CALIFORNIA ENERGY COMMISSION

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ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Laser-Based Silicon Carbide Wafer Manufacturing for Next-Generation High-Efficiency Power Electronics

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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

Silicon carbide power electronics represent a next-generation technology that has demonstrated substantial overall energy efficiency improvements across a broad range of products with higher voltage and higher-frequency operation in more compact forms. They have been used in notable, high-end applications including electric vehicles, industrial, electrified rail, and wind-energy power electronics, as well as electric grid transmission and electric vehicle charging infrastructure. The purpose of this project was to scale up and commercialize a novel laser-based manufacturing technology for the fabrication of silicon carbide wafers, which are the fundamental building blocks upon which silicon carbide power electronics are built. An initial proof-of-concept prototype was successfully taken and built out into a complete production line that demonstrated low-rate initial production. This project has demonstrated that the technology has the potential for zero material loss and throughput on the order of minutes, per wafer. This would result in dramatic cost reductions for conductive silicon carbide substrates that would enable the proven beneficial properties of this material system to make their way into advanced, next-generation power electronics for a wide variety of applications.

Keywords: Silicon carbide wafer, electric vehicle, power electronics

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Introduction

The cost of clean energy is rapidly declining due to manufacturing economies of scale and innovative technical developments. Silicon power electronics are current state-of-the-art components in switches, inverters, battery chargers, and battery dischargers. These enabling technologies are the key to grid integration of renewables and grid infrastructure modernization since nearly all electricity will flow through them in the coming decades. Power electronics based on silicon carbide-on-silicon carbide (SiC-on-SiC) have been demonstrated to substantially improve overall device efficiency through higher voltage and higher frequency operation in much smaller forms. They have been used in notable, high-end applications such as electric vehicles, industrial, electrified rail, and wind-energy power electronics, and electric-grid transmission and electric-vehicle charging infrastructure.

The primary downside to SiC-on-SiC devices is their much higher cost, which currently makes them out of reach for widespread adoption in most applications. This higher cost is dominated by the cost of the conductive SiC material itself. It is a difficult material system to grow with high purity, uniformity, and quality. After the material is successfully fabricated, it is sliced into wafers, which marks the starting point for device manufacturing. However, this slicing process is incredibly inefficient and wasteful. A wire saw coupled with diamond slurry is used for the cutting, but the diamond is only slightly harder than the SiC so the process is extremely slow (on the order of hours per wafer) and prone to mechanical damage in the final wafers. Moreover, the thickness of the final wafers is 350 micrometers , while the loss due to the cutting wire diameter plus the additional damaged material that must be removed is over 300 micrometers per wafer. This means that nearly 50 percent of the mass of the expensive, initial material is irrecoverably lost. The end result is 350-micrometer thick, 150-millimeter diameter conductive SiC wafers costing upwards of $1,300 per piece and it takes an exorbitant amount of time to produce.

Halo Industries, Inc., has demonstrated a new laser-based slicing technology to replace the wire saw for wafering the conductive SiC material used for SiC-on-SiC devices. This innovative technique is a variation on a process successfully developed and validated for slicing single crystal silicon ingots to produce solar and semiconductor wafers. Although the silicon approach uses significantly different lasers and optics, the core technical principles are the same as for SiC, leading to significant efficiencies in development. The technology has the potential for zero material loss and throughput, on the order of minutes per wafer. This could result in dramatic cost reductions for conductive SiC substrates, which could enable the proven beneficial properties of this material system to advance next-generation power electronics in a wide variety of applications.

Through the course of this project, Halo Industries successfully scaled up its initial proof-of-concept into a fully operational pilot production line capable of initial production to demonstrate to customers the capabilities of its technology. The company has achieved production metrics that significantly improve upon the quality, cost, and throughput of the traditional manufacturing approach, which has generated substantial commercial traction.

Project Purpose and Approach

This project achieved three critical objectives and was phased in by splitting the project period into three sequential stages, though each focused primarily on the project's overarching overall objective but also focused on preparatory work for subsequent objectives. The first objective was completion of design and engineering work to configure and build a pilot production system in conjunction with an existing, committed first customer. The second objective was to develop a stable, scalable supply chain and complete construction of the pilot production system, based on the final configuration developed in the first objective. Finally, the third objective brought the pilot production system online; upon meeting these three critical goals, the technology will be ready for immediate low-rate initial production and subsequent scaling to full-rate production.

