

What does CPV Need to Achieve in Order to Succeed?

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Abstract. The recent and dramatic reduction in flat-plate crystalline silicon (c-Si) technology has changed the competitive landscape for concentrator PV (CPV) systems. Three system cost targets are considered, $\text{€}1/W_p$ corresponding to the system cost of c-Si today, $\text{€}0.75/W_p$ corresponding to the likely c-Si cost in 2020 and $\text{€}0.5/W_p$ corresponding to a likely lower limit for c-Si in the long term. To compete successfully with c-Si, system efficiency needs to be raised from the present 30% to 40%, suggesting cell efficiencies of 50% and module efficiency of 44%. The module should be manufactured at an area cost below $\text{€}275/\text{m}^2$ which implies a packaged cell cost of $\text{€}3/\text{cm}^2$ and module + tracking cost $\text{€}190/\text{m}^2$.

INTRODUCTION

Cumulative CPV installation is presently estimated to stand at 360MW [1] and offers a particularly low embedded energy and hence low associated carbon emissions [2]. The technology enjoyed a strong rate of growth until a dramatic reduction in cost of crystalline silicon (c-Si) technology rendered much of the present technology uncompetitive. It is remarkable that the CPV industry broadly met expectations of analysts who have made cost projections [3, 4, 5, 6, 7, 8], but the technology has become victim of a collapse in the manufacturing cost of conventional crystalline silicon solar panels. To an extent, this was predicted due to the compounding effect that investment in a conventional technology has on costs [9] but the rate of cost reduction in c-Si technology is unprecedented. Since c-Si technology will set the standard price for PV electricity for decades to come, it is useful to explore where CPV can gain an edge over the incumbent c-Si technology and identify some of the broad technical and financial targets that need to be met in order to regain traction in the market.

SYSTEM COSTS

The costs of a PV system can be separated into two broad components, area related costs in units of $\text{€}/\text{m}^2$ and power related costs $\text{€}/W_p$. The expression below encapsulates the major costs for a CPV system and has been used to make comparisons against flat-plate, non-concentrating technologies in the past [5].

$$\begin{aligned} \text{System cost}[\text{€}/W_p] &= \frac{\text{Area cost}[\text{€}/\text{m}^2]}{\text{Rated power}[W_p/\text{m}^2]} + \text{BOS cost}[\text{€}/W_p] \\ &= \frac{\frac{\text{Cell cost}[\text{€}/\text{m}^2]}{\text{Concentration}} + \text{Module cost}[\text{€}/\text{m}^2] + \text{Tracking cost}[\text{€}/\text{m}^2] + \text{BOS cost}[\text{€}/\text{m}^2]}{\text{Standard Irradiance}[W/\text{m}^2] \times \text{System Efficiency}} \\ &\quad + \text{BOS cost}[\text{€}/W_p] \end{aligned} \tag{1}$$

The area related costs include the cell cost, module and encapsulation, tracking system (if required) and area related balance of system (BOS) costs (accounting for the PV mounting system, installation and cabling). The power related BOS costs (BOS cost[€/W_p]) account for the DC-AC inverter.

An up-to-date assessment of these costs was carried out in a survey of large, ground mount PV systems in Germany [10] and established that typical system costs of €1/W_p were routinely achieved using c-Si technology. These costs were further broken down into €0.55/W_p for modules, €0.11/W_p for inverters and €0.34/W_p for balance of system (BOS) costs. Further progress is expected in the evolution of these costs, so by 2020 the module cost is expected to drop below \$ 0.36/W_p [11] (€0.32/W_p¹) while inverter costs for large installations (> 500kW_p) are projected to drop to €0.06/W_p.

Some useful boundaries can be set by considering the likely evolution of a c-Si system prices. Figure 1a shows contours of fixed system cost as a function of area cost and system efficiency under the standard unconcentrated irradiance of 1000W/m². The area cost is plotted on a log scale to reflect the remarkable recent reduction in installation cost from many hundred Euros per square metre and system costs in excess of €4/W_p, to the present 2015 value of €1/W_p corresponding to €135/m² at a system efficiency of 15%. Looking towards 2020, a possible, yet aggressive scenario for c-Si could see the system efficiency rise to 17% and area costs drop to €120/m², resulting in a system cost of €0.75/W_p. Much further into the future, and as a likely limit for the present single junction c-Si technology, a system cost of €0.5/W_p might be achieved with a system efficiency of 23% and area cost €100/m².

