by Halo Industries and its first customer to verify that they met industry standard specifications. Moreover, process statistics from this run were compiled to provide an accurate determination of whether the pilot system met the target specifications for which it was designed. Success was quantified based on the quality of the wafers and whether the system met or exceeded the target process metrics.

The project scope of work was broken down into seven primary tasks. The first task involved general project action items, such as establishing requirements and processes for submitting project products and project administration and logistics, as well as technical advisory committee formation and meetings. The second through fourth tasks involved the bulk of the technical work for the project and each corresponded to one of the primary objectives previously discussed. The fifth task involved an evaluation of the project benefits at the beginning, middle, and end of the project. The sixth task involved technology/knowledge transfer activities to inform the public and key decision makers of the results of, and lessons learned from, the project. The seventh task involved preparing a production readiness plan to determine and present the steps that will lead to FRP of the technology.

CHAPTER 3:

Results

The project achieved a number of key results:

- The scale-up and validation of a novel solar wafer manufacturing technology to LRIP stage, going from pure research and development to production of hundreds of wafers per month. This is a key feasibility milestone that demonstrates the industrial viability of the technology. Investors are willing to fund further scale-up of a technology only when this milestone has been achieved. Similarly, customers will dedicate internal resources to qualifying a new technology for production only when this milestone has been met.
- A decrease in the costs associated with solar wafers and associated manufacturing infrastructure. Analysis shows a cost reduction of at least 49 percent for industry-standard silicon solar wafers. This is by far the most important metric in the solar industry. Reducing the solar wafer cost in half is a dramatic achievement but also an intuitive one if one considers that Halo Industries' laser-based technology can produce significantly more wafers from the starting ingot than a wire saw due to its near-zero material loss. Between 50 percent and 100 percent more wafers are produced, depending on which equipment configuration of the wire saw approach is being used as the point of comparison. Customers generally require at least a 20-percent improvement along a key metric to consider adopting a new technology. Investors have a similar threshold when determining whether it makes sense for them to invest in a new technology.
- An estimated absolute increase in the efficiency of solar power modules on the order of approximately 0.5 percent. Initial analysis indicates significantly fewer defects, such as microcracks, gouges, and the like, in Halo Industries wafers compared to traditionally manufactured wafers. This was an unexpected benefit of the laser-based wafering approach but intuitive in the sense that using less and more targeted energy to manufacture wafers would result in reduced collateral damage to the material. Although a 0.5-percent improvement may seem small, customers consider this a major benefit that allows the same solar installation to be more profitable.
- A reduction of the environmental impact of the manufacturing of silicon solar wafers, including a calculated 48-percent reduction in emissions and a 61-percent reduction in consumables compared to traditional manufacturing processes. Although the reduction in consumables factors directly into the total cost per wafer, the reduction in emissions and the general environmental impact of the manufacturing, which are more difficult to quantify, are factors that the entire Halo Industries team cares deeply about. Many investors are also similarly driven by a desire to make the world a better place by lowering the environmental impact of manufacturing. Additionally, many major customers have internal initiatives that emphasize a preference for environmentally friendly technologies and are often willing to pay a premium for them.

- Enabling of next-generation solar cell and module architectures. Results indicate that novel form factors such as thin flexible wafers can possibly enable unique new types of devices. Robust, flexible solar cells and modules would enable a dramatically reduced cost of installation. One can only imagine being able to climb up on a roof with a roll of solar modules that could simply be unrolled to cover the desired area and then affixed directly into the roof, much like a tarp. Many customers consider flexible solar the holy grail of the PV industry, but many technologies, not just thin, flexible wafers, are needed to make it a reality.

Additional research and development are needed to commercialize the technology, and Halo Industries is moving forward to lock in the resources required to accomplish this additional work. The company is executing an exciting engineering roadmap that will lead to further efficiency gains and ultimately lead to zero-consumable, fully automated production that will have the smallest possible environmental impact from manufacturing.

The work performed by Halo Industries is very technical in nature and does not involve any direct interaction with the public. All of the critical relationships needed for success and maximum impact are business-to-business relationships. Moreover, Halo Industries' core technology is composed of both patents and trade secrets that are important to protect. As such, the company has not done anything to promote its work to the public or policy makers. However, Halo Industries has worked tirelessly to win over customers and strategic partners to ensure that its efforts would be recognized and adopted by the broader industry. More details can be found on the company [website](http://www.halo-industries.com) at www.halo-industries.com. Significant success has been achieved on this front, and the company is negotiating partnerships with two of the major players in the solar industry. The next steps involve growing the production capacity of the technology as quickly as possible to ensure that its benefits are delivered broadly across the entire market. Halo Industries is working hard to secure additional funding through venture capital, government grants, loans, and customer commitments.

