Advanced cell and module design for solar LCOE optimization: Is the white glass–glass module the future?

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ABSTRACT

With the increasing number of solar installations, the PV industry is gradually shifting its focus from $/W to $/kWh. The development of advanced solar cells and modules needs to be addressed from a system performance optimization point of view. GCL's specially designed white glass–glass (WGG) module using advanced solar cells is taken as an example in order to demonstrate the 'one-stone-three-bird' methodology, i.e. the use of one product to reduce $/W cost, to improve system performance, and to increase lifespan, all at the same time. The outlook of the future module design for system optimization is also discussed.

Introduction

The estimated PV system installation capacity in 2016 was ~70GW worldwide [1], as shown in Fig. 1. In fact, the production volume in 2015 was around 200 times that in 2000, with a compound annual growth rate (CAGR) of over 40%. It has recently been noted that as the PV industry matures, the mindset is changing from $/W to $/kWh. While $/W is still a major driving force, the significance of other factors that influence the cost of energy must also be considered. In this regard, PV development is entering the era of $/kWh-oriented optimization.

"As the PV industry matures, the mindset is changing from $/W to $/kWh."

There is an old Chinese proverb that says, 'kill three birds with one stone'. The nature of solar energy is such that the main factor is the cost of the energy. One of the most important skills in the solar industry is to condense multiple process steps into one in order to maximize the cost reduction. The problem is, can one simultaneously lower the $/W, increase PV system efficiency, and lengthen the lifespan?

To answer this question, a levelized cost of electricity (LCOE) analysis will be the

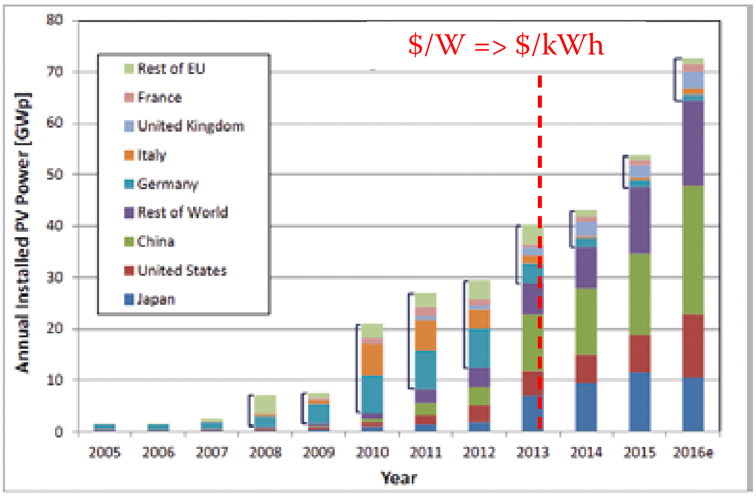

Figure 1. Annual PV system installations from 2005 to 2016 (data taken from Jaeger-Waldau [1]), and the industrial scenario shift from $/W to $/kWh.

$$\text{LCOE} = \frac{\text{Total life cycle cost}}{\text{Total lifetime energy production}} \tag{1}$$

$$\text{LCOE} = \frac{\text{Initial investment} - \sum_{n=1}^{N} \frac{\text{Depreciation}^{n}}{(1+\text{Discount rate})^{n}} \times (\text{Tax rate}) + \sum_{n=1}^{N} \frac{\text{Annual cost}^{n}}{(1+\text{Discount rate})^{n}} \times (1-\text{Tax rate}) - \frac{\text{Residual value}}{(1+\text{Discount rate})^{n}}}{\sum_{n=1}^{N} \frac{\frac{\text{Initial kWh}}{\text{kWp}} \times (1-\text{System degradation rate})^{n}}{(1+\text{Discount rate})^{n}}} \tag{2}$$

Equations 1 and 2.

starting point, followed by discussions of innovations along the value chain. A meaningful example – a white glass–glass module – will be used in order to demonstrate the one-stone-three-bird methodology in the optimization of $/kWh (Fig. 2). The system design outlook will then be discussed.

First principle: optimization of system LCOE

To solve a problem elegantly, experienced engineers begin their analysis with the first principle, i.e. the basic law that governs the issue to be addressed. Here, the objective is the optimization of system LCOE, which is defined by Equation 1 [2]; for solar generation, this equation can be separated into the components indicated in Equation 2 [3].

It can be seen that the LCOE is a function of initial system output, degradation ratio, initial investment, operation and maintenance cost, and depreciation of equipment. It is also related to the financial indices, such as tax rates and the rising interest rates for funds.

To simply the problem, and to focus on the influence of technical improvements on the LCOE, in this paper the loan payment, tax, insurance, discount rate and O&M costs are omitted in the calculations (Fig. 3). Moreover, the residual value at the end of life is always considered to be zero.

