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Industrial symbiosis in photovoltaic manufacturing

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ABSTRACT

As the solar photovoltaic industry has matured from MW-scale pilot plants to large-scale mass manufacturing, costs of solar cells have steadily fallen. To further drive down costs of solar electricity beyond grid parity, a new approach that is being used is to investigate how photovoltaic manufacturing fits into the industrial ecology of a region. Optimizing the utilization of the waste associated with photovoltaic manufacturing itself and its components, while carefully considering geographic proximity, allows for industrial symbiosis. Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage, involving physical exchange of materials, energy, water and/or by-products. Preliminary studies and industrial experimentation with co-production/co-location indicate that industrial symbiosis in photovoltaic manufacturing not only improves photovoltaic technology's already stellar life-cycle environmental performance, but also provides for additional revenue streams that can be used to further reduce photovoltaic device costs. For example, simply coupling a glass manufacturing plant making substrates to a GW-scale amorphous silicon thin-film photovoltaic manufacturing plant, and using recycled glass where technically viable, can lead to a reduction of 30,000 tons/year in raw materials and a 12% reduction in embodied energy. Coupling the glass plant to a greenhouse to make use of waste heat means that more than 700 tons of tomatoes can be grown each year. Both these material and energy savings and additional revenue streams contribute to lowering photovoltaic manufacturing costs, which will play a progressively more important role in photovoltaic manufacturing at the large (>GW) scale.

Introduction

Solar photovoltaic (PV) cells offer a technically sustainable solution to enormous projected future energy demands while helping eliminate the negative global destabilizing effects of the use of fossil fuels. With existing technologies, readily available materials and current conversion efficiencies found in manufactured solar modules, an insignificant fraction of terrestrially available sunlight is needed to power the global society [1]. Unfortunately, PV must further drive down costs to be economically competitive, due to both historic and current subsidies of conventional power [2–3] (including direct subsidies, e.g. the ability of oil and gas producers to treat as an expense rather than an asset the exploration and development costs [4]; and indirect subsidies, e.g. the artificial nuclear liability caps that enable the nuclear industry to exist [5]). This article explores the use of industrial symbiosis to help obtain economies of scale and increased manufacturing efficiencies for solar PV cells so that solar electricity can compete economically with heavily subsidized fossil-fuel-fired and nuclear-generated electricity.

Industrial symbiosis

In order to increase both the economic and the environmental performance of the manufacturing sector, large-scale PV manufacturers could be early adopters of industrial symbiosis. In industrial symbiosis, traditionally separate industries are considered collectively to gain competitive advantage by instituting the mutually beneficial physical exchange of materials, energy, water and/or by-products. The key benefits of utilizing industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity [6]. Such a system collectively optimizes material and energy use at efficiencies beyond those achievable by any individual process alone. Industrial symbiotic systems such as the now-classic web of materials and energy exchanges among companies in Kalundborg, Denmark have spontaneously evolved from a series of small innovations over a long time-scale [7]. To accelerate the process of creating teams of companies to work together for mutual benefit, it is possible to both 1) engineer the design of the new solar PV manufacturing plants to take advantage of industrial symbiosis and 2) provide appropriate policy incentives. Here, the first approach is considered.

Industrial ecology around photovoltaic manufacturing

Industrial ecology is usually regarded as the study of material and energy flows through industrial systems. It is easy to draw parallels between flows in natural systems (as studied by biologists and ecologists) and the flows in industrial systems. If industrial ecology were applied to PV manufacturing, while looking for potential sources of industrial symbiosis, a large-scale (e.g. GW or multi-GW) PV factory would represent the heart of the ecosystem, which can be referred to as a next-generation eco-industrial park. An eco-industrial park of this type has been proposed [8] and is made up of at least eight symbiotic factories as seen in Fig. 1. The simplified flow of energy and materials between the eight factories is shown in this diagram.

