NREL

Bottom-Up Costs and Market Analysis of the Horizontal Ribbon Growth (HRG) Technology

Cooperative Research and Development Final Report

CRADA Number: CRD-20-16762

NREL Technical Contact: Michael Woodhouse

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Office of Energy Efficiency & Renewable Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-7A40-87433
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NOTICE

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Cooperative Research and Development Final Report

Report Date: September 6, 2023

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Integrated Silicon Technologies, LLC (IST)

CRADA Number: CRD-20-16762

CRADA Title: Bottom-up Costs and Market Analysis of the Horizontal Ribbon Growth (HRG) Technology

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Solar Technologies Office

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$25,000.00
TOTALS	$25,000.00

Executive Summary of CRADA Work:

The American-Made Solar Prize is a prize competition from the U.S. Department of Energy that is designed to revitalize U.S. solar manufacturing. The competition aims to support the growth of U.S. solar manufacturing and reenergize American energy innovation by tapping into American's competitive spirit and the nation's unparalleled innovation ecosystem leveraging national labs, incubators, facilities and more. National Renewable Energy Lab (NREL) will provide technical and business advisement to the noted Solar Prize finalists. This CRADA will involve the development of a cost model of the CRADA Participant's horizontal ribbon growth (HRG) technology for making silicon wafers for solar cells.

CRADA benefit to DOE, Participant, and US Taxpayer:

- Assists laboratory in achieving programmatic scope
- Uses the laboratory's core competencies

Purpose:

IST is in the process of developing a new continuous process for making silicon wafers for solar cells. Preliminary estimates are that the process has the potential of cutting the wafering cost in half relative to Czochralski and subsequent wire or laser cutting. IST requests the specialists at the DOE's National Renewable Energy Laboratory (NREL) to provide a framework and results for bottom-up cost modeling of the HRG technology.

Statement of Work:

NREL and IST will work together to develop a bottom-up cost model of the horizontal ribbon growth process. For comparison to current monocrystalline and multicrystalline ingot and wafer technologies, the developed model will have the capability to calculate the CAPEX and OPEX costs of the HRG process. This project will also provide sensitivity analyses to key inputs including labor cost, electricity, and silicon raw material. The joint study will also investigate how the introduction of the HRG technology will impact the final module cost.

<u>Task Descriptions</u>:

The Participant will:

Participant Task 1: The Participant will participate in a monthly check-in with the NREL Principal Investigator. If a check-in meeting is missed two months in a row, the agreement may be cancelled by the American-Made Challenges Solar Prize team.

Participant Task 1 Result:

IST met regularly with the NREL Principal Investigator.

Participant Task 2: The Participant will supply NREL with current Excel models and reports that describe our current approach to cost analysis and the results to date.

Participant Task 2 Result:

The partners at IST provided information about the HRG process but did not provide the inputs needed to complete a cost model.

Participant Task 3: The partners at IST will be available for phone/video meetings as necessary and will assist in the development of the project.

Participant Task 3 Result:

IST met regularly with the NREL Principal Investigator.

Participant Task 4: IST will provide all information as needed about the design and implementation of the HRG process.

Participant Task 4 Result:

Monthly check-ins between the NREL principal investigator and the Participant were not maintained due to COVID-19 shutdowns at the Participant's laboratory. Instead, NREL and the Participant met approximately once per quarter.

NREL will:

Provide technical cost modeling and business support to develop finalist concepts in advance of Demo Day events. The technical advisement will include:

NREL Task 1: Evaluate IST's current approach to cost modeling and share best practices

NREL Task 1 Result:

At the request of IST, NREL shared the understood best practices in detailed cost modeling for the solar photovoltaic (PV) supply chain including wafers. The NREL methods and approaches are the result of more than 12 years of working with solar industry materials and equipment suppliers and integrated manufacturers.

The NREL method for preparing and reporting cost model results is intended to be similar to the methods used by publicly listed firms that report results to shareholders and financial system regulators. The U.S. generally accepted accounting principles (GAAP) and the International Financial Reporting standards (IFRS) provide the frameworks for this purpose.