When facing such low manufacturing costs, the key advantage that CPV systems holds is system efficiency. Figure 1b shows an enlargement of the system cost contours plotted on a linear horizontal axis to highlight the area costs that need to be beaten if CPV is to become financially attractive over c-Si by 2020. Present (2015) commercial CPV systems can attain system efficiencies of 30% and would therefore need to be manufactured below €275/m² to match today's large area ground mount c-Si system costs (€1/W_p). By 2020, the area costs would need to drop to below €210/m² to match the likely c-Si system costs and €130/m² to match the ultimate potential for c-Si. Only a couple of years ago, CPV systems were promoted with area costs of \$597 – 654/m² [7] (€537-589/m²), but these now need to be halved for CPV to become competitive with c-Si today and undergo further cost reduction to keep up with the relentless reduction in c-Si costs in the future.

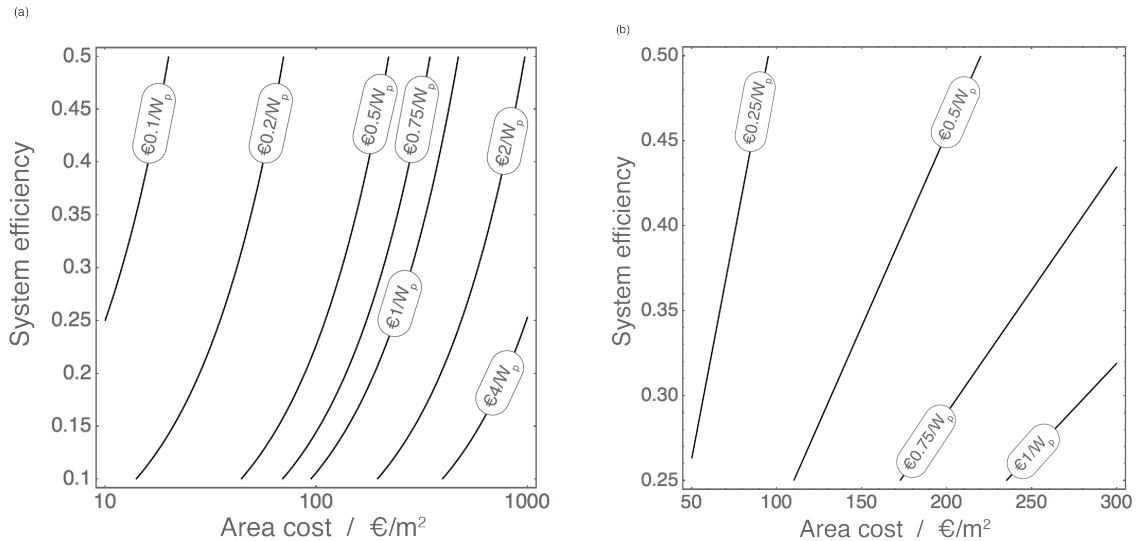


FIGURE 1. Contour plots of system cost [€/W_p] plotted as a function of system efficiency and total area cost[€/m²]. (a) shows an expanded, logarithmic area cost scale while (b) illustrates the system efficiency range relevant for CPV on a restricted linear area cost scale.

There remains an opportunity for reducing the manufacturing cost of CPV modules using highly automated and very high throughput assembly techniques, but the necessary investment will require significant market demand. To stimulate that demand, CPV systems need to achieve higher system efficiencies. Considering a notional 40% system

¹ Assuming the 2015 average exchange rate of €0.9/\$

efficiency target, manufacturing costs of $\text{€}275/\text{m}^2$ are permitted to achieve a $\text{€}0.75/W_p$ system cost, competing with the projected c-Si cost in 2020 and $\text{€}175/\text{m}^2$ to cross the $\text{€}0.5/W_p$ boundary that is considered in this paper to be the limit that c-Si technology can ever achieve.

