EMBODIED ENERGY OF SLIVER® MODULES

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ABSTRACT: Sliver® solar cells, invented and developed at the ANU, allow a reduction in the consumption of silicon by a factor of 5 to 12 compared with state of the art conventional crystalline silicon modules, resulting in a decrease in the number of wafers that need to be processed to produce a kW rated system by a factor of 15 to 30. Both of these features reduce the embodied energy of Sliver® modules. We have calculated an energy payback time of 1.5 years for Sliver® modules compared to 4.1 years for conventional crystalline silicon modules. The equivalent greenhouse gas emissions embodied in Sliver® modules also compares favourably to emissions from fossil fuel sources used for the generation of electricity in Australia.
Keywords: PV Module, Embodied Energy, Greenhouse Gas Emission

1 INTRODUCTION

The use of photovoltaic (PV) systems on a large scale in order to reduce fossil fuel consumption and greenhouse gas emissions requires that the energy associated with the construction, operation and decommissioning of PV systems be small compared with energy production during the system lifetime. That is, the energy payback time should be short compared with the system lifetime. A reduction in embodied energy of a PV system will have both economic and environmental benefits. In addition to the cost considerations, that currently drive the research and development in the PV field, it is desirable to quantify the energy embodied in new technologies. Energy embodiment is another useful criterion against which new and existing technologies can be compared [1].

A new technology has been developed that promises substantial reductions in the cost of monocrystalline (c-Si) solar cells and modules. Sliver® solar cells are fabricated using an innovative technology that yields a cumulative device area that is much greater than the surface area of the original wafer [2]. This translates into large decreases in processing effort and silicon usage, while maintaining all of the advantages of both c-Si and conventional device fabrication technologies. Furthermore, the size, thickness (flexibility) and bifacial nature of the cells create the opportunity for a wide variety of module architectures and applications. By connecting Sliver® cells in series, it is easier to build voltage than in conventional modules where the economies of scale favour large cells. Module output can be tuned from standard 12 V applications to several hundred volts for grid-connected applications. Strings of Sliver® cells with 200-400 V output only require lengths of a few tens of centimetres. Series strings can be connected in parallel to increase output current. These high voltage modules could allow for direct conversion from DC to AC without the requirement for voltage up-conversion.

In this paper, the energy embodied in a Sliver® module is compared to that of a conventional c-Si module. Further, the equivalent CO_2 emission embodied in a Sliver® module is compared to emissions during electricity production in Australia from coal and gas.

2 METHODOLOGY

A survey of recent studies on the energy payback time of PV modules was undertaken [1,3-8]. In this study, we have compared the energy embodied in Sliver® modules and the conventional PV module, SP75, manufactured by Siemens [7]. It is pointed out that the absolute values of the energy payback time are meaningful only within the bondaries of the problem as set by (1) the proper definition of the PV system boundary, and (2) the assumptions underlying the methodology employed in calculations. With this shortcoming in mind, the same methodology and data was used, as far as reasonable, in calculating the energy payback time of both a conventional and a Sliver® PV system. For reasons of transparency we now present our choice of methodology and the assumptions we have used in our calculations. The system boundary will also be described in the following discussions.

2.1 Embodied energy calculations

In an energy intensive product such as a PV panel the energy embodied in the materials far exceeds the energy embodied in the production machinery, and the latter can be neglected for practical purposes (i.e. first-order calculations). Indirect energy, such as for heating, lighting, office equipment and transport is a significant overhead and must be included.

In our analysis, the production and installation of a PV system has been divided into four sectors, each consuming energy (derived predominantly from fossil fuel) and contributing to greenhouse gas emissions:

- Production of the silicon wafer;
- Fabrication of the solar cells;
- Packaging of the solar cells to create a PV panel;
- Installation of many panels to form a PV system (balance of systems);

Production of Si wafers - For the sake of simplicity, the energy content of PV wafers is calculated assuming a simple flow of silicon from quartz to Czochralski ingot. Silicon wafers are produced from electronic grade Si (EG-Si), which in turn is produced from metallurgical grade silicon (MG-Si). MG-Si (98% purity) is used in large quantities in the steel and other industries, and is purified via the Siemens process to produce EG-Si. The

EG-Si is then melted into a Czochralski crytal puller to form a Si ingot. The ingot is sliced into wafers using a multiwire saw and abrasive slurry, whereby nearly half of the ingot is lost as sawdust. The ingot is typically sliced with a pitch of 0.5 to 0.8 mm to produce wafers with a thickness of 0.3 to 0.5 mm. For wafers used to manufacture Sliver® cells, the ingot is cut at a pitch of 1-2 mm. For the energy embodied in the production of Si wafers, we have used the data reported by Knapp and Jester [7].