To keep it simple, the three most significant factors are:

1. The initial investment, which is linked to module $/W.
2. PV system performance ratio (PR), which influences the energy yield.
3. Operational lifespan of the system.

The PR is an internationally introduced measure for the degree of utilization of an entire PV system, and is defined in more detail in IEC 61724 [4]. In practical terms, the PR is calculated as follows [5]:

$$PR = E_{specific} / H_{specific} \times 100\% \quad (3)$$

$$E_{specific} = E_{Feed\text{-}in} / P_{STC} \quad (4)$$

$$H_{specific} = H_{POA} / G_{STC} \quad (5)$$

where $E_{Feed\text{-}in}$ is the electricity fed into the grid; P_{STC} is the rated DC power of the modules; H_{POA} is the irradiation sum (energy) in the module plane; and G_{STC} is the irradiation corresponding to the irradiance intensity (1,000W/m^2) in standard test conditions (STC).

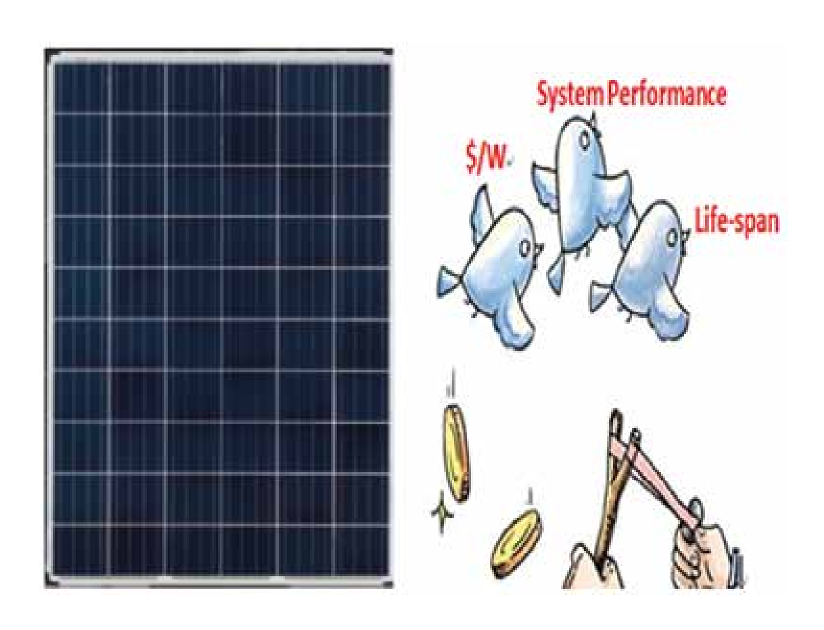

Figure 2. A white glass–glass module from GCL and the one-stone-three bird design methodology to illustrate optimization.

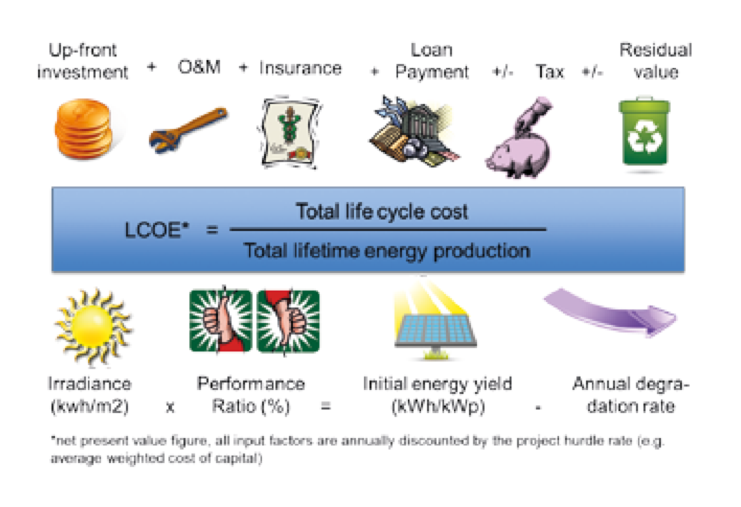

Figure 3. Graphic illustration of LCOE (courtesy of Thomas Reindl).

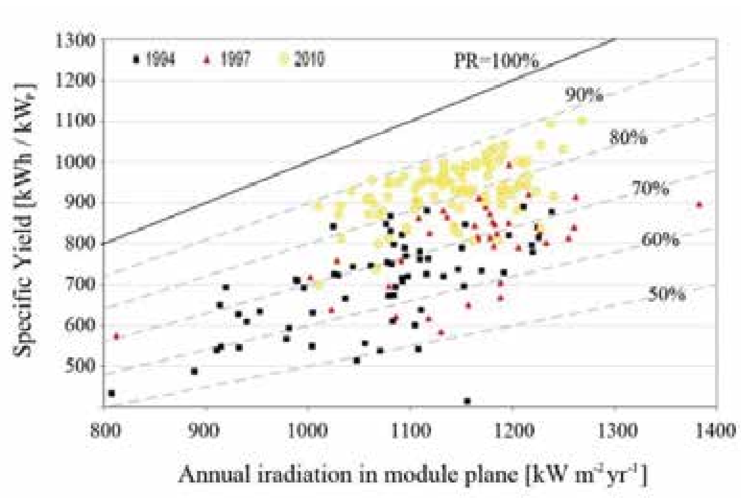

Figure 4. The change in PR values from 1994 to 2010 for German PV systems [5].