Such a collection of factories would be located close to a major population centre, to provide raw materials, labour and a ready market. The first factory (1) is a conventional recycling facility, which is used to source the glass and aluminium needed to fabricate the solar cell from recycled materials (when viable) and thus have a lower embodied energy (95% lower for aluminium and 20% for glass) [9]. The raw glass from the recycling plant is fed into a sheet glass factory (2) and (at least initially) melted using natural gas. The glass factory outputs cut sheets of 3mm-thick glass with seamed edges and low iron content in order to obtain a high solar transparency. Finally, the glass is tempered for mechanical strength and coated with a transparent conductor, such as tin oxide, zinc oxide or indium tin oxide, to be used as a thin-film photovoltaic substrate [8]. The symbiosis between the glass plant and the PV plant will be detailed in the next section.

The production stages in the glass factory that utilize large amounts of heat have integrated thermal recovery to provide lower grade heat for the other facilities and a multi-acre greenhouse complex (3a). In the greenhouse complex, plants can be grown year-round (northern climates) utilizing the waste heat from the

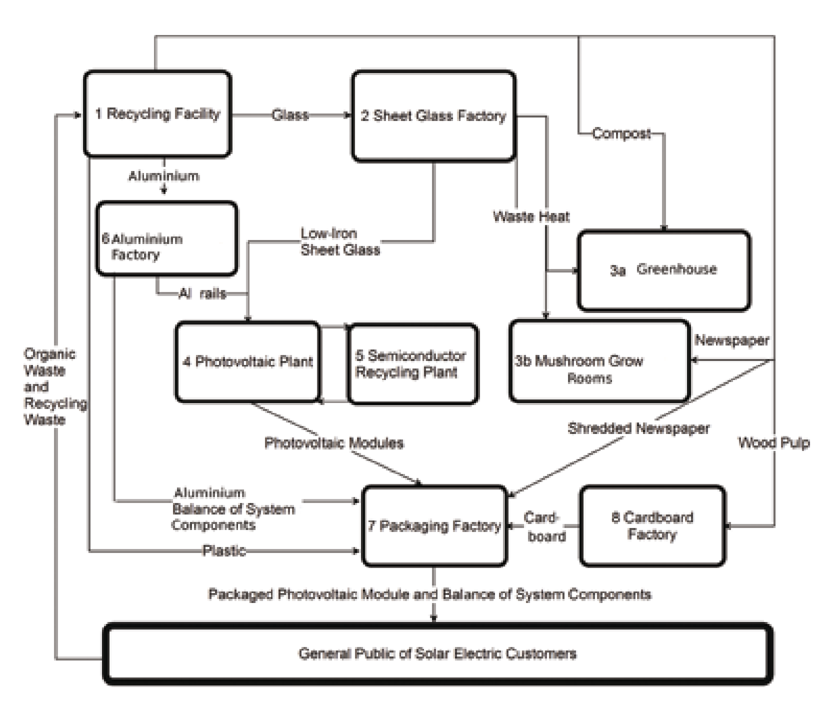

Figure 1. Material and energy flows of an eco-industrial park developed around photovoltaic manufacturing.

manufacturing plants in the eco-industrial park, and this approach will be detailed in a second example below. Similarly, the waste heat could instead (or in addition) be utilized to provide grow rooms for mushrooms (3b). In both agricultural plants, the food or other agricultural produce is sold outside of the park and the growing medium will be provided by the recycling facility (1), namely compost for the greenhouse (3a) and wood pulp or compost for the mushroom grow rooms (3b). In warmer climates, the waste heat could be used to drive absorption chillers to provide cooling (e.g. for an office building).

The substrates are then fed directly into the PV module plant (4), where a group of semiconductor and metal thin-film deposition systems create and pattern the active layers of the PV modules. All waste semiconductors and metals are captured and returned to a semiconductor recycling plant (5) to supplement the incoming and generally expensive high-purity materials going into the deposition systems. The output of the PV deposition and patterning lines will be solar PV modules ready for protective coatings and packaging.

