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Glass needs for a growing photovoltaics industry

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ABSTRACT

With the projected growth in photovoltaics the demand of glass for the solar industry will far exceed the current supply, and thousands of new float-glass plants will have to be built to meet its needs over the next 20 years. Such expansion will provide an opportunity for the solar industry to obtain products better suited to their needs, such as low-iron glass and borosilicate glass at the lowest possible price. While there are no significant technological hurdles that would prevent the flat glass industry from meeting the solar industry's projected needs, to do so will require advance planning and substantial investments.

1. Introduction/background

For any solar technology to succeed, it must scale up in a manner that is the least expensive without compromising quality. Not only must the solar-cell manufacturers scale up their own manufacturing processes, they must also ensure that their suppliers will be able to meet their demand. The 2005–2008 shortage of silicon needed to manufacture crystalline silicon solar cells is an excellent example of the problems that can occur when a supplier lags behind the development of an industry [1,2]. Although this was a temporary issue it raised the prices for these technologies, and provided a window of opportunity for thin-film applications to capture a bigger market share.

Most photovoltaic modules use glass. Crystalline-silicon technologies use glass cover plates to provide structural strength to the module and to encapsulate the cells. Thin-film solar technologies also often use glass as the substrate (or superstrate) on which the device is built [3]. In fact, for the majority of solar modules in production, glass is the single largest component by mass and in double glass thin-film PV, and it comprises 97% of the module's weight. Glass offers strength, rigidity, environmental stability, and high transmission, all inexpensively.

The modern flat-glass industry began in the 1950s, with the introduction of the Pilkington process (named for its inventor, Alastair Pilkington). This process, also known as the float-glass process, introduced a new technique for producing low-cost, high-quality sheets of flat glass. In float-glass manufacturing, molten glass is floated out on top of molten tin, creating a uniform sheet with a smooth, flat surface [4]. Float-glass manufacturing quickly replaced the older plate-glass method; now, it accounts for 90% of all flat glass produced [5]. The largest markets for flat glass are architectural (88% of the market) and automotive-glass (11%) [6].

The solar industry's demand for glass is currently less than 2% of the overall market. However, with the huge growth in the solar industry (and moderate growth expected in other glass markets), this situation is changing.

2. Glass supply and demand

2.1. The glass industry

2.1.1. The global market

In 2009 the flat-glass market was approximately 52 million metric tons, corresponding to 6.6 billion square meters (assuming 3 mm thickness) [5,6]. The total capacity was between 6.6 billion square meters and 8.3 billion square meters. Typically, demand shows a 4–5% growth per year [5]. The market price for 3 mm flat soda–lime glass is around \$3.00/m^2, translating into a value of approximately 20 billion dollars per year. Four major suppliers dominate the market: Asahi Glass, NSG/Pilkington, Saint-Gobain, and Guardian Industries, together accounting for 60% of flat glass production. A dozen or so companies supply the remaining 40% [5]. There are about 200 modern float-plants operating around the globe (Table 1). There are another 173 float-plants operating in China, but only about 50 of them are modern plants that are

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Table 1
Producers of flat glass.

	Plants	% of total production
Asahi	42	16
NSG/Pilkington	31	12
Guardian	27	10
Saint Gobain	27	10
Taiwan Glass	14	5
China	50	19
Others	67	26
Total	258	100

capable of producing high quality flat-glass suitable for the solar industry.

All four of the major producers of flat glass (and many of the smaller ones) are integrated vertically with the architectural- and automotive-glass industries. Three (Asahi, NSG, and Saint Gobain) also produce glass for the display market (plasma and LCD panels).

Many glass companies (including all of the big four) have glass-coating facilities (chemical vapor deposition and physical vapor deposition), as well as further value-added operations (such as lamination, tempering, and fabrication). The exceptions to this are the domestic Chinese glass manufacturers, many of whom are solely glass producers [7,8]. After this additional processing, the value of the flat glass market is 60 billion dollars a year [6].