The fixed costs for production include the initial capital expenditure (CapEx) in manufacturing equipment, building, and facilitation. The variable costs for production, or operational expenditures (OpEx), are defined by materials, labor, utilities, and maintenance. Fixed and variable costs lead to calculation of the cost of goods sold (COGS). NREL described these items and provided a cost model template for calculating the COGS.

The other expenses recorded in the GAAP and IFRS framework include research and development (R&D) and Sales, General and Administration (S, G&A). Those items are typically reported separately in financial statements from the COGS. To provide returns to investors and shareholders, some measure of profit is also presumably necessary over the long-term. The inclusion of these overhead expenses and profit defines what is called the factory gate "minimum sustainable price", or MSP. Additional costs for delivery to a solar project may include taxes, import tariffs (if applicable), and shipping.

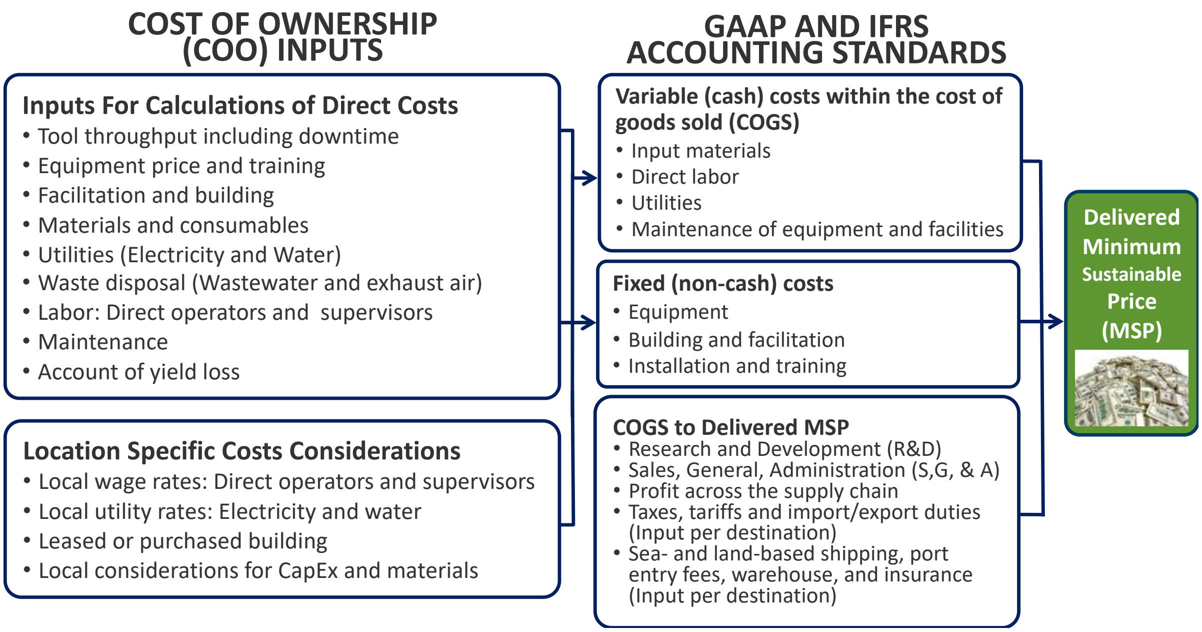

Figure 1. Methods and calculation approaches provided by NREL and reviewed by IST.

These methods were reviewed with IST. Training was provided for calculating the CapEx (fixed costs) and OpEx (variable costs) for the HRG process and analysis was provided for comparison to current monocrystalline ingot and wafer processing.

NREL Task 2: Provide current input parameters concerning the cost of Czochralski crystallization and wire/laser sawing to make wafers.