CPV AREA COSTS

For a CPV system, the area costs are broken down into their component parts according to equation 2.

$$\text{Area cost}[\text{€}/\text{m}^2] = \frac{\text{Cell cost}[\text{€}/\text{m}^2]}{\text{Concentration}} + \text{Module cost}[\text{€}/\text{m}^2] + \text{Tracking cost}[\text{€}/\text{m}^2] + \text{BOS cost}[\text{€}/\text{m}^2] \quad (2)$$

It is instructive to consider how solar concentration and cell cost affect the overall area cost. Two scenarios are considered, one with a relatively high packaged cell cost $\text{€}10/\text{cm}^2$ representative of manufacturing in 2012 [7] and another lower estimate of $\text{€}3/\text{cm}^2$ reflecting cost reduction in a future high volume manufacturing scenario. To reduce the number of unknown variables, the area related BOS costs are assumed to remain fixed at $\text{€}55/\text{m}^2$ which is derived from the 2015 analysis of large ground mount systems [10] assuming a 15% system efficiency. This assumption is justified to an extent in that BOS costs in Germany are already among the lowest globally and the subsequent analysis in this paper shows that other terms dominate the area cost for all but the very cheapest CPV systems. Contours of constant area cost are plotted in figure 2 as a function of Module cost $[\text{€}/\text{m}^2] + \text{Tracking cost}[\text{€}/\text{m}^2]$. The pie charts show the relative share of the area cost for the particular area cost contour on which they are located and at a particular concentration (either 500, 750, 1000 or 1500X).

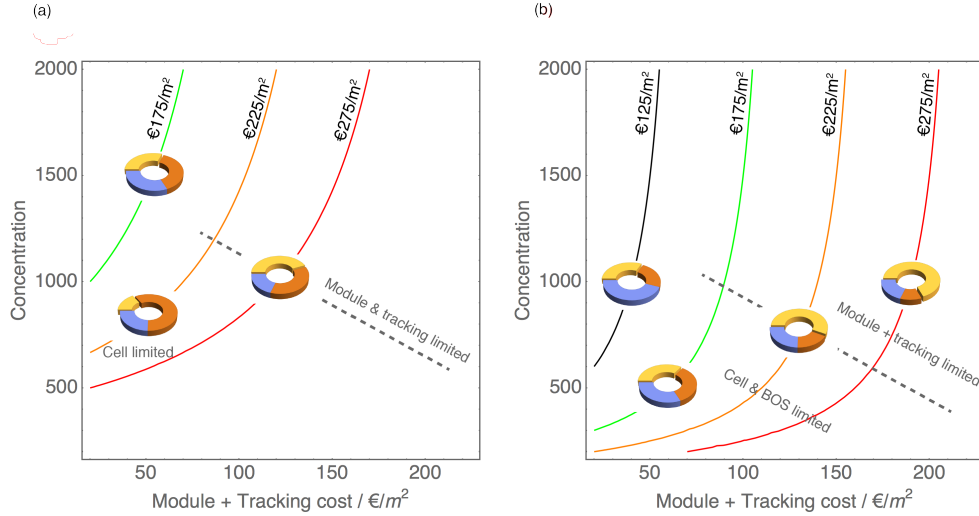


FIGURE 2. Total area costs $[\text{€}/\text{m}^2]$ plotted as a function of Module cost + Tracking cost and concentration for two packaged cell costs (a) $\text{€}10/\text{cm}^2$ and (b) $\text{€}3/\text{cm}^2$. The pie charts show the breakdown between Module + Tracking cost in yellow, Packaged cell cost in red and BOS cost in blue.

High Cell Cost Scenario

As discussed earlier, the $\text{€}275/\text{m}^2$ contour sets the parity point with c-Si for a CPV system with 30% system efficiency today, or a 40% system efficiency in 2020. In the high cell cost scenario ($\text{€}10/\text{cm}^2$) it is clear that at 500X concentration, the cell cost dominates and it is not possible to attain parity with c-Si without achieving module+tracking costs below $\text{€}50/\text{m}^2$ which would be extremely challenging under any concentration. Concentrations above 1000x are therefore required to compete with c-Si in this high packaged cell cost scenario, but these solar concentrations will

require higher optical and tracking precision which in turn will be challenging to achieve at such low module+tracking costs.