2.1.2. Types of flat glass

The three types of flat glass still produced in any volume are float glass, rolled glass, and drawn glass. Of these three, float glass accounts for 90% of the market [5]. On a large scale, float glass offers the best quality, highest yields, and at lowest price.

Rolled glass is used for manufacturing patterned- and wired-glass, since it cannot be made with completely flat surfaces [9,10]. It is formed by running softened glass between two rollers, at least one of which is patterned. Patterned glass (also called figured glass) is sometimes used for crystalline silicon module cover glass. A shallow pattern to the glass diffuses the reflection of the front surface of the module, improving the appearance. Deeper patterns will actually reduce the reflection from the front surface of the module, but the deep patterns can act as a trap for water and dirt.

Drawn glass, wherein the molten glass is drawn through rollers, is an older technology that is being replaced by the float process [11] for large-scale production, but there are still some operational plants, notably in China [12].

Most flat glass is soda–lime glass, viz., it is composed, at a minimum, from silica, sodium oxide, and calcium oxide; however, most also contain oxides of magnesium, iron, titanium, potassium, and aluminum. Soda–lime glass is produced because the softening point of silicon dioxide is 1500–1670 °C [13]; hence, melting silicon dioxide to form flat sheets is very expensive. By adding sodium oxide, the softening point is lowered to 550–750 °C [14]. However this makes the glass water-soluble so other materials, such as calcium oxide, are incorporated to provide chemical resistivity. Although glass can be made from pure silicon dioxide for specialty applications, the cost is prohibitive for large-scale use [15].

A few varieties of glass not as common as regular soda–lime glass may offer some advantages for solar modules. One type is low iron glass. There are various grades of low iron glass, with iron content as low as 100 ppm (regular soda–lime is around 1000 ppm) [14]. Glass containing less iron oxide has higher solar transmission, engendering more efficient solar cells. Solar transmission for soda–lime glass is around 85%; the solar transmission for low iron glass can be above 91% [16]. Producing these particular glasses costs more than standard soda–lime glass, and for most applications it is not worth the extra cost. For the solar industry, though, the transmission gained may be worth the slightly increased expense.

There are also low- or no-alkali glasses. The alkali elements in soda–lime glass (sodium, calcium, potassium, magnesium) can diffuse out of the glass (particularly under thermal load or applied voltage) and affect thin-film solar cells [17]. Glasses such as borosilicates or fused quartz contain little or no alkali elements, and so they are often used in laboratory glassware. Because they must be processed at higher temperatures than those of soda–lime glass (the softening point of borosilicate glass is 820 °C), and are not made in large volumes using the float process, their cost is prohibitive for many applications [18].

2.1.3. The float glass process

The dominant method of making flat glass is the float-glass process. First, after mixing the raw ingredients in the batch house, they are fed into the furnace and melted at 1550 °C. Thereafter, the melted glass flows onto the top of a bath filled with molten tin at 1050 °C. The atmosphere in the bath is a mix of nitrogen and hydrogen that prevents the oxidation of the tin. Because tin has a higher density than glass the glass spreads out on top of the tin, giving it a smooth, even surface. Some tin incorporates into the surface of the glass in contact with the bath; this side of the glass is referred to as the tin side, as opposed to the air side. Next the glass passes into the annealing lehr, a long oven with a temperature gradient, where the glass is slowly cooled to 40 °C to prevent it from cracking [14]. It is also possible to apply a coating (anti-reflection, TCO, etc.) either within the tin bath or just after the tin bath via chemical vapor deposition. Finally, the glass is inspected for defects, coated with Lucite separating media to prevent scratches when the glass is packed and shipped, and cut to the required size.

A typical float-glass line produces 500–700 tons of glass per day, with the largest plants producing 1000 t per day [19,20] i.e., equivalent to 20–40 million square meters of glass per float line per year. The cost for a new float plant in Europe or North America is typically around 150–200 million dollars (100–150 million Euros) [19]. Ongoing research aims to develop float plants that can be built with lower capital expenditures such as using submerged combustion melting, an alternative design for the melting furnace that could greatly reduce capital costs [21]. Float plants are designed and built either by the glass producers themselves, or by engineering firms specializing in such construction such as Toledo Engineering Company, Five Steins, and DTEC. To build a new float plant in North America or Europe typically takes 2–3 years [22].