NREL Task 2 Result:

An overview of the Czochralski (CZ) crystallization process—and ingot cropping, squaring, polishing and wafer slicing—is given below in Figure 2. NREL provided IST a breakdown of costs for Czochralski ingot formation; cropping, squaring, grinding, and gluing to glass; diamond wire wafer slicing; and wafer cleaning, singulation and metrology.

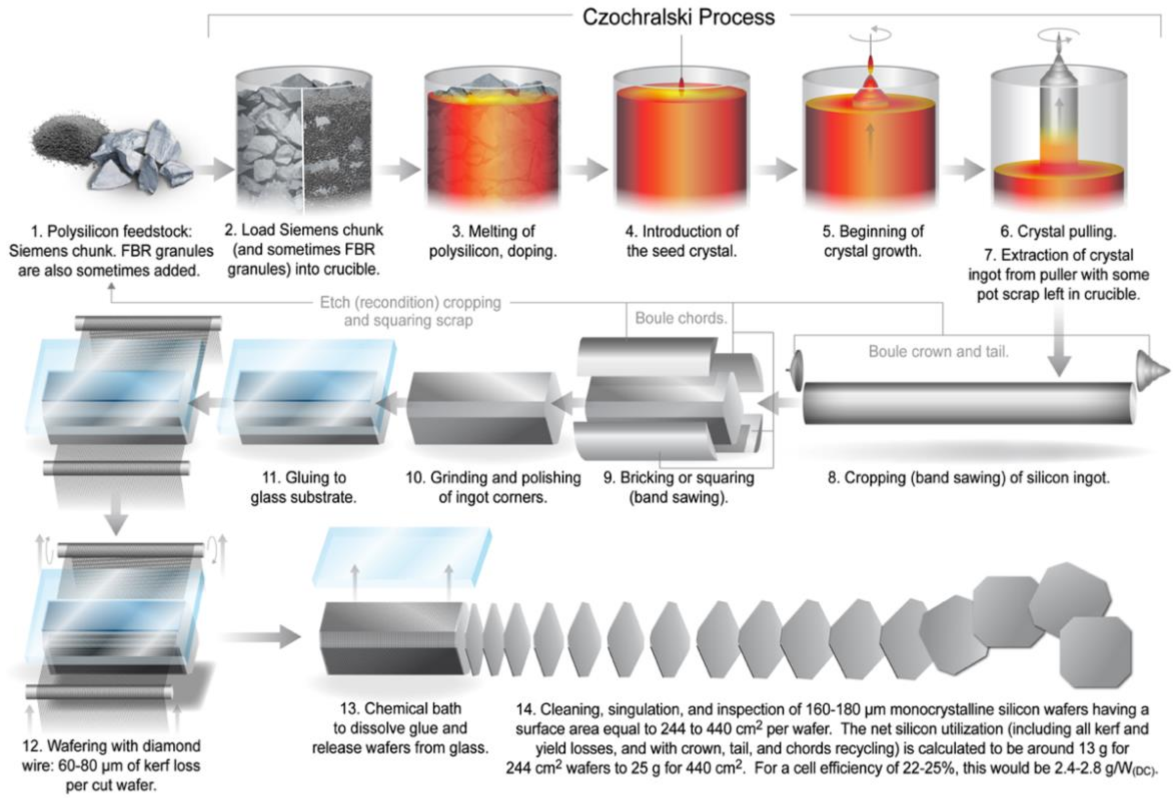

Figure 2. Graphical overview of the traditional CZ route to crystalline silicon ingot and wafer formation.

NREL provided sensitivity analyses to key inputs for traditional Czochralski (CZ) and wafering including labor, electricity, and material costs. The most direct and relevant way to accomplish this was to examine the technology-driven cost parameters and regionally specific costs considerations (Figure 1). An overview of those factors is given in Table 1 and results are given below in Figure 3.

Table 1. Key input parameters for CZ ingot and wafer cost of ownership calculations.

