



## Counting the true costs

Every incremental improvement manufacturers make can lead to the extra edge over competition. There are many ways of achieving this goal and **Simon Jelley** from **42 Technology** discusses how they helped **Circadian Solar** look at their overall operating process and how system-wide cost analysis has helped maximise their solar competitiveness

Solar installations need to be cost effective throughout the entire system to ensure they are competitive in delivering energy at the market price. The goal of the solar industry is cost parity – being able to provide energy at the same price or lower than the cheapest suitable alternative source of energy for a particular need.

This milestone was achieved many years ago for satellites due to the excessive cost/kg for space launch. The landmark cost parity against off-grid diesel generation has already been reached with solar now the cost effective option, increasing its credibility alongside traditional energy sources.

All eyes are now looking towards the next major goal: cost parity with grid power, and it is not that far off either. Energy prices continue to rise steeply with increasing fuel costs, UK energy supplier Scottish Gas announced a 19% increase in residential gas prices in June with other companies expected to follow, while developments steadily make PV generation a cheaper option.

Feed-in tariff reductions and scheduled depressions, not just in the UK but across Europe indicate that the solar industry is already delivering economies of scale, efficiency improvements and other cost-reduction measures.

Cost parity is becoming a reality, and the solar industry is bracing itself for the boom that this coming of age will bring. It is clear that as “if” becomes “when”, those involved early are in for the greatest returns. But it is unlikely there will be a distinct ‘Parity Day’, when solar suddenly becomes the cost effective option to meet the world’s growing energy needs because there are so many different factors varying across the globe.

This article describes the pressure for cost reduction, and how analytical modelling can be used to achieve cost reductions. Four important improvements are explained, based on some work that 42 Technology carried out for Circadian Solar’s on their concentrating photovoltaic (CPV) solar technology: accepting a wide spacing of solar arrays to maximize collected energy; using surplus modules to allow for reduced output due to failures in harsh environments; using low cost, thermally conducting aluminium components to dissipate the heat and maintain performance over life; and ensuring optical alignment with innovative technology.

### Achieving grid parity

The attainment of grid parity will be strongly linked with location as it is so sensitive to local climate, latitude and local grid power price. The boom in solar that will follow grid parity is likely to appear first in tropical sunny regions before spreading into progressively more northern and cloudier regions as the costs drop relative to traditional energy sources. For example, PV parity with grid prices has already been reported in Hawaii where the climate is sunny and imported fuel expensive.

Attainment of parity is also affected by the economic environment. As with all ‘no fuel’ power generation, there is a relatively high initial capital requirement, followed by relatively low running costs compared with fuel burning options, which is where the payback comes. Economic viability has to be assessed by comparing the life costs against the total energy generated, with the resulting cost per kilowatt-hour (kWh) figure being compared with a more traditional “grid” price.

It is however very important to include adjustments for the time value of money because the benefits are in the future, whereas the costs are accrued up front. To attract investment the installation needs to offer a return that is competitive with the rest of the market, and here one thing is clear, the lower the cost per kWh, the more investors will think the investment opportunity is bankable.