Float plants are normally sited near a silica source, and often near a customer's facility, to minimize transportation costs, which can be 15% of total costs [5]. Also they are often built in areas with low electricity costs, since the float process is energy-intensive; a plant uses 14 million therms (410 million kilowatt hours) of energy per year [23]. However the process is simple, so float plants have low labor costs as a percentage of total expenses (energy and materials are both much larger); hence, locating near a source of cheap labor is not particularly advantageous.

2.1.4. The architectural market

The architectural glass market is the single largest flat glass market, at about 39 million tons per year in 2007 [6] and has been growing at about 5% per year [5]. The US Congress has considered legislation (the Waxman–Markey act) that could force new construction to use more triple-pane insulated glazing units [24]. Similar changes in energy code are underway in the European

Union [25]. If the energy codes do mandate using this technology in more applications, the demand for glass from the architectural sector will be driven substantially higher.

2.2. The solar industry

2.2.1. The global market

Fifteen years ago, solar modules were a niche item. Their cost per watt was far from competitive with grid electricity, and their only value was for applications where it was too difficult to tie into the grid or for devices (such as calculators) that needed a portable source of low power. Solar-module production in 1998 was around 150 MW [18]; since then, the solar market roughly doubled every two years. In 2009, about 9 GW of solar modules were produced [26] and the estimated 2010 annual production capacity is about 11 GW. This represents an almost 50% growth per year of production during the last decade, that is widely expected to continue for the near future.

In the 1990s and into the 2000s, the solar module market almost entirely comprised crystalline silicon-based technologies. In 2007 it still accounted for 90% of the market, with the remainder coming from thin films [27]. In 2009 the percentage of thin films was up to 18% [26], with CdTe accounting for around 12% [28].

2.2.2. Types of solar modules

Conventional crystalline-silicon solar cells (single and poly-crystalline) were the first commercial solar technology, and they still make up most of the modules produced. Most such modules use a single pane of glass, called a cover plate, and have a non-glass back cover [29]. Hence, for every 1 m^2 of module, 1 m^2 of glass is required. This glass may be tempered to provide additional strength; it also may be coated with anti-reflective coatings or it may be patterned to scatter light.

Thin film technologies and, more specifically, CdTe modules have become a very large segment in the solar-panel market. These modules are built by depositing the device's layers onto a sheet of glass in a superstrate configuration, wherein light enters the solar cell through the glass substrate. A glass back plate, laminated to the superstrate, encapsulates the device [30]. Thus, for each square meter of a solar module, 2 m^2 of glass is required. Other thin film modules are a mix, some using two plates of glass for each module, some only a single plate, or some other type of substrate.

Thin-film PV production is expected to continue to grow faster than the industry as a whole due to lower production costs. This expansion might dramatically drive up the rate of increase in the demand for glass from the solar industry because an increase in production of CdTe modules consumes twice as much glass as the same increase in production of c-Si cells. Furthermore the efficiency of CdTe modules is lower than that of crystalline silicon modules, so they generate fewer watts for every square meter of glass they use.

2.3. The solar industry and the glass industry

At \$3.00/m^2, glass is a moderately large component of the cost of the solar module. For a typical CdTe PV module this works out to \$0.06 cents per watt, or 6–7% of their current stated production [30]. Additional processing by the glass manufacturer, however, such as tempering, edge grinding, hole drilling (for the back plate), or transparent conductive oxide (TCO) coating may result in the final cost to the module manufacturer being \$6.00–12.00/m^2, or \$0.12–\$0.17/W for a module. This is a substantial portion of the overall expense of generating modules, especially in a roadmap for grid parity targeting \$0.50–\$0.70/W module prices [31].

Table 2
Calculations for flat-glass demand from solar industry.