For a better understanding, in the case where $H_{specific} = 1$ (i.e. the in-plane irradiation equals 1,000W/m^2), the PR in Equation 3 reduces to the ratio of system output power to the nameplate power of the panel. The PR represents the overall effect of losses on the PV system's rated output due to array temperature, incomplete utilization of the irradiation, system component inefficiencies or failures.

As shown in Fig. 4, Reich et al. [5] from Fraunhofer ISE have determined the monitored specific yield as a function of total plane-of-array irradiation of PV systems. An improvement in PR with time is clearly seen: the PR is ~65%, 75% and 85% for the years 1994, 1997 and 2010 respectively.

Nobre et al. [6] from the Solar Energy Research Institute of Singapore (SERIS) has demonstrated that the PR is strongly influenced by temperature, soiling, shading, mismatch, etc. If the effects of these factors are reduced, the PR can be improved by ~8%, as shown in Fig. 5.

Innovation along the value chain

The most significant technical innovations that are relevant to Si-based solar technology are listed in Table 1. From this list the best solutions in terms of reducing LCOE have been selected for discussion.

For Si materials, the improved Siemens method is dominant, and companies are seeking locations with lower electricity prices in order to reduce cost. The modified Siemens, fluid-bed reactor (FBR) and metal-Si methods are being launched into mass production by GCL, REC and Elkem respectively. In the case of wafers, larger Si casting blocks (8×8), casting mono (>90% mono), continuous CZ mono (10 silicon rods using one crucible), diamond wire slicing, and direct wafering (e.g. technology from companies such as 1366/Crystal Solar/ Amber Wave) are noted.

For cells, notable innovations include:

- finer lines below 40μm line width;
- five-busbar (5BB);
- multibusbar (MBB, 12–18 busbars);
- black-Si texturing (reactive ion etching, or metal catalyst chemical

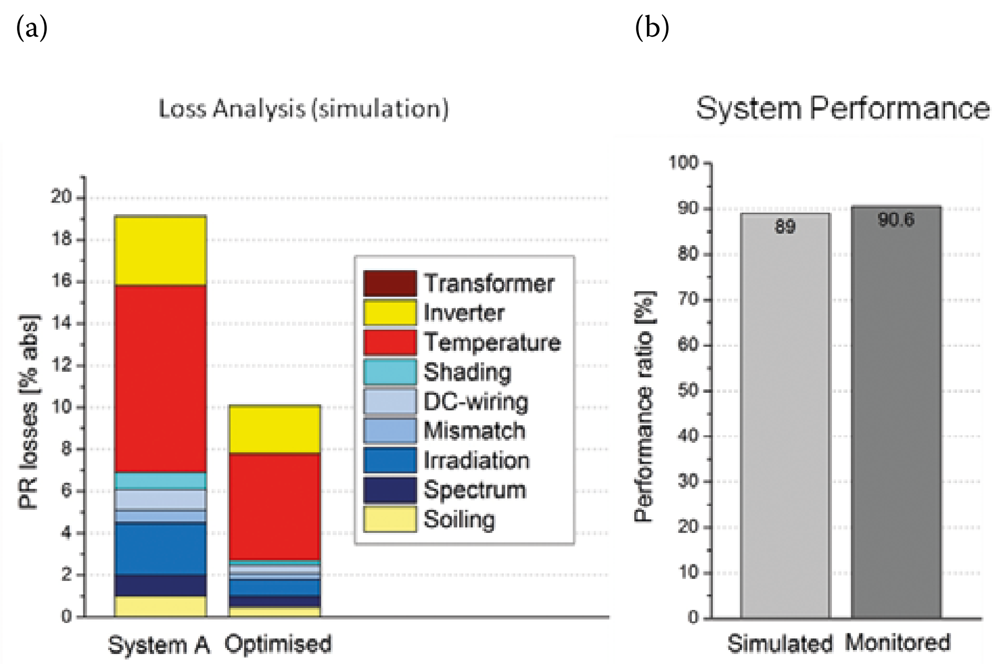

Figure 5. (a) Comparison of the PR for an actual PV system (system A) and a simulated 'optimized' PV system. Also shown is a breakdown of the individual loss factors that influence the PR. (b) Actual system performance of a real-world demonstration system at the Solar Energy Research Institute of Singapore (SERIS). This system has been operating at~90% since 2012 [6].