It is difficult to describe detailed technical results without revealing trade secrets or other proprietary Halo Industries intellectual property in this public report format. However, many critical technical lessons were learned during the project and the resources allocated to the project were efficiently spent. Nearly a dozen engineering design and validation iteration cycles were performed to refine the technology to a level where it was capable of commercial-scale production. Laser technology is generally much more performant than the traditional wire saw, but the primary challenge to scaling it is achieving very high throughputs compared to a parallelized and automated mechanical process. This can be overcome with innovative approaches and technology, but the broader cost structure must remain attractive. Another painful lesson learned was that all complex technical projects take significantly longer than expected, especially due to the unknowns when a project is started. Halo Industries encountered many unexpected technical issues that slowed development in certain areas. The team had to come up with a wide array of novel solutions to unblock the path forward. Another key lesson learned was that the ecosystem for solar manufacturing has been heavily degraded in the United States, to the extent that that domestic supply chains are tenuous and downstream customers/partners that can take Halo Industries solar wafers and make solar cells and modules in meaningful volume are all currently located in Asia. To rebuild solar

manufacturing domestically, the United States will likely have to focus on next-generation technology and ensure that support is given to the entire ecosystem that supports it. These painful lessons were necessary to build up the core knowledge and expertise that was necessary to make the overall project a success. There were also a number of challenges on the supply chain front, especially during the Covid pandemic, that dramatically lengthened lead times for certain items that were critical to the project. Due to the sensitive technical nature of the project, interactions with the public were minimized, so no public presentations were given or publications made. However, during the course of the project, Halo Industries developed and deployed a website to communicate its top-level efforts with investors, customers, partners, and the general public. That [website](http://www.halo-industries.com) can be accessed at www.halo-industries.com.

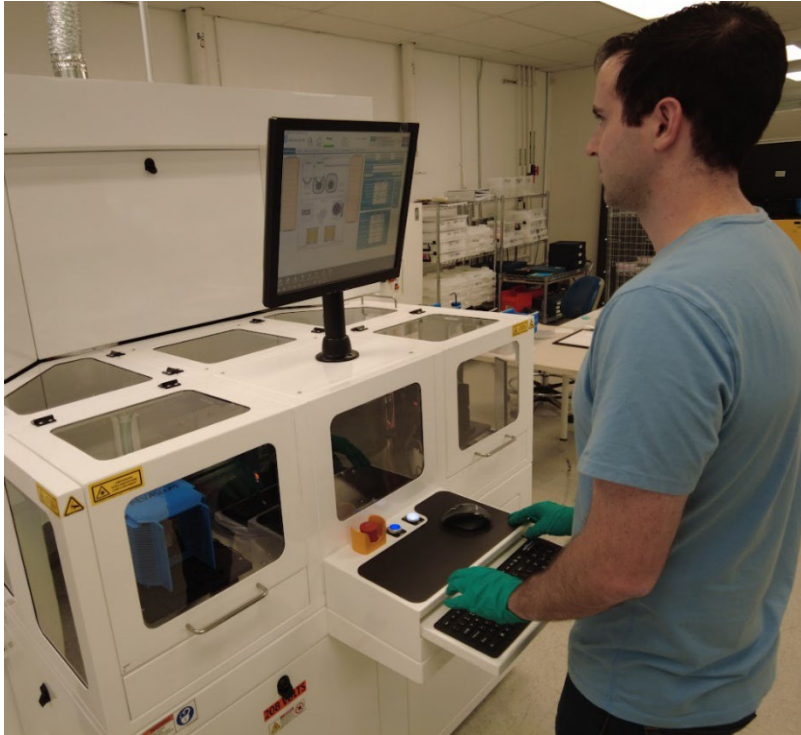
Although proprietary technical information cannot be shared in this medium, Figure 3 through Figure 8 capture the essence of the Halo Industries production line and the final product itself. Some are slightly blurred to mask key confidential details of the production process.