Technology-Driven Cost Drivers	
Silicon Utilization	18 g/wafer +/- 1 g/wafer
Initial Capital Expenditure (CapEx) for Equipment	$0.06—0.10/Wdc
Initial Capital Expenditure (CapEx) for Building and Facilitation	$0.03—0.05/Wdc
Total Direct Employees per Shift	50—70 per GWdc
Electricity	0.7—0.8 kWhac per wafer
Primary Materials	Polysilicon, Quartz Crucibles, Hotzone Hardware, Argon, Brick Shaping and Gluing Materials, Diamond Wire, Wet Chemical Clean
Regionally Specific Costs Drivers	
Hourly Rates for Direct Operators	$2—25 per hour
Electricity Rates	$0.05—0.22/kWh
Delivery Costs for Materials and Equipment	5—20%

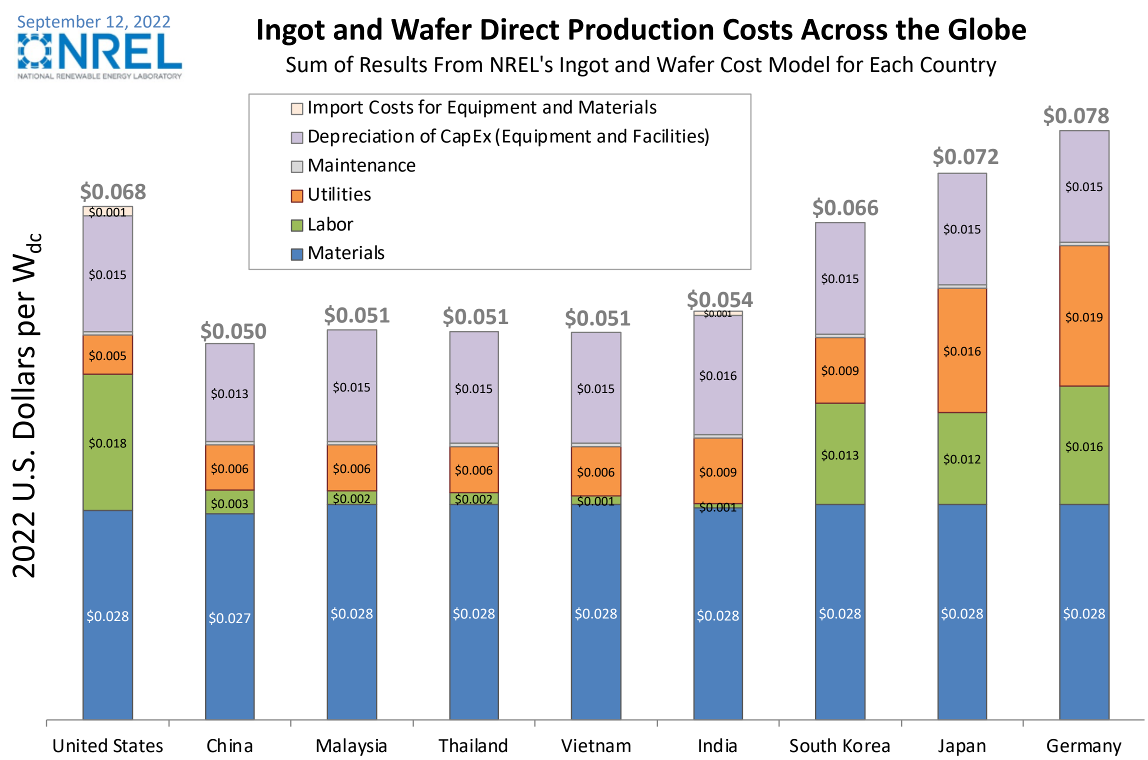

Figure 3. International costs comparisons for non-silicon ingot and wafer production costs including sensitivities around labor and electricity.

NREL Task 3: Help develop cost models for HRG

NREL Task 3 Result:

The first phase of this project involved learning about the HRG process and the potential advantages. To help develop cost models for HRG, NREL provided IST with a cost model template. The Excel template is the most direct way to share calculation methods and to identify the relevant input data that is needed. The model can be used to calculate the CapEx and OpEx costs of the HRG process.