Si	Wafer	Cell	Module
FBR	Large Si block (8×8)	Fine line/5BB/MBB	**White double-glass**
Siemens Si	Casting mono	**Black – Si texturing**	Bifacial double-glass (n-type, PERC)
Metal-Si	**Diamond wire (DW)**	DW wafer direct texturing	High-voltage (1,500–3,000V)
	Continuous CZ mono	**p-PERC/n-PERL**	**CTM enhancement (twin, high-density)**
	Direct wafer	HJT cells/TOPCon	96× supersize (single-axis tracking)
		Hydrogenation	SMART (MPPT+)
		C-Si tandem cells (e.g. Si+perovskite)	Local (optimized spectrum/ structure)

Table 1. Summary of significant technical innovations along the value chain.

etching) and direct texturing for diamond wire slicing multicrystalline Si wafers;

- p-type passivated emitter rear cell (p-PERC) concepts;
- n-type passivated emitter and rear locally diffused (n-PERL) devices;
- heterojunction cells (HJT) and new TOPCon concept cells;
- hydrogenation, which improves carrier lifetime;
- C-Si/perovskites tandem cell structures.

In the case of modules, notable innovations include:

- white double-glass designs;
- bifacial double-glass designs incorporating n-PERL or p-PERC cells;
- high-voltage modules (1,500–3,000V);
- high-efficiency modules with significant cell-to-module (CTM) power enhancement (half-cut twin-cell modules for 2.5% power enhancement, or high-density modules for 10% power enhancement).

Also listed in Table 1 are 96-cell supersize modules for single-axis tracking, smart modules, and local modules with customized spectrums or structures that are designed for specific locations.

The two hottest topics in recent years – namely diamond wire wafer slicing + black Si, and advanced passivation (p-PERC/n-PERL) – will be used as examples for analysing the impact on LCOE or on $/kWh.

As a rough guide for comparison purposes, a reduction in $/kWh of ~4% is estimated through the use of diamond wire wafer slicing; this reduction mainly arises from the cost saving in $/W for Si materials. The calculation assumes a 20% Si material cost saving from using diamond wire technology as a result of a reduction in line spacing associated with diamond wire; this translates to a $/W saving in module cost of ~8%. If it is assumed that a module constitutes 50% of the initial investment in Equation 2, then the reduction in LCOE or $kWh is ~4% (omitting the influences from financial loan, discount rate, insurance, O&M costs, etc.). In the case of multicrystalline solar cells, only with those solutions listed in Table 2 can diamond wire wafer be used in solar cell production; this introduces some complexity in the production line.

For comparison purposes (and omitting the influences from financial loan, discount rate, insurance, O&M costs, etc.), a reduction in $/kWh of roughly 7% is estimated through the use of advanced passivation of solar cells, such as p-PERC (Fig. 6). From Equation 2, an increase of ~1.5% in solar cell efficiency corresponds to a reduction of ~8% in initial investment. The increase in manufacturing cost (for example resulting from passivation equipment depreciation) is considered to be 2% $/W for a module, or 1% for the initial investment in Equation 2.

No.	Solutions	Cell efficiency	Cost	Sensitivity to wafer process	Market
1	RIE (reactive ion etching) (Dry black Si: wafer surface is bombarded with directional reactive ions to form the texture)	+0.5–0.8%	High ~$2m/line	Not sensitive	High efficiency
2	MCCE (metal catalyst chemical etching) (Wet black Si: Ag, Cu ion-assisted etching to form nano-deep holes. Texture is formed after widening of the holes)	+0.3–0.6%	Low ~$0.5m/line	Sensitive to - grain orientation	Main-stream market
3	Additives (Direct texturing process)	–0.2~0.05%	Zero	Sensitive to - slicing damage	Low cost

Table 2. Comparison of three texturing technologies for diamond wire wafer slicing.