Figure 3: Production Line Tools for Preprocessing Raw Silicon Material



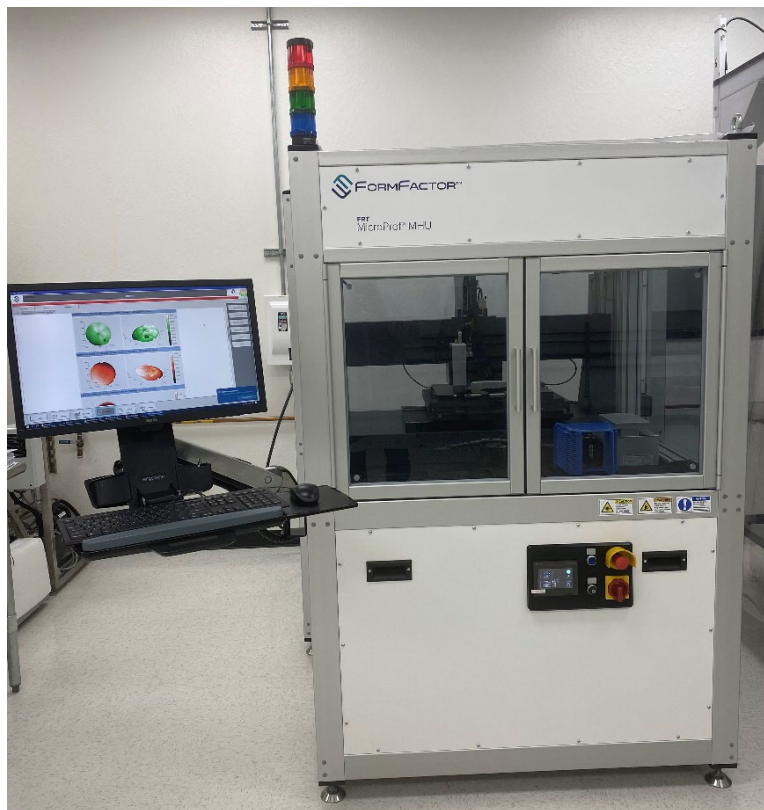
Source: Halo Industries

Figure 4: Production Line Tool for Resurfacing Silicon Wafers



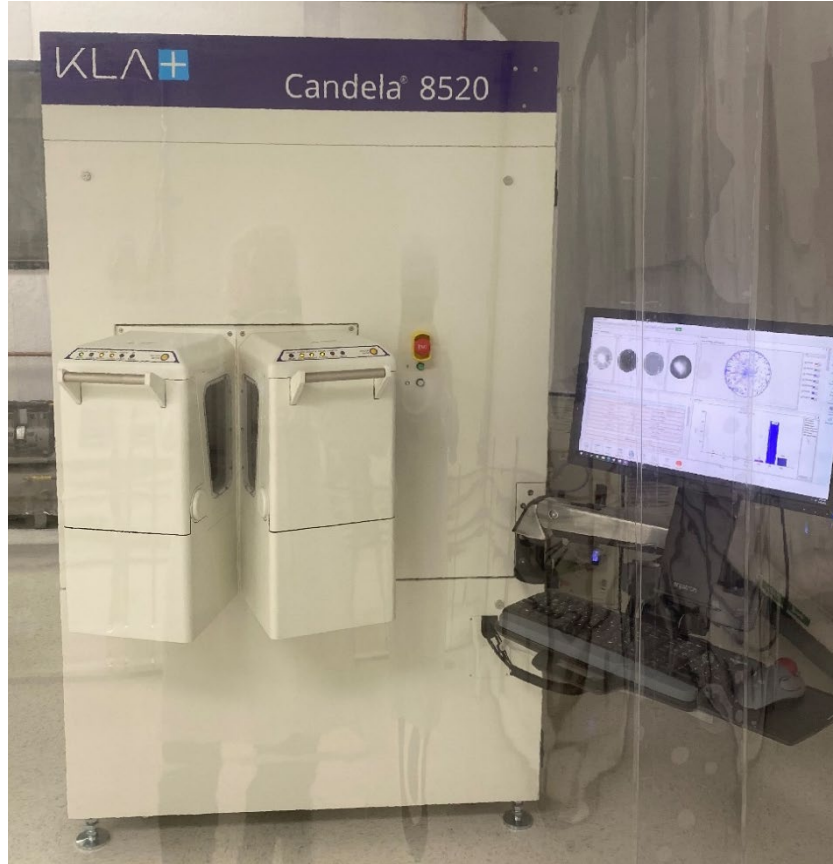
Source: Halo Industries

Figure 5: Production Line Tool for Measuring the Geometry of Silicon Wafers



Source: Halo Industries

Figure 6: Production Line Tool for Measuring the Defects in Silicon Wafers



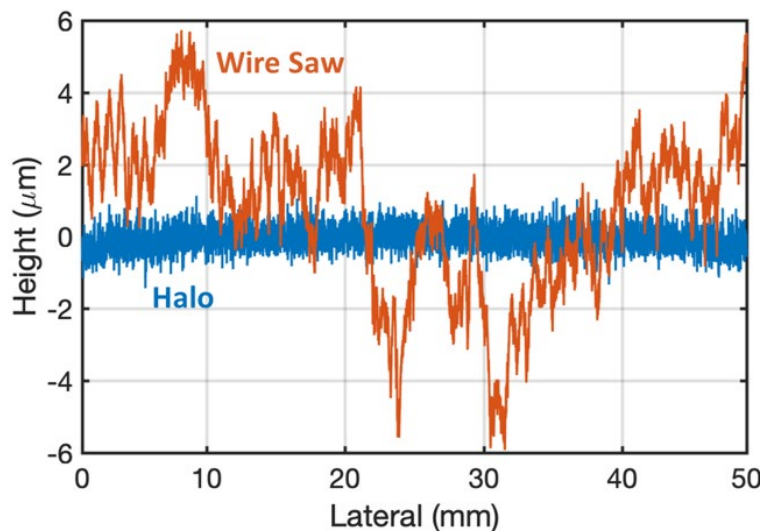
Source: Halo Industries

Figure 7: Fully Finished Solar Wafers



Source: Halo Industries

Figure 8: Wafer Specification Comparison Between Halo Industries Laser-Based Wafering and the Traditional Wire Saw Process



Source: Halo Industries

The most direct benefit of Halo Industries' technology involves energy cost reductions to California electricity ratepayers. This benefit can be broken down into three principal components. The first is the cost reduction associated with utility-scale solar installations. In its "Solar Market Insight Report," the Solar Energy Industries Association (SEIA) estimates that the United States national average turnkey installed cost for utility-scale deployments is approximately \$1.00/watt (W). At approximately \$0.40/W, the solar module cost was the largest element of that total. SEIA additionally estimates that the solar wafer accounts for 30 percent to 40 percent of the module cost. Assuming the midpoint of that range, the wafer cost portion comes out to \$0.14/W. Halo Industries' technology has been proven to reduce the cost of existing, industry-standard solar wafers by approximately 50 percent and will thus reduce the installed cost for utility-scale deployments by approximately \$0.07/W. As an example, for a 100-megawatt (MW) installation, the cost will be directly reduced by \$7 million.

