Cleaner Production via Industrial Symbiosis in Glass and Large-Scale Solar Photovoltaic Manufacturing

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Abstract—In order to alleviate production costs and increase the environmental performance of solar photovoltaic manufacturing, an eco-industrial park for GW-scale production of PV is proposed. This article quantifies the inputs and outputs for the glass manufacturing component of such a system using standard manufacturing techniques. Utilizing industrial symbiosis in this way, potential reductions for such a plant were found to be about 30,000 tons/year in raw materials and over 220,000 GJ/year in embodied energy.

Keywords: cleaner production; industrial ecology; industrial symbiosis; glass; photovoltaic; recycling; renewable energy; solar

I. INTRODUCTION

Solar photovoltaic (PV) cells, which convert sunlight directly into electricity, are a technically-viable, sustainable, and environmentally-friendly method of providing energy [1]. This environmental promise of PV is limited by economics. With no additional technical improvements, the cost of solar electricity could be competitive with conventional electricity if solar cells were produced on a large scale [2]. For a PV factory producing on the GW-level per year an expected threefold reduction in prices is predicted [3]. Such a facility can be optimized using industrial symbiosis (IS), where traditionally separate industries collaborate to competitive advantage by exchanging byproducts [2,4]. IS can be identified as relationships between independent entities that benefit more while working collectively than when acting alone. IS is also seen as a byproduct of industrial ecology [5], where separate entities in close proximity collaborate to better manage their entire materials life cycle thus ultimately benefitting the environment by reducing pollution and consumption of natural resources [4]. A key factor in industrial symbiosis is the proximity of separate industries that can naturally evolve or systemically develop into a mutually beneficial relationship.

In this paper, an IS system is considered in which the output of an entire glass manufacturing factory is made for solar grade glass suitable for PV applications. In order to optimize this component of a PV manufacturing eco-industrial park, this paper identifies current solar glass compositions and characteristics, and investigates quantitative aspects related to materials and energy required to produce large quantities of such glass. The energy and materials associated with this process are calculated and analyzed for potential cost and emission reductions. Finally, waste outputs including heat are considered for use in other facilities that are co-located with the plant. The feasibility of lower emission production of PV modules using this strategy is evaluated.

II. GLASS FOR PHOTOVOLTAIC MANUFACTURING

In order to drive down the costs per unit peak power of PV, all of the material inputs entering the solar cell factory should be optimized for solar cell production. The most critical component in a large PV manufacturing is the sheet glass factory that would provide substrates and back cladding for the PV. Optimization occurs if the demand for the glass materials is large enough to warrant a dedicated line that produces solar grade glass. This is necessary because glass specifically manufactured without iron for solar cells can increase the sunlight entering the cell by about 15% and have a corresponding improvement in device performance [2]. At current solar PV manufacturing lines for thin films, altering the glass recipe for small batches is uneconomic, but this would be reversed at scales of one hundred times (two orders of magnitude) current PV manufacturing lines [4]. Sheet glass is rarely customized for PV cell production and no mass production facilities exist that specifically serve the PV industry.

III. METHODS OF MASS PRODUCTION

A. Raw Material

Historically, solar grade quality was identified as glass with low iron content and high transmissivity with total spectrum transmittance ratings of over 90%. Newer
research and industrial practices suggest using more complex compositions that are specifically tailored for PV cell applications. One favorable composition based on a patent application suggests a total solar spectrum transmittance of ~92% at 4 mm thick (wt.% 67-75 SiO₂, 10-20 Na₂O, 5-15 CaO, 0.001-0.05 Fe₂O₃, <0.0038 FeO, and less than 0.1% of other impurities) [6]. It can be assumed that the mass production of this composition would not differ from established methods of sheet glass manufacturing. In float manufacturing in particular, the molten material has to be handled at a viscosity between 103 and 104 poises to prevent detrimental machine erosion and provide enough flow for a continuous sheet flow [7]. Using the Vogel-Fulcher-Tammann (VFT) equation, for calculating viscosity behaviour above the transition temperature, a glass of the foregoing composition would require a temperature of 1024°C to 1191°C to acquire the necessary viscosity level [8] and thus is consistent with traditional manufacturing.