Sliver® cell fabrication and packaging into a panel – Conventional cell fabrication entails a sequence of high temperature diffusion, oxidation, deposition and annealing steps. After cell fabrication is complete, conventional Cz cells are trimmed to make a pseudosquare solar cell. The cells are then encapsulated to make a PV panel with a typical packing factor of ~90% (i.e. 90% silicon and 10% open space between the cells). Following metallization, the cells are connected into strings with copper tabs. Panel formation entails the lamination of the cells behind glass with EVA and Tedlar using heat and pressure. A junction box is mounted on the back of the panel. In most cases, an aluminium frame is placed around the panel perimeter. The aluminium frame represents a significant fraction of the panel's embodied energy, but it is not required with some panel mounting systems. Determination of the energy content of aluminium is not clear-cut, since it depends on the fraction that is recycled. About half of Australian aluminium is recycled. It can be readily recycled again when the panel's life is completed (~30 years later).

In addition to the conventional processes of oxidation, high temperature diffusion and metallization, the fabrication of Sliver® cells requires micromachining [2], making the overall Sliver® cell processing radically different from conventional cells. However, the panel assembly materials and techniques are similar. Sliver® cells are typically mounted in a module with a spacing equal to the cell width.

Balance of system (BOS) - BOS comprises wiring, power electronics, foundations, support frames, transport and installation. In a system installed in an open field, the foundations are typically concrete while the support frames are steel. Both of these materials are energy and carbon dioxide intensive. In a system installed on a building roof, the foundations can generally be dispensed with. In addition, if the PV array forms part of the roof structure then the energy embodied in the displaced roof components can be set against the embodied energy in the PV array. The energy payback time for the BOS components is much smaller for roof-mounted systems than for systems deployed in open field. Systems deployed in open fields will generally (1) have smaller inverter and electrical resistance losses, (2) have unimpeded access to sunshine, and (3) often be in sunnier regions than cities. On the other hand, distribution losses will be higher. Frankl and coworkers [5] estimate that placing panels on roofs consumes around 500 MJ (thermal) per m^2, mostly for the supply of steel supports.

Fossil fuel use during PV system operation and decommissioning (or any other end-of-life processing) is negligible. Virtually all of the fossil fuel energy consumed and CO_2 production associated with PV systems arises from the initial production and installation of the system.

All energy forms were converted into their electrical energy equivalents – i.e. kilowatt-hours electric (kWhe). Sydney, with an average solar insolation of 1926 kWh/m^2/yr, is the location used in our comparison. The PV panels are assumed to be mounted on a fixed frame facing north and tilted at the latitude angle. Sydney has good insolation compared with central and northern Europe (30-70% larger), but similar to southern and western states in the USA and southern Europe.

The actual electrical output of the PV system is the irradiation multiplied by the average system efficiency. The single crystalline silicon solar cells in conventional modules are assumed to have an efficiency of 15% under standard testing conditions while slivers are assumed to be 18% efficient. The average operational efficiency is 75% of the rated efficiency. This takes account of real-world losses, such as losses associated with array availability (99%), the proportion of time that the array is unshaded (95%), elevated cell temperature efficiency ratio (91%), the absorption efficiency (97%) (capture of light at oblique angles or dirty glass) and the electrical efficiency (90%) (losses associated with the inverter, transformer and transmission).

2.2 CO_2 equivalent intensity of coal, gas and Sliver® modules

Annual CO_2 equivalent emissions from coal and gas were obtained from data published by the Australian Coal Association [9] and the Australian Gas Association [10], respectively. The CO_2 equivalent intensity of a PV system in Australian has been estimated from the energy payback time using a national average CO_2 equivalent intensity for electricity production equal to approximately 0.98 kg of CO_2 per kWh [11]. A Sliver® module lifetime of 30 years is used to calculate the yearly CO_2 equivalent emission of the PV system.

3 RESULTS AND DISCUSSIONS

3.1 Comparison of energy payback times

Calculation of the energy content of a Sliver® and conventional panel follows the methodology and data of Knapp and Jester [7]. This study looked at actual process energy consumption data for the production of 5 million solar cells at a Siemens plant in 1998/9. The data is generally consistent with a range of other studies [3-6,8], with the following exceptions:

- Energy consumption for production of EG-Si was at the low end of the range;
- Energy consumption for the Cz ingot growth and slicing process was considerably below other data. It is clear that the cost of Cz ingot production in a solar cell factory is much lower than in an IC plant. Solar cell manufacturers take shortcuts. Since cost and energy content are closely related, data derived from the IC industry (as used in other studies) will overstate energy use for solar cells.

In this study, IC industry data is adopted for the energy intensity of silicon and Cz ingot production for Sliver® cells while the data from Knapp and Jester [7] is adopted for conventional modules. For similar Si usage, the energy intensity will therefore be 1.7 times larger for Sliver® than for conventional cells. This is in line with the likelihood that high-efficiency Sliver® cells will be made from superior grade Si wafers. It is assumed that the energy intensity of Sliver® processing is 3 times larger per wafer than for Siemens cells because of the greater complexity in cell processing. The assumptions and details of key parameters used here are summarised in Table I.