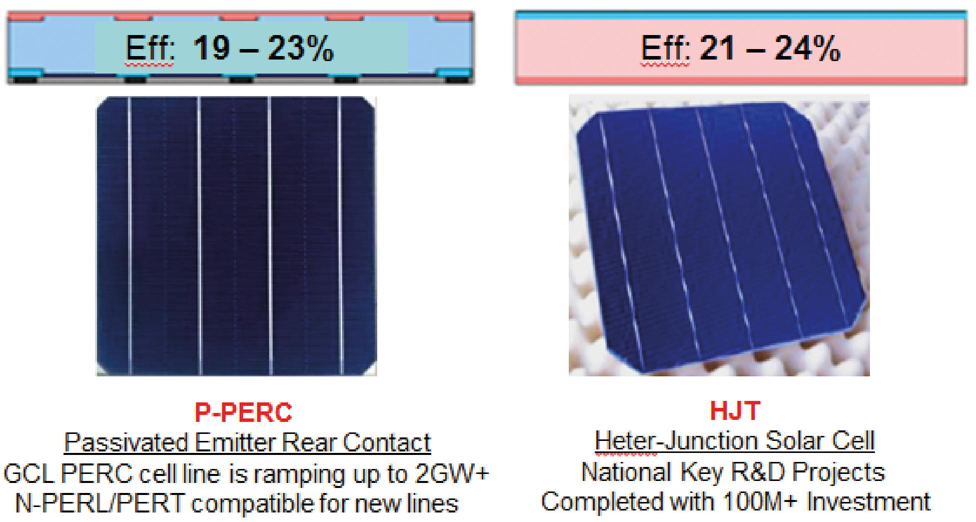

Figure 6. Examples of solar cells with advanced passivation: p-type passivated emitter rear cell (p-PERC) and heterojunction cell (HJT).

An additional advantage of advanced passivation is that the open-circuit voltage of a solar device is improved, such as in the case of PERC. This translates to the optimization of the temperature coefficient of a solar module. For an improvement of 0.02 in the temperature coefficient, the electricity output can be increased by 1% at an environment temperature of 75°C; with reference to Fig. 5, this represents an improvement in the system PR.

From the above analysis, the diamond wire case addresses mainly a $/W cost reduction for the module. In the PERC case, however, not only is there a reduction in $/W, but also the system performance is improved. Nevertheless, a reduction in $/kWh by more than 10% through the use of a single technology would appear to be an extremely difficult task.

An example of the one-stone-three-bird approach

In this section, the third factor that has an impact on LCOE – the lifespan – is considered with reference to GCL's white glass–glass (WGG) module. The reduction in $/kWh for this type of module and its solution packages is estimated to be ~20%.

The advantages of a glass–glass (GG) module, well known in the solar industry [7,8], include:

- Five (or more) years' additional performance warranty (30 years vs. 25 years)
- Lower year-to-year degradation (0.5%/year vs. 0.7%/year)
- Resistance to PID (potential-induced degradation)
- Resistance to power loss caused by dust/snow accumulation
- Lower operation temperature
- Resistance to hot-spot effects, and fireproof properties
- Resistance to microcracks and snail-track defects
- Resistance to friction from airborne sand
- 1,500V system voltage

Most of those advantages will already have been reflected in the commercial terms of the product.

As shown in Fig. 7, the degradation of a standard module over 25 years is 100%, 97.5%, 96.8%, 96.1% ... 81.4%, 80.7%. Here, the degradation is 2.5% for year one, mainly due to boron–oxygen (B–O) effects, etc. in the solar cell; for year two onwards, the degradation is 0.7% because of the packaging materials, etc. In comparison, the degradation of a GG module over 30 years is 100%, 97.5%, 97%, 96.5% ... 86%, 85.5%, 85%, 84.5%, 84%, 83.5%, 83%; the degradation in this case is 0.5% for year two onwards. Glass is a better packaging material than polymer materials in terms of stability.

A GG module is expected to produce ~21% more electricity as a result of its longer lifespan and lower degradation rate. With reference to Equation 2, an increase of 21% in total energy production in the denominator leads to a decrease in LCOE of 17% (with simplifications of the problem, where financial loan, discount rate, insurance, O&M costs, etc. are not considered).

It is common for no frame to be used in a GG module design; as a consequence, a glass–glass module will be not be susceptible to PID, since this type of degradation is believed to be caused by the potential difference and the short distance between the frame and the solar cells. Moreover, dust or bird droppings usually accumulate along the standard Al frames, causing shading as well as an increase in temperature. For a no-frame glass–glass module, however, dust, bird droppings, or snow in winter can be removed by wind-blowing, gravitational-sliding, or rain-washing effects. In addition, because air can flow more freely and quickly beneath the modules, the temperatures within the modules are lower. As a result of these anti-dust and low-temperature effects, a GG module will increase its electricity output by another 3%.

Because of the mechanical strength and physical properties of glass, a GG module is resistant to microcracks. In fact, lab experiments have been carried out to show that even a person standing on top of a GG module will not cause microcracks, whereas they are easily caused when a normal backsheet module is stepped upon. Glass also has a low water vapour transmission rate. The anti-microcrack and anti-vapour properties prevent the forming of other defects, for example snail-track defects. A GG module is also resistant to hot spots as well as being naturally fireproof. In desert environments, a GG module also demonstrates high resistance to friction from airborne sand.