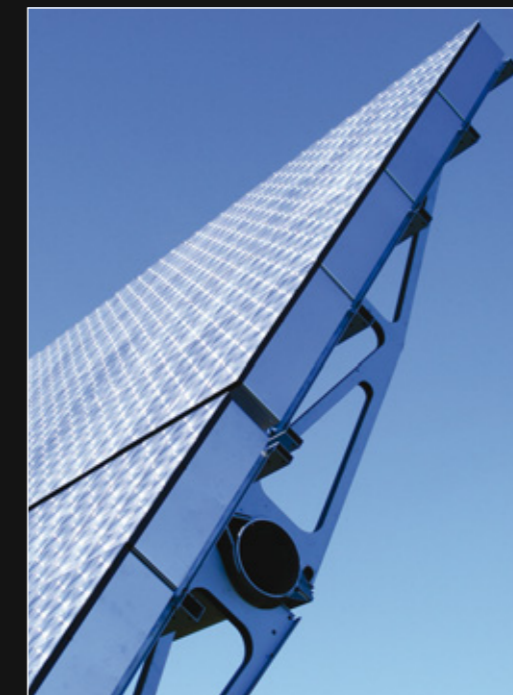
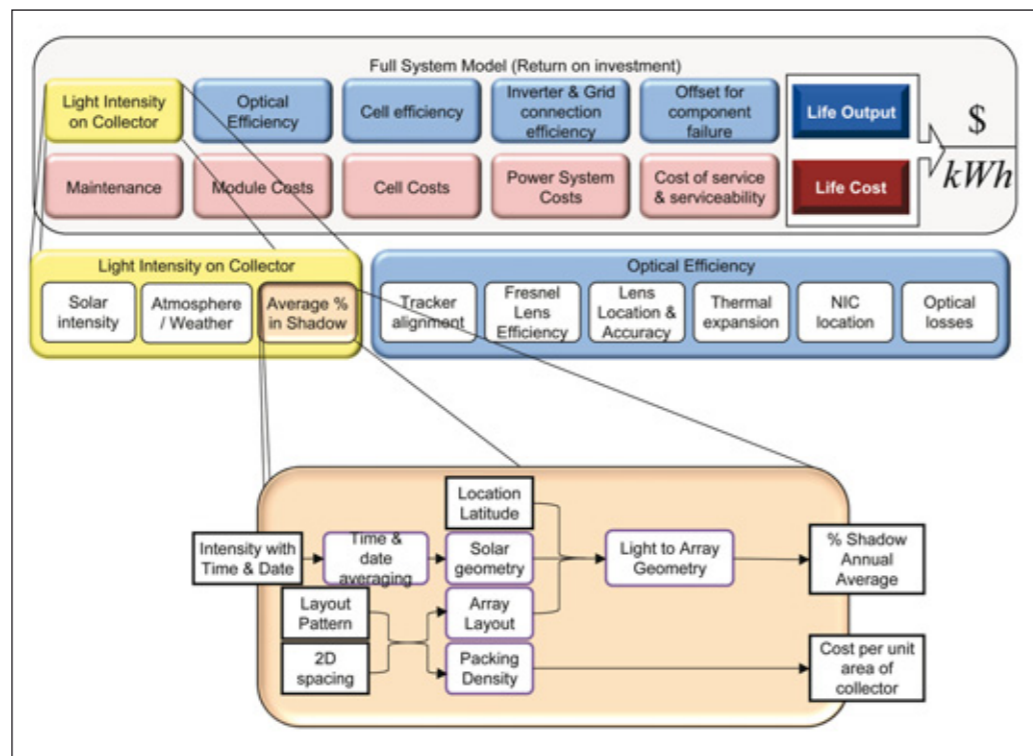


Figure 1: Highly efficient solar systems – shown here – are critical in securing grid parity from solar power but advanced mathematical modelling is also helping to clarify all the system interdependencies associated with the design and operation of large-scale farms

Figure 2: Using a modular block model allows early estimates to be refined by expanding to an appropriate level of detail as required. Top level estimates can be replaced with calculations based on detailed estimates, which can themselves be replaced with mathematical calculations, test data and proposed decisions



Cost analysis finds the right balance

A lot of recent focus has been put on reducing cell costs and increasing their efficiency but this is only part of the story. The costs are system wide, so logically the cost reduction should also be system wide. The entire system is a value chain, without which the cell would hold little value, and cost reduction and efficiency gains are not just limited to the cell. UK solar technology company Circadian Solar is championing a system-wide approach, often stating how much 'holistic design' is enabling them to leverage their efficient multi-junction cell technology.

To allocate development effort appropriately, cost and efficiency losses for the whole system need to be identified, mapped and prioritised to enable development focus on the areas of greatest potential gain. Identifying key sources of costs and losses can also highlight easy wins, where a simple change can significantly boost performance.

A block model of the system is a very powerful way of processing this information simply, where top level effects of any proposed changes can be seen quickly, aiding design decisions throughout the development. The modular nature of the block model allows the system to be sketched out with top level estimates during the early design, and detail to be added later. As the block model shows the relevant interactions of any changes, not only can the effects be visualised in percentage terms without the need for overly accurate first estimates,

but also it is immediately clear which factors have significant sway on the outcome. Several important factors impacting on the cost-benefit analysis are addressed below, with focus on their implications for design and where to assign development effort. These are drawn from and discussed in the context of the recent work 42 Technology completed for Circadian Solar but the points raised are general and are intended to be broadly applicable to solar, rather than being specific to this CPV system.

