Simulations for Solar

EMIX uses multiphysics simulation to optimize its cold crucible continuous casting process for the manufacture of photovoltaic-quality silicon.

by **CHRIS HARDEE**

The massive semiconductor industry is built on a firm foundation of micro-thin wafers of silicon. Those wafers serve as the basic building block of integrated circuits (IC), where the innate conducting properties of the elemental metal create the communication pathways for all modern computers and electronics.

Yet another technology in which silicon plays a key role is in the manufacture of photovoltaics (PV). In this growing alternative energy application, silicon-wafer-based solar cells are used to convert photons from the sun into earth-bound electricity. Solar energy is seen by many as a power source that has great potential. However, solar manufacturers must find ways to decrease the cost per unit of power generated before the technology will be truly competitive with more mature fossil-fuel technologies.

"Depending on the price of polysilicon, about 30% of the final sale price of a solar cell is a function of the cost of the silicon alone," says Dr. Julien Givernaud, a research engineer at EMIX, part of the French subsidiary of Grupo FerroAtlántica. Givernaud works on the optimization of the inductive cold crucible and associated equipment used to purify silicon for photovoltaics. "Lowering silicon production costs while increasing its purity is critically important in this industry."

→MANUFACTURING PV-QUALITY SILICON

In nature, silicon is the second most abundant element by mass in the earth's crust. For photovoltaic applications, metallurgical silicon (which is 99.9% pure) must be processed into a higher-purity grade containing no more than one part-per-million impurity (99.9999%). Purity is important because it directly influences the amount of electricity a solar cell can produce from incoming sunlight—a measure called the photovoltaic conversion efficiency.

There are a number of competing manufacturing processes that transform silicon from its natural state to solar-cell ready. "Our continuous cold crucible casting, or 4C process, is a very innovative method for manufacturing PV-quality silicon," says Givernaud, who uses the COMSOL Multiphysics® software to optimize production parameters. The company holds several patents and an exclusive worldwide operating license for the technology.

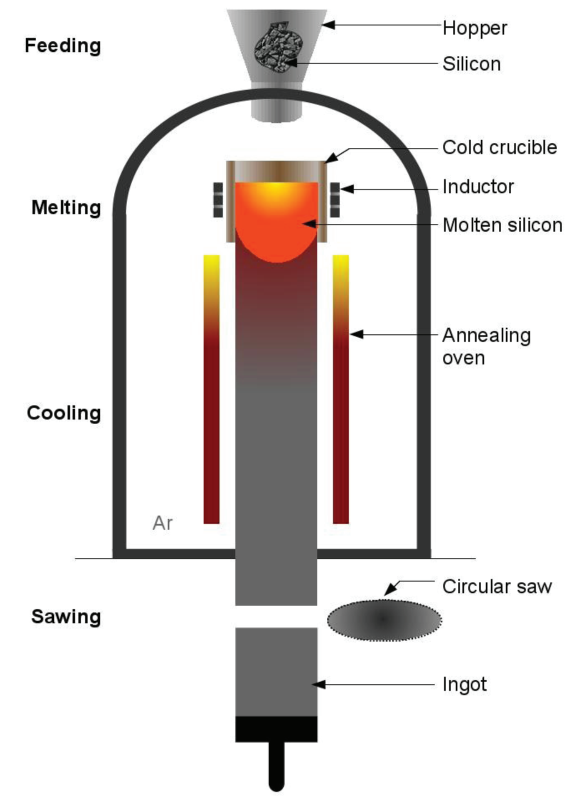

FIGURE 1. The schematic illustrates the cold crucible continuous casting (4C) process used to make silicon for photovoltaic applications. Silicon stock is fed into the system's hopper at the top, then heated, cooled, and cut into ingots.

In the 4C process, silicon feedstock is fed into a water-cooled crucible where it is inductively heated to its melting temperature of 1,414 °C. It is then electromagnetically mixed in the crucible where Lorentz forces prevent contact between the crucible and the silicon melt, and the strong stirring homogenizes species concentrations at the solid-liquid interface, enhancing crystallization conditions. This results in high purity (see Figure 1).

Following mixing, the melt is then "pulled down" through the open-bottom crucible, where it cools and solidifies using a carefully controlled annealing process. The continuously produced silicon rod is next sawed into ingots, which are sold to PV manufacturers who, in turn, slice them into the 200-micrometer-thick sections used to make solar cells.

→SIMULATION IMPROVES PHOTOVOLTAIC PRODUCTION EFFICIENCY

While relatively simple in concept, EMIX's 4C process involves numerous manufacturing variables. This is where simulation comes in. Givernaud has performed countless calculations using simulation to examine, for example, the cooling method, the pull rate, crucible and coil shapes, and the characteristics of the furnaces. He has also analyzed the effect of the electromagnetic field, the shape of the solid-liquid interface, and the effect of elastic stresses on crystallization behavior.

Engineers at EMIX have been using multiphysics simulation for eight years—almost as long as they have been in the PV silicon business—to evaluate the production process. "COMSOL Multiphysics is easier to use than the FEA tool in my previous job," says Givernaud. "I create all of my geometries directly in COMSOL. The model is very easy to mesh. It's simple to switch between physics, and the solver is very fast and efficient. All-around, it's an intuitive and powerful tool."