Key Results

Key results achieved in this project were:

- The scale-up and validation of a novel conductive SiC wafer manufacturing technology to the low-rate production stage, from pure research and development to the production of hundreds of wafers per month; this enabled qualification with customers as well as significant venture-capital investment interest.
- A decrease in the costs associated with SiC-on-SiC power electronics and associated infrastructures; analysis shows a cost reduction of at least 54 percent for industry-standard SiC wafers.
- An increase in the efficiency of SiC-on-SiC power modules; initial analysis indicates 26 percent fewer defects in Halo Industries wafers, compared with traditionally manufactured wafers, resulting in SiC devices with higher reliability and overall performance.
- A reduction of the environmental impact of the manufacturing of SiC-on-SiC power electronics; a calculated 48 percent reduction in emissions and 61 percent reduction in consumables when compared to traditional manufacturing processes.
- Enabling of next-generation SiC-on-SiC power electronics and module architectures, where results indicate novel form factors such as thin, flexible wafers can enable unique power electronics architectures.

These key results either meet or exceed the original performance metrics set out at the beginning of the project. No additional research and development is needed to commercialize the technology, and Halo Industries is moving forward rapidly to lock in sales agreements. Nevertheless, the company is also executing an exciting engineering roadmap that will lead to further efficiency gains and ultimately lead to zero-consumable, fully-automated production with the smallest possible environmental impact.

Next Steps

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 SiC market. Halo Industries is working to secure additional funding through venture capital, government grants, loans, and customer commitments.

Benefits to California

This project will result in ratepayer benefits including greater electricity reliability, lower cost, and increased safety by reducing the price and increasing the efficiency of electric grid transmission and electric vehicle charging infrastructure. It will additionally enable the large-scale adoption of next-generation, high-efficiency power electronics architectures in electric vehicle, industrial, electrified rail, and wind-energy applications. The lower-cost benefit is the most direct and visible since it will be reflected in ratepayer monthly energy bills due to the enhanced electrical efficiency of a broad range of products, in addition to reductions in residential, commercial, and utility-scale renewable-energy costs. Greater reliability and safety are primarily due to the proven increases in reliability and safety of SiC-on-SiC when compared with traditional power electronics, especially when considering next-generation product architectures uniquely enabled by Halo Industries' technology. By empowering all Californians, regardless of income, to affordably choose clean, renewable energy for their properties (as well as for their electric vehicles), this project will reduce dependence on the electricity grid infrastructure, which would help ensure greater electricity reliability. Increased safety is also achieved due to the increase in renewable energy resources' share of California's electricity generation; that generation will be driven by the benefits of this project as well as by development of next-generation, efficient, solid-state grid transmission hardware that is much less likely to fail. Decentralized generation and lower energy demand, coupled with this upgraded infrastructure, will alleviate the burdens on the state's complex electrical transmission grid. Another important benefit associated with Halo Industries' unique wafer fabrication technology would be a considerable reduction in greenhouse gas emissions originating from conductive SiC wafer manufacturing.

CHAPTER 1: Introduction

The cost of clean energy is rapidly declining due to manufacturing economies of scale and innovative technical developments. With bold, forward-looking electric vehicle (EV) and renewable energy mandates, many states have already charted courses to a clean-energy future over the next decades; but there is more to be done before this transition can be fully realized. Detailed analyses indicate that in a future where renewable sources dominate energy generation and EVs are widely adopted, the efficiency with which energy is routed, stored, or converted for other end uses will be increasingly important.

Silicon power electronics are current state-of-the-art components such as switches, inverters, battery chargers, and battery dischargers. These enabling technologies are keys to the grid integration of renewables and grid infrastructure modernization. Unfortunately, despite significant technical advances, there are few improvements to existing silicon devices, and their performance is still far from optimal. Power electronics based on silicon carbide on silicon carbide (SiC-on-SiC) have been demonstrated to substantially improve overall device efficiency through higher voltage and higher frequency operation, but in much smaller forms. They have been used in high-end applications such as in EVs, industrial, electrified rail, and wind energy electronics as well as in electric grid transmission and EV charging infrastructures.