Assumptions		
Worldwide flat glass production in 2006 [6]	5.00×10^9	m^2
% of capacity [6]	70	%
Percent growth per year [5]	5	%
Watts per square meter of glass	162.5	W
PV production in 2009 [26]	9.34×10^9	W
% growth in PV per year	30–50	%
Cost of a float plant [19]	200	Million dollars
Max. float-plant capacity (per year) [20]	4.30×10^7	m^2
Calculated values		
2006 Flat-glass production capacity	7.1×10^9	m^2
2009 Flat-glass production capacity	8.3×10^9	m^2
Square meters of glass used for PV in 2009	5.7×10^7	m^2
% of total flat glass market used in PV	0.7	%
Capital costs to double float capacity	38.5	Billion dollars
Capital costs for 10 × capacity	346	Billion dollars

As of 2009, the solar industries demand for flat glass accounted for 0.7% of all glass produced; we projected that this increased to 1.5% in 2010. With the industry's rapid growth, projections show that it could consume current world capacity in a little over a decade and many times that within two decades. Table 2 below lists the assumptions for these calculations. As an example we assumed a 75% market share of single-glass 20% efficient silicon modules and a 25% share of double-glass 11% efficient thin-film modules, giving an average of 162.5 W/m^2 of glass. Plotted are the annual glass consumptions for three different annual rates of increase for the PV industry (Fig. 1). From 1998 to 2009 the rate of growth has been almost 50%. It may be unlikely that the growth rate will remain this high going forward. Still, an annual growth percentage of 30% would delay only until 2036 the year the solar industry would require 10 times the current capacity, a relatively small change. Projections of glass demand from NREL [32] are on line with our results. A key finding is that, regardless of how long it takes, for PV to meet a significant portion of the world's energy demands, multiple terawatts of annual production capacity will be required, which will necessitate an unprecedented expansion in capacity of the flat glass industry.

To double the flat-glass capacity will require building 192 new float plants, each with a 1000 tons per day capacity, at an expense of 27–36 billion dollars (in today's value). To increase output to 10 times current capacity will require building an additional 1523 float glass plants for a capital investment of 245–327 billion dollars, i.e., almost 20 times the value of the current annual flat-glass market.

With numerous additional float plants being built specifically for the solar industry, it would also make sense to locate the float-plants near the solar module production centers. It may even be possible to integrate the glass manufacturing and module production in the same facility. The float plants could be sized to match the module production lines although, with current technologies, glass plant sizes smaller than 300 tons a day (corresponding to ~750 MW/yr of thin-film PV production), will result in higher glass production costs.

2.4. Recycling flat glass

Recycling flat glass is a straightforward process: broken glass (called cullet) is simply fed into the furnace and melted along with the other raw ingredients. This requires the glass to be substantially free of contaminants [33]. Lower quality cullet can be used in