Spacing collector arrays

Models also allow computation of complicated interactions that are difficult to estimate, while allowing easy changes to other variables. For example, the effect of collector array spacing on the output yield in a CPV farm is a complex function of the solar geometry at the latitude of the site and the layout of the arrays.

To assess the effect, the proportion of collectors that are in shadow must be averaged across all times of day and over the year. Once we have a figure for the proportion of collector area in shadow averaged over the year we can simply treat that area as 'waste'. This allows us to optimise the spacing using the modular model approach. The cost per unit area of collector is defined elsewhere in the model, so we can associate a cost to the wasted collector area in dense packing densities.

Similarly, we can input land costs per unit area giving a cost function for sparse packing densities

then try different spacing layouts with the arrays to optimise the amount of unshaded collector area; in other words, the fraction that provides income, per unit cost, where the cost of all the collector area and land area is included. Optimum spacing is often surprisingly sparse and in one analysis for a particular site in the sunbelt region, the balance led to an optimal packing density (ratio of collector to land area) of about 13%. For this case, the cost saving on \$/kWh between 40% and 13% packing density was found to be up to 7%.

By using a measure of output yield per unit unshaded collector area we can then estimate the area of land required, the total area of collector and the costs associated with these. Using the model then shows how a cost reduction in the collector modules reduces not only collector costs, but also the cost of land, as the optimal spacing becomes denser. This may reveal some optimisations that might otherwise have been ruled out if assessed without considering which interactions are actually cost effective. As well as being able to adjust inputs based on changes to other parts of the system, the modular nature of the model allows more detail to be added once known. For instance, once the exact site has been identified weather data can be added to include known weather patterns. Weighting the shading average with data on sunshine levels by time of day and year gives an estimate of the average proportion of collector shaded during the sunny periods where revenue is generated.

Minimising the impact of potential failures

Many solar systems are installed in very aggressive environments with sand storms eroding exposed parts, strong UV from the bright sun and heavy thermal cycling between hot and cold. Enclosures are designed to give good protection from the elements but it is only cost effective to protect modules to a degree. So another challenge to system designers is what to do if the worst does happen and a module fails. It needs to be considered: when to replace failed modules, when not to, and whether it is worth designing the system to allow for easy replacement at all. There will always be a failure rate of collector modules, especially in large, multi-megawatt installations when the number of modules can be counted in hundreds of thousands. The way to decide whether it is cost effective to replace a failed module is similar to analysing how cost effective a complete system is in the first place because there are similar upfront costs and payback times. First, the upfront cost needs to be adjusted for the cost of raising money a length of time ahead of the payback – effectively the cost of delaying that return. Secondly, the payback must occur within

the remaining life of the installation. This immediately highlights that units should not be replaced towards the end of the solar farm's life. Although the cost of replacing modules is likely to be lower than installing the same number of modules as additional capacity at the start, additional upfront modules will be present for full life, and so are likely to achieve greater return on investment. Another difficulty with replacing modules is finding which module has failed. This means that it might well be worth installing additional capacity at the start and accepting a decline in output over time.

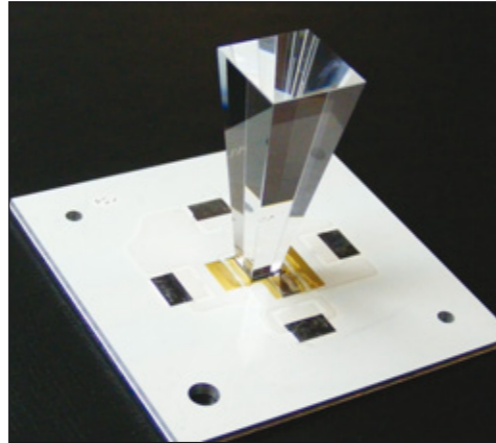
On top of this, if the systems are designed not to have replaceable modules, the complexity and cost of the module and the array holding it will be reduced, and with fewer seals and electrical connections the overall reliability may increase too. On the other hand, if the module costs are less significant than the rest of the system such as the tracker and inverter costs, then it may be worth designing modules to be changed quickly and cheaply to maximise use of the more expensive components.