The primary downside to SiC-on-SiC devices is their much higher cost, which currently puts them out of reach for widespread adoption in most applications. This higher cost is dominated by the cost of the conductive SiC material. It is a difficult material system to grow with high purity, uniformity, and quality, but a handful of national manufacturers have mastered it. After the material is successfully fabricated, it is sliced into wafers, which are the starting point for device manufacturing. However, this slicing process is both inefficient and wasteful. A wire saw coupled with diamond slurry is used for the cutting, but the diamond is just slightly harder than the SiC so the process is extremely slow, on the order of hours per wafer, and prone to mechanical damage in the final wafers. Moreover, the thickness of the final wafers is 350 micrometers (μm), while the loss due to the cutting wire diameter, plus the additional damaged material that must be removed, is over 300 μm per wafer. This means that nearly 50 percent of the mass of the expensive, initial material is irrecoverably lost. The end result is 350-μm thick, 150-millimeter diameter conductive SiC wafers that cost upwards of $1,300 per piece and take an exorbitant amount of time to produce.

Halo Industries has conceived and demonstrated the initial proof of concept for a unique, new laser-based slicing technology to replace the wire saw for cutting the conductive SiC material used in SiC-on-SiC devices. This innovative technique is a variation of a process successfully developed and validated for slicing single-crystal silicon ingots to produce solar and semiconductor wafers. Although the silicon approach uses significantly different lasers and optics, the core technical principles are the same as for SiC, leading to significant efficiencies in development. The technology could potentially achieve zero material loss and throughput on the order of minutes per wafer. This would result in dramatic cost reductions for conductive SiC substrates that would enable the beneficial properties of this material system to make their way into advanced, next-generation power electronics for a wide variety of applications, including for power components in EVs and their associated charging infrastructures.

Throughout the course of this project, Halo Industries scaled up its initial proof-of-concept into a fully operating pilot production line capable of low-rate initial production (LRIP) to demonstrate the capabilities of the technology. Halo Industries is currently negotiating long-term sales agreements with multiple customers to continue scaling up its operations.

The project achieved three critical objectives and was phased in by splitting the project period into three sequential stages; each one primarily focused on one objective, but also included preparatory work for subsequent objectives. The first objective was the completion of the design and engineering work to configure and build a pilot production system that meets a set of industrially relevant process metrics determined in conjunction with an existing, committed first customer. The second objective was to develop a stable, scalable supply chain and complete construction of the pilot production system based on the final, validated configuration developed as the end product of the first objective. Finally, the third objective brought the pilot production system online, demonstrating that it can achieve or exceed the process metrics and produce a quantity of SiC wafers that both meet industry-standard specifications and are validated by Halo Industries' existing customer. Upon meeting these three critical goals, the technology will be ready for immediate LRIP and subsequent scaling to full-rate production.

This project will lead to technological advancements and breakthroughs that overcome barriers to achieving California's mandated energy goals by demonstrating and validating a novel conductive SiC wafer manufacturing technology, which would generate significant long-term benefits in the power electronics field. Those benefits include decreasing costs associated with SiC-on-SiC power electronics, increasing energy efficiency in a broad range of products, reducing environmental impacts from the manufacturing of conductive SiC wafers, and enabling large-scale adoption of next-generation power-electronics architectures. Since energy efficiency is essential to achievement of the state's ambitious environmental mandates, these benefits will accelerate the timeline for achieving the targets, reduce the financial burden on both the state and ratepayers, and reinvigorate the California manufacturing sector by providing highly skilled jobs and a leadership role in the high-tech materials industry.

CHAPTER 2: Project Approach

The first project objective, which involved the engineering and design work to configure the pilot production system, was achieved through leveraging the expertise of the existing project team, which successfully completed the prototype development of this technology over six years while adding full-time industry veterans and contractors with relevant experience. An industry-standard approach of staged reviews and third-party validations was taken. Success was quantified based on whether target process metrics were met or exceeded in the final system configuration. The second objective, which involved the construction of the pilot production system, was achieved using the same experienced team that completed the engineering and design work. Trusted suppliers, experienced with California-based businesses, provided various elements of the system. These elements were individually tested, integrated, and modified as necessary. Success was quantified by completion of the work on schedule and within budget. The third objective, which involved the validation of the pilot production system, was also achieved. The pilot system was brought online, and end-to-end operation was verified. Modifications to both the equipment and processes were required, and carried out with minimal overall impact. With the system in working order, a validation run was completed to manufacture a statistically meaningful number of conductive SiC wafers and capture production metrics. The wafers were thoroughly characterized by Halo to verify that they met industry-standard specifications. Success was quantified based on the quality of the wafers and whether the system met or exceeded the target process metrics.