These temperatures indicate that glass manufacturing is a high energy process. For flat glass, average specific energy requirements per tonnage are close to 0.3 MMBtu for batch preparation, 6.5 MMBtu for melting and refining, 1.5 MMBtu for forming, and 2.2 MMBtu for post-forming and finishing for a total of 10.5 MMBtu per metric tonne or approximately 11 GJ/tonne [9]. For a 1 GW (10⁹ W) solar factory the volumetric output of glass is determined assuming that every meter square of a solar module can produce 100 W of power. At a glass thickness of 3 mm, 1x10⁷ m² of sheet glass/year is needed. The density of the composition can be calculated using Fluegel’s statistical modeling of 6719 compositions to be about 2.49 g/cm³ [10]. For the glass production a total of 30,000 m³ (74,700 tonnes) of material is necessary for which a mean energy requirement of about 828,000 GJ/year. This is for the front glass. For both the front and the back all values are doubled in the standard process.

This energy requirement mentioned above is an estimated mean value that is subject to variations derived from the glass manufacturing process involving materials purification, melting, extraction, and cutting based on 11 GJ/ton. It does not, however, include transportation costs that can constitute a significant energy investment. Knowing that the average fuel efficiency of transportation via rail is approximately 100 tonnes mile/gal and by truck is 41 tonnes mile/gal [11], and that diesel fuel has an energy density of 148.3 MJ/gal [12], in a given year, the materials would require approximately 110 GJ for each mile of transportation using train and about 270 GJ using trucks. This would mean that a manufacturing facility can be as far as 7,500 miles away from its silicate source such that the energy consumption of the material transportation does not exceed the actual manufacturing of the sheet glass using trains and 3,000 miles with trucks.

B. Recycled Glass

Due to the importance of the composition of the front glass, it would be impractical to obtain the necessary quality based on current recycling methods because glass recycling facilities are incapable of controlling the exact composition content and would possess high levels of contaminant that affect the transmittance of the glass. Fortunately, by taking care to control the evolution of the microstructure during growth of amorphous silicon, the deposition of cells with equivalent performance in both substrate and superstrate configurations is possible, thus allowing the high-quality glass to be used as the base for growing the cell or as a simple cover [13-15]. Glass placed at the bottom of the module for encapsulation, does not require particular transmittance capabilities and therefore, could use recycled glass.

Raw glass from the recycling plant will be fed to a sheet glass factory and melted using natural gas. Natural gas is a greenhouse gas producer and more environmentally friendly methods of generating the energy needed will be considered in the future. Generally, the high quality requirements of flat glass prohibit the use of post-consumer waste glass. However, the glass industry is exploring a method to eliminate problems with color contamination by using thin plastic coatings, which would vaporize during re-melting without affecting the quality of the new glass [16]. This would benefit the industry considerably because using recycled glass has several benefits:

i) lowering the consumption of raw materials,
ii) reducing the release of CO₂ formed in the chemical reaction of raw materials,
iii) increasing the life of the furnace by up to 30% due to lower melting temperatures,
iv) reducing energy use during the melting stage of production and thus reducing additional greenhouse gases and operating costs, and
v) reducing the costs associated with pollution abatement due to lower emissions of NOₓ, SO₂ and particulates [16-18].

Recycled glass used in sheet glass and roll manufacturing can provide up to 2.35% savings in energy for each 10% cullet used in the mix [9,19]. A recycling method using vibratory and mechanical crushing devices claims up to 40% use of crushed cullet in glass mixtures, though most flat glass manufacturers do not recommend an excess of 20% cullet content [9,20]. Thus, up to 0.9 GJ/tonne can be conserved if using recycled glass assuming the cullet content could be increased to 40%.
IV. POTENTIAL EMBODIED ENERGY AND MATERIALS SAVINGS USING INDUSTRIAL SYMBIOSIS OF GLASS