Similarly to how glass from the recycling facility (1) could be used as raw material for the glass factory (2), the aluminium extracted from common drinking cans in the recycling facility (1) is fed into an aluminium fabrication factory (6) that will produce coated aluminium rails to be used for the racking components of the PV modules from the plant (4). The aluminium rails are extruded and used to provide a simple and inexpensive means of attachment to rooftops, ground-mounted systems or building-integrated PV installations. In addition, the extruded aluminium rails could be designed into the ground mounting and flat-roof mounting balance of system components. Again, as with the glass manufacturing plant (2), waste heat will be recovered and used in the symbiotic collective or to heat the greenhouse (3a) or mushroom grow rooms (3b). Next, in the packaging factory (7), the solar panels are interconnected if necessary and sprayed with a protective polymer coating to seal them to the environment. Some of the constituents of the polymer coating could again be acquired from the recycling facility (1), using common polymer chemistry. The panels are then wired with quick connects so they can be easily installed in the field by connecting to each other, or to an inverter or a battery bank. Finally, to prevent damage, the panels are packaged for shipment in cardboard boxes from the factory (8), which would gain its raw materials from the recycling facility (1), and the panels possibly cushioned with shredded newspaper, again from the facility (1).

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By co-locating these factories in the eco-industrial park, both the transportation costs and the transportation energy between them can be minimized, and many of the inputs for the solar PV plant can actually come from waste products generated in the surrounding population centres. It is important to note that each factory should be scaled appropriately for the symbiotic system and should be individually profitable so that independent businesses can replicate this model by co-locating and benefit from industrial symbiosis in future facilities. To understand how this scaling needs to take place, the

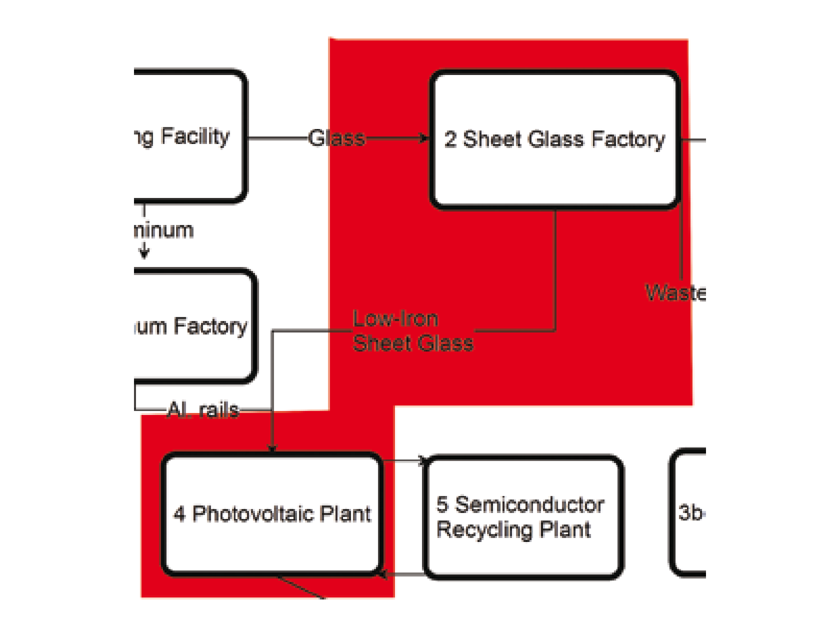

Figure 2. Detail of industrial symbiosis between PV and glass manufacturing.

relationship between PV manufacturing (4) and a glass factory (2) are quantified below.

Industrial symbiosis between PV and glass manufacturing

Building an industrially symbiotic system around the PV manufacturing plant (4) involves optimization of the other plants around it. Here the potential symbiosis of co-locating the glass plant (2) and the PV plant (4) as seen in Fig. 2, and using recycled glass, will be investigated.