The project statement of work was broken down into four primary tasks. The first task involved general project action items such as establishing requirements and processes for submitting project products, project administration and logistics, technical advisory committee formation, and meetings. The second task involved the bulk of the technical work for the project and consisted of three subtasks which corresponded to one of the primary objectives discussed here. The third task involved an evaluation of the project benefits at the beginning, middle, and end of the project. The fourth task involved technology/knowledge transfer activities to inform the public and key decision makers of the results of and lessons learned from this project.

Regarding the fourth task, the work performed by Halo Industries is very technical in nature and does not involve direct interaction with the public. All the critical relationships needed for success and maximum impact are business-to-business relationships. Halo has worked tirelessly to win over customers and strategic partners to ensure that its efforts are recognized and adopted by the broader industry. Significant success has been achieved on this front and the company is negotiating long-term sales agreements with two of the major industry players in the SiC space.

The project was managed by a dedicated project manager at Halo Industries. The scaling up and commercialization of this technology is the company's sole and core activity, so all available resources were used to achieve these goals during the project period. Through prior successful projects, the company has demonstrated that it has the proper organizational and accounting structures to execute on these types of projects with efficiency, transparency, and traceability.

CHAPTER 3: Results

The key results achieved through this project were:

- The scale-up and validation of a novel conductive SiC wafer manufacturing technology to LRIP stage, from pure research and development to production of hundreds of wafers per month, enabling both qualification with customers and significant venture capital interest.
- A decrease in the costs associated with SiC-on-SiC power electronics and associated infrastructure. Analysis showed a cost reduction of at least 54 percent for industry-standard SiC wafers.
- An increase in the efficiency of SiC-on-SiC power modules. Initial analysis indicates 26 percent fewer defects in Halo Industries wafers when compared to traditionally manufactured wafers, resulting in SiC devices with greater reliability and overall performance.
- A reduction of environmental impacts from manufacturing SiC-on-SiC power electronics. The team calculated a 48 percent reduction in emissions and a 61 percent reduction in consumables when compared with traditional manufacturing processes.
- Enabling of next-generation SiC-on-SiC power electronics and module architectures, indicating that novel form factors such as thin, flexible wafers are possible in unique power electronics architectures.

These key results either meet or exceed the original performance metrics set out at the beginning of the project. No additional research or development are needed to commercialize the technology, and Halo Industries is moving forward rapidly to lock in sales agreements. Nevertheless, the company is also executing an engineering roadmap that will lead to further efficiency gains and potentially lead to zero-consumable, fully-automated production with the fewest possible environmental impacts from manufacturing.

It is very difficult to describe detailed technical results without revealing trade secrets or other proprietary intellectual property in a public format. However, many critical technical lessons were learned during this 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 can meet commercial-scale production. These lessons were necessary to build up the core knowledge and expertise necessary to ensure the overall project's success. There were also numerous challenges on the supply-chain front, especially during the COVID-19 pandemic, which dramatically lengthened lead times for certain items critical to the project. Due to the sensitive technical nature of the project, interactions with the public were necessarily minimized. Throughout the project, however, Halo Industries developed and launched a website (http://www.halo-industries.com/) to communicate its non-proprietary efforts with investors, customers, partners, and the public.

Although proprietary technical information cannot be shared in this report, the figures following capture the essence of the Halo production line and the final product itself. They are slightly blurred out to mask key confidential details of the production process. Figure 1 shows some preprocessing tools, which take the raw blocks of SiC and prepare them for the laser process by ensuring certain key geometric and surface specifications.

Figure 2 displays a high-quality SiC wafer polishing system that produces the final ultra-smooth finish on all the wafers before they go out to customers.

Figure 1: Production Line Tools for Preprocessing the Raw Silicon Carbide Material

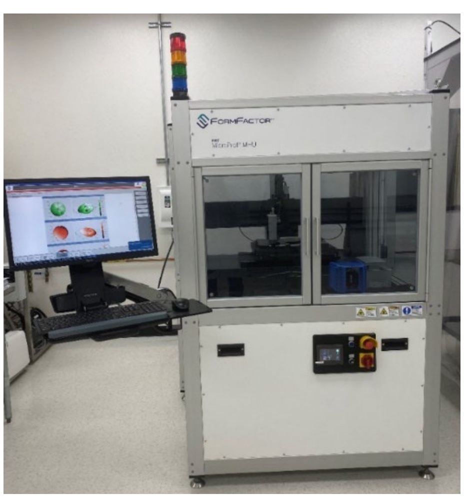
Source: Halo Industries, Inc.