A closely related design target is reducing the implications of potential failures, as some components are critical for an entire module to function, and a failure would prevent the whole module from generating power. In this case, it may be worth arranging the system in such a way that the implications of a component failure are reduced; for example by reducing the number of cells wired in series so that one local failure 'wastes' fewer connected cells in a string.



Figure 3: Deep drawn module with 30 cells is easily handled by one person to facilitate assembly and maintenance. 96 modules are mounted together on a tracker to make up each array

*Figure 4: Using a NIC as a secondary concentrator allows the system to be less sensitive to misalignment by being a larger target for the primary optics without need for a increasing the cell size. Total internal reflection channels light from the wider receiving surface to the cell attached to the narrower base*



Careful system-wide design needs to be followed to ensure best decisions based on the specific factors of the system in question. Once again, the modelling approach can help here by modelling failure rates associated with different options.

#### Module design for cost effective efficiency

Economies of scale are essential to deliver the \$/kWh figures needed for grid parity. Feed in tariffs are being used in many countries to help remove the 'chicken and egg problem' of not being able to mass produce solar collectors until sales are achieved that rely on the low costs of mass production in the first place. To maximise the savings from mass production, systems and sub components needs to be designed for manufacture and assembly. For example, modules for CPV systems are cheaper when arrays are designed to hold large numbers of identical units. But module size is inevitably a trade-off: too small and there is too much extra material adding cost and weight; too big and tolerances become an issue. Keeping the modules smaller prevents thermal expansion in the module lens from affecting optical alignment. This results in very large numbers of modules required for utility scale systems, demanding similar production techniques to those needed in the automotive or high volume consumer electronics sectors.

Heat dissipation is also a major issue for module efficiency, as temperature increases adversely effect cell efficiency, yet cells are obviously subjected to intense solar radiation! Being able to wick this heat away in a cheap, efficient manner can lead to real efficiency improvements.

#### Optical alignment for CPV systems

Low cost production is essential but precise optical alignment is also critical as the light needs to be focussed perfectly on the small cell to achieve high efficiency. Deep drawn aluminium was found to offer significant benefits as a module housing, as it

is cheap, thin, thermally conductive and lightweight, but also stiff enough to preserve optical alignment. Focussing can also be affected by tracker accuracy, wind flexure in the array structure, mounting alignment of the lens, cell and module, and the accuracy of the lens optics. The accumulated tolerance error from all the sources of misalignment cannot allow concentrated light to miss the cell, or the efficiency will rapidly deteriorate.

Equally, the system cannot be overly expensive. Bigger cells are easier targets but they add extra cost. Modelling tolerance stack and module costs shows that using a secondary, non-imaging concentrator (NIC) allows the perceived target size for the concentrated light to be larger without significantly increasing costs. The NIC works by using a large receiving surface to collect light from the lens with a relatively small acceptance angle, then by total internal reflection similar to that seen in fibre optics, the light is conveyed to the narrower end of the NIC, where it shines onto the cell.

#### Conclusion

This article has discussed several important technical considerations for reducing the cost of large CPV solar farms, and how modelling can be used to optimize the balance between cost and efficiency.

A full system approach is the most balanced and efficient way to ensure cost effectiveness, not just in solar but indeed in any complex system. To help with this, companies with specific expertise or technologies are increasingly bringing in consultancies to add value in other areas, or even leading a system-wide cost optimisation programme to improve competitiveness.

Solar PV system designers need not only consider the cost hierarchy of the cell, the module and the system, but also the top level of the installation to include all aspects of the life cost. Taking a total system view to apportion technical development effort along each link in the value chain makes it easier to identify the big wins within the system, with the aim of making the system more cost effective as a whole. This holistic approach is best to address efficiency, reliability, serviceability and cost reduction of manufacture, assembly and installation; all leading to a lower cost per kWh and therefore a more competitive system, getting solar ever closer to grid parity and a better clean energy option to meet future demand.