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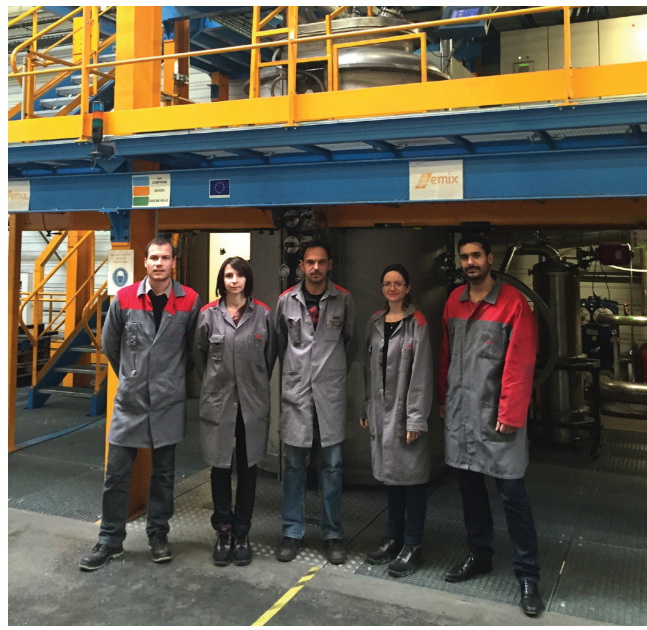
Givernaud's most recent modeling studies have involved both multiscale electromagnetic and 3D continuous casting simulations. His electromagnetic simulations permitted the estimation of inductance and impedance, as well as the optimization of the crucible design to improve electrical efficiency (see Figure 2). The continuous casting simulations allowed for the input of parameters such as electromagnetic power, crystallization rate, height of the crucible cooling zone, and after-heater temperatures. The combined results of these studies have led to a compromise between high production rates and low stresses in the ingots.

In the various simulations, the Heat Transfer in Fluids and Laminar Flow interfaces in COMSOL were used to calculate phase change in the silicon as it solidified in the crucible. Calculations for a cylindrical test crucible, when validated, will be applied to a larger crucible utilized in the commercial process.

"There has been very good agreement between our simulations and experiments for the pilot process," says Givernaud. "Simulation helped us to reach good crystallization parameters, improve the electrical efficiency of the industrial size crucible, and reduce the number of tests on the pilot furnace." He further adds that the latest series of simulations have, in theory, demonstrated energy savings of approximately 15% and pulling-rate increases of about 30%, which makes the 4C method far more productive than other standard silicon crystallization processes.

Industry-wide, manufacturers are striving to reduce silicon-wafer cost and improve purity for PV applications. Increased share in a growing solar marketplace will be the reward for the companies that develop the most commercially viable solutions. "Multiphysics simulation has helped us to identify some processes that will be tested soon on the industrial scale," says Givernaud, who expects that EMIX will break new ground with innovations the company has been working on. ❖



The R&D team at EMIX stands in front of a silicon production furnace (from left to right): Julien Givernaud, Elodie Pereira, Nicolas Pourade, Florine Boulle, Alexandre Petit.

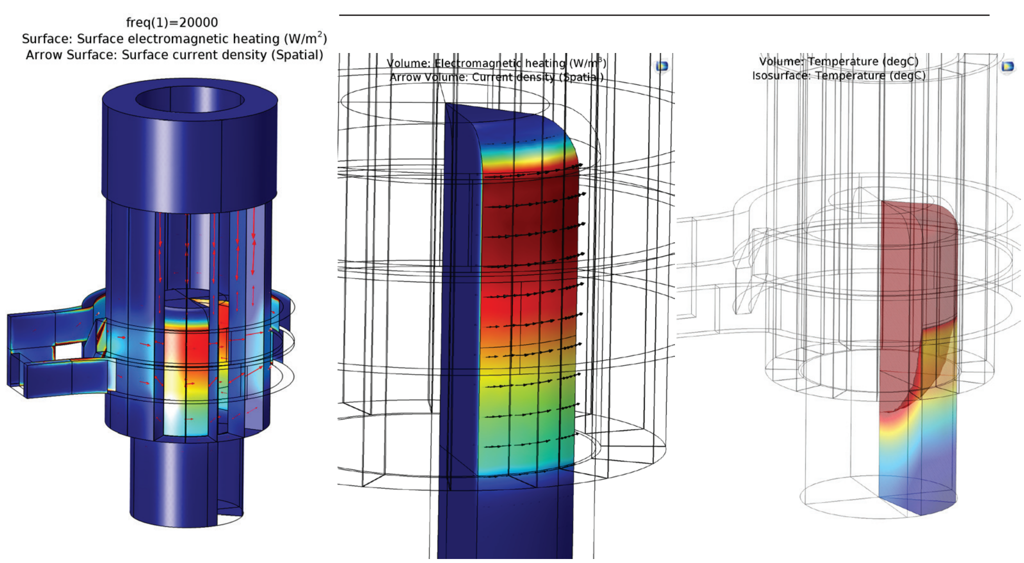


FIGURE 2. The model of the cold crucible has been used to predict the electromagnetic heating of the crucible (left) and molten silicon (center) and the triple-point liquid/solid/gas interface (right) where red/yellow represents the melt and blue/green represents the solid phase.