NREL Task 4: Develop estimates of HRG wafer production and module costs

NREL Task 4 Result:

The principal advantages of the HRG process are to remove ingot formation and cropping, squaring, polishing and wafer slicing (Figure 2). By replacing ingot formation and slicing with direct HRG, this new process could lead to a simpler manufacturing process with fewer steps. The HRG process could also lead to less material loss, principally by eliminating kerf loss (Step 12).

The value of eliminating kerf loss is dependent upon two factors: The amount of kerf loss, which is driven by the diameter of the sawing wire, and the cost for the silicon. Figure 4 quantifies the impact of the amount of kerf loss and silicon raw material cost to final module costs. The range of kerf loss covers the values given in the 2022 International Technology Roadmap for Photovoltaic (ITRPV) and market pricing for polysilicon as high as $50/kg, which covers the polysilicon shortage experienced in 2022. Prices have declined dramatically since then and the long-term sustainable market price for solar grade polysilicon is expected to be in the $10—20/kg range.

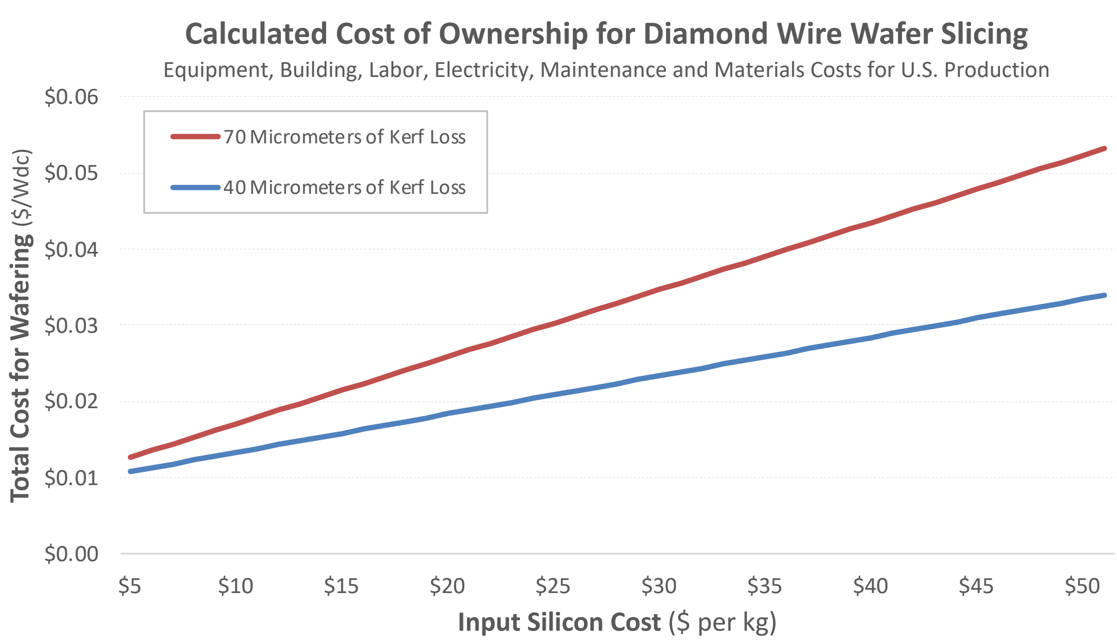

Figure 4. Range of expected ability to lower final module costs by eliminating kerf loss and the diamond wire wafering step.

This analysis can be used to estimate HRG wafer production and module cost advantages considering the elimination of kerf. All else being equal, the costs savings given by Figure 4 could be subtracted from the costs for U.S. production given in Figure 5, which is based upon a benchmark MSP for polysilicon equal to $18/kg and 65 micrometers of kerf loss per wafer. The potential value for the HRG process is expected to be greater if polysilicon costs rise again in the future.