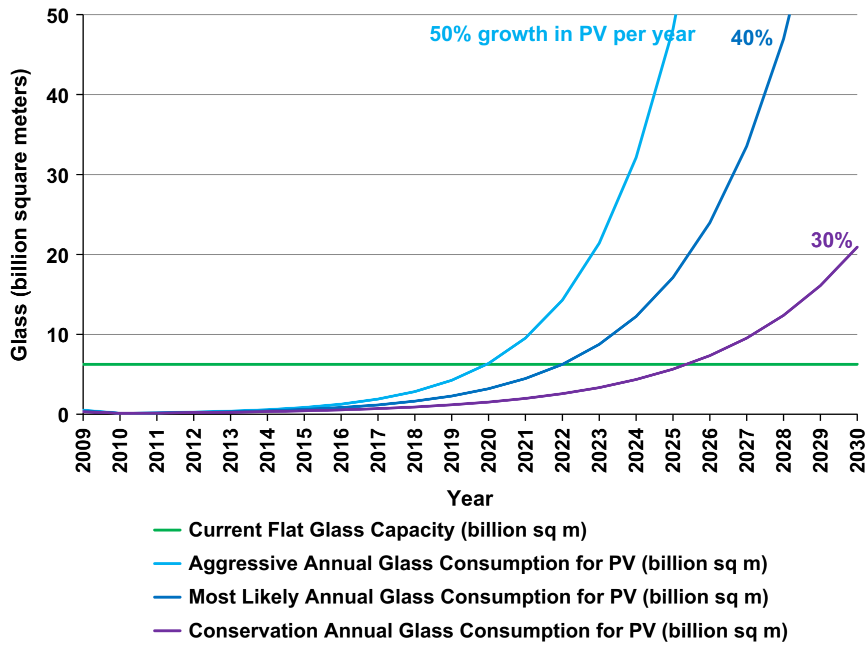

Fig. 1. Consumption of glass by PV, and current world capacity.

container glass or fiberglass production. It is typical for a float line to use 15–30% cullet in the feedstock.

Flat glass used in solar modules must be processed at end-of-life to separate the glass from the other materials present. In particular, valuable materials such as tellurium and indium are present in the thin films deposited on the glass in CdTe and CIGS solar modules. A variety of technologies exist to accomplish this [34], but further research is needed.

3. Conclusions

Data clearly show that if current growth trends continue the demand for flat glass from the solar industry will surpass current capacity in just over a decade. Further, within 20 years, that industry will require more than 10 times the current worldwide capacity. It now costs up to 200 million dollars and 2–3 years to build a new float-plant, and glass manufacturers are unwilling to take a risk on expanding unless they are sure that the demand will be there. A cost optimized float plant produces between 15 and 40 million square meters of glass a year, the equivalent of 2.5–6.5 GW of solar modules (assuming a 75% c-Si, 25% thin film mix). At a quarter to half of the current annual production of solar modules, this seems like a large number. Nevertheless, it is critical to remember that even though the solar industry has grown hugely over the last 10 years, it is still several orders-of-magnitude smaller than it will need to be before solar energy plays a significant role in the energy market. For the solar industry to reach a size where it can provide a significant portion of energy needs, thousands of new float plants will have to be build; only a few hundred currently are in use.

Glass currently makes up 12–20% of the production costs of CdTe modules, the currently least-expensive modules. As the costs of module production continue to lower, this percentage also will increase. Crystalline-silicon modules use less glass per module, and have higher watts per module, and hence, glass is a smaller component of their cost. If there is a temporary shortage of flat glass as its production lags behind the growth of the solar industry it could drive up the price of thin-film modules, while having a smaller effect on crystalline silicon ones. This might temporarily, at least, tip the production cost-balance in favor of the latter. As the solar industry expands, and more float-glass facilities are built or existing ones are converted to running glass for photovoltaic applications, there will be an opportunity for solar manufacturers to obtain products, such as low-iron glass, at the low prices that large scale production delivers.

The flat-glass industry is a mature one unaccustomed to exponential growth and, by nature, is a conservative industry. Even if the glass industry actively prepares to meet the increasing demand such a rate of expansion may tax the engineering design firms that have experience building float plants, and also strain the ability of glass manufacturers to adequately staff their facilities with experienced personnel. However, without the substantial investment required for flat-glass production, the solar industry could experience a shortage within the next 20 years more severe than the silicon shortage of the mid 2000s.

4. Further R&D needs

We compared the projected growth of the solar industry over the next 20 years to the likely available flat glass supply, and demonstrated that the production of flat glass must increase dramatically to support the growth of the solar industry. One of the main hurdles to expanding this manufacturing capacity is the high capital costs of a float plant. Research into ways of reducing capital expenditures for new plants would offer a pathway to a cheaper way of expanding the flat-glass supply. Additionally, more data are needed on a variety of glass products that currently are not economically feasible to use in production. Boro-silicate glass, for example, offers technical advantages, such as no alkali diffusion, high transmission, and high strength (allowing for thinner plates). Research is needed into whether scaling up to large-volume production, or using alternative production methods, could make such products economically feasible for solar modules, and ensure their improvement.

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