This cost reduction estimate does not include the other substantial benefits of Halo Industries' technology, such as the improvements in overall module efficiency and the increased operational efficiencies associated with manufacturing both solar modules and cells. These are much more difficult to calculate, as they depend on a variety of manufacturer-dependent specifics, but they could account for another \$0.05/W to more than \$0.20/W in savings. Looking at module efficiencies, the U.S. Department of Energy National Renewable Energy Laboratory's¹ cost report for solar power systems indicates that the average California module efficiency is 19.1 percent, while individual cell champion efficiencies can reach as high as 27 percent. One of the core value propositions of Halo Industries' technology is its ability to close this efficiency gap through its ultra-high quality solar cell wafer material, which will result in not only higher average cell efficiencies but also a much tighter standard deviation on those

¹ The name of the National Renewable Energy Laboratory has been changed to the National Laboratory of the Rockies

cell efficiencies, leading to reduced module fabrication costs as well as module efficiencies much closer to those of the individual cells. Although it is unlikely that module efficiencies close to 27 percent will be reached, it is reasonable to estimate that 24 percent is ultimately achievable as a conservative baseline. This absolute 5-percent module efficiency increase over current levels would mean that a particular utility-scale project could use more than 20-percent fewer modules to meet its capacity targets, effectively reducing cost by approximately \$0.20/W. As an example, for a 100-MW installation, the cost would be directly reduced by approximately \$20 million. These types of cost reductions at the utility-scale level will lead to lower electricity prices for California ratepayers who source their energy from solar generation and to a reduced financial burden on utilities themselves. This will promote faster solar deployment to meet the state's energy goals as well as enable a reduced land-use footprint for these deployments so that environmental impact concerns are mitigated.