Low Cell Cost Scenario

The low packaged cell cost scenario ($\text{€}3/\text{cm}^2$) opens up more possibilities since a 500X system can now meet the ($\text{€}275/\text{m}^2$) area cost with ($\text{€}150/\text{m}^2$) module+tracking costs. Concentrations above 1000X in this low packaged cell cost are in almost all cases module+tracking cost limited and notably CPV can compete with c-Si in 2020 with a 40% system efficiency and module+tracking cost of ($\text{€}190/\text{m}^2$). It is worth noting that an unlikely situation where the costs become BOS limited occurs only at very low module+tracking cost. While the costs remain very aggressive, there are windows of opportunity for CPV in this low packaged cell cost scenario.

CELL, MODULE & SYSTEM EFFICIENCY

Remarkable progress has been achieved with cell efficiency, with both peak efficiency and concentration rising steadily towards 50% and 1000X respectively. Present quad junction solar cells have achieved efficiencies of 46% and have the potential to achieve efficiencies as high as 50% when fully optimised. Up-to-date values for cell, module and system efficiencies [1] show some narrowing of the cell and module efficiency. While achieving a cell efficiency of 50% is symbolic, it would enable present module designs to achieve system efficiencies of 40%. However, the highest efficiency CPV solar cells are also the most complex to manufacture, presently involving multiple wafers and/or epitaxial release steps [12]. As discussed earlier, high concentration incurs higher module and tracking costs, so any cell technology that can approach the low packaged cell cost of ($\text{€}3/\text{cm}^2$) while achieving 50% cell efficiency will provide significant relief to the considerable challenge of manufacturing a high concentration (likely > 750X) module+tracker at costs below $\text{€}150/\text{m}^2$.

It is important that the remarkable efficiency delivered by the CPV cell is carried through to module and system level. Narrowing the gap between cell and module efficiency while achieving very low area cost demands fast, precise and reproducible assembly which can be achieved with a high degree of automation. The present gap between module and system efficiencies is arguably acceptable, but more needs to be done to narrow the efficiency gap between most cell and module efficiencies. It also remains important to ensure high system efficiency over the lifetime of operation.

LEVELISED COST OF ELECTRICITY

The cost of electricity produced by a PV system can be estimated by calculating the Net Present Value (NPV) of the PV system costs and dividing by the discounted quantity of electricity produced, resulting in the levelised cost of electricity (LCOE). For a PV system, the majority of the costs are incurred during the construction phase, so the LCOE is expressed by equation 3:

$$LCOE = \frac{I + \sum_{t=1}^n \frac{M_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (3)$$

where I is the investment cost, M_t is the annual operation and maintenance cost, r is the discount rate, E_t the annual electricity yield and n is the number of years of operation.

To make a general calculation of LCOE, the annual electricity yield is estimated from a capacity factor such that $E_t = \text{Rated capacity} \times \text{capacity factor} \times 31.536 \times 10^3 \text{seconds}$. Here the capacity factor is primarily determined by the location and orientation of the PV collector, but also encapsulates mismatch and temperature related losses that would normally be accounted by a performance ratio. Degradation of the module is accounted for by applying a 0.5% reduction of E_t per annum, a O & M cost estimated at $\text{€}0.013/W_p/p.a.$, a discount rate of 8% and a 30 year operation is assumed. Under these assumptions, the LCOE was calculated as a function of system cost and capacity factor and shown in figure 3.

LCOE values of $\text{€}0.06/\text{kWh}$ are achieved with a system cost of $\text{€}1/W_p$ and capacity factor of 20% and reducing the system cost results in the LCOE becoming less sensitive to the capacity factor. For c-Si, capacity factors of 22% have been reported with single axis tracking c-Si panels [13]; at latitudes where CPV is relevant, single axis tracking increases the energy yield by approximately 20% [14, 16] thereby increasing a 20% capacity factor for fixed flat plate