Figure 2: Production Line Tool for Polishing the Final Silicon Carbide Wafers

Source: Halo Industries, Inc.

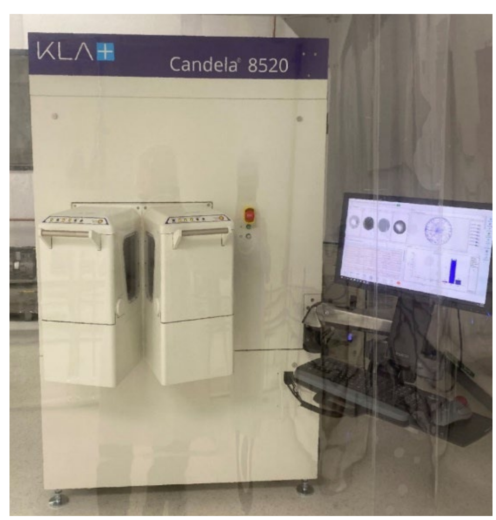
Figure 3 and Figure 4 present two important metrology systems that measure geometry and defects, respectively. Each wafer that is shipped includes details on its various geometry and defect specifications because these are important data points for downstream device processing.

Figure 3: Production Line Tool for Measuring the Geometry of the Final Silicon Carbide Wafers



Source: Halo Industries, Inc.

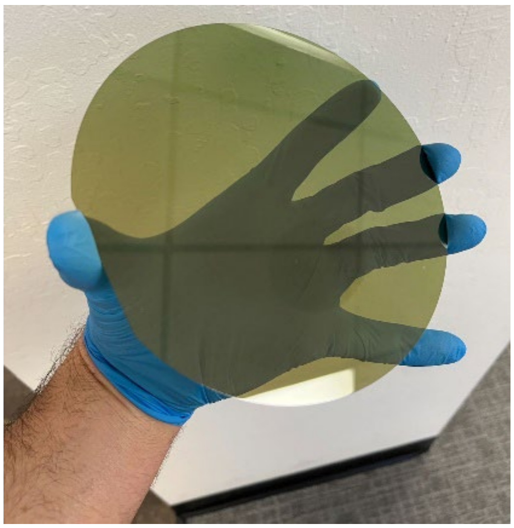
Figure 4: Production Line Tool for Measuring Defects in the Final Silicon Carbide Wafers



Source: Halo Industries, Inc.

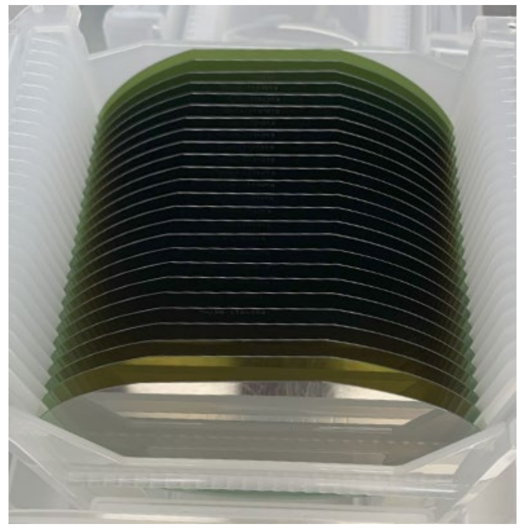
Figure 5 shows a typical, fully finished SiC wafer that will be used for EV power electronics. The green color comes from its heavy doping with nitrogen to make it electrically conductive. The shape of the wafer is precisely controlled, and the surfaces are polished to a low roughness (about the same as the distance between two oxygen atoms in an oxygen molecule in the atmosphere). Finally, Figure 6 displays a cassette of finished wafers ready for shipment. All wafers are thoroughly cleaned for particles, organics, and trace metals, then packaged and sealed in an industry-standard shipping cassette.

Figure 5: Fully Finished Silicon Carbide Wafer Ready for Final Cleaning and Shipment



Source: Halo Industries, Inc.

Figure 6: A Complete Cassette of Silicon Carbide Wafers Ready for Shipment to a Customer



Source: Halo Industries, Inc.