The optimization of the glass plant component of the PV eco-industrial park in Fig. 1 is achieved through first quantifying the raw materials and energy requirements required for the production of glass needed by the PV plant, and then allocating the by-products of the glass manufacturing factory to other elements of the PV eco-industrial park. The sheet glass factory provides both substrates and, potentially, 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 with low iron content for PV cells can increase the sunlight entering the cell by about 15% and deliver a corresponding improvement in device performance [8]. In current solar PV manufacturing lines for thin films, altering the glass recipe for small batches is uneconomic, but this is reversed at large scales of manufacturing [10]. Sheet glass is rarely customized for PV cell production (although this is rapidly changing as PV manufacturers couple with glass manufacturers). A recent study quantified the energy savings for a 1GW PV factory constructed due to energy policy in Ontario, assuming a PV output of 100W/m^2, 3mm-thick glass and the use of 40% recycled cullet for the back glass [11].

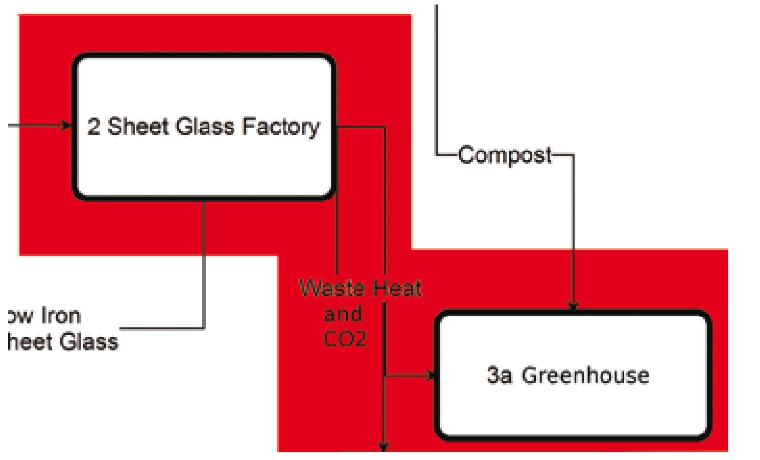

Figure 3. Industrial symbiosis between glass manufacturing and a greenhouse complex.

As can be seen in Table 1, the major benefit of the industrial symbiosis between a PV plant and a glass plant is dramatically reduced transportation energy costs, as well as a reduction in the energy required to produce the back glass, due to the increased allowable cullet content. The transportation numbers assumed a specific energy of 110GJ/mile over a distance of 286 miles (461km). It can be seen that in this case the industrial symbiosis optimum uses 12% less energy, which equates to 5266 tonnes of crude oil. In addition, reductions of 30,000 tons/year in raw materials are achieved if using cullet. These savings in energy and materials can be directly related to reductions in economic costs.

Embodied energy	Status quo (GJ)	Industrial symbiosis (GJ)
Front glass	827,500	827,500
Back glass	827,500	761,300
Transportation	155,000	~0
Total	**1,810,000**	**1,588,800**

Table 1. Energy use per GW PV [11].

Industrial symbiosis between glass manufacturing and a greenhouse complex

As was examined in the previous section, coupling two industries together so that one (the glass plant) conventionally feeds the other (PV plant) is not particularly revolutionary and is common in many industries. Where industrial symbiosis really begins to stand apart from conventional industry is when groups of companies can work together as a team and begin to eliminate waste by finding by-product synergies. If the glass plant is examined, it is clear that its two primary 'waste' products are heat and carbon dioxide.

A recent study developed a technical and economic methodology to determine the viability of establishing 'waste heat greenhouses', which use the waste heat from industrial processes in northern climates [12]. A case study was presented of an exchange between a tomato greenhouse and a sheet glass manufacturing plant (ideal for fabricating substrates for the PV industry) as shown in Fig. 3.

The glass plant in the case study produces 500 tons of glass per day, making it a mid-sized float glass operation [13], and utilizes 1.25PJ of natural gas a year [14]. The entire waste heat system is shown in Fig. 4 with the proposed structure and energy flows.