Table I: Summary of assumptions and the energy payback time (years) for Sliver® and conventional PV panels.

	Sliver®	Conven.
Wafer thickness	1.5 mm	0.35 mm
Kerf loss	0.26 mm	0.26 mm
Sliver cutting pitch	0.1 mm	-
Overall yield	85%	90%
Cell packing factor in the module	50%	90%
Cell efficiency at standard conditions	18.0%	15.0%
Silicon utilisation (kg/kWp)	1.7	14.6
Wafers (150mm) processed per kWp	23	580
Ingot production energy (kWhe/kWp)	568	3302
Cell production energy (kWhe/kWp)	151	1263
Panel assembly energy (kWhe/kWp)	1033	1033
Total panel energy (kWhe/kWp)	1863	5598
BOS energy (kWhe/kWp)	359	383
Annual AC output per kWp (kWhe/kWp)	1443	1443
Energy payback time	**1.5 yrs**	**4.1 yrs**
CO_2 coefficient (electricity, 1 kg/kWhe)	0.05	0.14

The energy payback time of a Sliver and a conventional module is 1.5 and 4.1 years respectively. Frameless panels will have an energy payback time about 0.2 years less than for panels with aluminium frames. A breakdown in the energy payback time (EPBT) along the four components discussed in section 2.1 is given in Table II.

Table II: Breakdown of EPBT into the four main PV system components.

Component	Sliver® (yrs)	Conven. (yrs)
Silicon ingot	0.5	2.3
Cell fabrication	0.1	0.9
Panel assembly	0.7	0.7
Balance of systems	0.2	0.2
Total EPBT	**1.5**	**4.1**

The above breakdown highlights the definitive competitive edge of the Sliver® technology over current technology regarding the usage of Si in PV module fabrication.

3.2 Comparison of greenhouse gas emissions

We now compare the CO_2 coefficient of Sliver® modules to those of coal and gas in the Australian context. In Australia, electricity production is predominantly by means of coal-fired power stations. The Australian Coal Association (ACA) and the Australian Gas Association (AGA) have produced environmental assessments of the production of electricity from coal and gas. Both studies emphasise the importance of a complete life cycle analysis. In the case of natural gas, fugitive emissions of methane are included. On the other hand, the attraction of direct space heating and heating of water with gas, in terms of overall greenhouse emissions, is pointed out. In the case of coal, fugitive emissions such as methane from coalmines are included. On the other hand, the ability to use waste products to reduce net greenhouse emissions has been analysed. For example, fly ash can be used as an extender in cement production. This 'displacement credit' could potentially reduce the greenhouse intensity of existing coal fired electricity power stations by around 10% if all the fly ash were to be used. The ACA and AGA studies are in good agreement with each other with respect to the greenhouse intensities of the production of electricity from coal and gas. The greenhouse gas intensities for coal and gas (taken from Refs. [9] and [10]) are shown in Fig. 1.

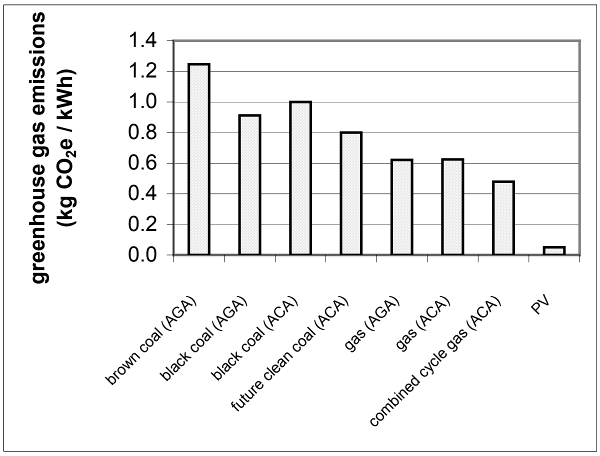

Figure 1: Greenhouse gas intensities for the production of electricity from coal, gas and PV in Australia.

Using a national average CO_2 equivalent intensity for electricity production of approximately 0.98 kg CO_2 per kWh and a Sliver® module lifetime of 30 years, we have calculated a CO_2 coefficient of 0.05 kg/kWh for the PV system. This value compares around 20 times more favourably than the national average of electricity production using coal (Fig. 1).

4 CONCLUSIONS

Sliver® modules, including balance of systems energy, have an energy payback time of about 1.5 years when mounted on a house roof in Sydney compared with 4.1 years for a conventional PV module. The energy content of Sliver® modules is dominated by panel assembly, which divides approximately evenly between materials and assembly processes. The energy content of the silicon, which dominates in conventional modules, is only about a quarter of the energy content for Sliver® modules. Sliver® modules have a CO_2 equivalent coefficient of 0.05 kg/kWh, which is approximately 20 times smaller than the national average of electricity production in Australia.

5 ACKNOWLEDGMENTS

Financial support from the Australian Research Council is gratefully acknowledged.

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