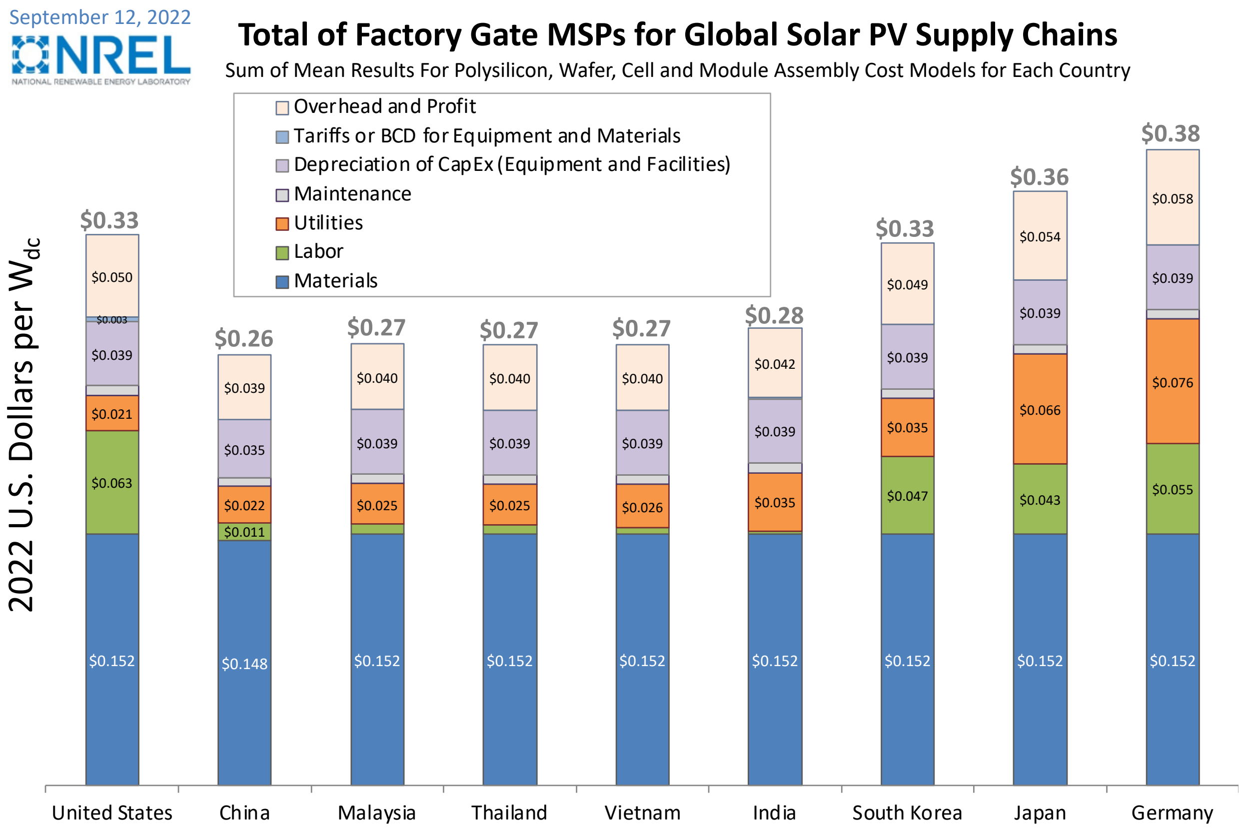

Figure 5. 2022 Benchmark MSPs for module production across nationally integrated supply chains.

NREL Task 5: The Principal Investigator agrees to provide the following to DOE Office of Scientific and Technical Information (OSTI): (1) an initial abstract suitable for public release at the time the CRADA is executed; (2) a final report, within thirty (30) days upon completion or termination of this CRADA, to include a list of Subject Inventions; and (3) other scientific and technical information in any format or medium that is produced as a result of this CRADA.

NREL Task 5 Result:

This report meets the CRADA Final Report deliverable to complete the requirement in accordance with Article X.

Subject Inventions Listing: None

ROI #: None