CHAPTER 4: Conclusion

This project could potentially deliver the California ratepayer benefits of greater electricity reliability, lower costs, and increased safety by reducing the price and increasing the efficiency of electric grid transmission and EV charging infrastructure. It could also enable large-scale adoption of next-generation, high-efficiency power electronics architectures in EV, industrial, electrified rail, and wind-energy applications. Lower cost is the most direct and visible benefit since it would reduce ratepayer energy bills by increasing electrical efficiency in a broad range of products and reducing residential, commercial, and utility-scale renewable-energy costs. Greater reliability and safety are primarily due to proven increases in the reliability and safety of SiC-on-SiC, especially when compared with traditional power electronics. By empowering all Californians, regardless of income, to affordably choose clean, renewable energy for their properties and EVs, this technology will reduce dependence on electric grid infrastructure and ensure greater electricity reliability. Increased safety is also achieved due to the increase in renewable energy's share of California's electricity generation driven by the benefits of this project, as well as by development of next-generation, efficient, solid-state grid transmission hardware that is much less likely to fail. Decentralized generation and lower energy demand, coupled with this upgraded infrastructure, will alleviate the burdens on the state's complex electrical transmission grid and help prevent tragic accidents such as fires ignited by aging infrastructure.

This project will lead to technological advances and breakthroughs that overcome barriers to achievement of the state of California's statutory energy mandates by demonstrating and validating this novel conductive SiC wafer manufacturing technology and generating significant long-term benefits in the power electronics field. These benefits include a decrease in costs associated with SiC-on-SiC power electronics, an increase in the energy efficiency of a broad range of products, a reduction in the environmental impacts of manufacturing conductive SiC wafers, and the enabling of large-scale adoption of next-generation power electronics architectures. Since energy efficiency is at the heart of California's efforts to achieve its energy goals, these benefits will accelerate the timeline for achieving these targets, reduce the financial burden on the state and utility ratepayers, and reinvigorate the California manufacturing sector to provide additional high-skilled jobs and a resurgent technological leadership role in the high-tech materials industry.

Another important benefit of this unique wafer fabrication technology is a considerable reduction in greenhouse gas (GHG) emissions. Estimates from the National Renewable Energy Laboratory indicate that each silicon carbide wafer takes approximately 100 kilowatt-hours (kWh) of electricity to produce. Comparable wafers produced with Halo's technology have been calculated to deliver a total energy cost of only 40 kWh. The bulk of this savings comes from the fact that nearly twice as many wafers are produced from the same amount of source material by using Halo's technology as opposed to the conventional wire saw technique. Additional savings come from end-to-end wafer manufacturing process simplifications attained through adoption of Halo's technology, as well as through the inherent energy efficiency of the equipment itself. According to industry analysts, roughly 100 million SiC wafers were produced in 2019. This estimate does not account for yield losses at various stages of the manufacturing process, which can be severe in this field. The manufacturing energy savings associated with the adoption of Halo's technology at scale would have been 6 billion kWh in 2019. Converting this into GHG emissions 0.730 pounds carbon dioxide equivalent per kWh (CEC, 2024) saved over two metric tons of carbon dioxide emissions in 2019. Moreover, estimates from industry partners indicate that each conductive SiC wafer requires approximately 11 gallons of water, primarily due to its use as a coolant during the wire saw step and subsequent, unavoidable cleaning steps. Halo Industries' technology completely eliminates these steps and does not require the use of water, leading to potential annual savings on the order of 1.1 billion gallons of water, given current production levels. Given the rapid growth of the industry, the number of wafers produced is expected to increase dramatically over the coming years.

Due to the overwhelming success of this project, Halo Industries is currently in high volume production and aggressively working to further scale its production capacity. The company is currently producing 1,000 wafers per month but is negotiating sales agreements with the potential to scale to 24,000 wafers per month in 2024.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
CEC	California Energy Commission
EV	electric vehicle
GHG	greenhouse gas
kWh	kilowatt-hour
LRIP	low-rate initial production
μm	micrometers
SiC	silicon carbide

References

CEC (California Energy Commission). 2024. "Attachment 14 - References for Calculating Energy End-Use and GHG Emissions." Emissions Factors tab. Available at https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.energy.ca.gov%2Fsites%2Fdefault%2Ffiles%2F2022-04%2F14_GFO-21-304_Att_14_References_for_Calculating_Energy_End-Use_and_GHG_Emissions_ADA.xlsx&wdOrigin=BROWSELINK.

Project Deliverables

The Project deliverables included the:

- Pilot Production System Engineering and Design Report
- Pilot Production System Construction Report
- Pilot Production System Test Plan
- Pilot Production System Validation Report
- Kickoff Meeting Benefits Questionnaire
- Midterm 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.