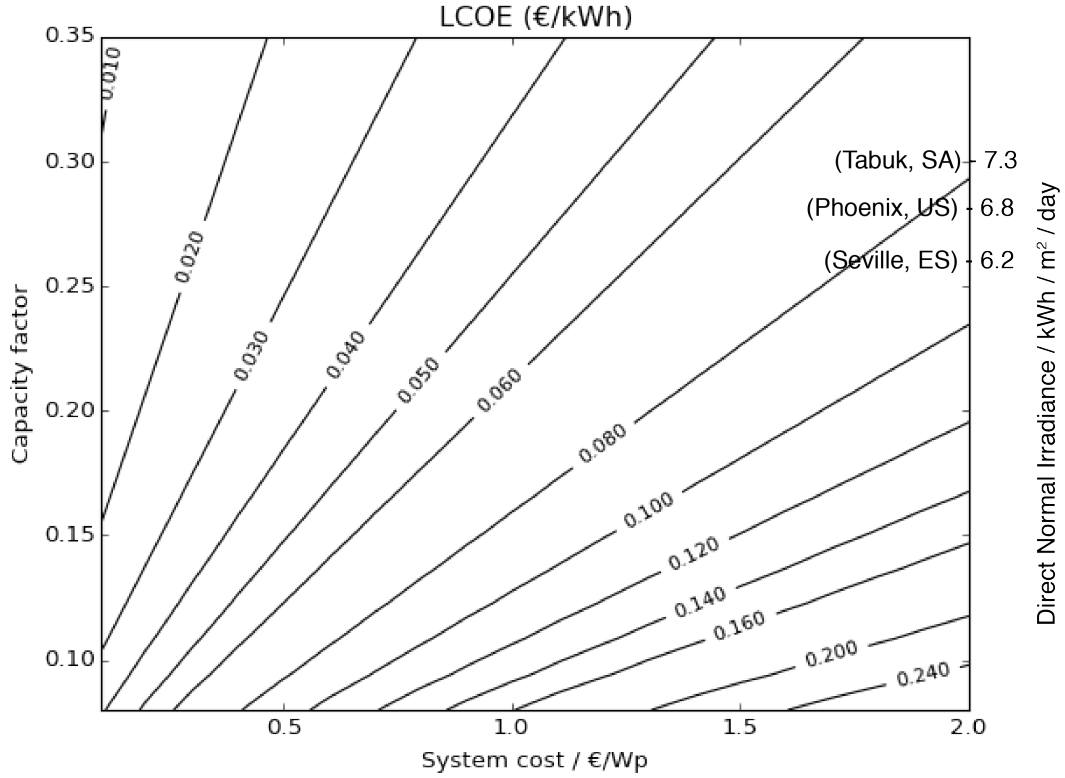


FIGURE 3. Levelised Cost of Electricity (LCOE) plotted as a function of capacity factor and system cost assuming: degradation of the module at 0.5% per annum, a O & M cost estimated at $\text{€}0.013/W_p/\text{p.a.}$, a discount rate of 8% and a 30 year operation.

to 24% for single-axis tracked modules [15]. An upper limit to the capacity factor for CPV systems is set by the direct normal irradiance at different locations and shown on the secondary vertical axis. Practical CPV capacity factors will be lower than these limits, but it is clear that CPV systems have the opportunity to operate at some of the very highest capacity factors possible with terrestrial solar radiation. III-V multi-junction CPV systems also have low temperature coefficients of power with values of $\beta = -0.00106/K$ in comparison to mono c-Si that has a temperature coefficient of $\beta = -0.0045/K$. At a cell operating temperature of 60°C , the temperature coefficient for a CPV system will provide a 2% premium in capacity factor over mono c-Si. CPV systems therefore hold some inherent benefits over fixed flat-plate c-Si in regions of high DNI, but much of the tracking advantage is lost if the c-Si panels are also tracked leaving the superior operation at high ambient temperature as the principle benefit at system level.

CONCLUSION

CPV technology can compete with c-Si silicon technology but must now achieve high system efficiencies while maintaining low area costs. c-Si technology is presently installed at $\text{€}1/W_p$ and is projected to drop to $\text{€}0.75/W_p$. Given an ultimate system efficiency limit for c-Si of 23%, the system cost for c-Si technology is unlikely to drop below $\text{€}0.5/W_p$. For CPV technology to compete successfully, it must provide a premium over c-Si. This is most easily achieved with a system efficiency of 40% and area costs below $\text{€}275/\text{m}^2$ (by 2020) or below $\text{€}175/\text{m}^2$ to remain competitive against c-Si in the long term. Achieving a 40% system efficiency suggests a module efficiency of 44% and cell efficiency of 50% at 1000X manufactured at a packaged cell cost of $\text{€}3/\text{cm}^2$.

ACKNOWLEDGMENTS

NJED gratefully acknowledges financial support through a Royal Society Industry fellowship. PS would like to thank the Grantham Institute Climate Change and the Environment and Climate KIC for a PhD scholarship. JN would like to acknowledge the Royal Society for a Wolfson Merit Award.

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