Some of the glass needed to fabricate the solar cell could be recovered from recycled materials, saving about 20% in embodied energy [21]. Another advantage of developing a symbiotic eco-industrial park dedicated to PV manufacturing is that very little transportation costs are required for material moving between the different components of the park. For example, the crushed cullet created by the glass recycling facility could be fed directly into the glass manufacturing plant (preventing shipping of roughly 30,000 tonnes of raw material/year) based on the assumption of up to 40% cullet. To quantify these savings the transport energy for the manufactured glass to a PV manufacturing plant for the status quo was assumed for Pilkington’s float glass factory in St. Helen’s, Ontario to a hypothetical PV producer in Kingston, Ontario. Table I summarizes the embodied energy for the status quo case and an IS system (44,820 tonnes of raw material, 29,880 tonnes of glass cullets for back glass and no transport energy). This would require an additional melting tank and glass drawing line in parallel to the pure glass. This would drive up initial investments, which would be repaid in energy savings.

TABLE I. COMPARING ENERGY COMPOSITION BETWEEN REGULAR SHEET GLASS FACTORY AND IS EQUIVALENT

<table>
<thead>
<tr>
<th>Embodied Energy</th>
<th>PV Status Quo</th>
<th>PV IS Optimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Glass</td>
<td>827,500 GJ</td>
<td>827,500 GJ</td>
</tr>
<tr>
<td>Back Glass</td>
<td>827,500 GJ</td>
<td>761,300 GJ</td>
</tr>
<tr>
<td>Transport Estimate</td>
<td>155,000 GJ</td>
<td>~0 GJ</td>
</tr>
<tr>
<td>Total</td>
<td>1,810,000 GJ</td>
<td>1,588,800 GJ</td>
</tr>
</tbody>
</table>

As can be seen in Table 1, even without the addition for the raw material transported by truck (IS case would use 108 GJ less/mile) IS optimum uses about 12% less energy. The 221,000 GJ saved every year is equivalent to the burning of 5,300 tons of crude oil.

In addition to reduced primary energy and potential embodied energy, the waste heat associated with glass manufacturing can be used for other components of an industrial symbiosis. Up to 30% of the energy used for the glass melting furnace can be lost through flue gas exiting the stack [22]. When harvested this energy can provide heat for greenhouses and mushroom grow rooms, for example.

The average glass melting process consumes 6.9 GJ/tonne (6.5 MMBtu/tonne) [9] to 9.9 GJ/tonne (9.4 MMBtu/tonne) for flat glass regenerative furnace types (these furnaces constitute up to 80% of the flat glass industry) [22,23]. At 30% losses, there is approximately 2.1-2.9 GJ/tonne of potential energy available for greenhouse and mushroom grow rooms. At an annual production of 149,400 tonnes for both front glass and back glass, there will be between 314,000 and 444,000 GJ of energy available for these components.

V. THE GLASS COMPONENT OF AN ECO-INDUSTRIAL PV MANUFACTURING PARK

The simplified graphical representation of the glass manufacturing component of an eco-industrial PV manufacturing plant is shown in Fig. 1. In Fig. 1, the primary inputs are supplied from raw silicate sources, glass recycling facilities, and power (either through power production facilities or fuel). The input would include 80,000-90,000 tonnes of SiO₂, 11,900-23,900 tonnes of Na₂O, 6,000-18,000 tonnes of CaO, 1.2-60 tonnes Fe₂O₃, and <4.5 tonnes of FeO for the discussed solar grade composition. Also, an input of 30,000 tonnes of glass cullets, 1,600,000 GJ of primary energy and up to 432 GJ/mile of potential embodied energy is required.

The primary outputs consist of the glass itself, thermal energy, and emissions that can either be scrubbed or in the case of CO₂ used to foster plant growth in greenhouses. Besides the 149,400 tonnes of front and back glass, it should be noted that up to 444,000 GJ of energy can be utilized for grow rooms and greenhouses.

VI. CONCLUSION AND FUTURE WORK

This paper shows the dedication of a glass factory to solar grade sheet glass can save both energy and materials. Utilizing industrial symbiosis in this way, potential reductions for a 1 GW thin film manufacturing plant were found to be about 30,000 tons/year in raw materials and over 220,000 GJ/year in embodied energy.

Future work will determine the effect on emissions and any potential reductions or reuse of waste material resulting from the glass production process. Furthermore, an economic analysis would provide a financial case for the implementation of a glass factory component in a large scale solar photovoltaic industrial symbiotic system.
REFERENCES