Last, but not least, because of the excellent isolation properties of glass, the GG modules from GCL are 1,500V voltage ready; this increases the string length by 50% compared with a 1,000V system, further reducing the cost of initial investment (fewer inverters, combiner boxes, cables, etc.) It is estimated that the 1,500V voltage system also helps to increase the power

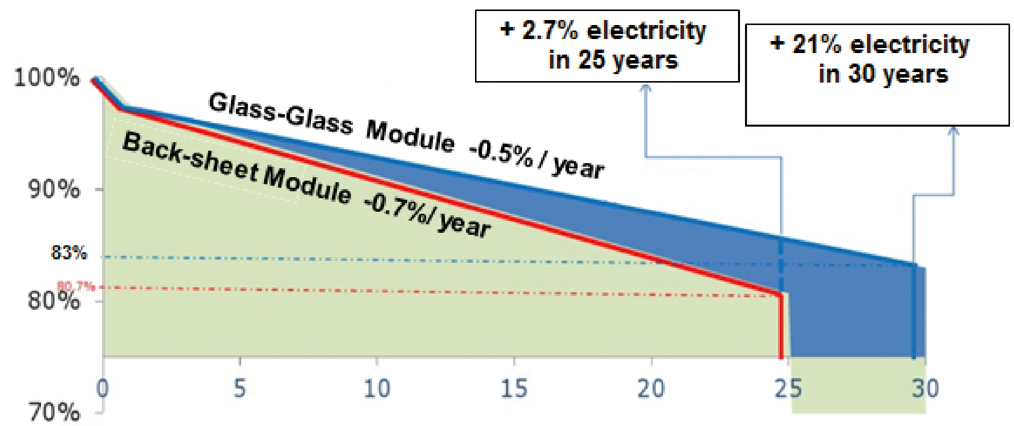

Figure 7. Comparison of the electricity output of a normal backsheet module and a glass–glass module. The degradation value of 0.7% or 0.5% will be specified in the manufacturer's warranty.

output by 1–2% as a result of lower energy losses.

In the case of a GG module with the same $/W cost as a normal module, the LCOE cost reduction is ~ 20% for the GG module (neglecting influences from financial loan, discount rate, insurance, O&M costs, etc.); this is extremely significant in terms of LCOE cost saving.

In the real world, however, the market share of GG modules is only 2–5%, which seems contrary to expectations. Why so small? Three reasons can be identified:

1. The $/W cost is high for a GG module (because of transparency).
2. The installation method is not optimized against breakage.
3. The $/kWh cost is high for a GG module (inadequate system design).

1. Reduction of $/W cost: GCL's white GG design

Transparent GG (TGG) modules are widely used in building-integrated PV (BIPV) as semi-transparent walls, windows or roofs. Because of the losses of light energy, mainly between the solar cells in a TGG module, the $/W cost for a TGG module is ~2–20% higher than that of a normal module. This value depends on the transparency of the TGG module: the higher the transparency, the higher the $/W cost.

> "A WGG module produces at least 5W more power output than a TGG module, while its $/W cost is comparable to that of a standard backsheet module."

The structure of the WGG module developed at GCL is shown in Fig. 8: from top to bottom, glass, transparent EVA, solar cells, white EVA/POE/glaze, and glass are layered one by one. The white EVA (or POE, or ceramic glaze) is used as a reflector to guide the light into the module. White EVA has a better reflection rate than a normal backsheet; instead of a power loss, there is a power gain through using the WGG module design. A WGG module produces at least 5W more power output than a TGG module, while its $/W cost is comparable to that of a standard backsheet module. The first problem has therefore been addressed.

2: Installation optimization: GCL's patented method

Fig. 9 shows the most common installation method for a GG module.

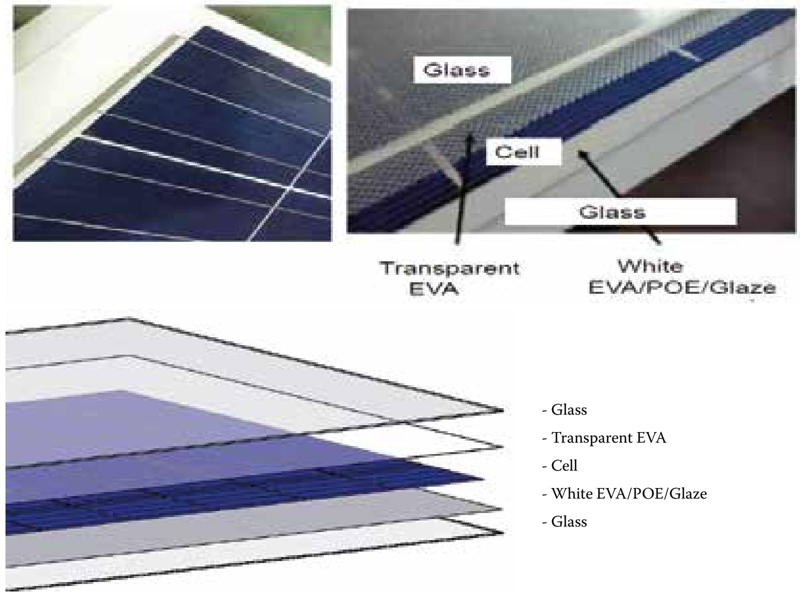

Figure 8. Layered structure of a white glass–glass (WGG) module.