The second principal component of Halo Industries' benefit of energy cost reductions to California electricity ratepayers involves commercial scale installations. In its "Solar Market Insight Report," the SEIA estimates that the United States national average turnkey installed cost for commercial scale deployments is approximately \$1.50/W. The solar module cost is \$0.40/W of that total, so a similar analysis indicates that Halo Industries' proven reduction in wafer cost will reduce commercial scale solar deployment cost by \$0.07/W. A similar analysis to the previous utility-scale example also applies with respect to module efficiency and operating efficiencies related to cell/module manufacturing. This could lead to a 20-percent reduction in the number of modules used to meet a capacity target, which is effectively a \$0.30/W additional cost reduction in this use case. An important differentiator when it comes to commercial deployments is the importance of the installation footprint. A number of SEIA studies have indicated that a reduction of 15 percent or more in the area required for solar installations could meaningfully increase the number of commercial installations by making this option economically attractive to a much larger number of businesses that currently have limited rooftop space constraints.

The third principal component of Halo Industries' benefit of energy cost reductions to California electricity ratepayers involves residential scale installations. In its "Solar Market Insight Report," the SEIA estimates that the United States national average turnkey installed cost for residential scale deployments is approximately \$2.80/W. The solar module cost is again \$0.40/W of that total, so a similar analysis indicates that Halo Industries' proven reduction in wafer cost will reduce residential scale solar deployment cost by \$0.07/W. A similar analysis to the previous utility-scale example also applies with respect to module efficiency and operating efficiencies related to cell/module manufacturing. This could lead to a 20-percent reduction in the number of modules used to meet a capacity target, which is effectively a \$0.56/W additional cost reduction in this use case. Since the average system size in the United States is 6 kilowatts, there is a total potential cost reduction of \$3,780 or more for the average homeowner who is switching to solar. Moreover, this analysis does not count the difficult-to-estimate benefits associated with Halo Industries' enabling of next-generation cell and module architectures that use ultra-thin, flexible silicon not just to reduce cost but also to reduce module weight and facilitate much simpler rooftop installation processes. Since installation costs are now the largest factor in the residential market, these important

advantages could meaningfully reduce the cost gap and bring residential scale solar much closer to cost parity with utility-scale solar.

Another important benefit associated with Halo Industries' unique wafer fabrication technology is a considerable reduction in GHG emissions originating from solar wafer manufacturing. Estimates from the National Renewable Energy Laboratory currently indicate that each solar wafer takes approximately 1.3 kWh to produce. Comparable wafers produced with Halo Industries' technology have been measured and calculated to have a total energy cost of only 0.6 kWh. The bulk of this savings comes from the fact that nearly twice as many wafers are produced by using Halo Industries' technology as opposed to the conventional wire saw technique to cut a given solar-grade silicon ingot into wafers. Additional savings come from end-to-end wafer manufacturing process simplifications attained through the adoption of Halo Industries' technology, as well as from the inherent energy efficiency of the Halo Industries equipment itself. Since standard, individual solar cells produce approximately 4 watts of power and the total solar PV capacity installed in 2023 was approximately 408 gigawatts, one could estimate that roughly 100 billion solar wafers were produced to enable this. This estimate does not take into account yield losses at various stages of the manufacturing process or the small share (less than 10 percent) of the solar market that is taken by non-silicon solar cell technologies. Using a conservative estimate of 100 billion solar wafers, the manufacturing energy savings associated with the adoption of Halo Industries' technology at scale would have been 70 billion kWh in 2023. Converting this into GHG emissions, using the reference provided by the Electric Program Investment Charge of 0.730 pounds of carbon dioxide equivalent per kilowatt-hour saved, a total of more than 23 metric tons of carbon dioxide emissions would have been prevented in 2023.

CHAPTER 4:

Conclusion

The State of California and its institutions have committed to transitioning the state to renewable energy generation through the passage of Senate Bill 350, which set a target of 50 percent renewables by 2030, and Senate Bill 100, which increased the 2030 target to 60 percent and added a 100 percent target by 2045. Solar PV will constitute the vast majority of the additional generation capacity to meet Senate Bill 350 targets. However, most solar analysts agree that the world has now reaped the primary benefits of solar production capacity scaling and new innovations are needed to drive down costs and accelerate adoption. Halo Industries' technology will play a crucial role in continuing the downward trend in solar pricing by reducing the cost of existing solar wafers by nearly 50 percent; this technology significantly improves solar cell/module efficiencies through its superior quality wafers, and ultimately provides even more benefits as thin, flexible, next-generation solar architectures are enabled by the novel production process.