In addition to the heat, the carbon dioxide (CO_2) can, if properly treated, also be useful to the greenhouse complex. Modern greenhouse operations utilize CO_2 enrichment in order to increase crop yields. Particularly in a tightly sealed greenhouse being heated in the wintertime, CO_2 enrichment is required, as a minimum, to maintain the atmospheric concentration of CO_2 at ambient levels (around 380ppm) to account for plant photosynthesis [15]. In Canada, using extremely conservative estimates, it has been found that a sheet glass plant could support a greenhouse complex of about four acres, where 700 tons of tomatoes can be grown each year and can offset between 1000 and 2000 tons of CO_2 annually. Additionally, it has been shown that over a 20-year campaign with a 10% minimum acceptable rate of return (MARR), the waste heat system is significantly less expensive to operate than a purely natural gas system. Finally, the addition of a waste heat greenhouse can reduce the costs of emissions compliance for a company, as the deferred costs of liquid CO_2 can fund millions of dollars for emissions reduction retrofits [12].

The bottom line of this analysis is that, from the greenhouse perspective, the waste heat system is significantly more economic to operate than a purely natural gas system. These economic gains can be transferred to the glass factory since the by-products (heat and CO_2) can be sold for a profit, which can thus lead to a further reduction in glass costs, in turn providing the potential to reduce the costs of PV modules. These savings can provide a significant competitive advantage over those PV manufacturers who do not look beyond their own gates for synergies.

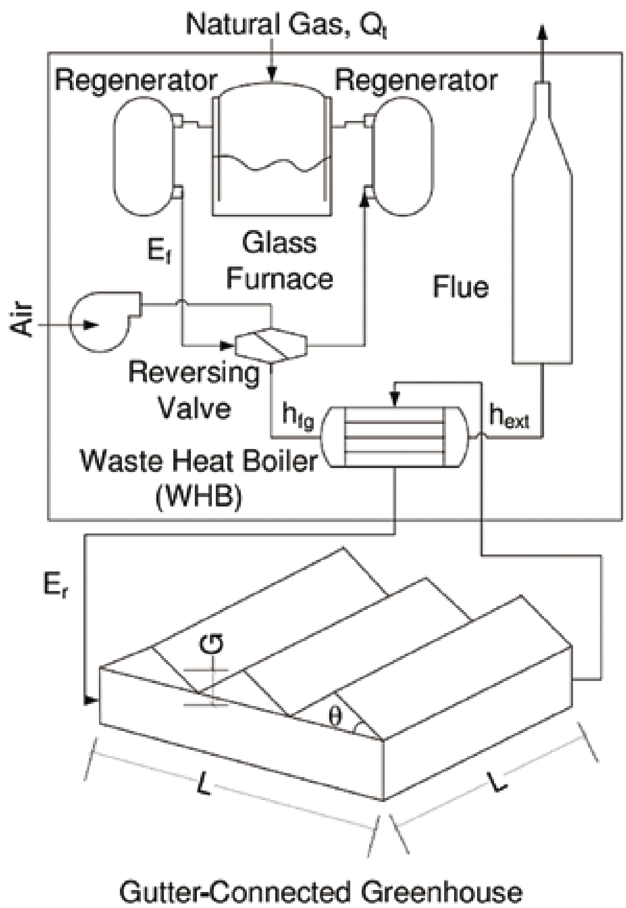

Figure 4. Detail of industrial symbiosis between glass manufacturing and a greenhouse complex showing system structure and energy flows.

Conclusions

This article summarized the technical requirements and some of the preliminary work for a symbiotic industrial system around solar photovoltaic manufacturing, to increase manufacturing efficiency and improve ecological impact while reducing costs. This set of technical concepts, coupled with potential incentive-based policies formulated to encourage them, can be viewed as a medium-term investment by a government interested in speeding up the advance of renewable energy and creating green jobs, which will not only see financial return directly, but also lead to an improved global environment, enhanced national energy security and international favour.

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