The procedure is simple and convenient for the module manufacturers, but there are some shortcomings:

1. The method is not foolproof: any mistake in installation (e.g. the metal presser directly touching the glass) will lead to glass breakage.
2. Neighbouring modules impinge on each other: if a broken module on the left side drops, the clamping strength is lost for the module on the right side. One broken module can lead to module breakages in the same row.

Fig. 10 shows the patented GCL installation method. The core of this innovation is a module with a metal installation base, which is attached to the GG module by structure glue. There is no stress from metal parts pressing on the side edges of the glass. The installation base is fixed to the cross beam by a fixer; any unevenness of the mechanical stress will be applied only to the regions between the metal installation base and the fixer.

The rubber fixer in the graph is optional and not functionally required. The GG module is safe by design. The new design (Fig. 10) passed a 6,000Pa mechanical loading test for the horizontal installation. The new design also speeds up installation and saves labour, because there are fewer installation steps and a lower level of skill is needed.

Another possible solution is to use the back-side hook concept in a GG module, a technique that is also widespread in the industry. As shown in Fig. 11, the method serves well if there is a good fit between the beam

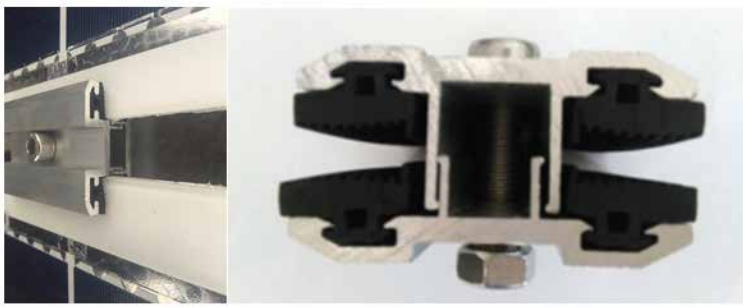

Figure 9. The standard clamps used in common GG installations. This is not a foolproof design, and appropriate skills for proper installation are necessary.

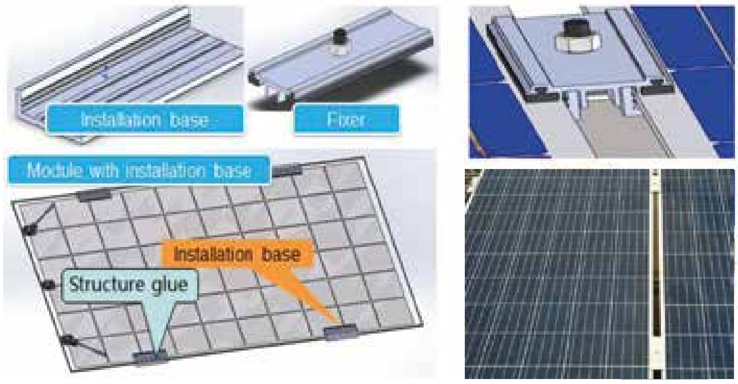

Figure 10. The GCL patented installation method. This foolproof design eliminates breakages resulting from stress to the edges of the glass, as well as increasing the speed of installation at the same time.

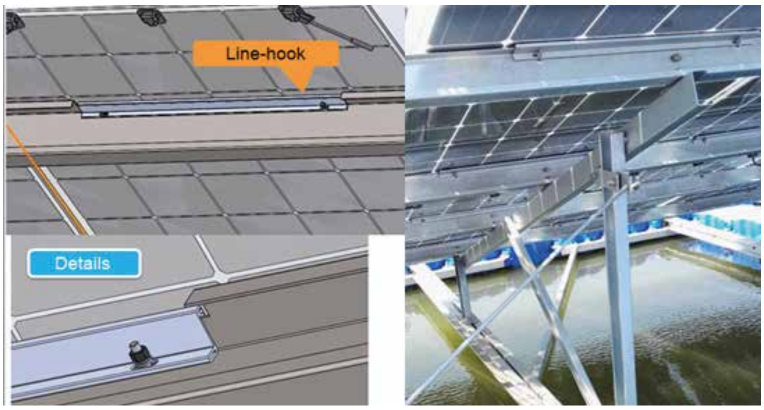

Figure 11. The installation of a GG module by the line-hook (back-side hook) method.

design and the back-side hook module. In the case of any misalignment or changes in the relative position of the beam and the hook, however, the difficulty of installation will increase. The installation using a back-side hook requires the employment of workers with more skills; in addition, this method could not in future be applied to bifacial modules. The GCL-patented GG module with an installation base is therefore considered to be the best solution for tackling the second problem that prevents the GG module from dominating the market.

3. Reduction of $/kWh cost: GCL's system design

There is a natural link between the first and third reasons for the small market share of GG modules. The TGG solution is generally requested by end users, especially for agriculture-related applications, where a certain degree of transparency is necessary for the plants or animals beneath the solar module roof. If the transparency on the module side is provided using the TGG solution, however, the $/W cost and the $/kWh cost are higher.