This project was designed to scale up a novel silicon wafer manufacturing process to achieve the target performance shown in Table 1. Although the achieved performance fell a bit short of the aggressive targets, the core objective of demonstrating the feasibility of the core technology to manufacture in volume was met in the eyes of customers and investors.

Table 1: Target and Achieved Project Performance Metrics

Performance Metric	Target Performance	Achieved Performance	Significance of Metric
Wafer production throughput	20 sec/wafer	approximately 116 sec/wafer	Though the aggressive target was not met, achieved performance meets the bar for production scale.
Wafer production yield	95%	89% average	A yield greater than 80% is required for industrially relevant production.
Wafer total thickness variation	5 μm	less than 5 μm	Tighter total thickness variation leads to improved solar module performance.
Wafer surface roughness	2 μm	1-2 μm	Lower wafer surface roughness reduces solar cell fabrication cost, increases cell fabrication yield, and improves cell efficiency.
Wafer manufacturing cost savings compared to wire saw	50%	49%, based on cost of operations model	Cost is the primary driver for the adoption of new solar technologies.

Source: Halo Industries

Building on the success of this project, Halo Industries is currently aggressively working to further scale its production capacity. The biggest hurdle is the fact that significant partnerships with Chinese companies would be necessary to achieve major deployment scale and this is problematic from a technology risk and business execution standpoint. However, Halo Industries considers this project a successful example of how public capital can be strategically used to de-risk and refine a clean energy technology to increase the chances of its broader commercialization.

Benefits to California Ratepayers

This project will result in the ratepayer benefits of lower costs, greater electricity reliability, and increased safety by reducing the price and increasing the efficiency of solar modules as well as enabling next-generation solar cell and module architectures. The lower cost benefit is the most direct and visible, as it will entail reductions in ratepayer monthly energy bills as well as \$0.13/watt to \$0.63/watt reductions in residential, commercial, and utility-scale solar installation costs.

Greater reliability is primarily due to the overall increase in affordability of residential and commercial installations, especially when considering next-generation module architectures uniquely enabled by Halo Industries' technology. By empowering all Californians, regardless of income class, to affordably choose solar on their properties, this project will reduce their dependence on electrical grid infrastructure that could be affected by various adverse events, thus helping ensure greater electricity reliability.

Increased safety can be achieved due to the significant increase in the solar PV share of California electricity generation that will be driven by the benefits of this project. Decentralized solar generation will alleviate the burdens on the state's complex electrical transmission grid and help prevent tragic accidents such as the devastating fires that are caused by this aging infrastructure.

This project is also expected to deliver environmental benefits, as solar wafers fabricated with existing methods take approximately 1.3 kWh to produce, while those made with Halo Industries' technology require only 0.6 kWh. Since 20 billion to 30 billion solar wafers are made annually, substantial waste, water usage, and emissions can be avoided with the adoption of the technology advanced in this project. Additional qualitative benefits associated with this project include the creation of high-skilled solar manufacturing jobs in the state. These will be enabled by the technology's inherently low cost, process efficiency, and high degree of automation, which ensure that it will be cost competitive even with global jurisdictions having the lowest labor costs.

List of Terms/Glossary

Term	Definition
μm	micron or micrometer
FRP	full rate production
GHG	greenhouse gas
kg	kilogram
kWh	kilowatt-hour
LRIP	low rate initial production
MW	megawatt
non-thermal separation	replacing thermal separation processes, such as evaporation and distillation, with processes that remove the thermal energy required for separation and strictly rely on electrified processes (for example, reverse osmosis)
PV	photovoltaics
SEIA	Solar Energy Industries Association
W	watt

Project Deliverables

The project deliverables are summarized in the list below:

- Pilot Production System Engineering and Design Report
- Pilot Production System Construction Report
- Pilot Production System Test Plan
- Pilot Production System Validation Report
- Kick-off Meeting Benefits Questionnaire
- Mid-term Benefits Questionnaire
- Final Meeting Benefits Questionnaire
- Final Report

Project deliverables, including interim project reports, are available upon request by submitting an email to pubs@energy.ca.gov.