A fitting solution is to provide the transparency through a systematic combination of a WGG module and a light-splitting plate (LSP), as shown in Fig. 12. First, the WGG modules and LSPs are arranged in an alternating sequence in order to provide a certain degree of transparency. The mini-structures in the LSP guide the light so that it is evenly distributed. Since different plants and vegetation have different light-saturation and light-compensation points, the system design should take these factors into account. LSPs can be constructed using cheap acrylic materials, and so they cost much less than modules.

The combination of the WGG module, the GCL installation method, and the LSP design of the GCL system is a promising solution package for boosting the prevalence of GG modules in the near future. Table 3 summarizes $/W and $/kWh cost-reduction comparisons of diamond wire wafer, advanced passivation and GG modules; it clearly shows that WGG proves superior from a $/kWh point of view.

"The combination of the WGG module, the GCL installation method, and the LSP design of the GCL system is a promising solution package."

Future design outlook

In order to further reduce the LCOE of a solar power system, more work needs to be done in this direction. One line of investigation, for example, is the use of half cells: the GCL twin module is able to reduce the internal operating joule loss by 75%. An increase in electricity energy output of 2–5% was observed in GCL's experimental solar system set-up on hot days.

In another example, n-PERT bifacial solar cells can increase the electricity energy output by 5–20% under certain conditions, where the back-side reflection of light can be properly utilized. Other examples include the 96-cell supersize module for tracking applications, 3,000V high-voltage modules, and high-density modules, to name a few.

Future innovations may be summarized by separating them into the following categories:

1. System power output optimizations, including trackers, lower concentration design, bifacial cells and module design, 1,500–3,000V systems, smart modules, complementary multiple-energy source systems, etc.

2. Cell efficiency improvement, such as p-PERC, n-PERL, n-PERT bifacial cells, TOPCon cells,

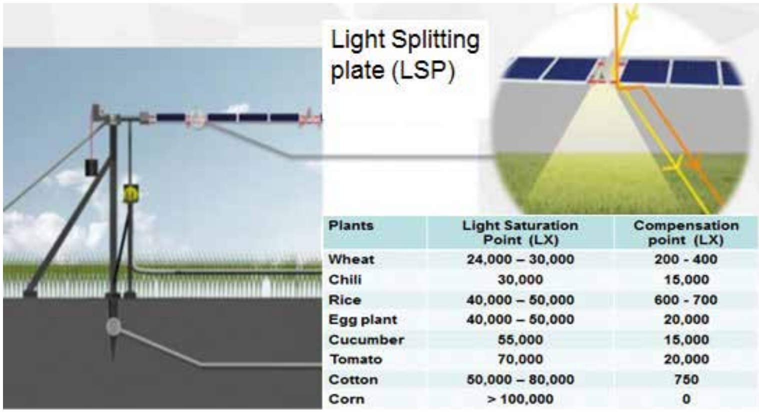

Figure 12. Schematic of a GCL white glass–glass module and light-splitting plate design. Examples of the light-saturation and light-compensation points for various plants are listed [9].

Category	$/W	$/kWh	Dominant factors
Diamond wire	8% ⇩	4% ⇩	Si materials saving
Advanced passivation	2% ⇧	6% ⇩	Cell % efficiency increase
TGG module	2–20% ⇧	10–20% ⇩	Lifetime, and power output
GCL WGG + LSP	2% ⇩	20% ⇩	Lifetime, and power output

Table 3. Changes in $/W or $/kWh for different techniques compared with the diamond wire baseline. (To simplify the problem, the LCOE calculations in this table omit the financial load cost, discount rate, O&M costs and insurance costs [3].)

hydrogenation, and Si/perovskite tandem cells, etc.

3. Module efficiency improvement, including half-cell size modules, high-density modules with 1/3, 1/4, 1/5, 1/6 cell sizes, optical engineering of the modules, and Si/CdTe/perovskite tandem modules.

4. Material cost saving: diamond wire with 35µm diameter using new metal materials, thinner wafers of 100µm thickness, as well as kerf-less direct wafers, etc.

5. Special modules that are designed for different applications, especially for different locations or different climates.

6. Last, but not least, the reduction of O&M, insurance and financial costs is crucial for LCOE reduction.

Because of the limitation on solar cell efficiency, however, the improvements that are seen in the semiconductor or software industries by an order of magnitude (i.e. 10 times better) are not possible in the solar industry. Since solar energy is all about cost, it is still necessary to use a one-stone-three-bird approach for reducing the LCOE. The good news is, most solar technologies are compatible with each other: for example, the WGG module is well suited to PERC, half cells, n-type cells, and bifacial cells (white only in between the cells), as well as to high voltages of 1,500–3,000V. Given this, the authors believe that the one-stone-three-bird WGG module should prove superior in the near future.

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