# Manufacturing cost and market potential analysis of demonstrated roll-to-roll perovskite photovoltaic cell processes

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## ARTICLE INFO

## ABSTRACT

Perovskite photovoltaic solar cells and modules can be manufactured using roll-to-roll (R2R) techniques, which have the potential for very low cost production. Understanding cost barriers and drivers that will impact its future commercial viability can beneficially guide research directions. Because processes, materials and equipment for manufacturing are still under development, it is difficult to estimate these costs accurately. We use a cost method developed to allow for uncertainty in the input assumptions to analyse three demonstrated R2R compatible manufacturing sequences and two potential optimised sequences. Using these novel methods, we have identified and quantified key cost barriers; high cost materials P3HT and PCBM, the use of evaporation for the rear metal deposition, and the transparent ITO coating. We project that technology developments in these key areas would halve the expected manufacturing cost to US\$37/m ± 30%. With 68% GFF, 10% PCE and a 3 year lifetime, such R2R perovskite modules would be competitive with existing flexible PV products in the market on a \$/W and power to weight basis. To compete with Si and CdTe in the flat plate PV market, PCE and lifetimes in excess of 15% and 15 years respectively would be required.

## 1. Introduction

The perovskite photovoltaic technology has seen extraordinarily fast progress over the past 5 years, with efficiencies for single cells now exceeding 20% [1]. One of the key advantages of this technology is its compatibility with flexible substrates. Di Giacomo et al. [2] summarise some of the recent work and potential advantages of perovskite solar cells made on flexible substrates. Advantages include the creation of flexible and lightweight modules, which could serve a different market to the fixed, long lifetime PV installations common today. Another important advantage is that it opens up the possibility of very high throughput manufacture, through the use of roll-to-roll (R2R) manufacturing, which can drive down manufacturing costs significantly.

R2R processing with flexible substrates is more challenging than processing on glass, as discussed by Schmidt et al. [3] Flexible substrates are less thermally stable than glass, restricting processes to lower temperatures. R2R processing also requires specific coating or printing methods that are compatible with high throughput and a continuous substrate. These constraints limit the material and process options, leading to difficulties - for example, finding a suitable back electrode that makes good contact but does not damage the deposited active layers.

Since low manufacturing cost is one of the key drivers behind interest in developing R2R manufacturing processes, it is important to ensure that researchers understand the cost drivers and any potential high cost barriers in the technology so that they are able to address and solve them while they are developing the technology. By focusing efforts in overcoming cost barriers whilst continuing to improve the cell and module performance, a technology would likely reach commercial viability more quickly.

In order to understand these cost drivers, it is necessary to estimate the future manufacturing cost of the technology. There is a broad spectrum of methods and level of detail that can be used to do this, and the optimum method will depend on the situation. At the simple end of the spectrum, a "back of the envelope" calculation can be done, focusing on a small number of most likely cost drivers. At the complex end of the spectrum, a very detailed bottom-up calculation can be done of all the manufacturing steps. A cost analysis that is less detailed runs the risk of overlooking an important factor, whilst one that is too complex can take too long or use too many resources to complete. This latter problem is particularly important when a technology is still in early development, and where significant changes are expected within a short time.
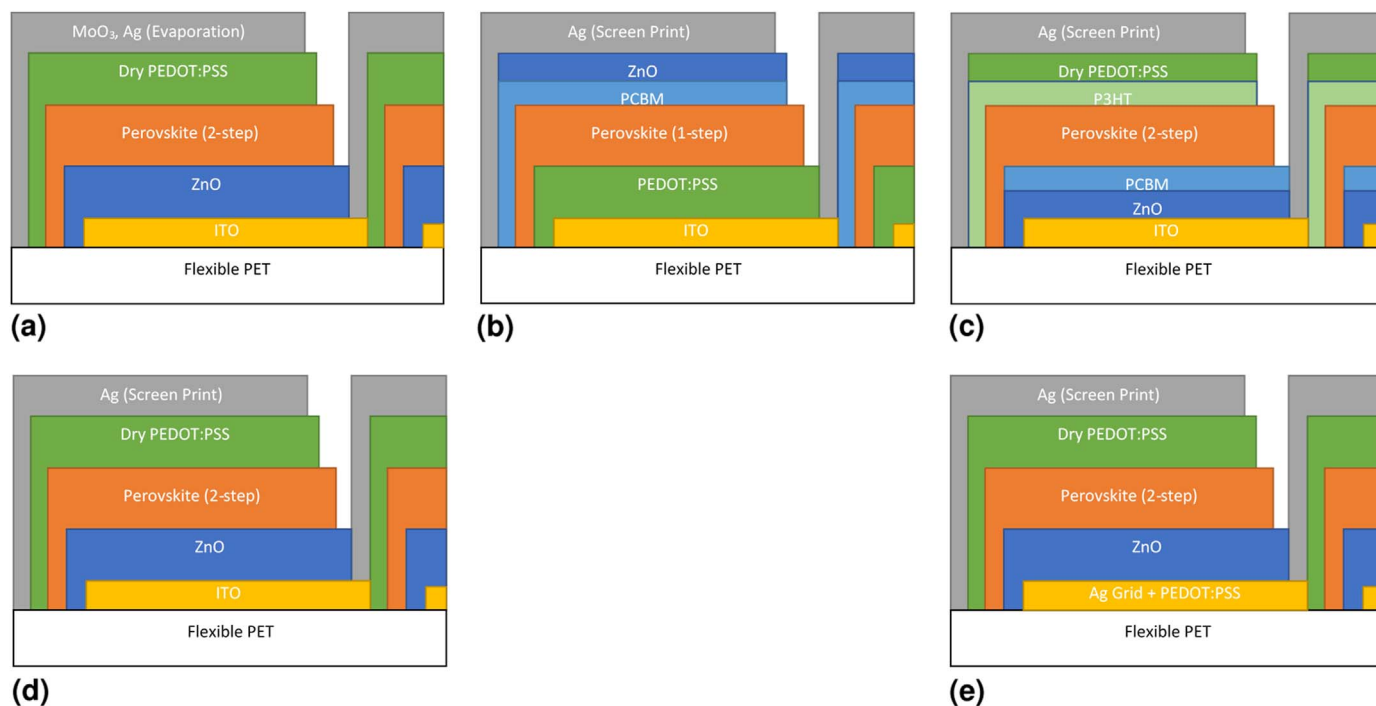
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**Fig. 1.** Structure of (a) Sequence A, the demonstrated CSIRO process (b) Sequence B, the demonstrated DUT 1-step process (c) Sequence C, the demonstrated DUT 2-step process (d) Sequence D, a combination of low cost active layers from Sequence A and low cost rear metal from Sequences B and C, and (e) Sequence E, the same as Sequence D, but with a Flextrode substrate replacing the ITO.

In previous work (Chang et al. [4]), we have reported a cost analysis methodology that is suitable for use on solar technologies that are not yet commercialised. It is on the more complex end of the cost analysis spectrum, being a bottom up approach that calculates the cost of every manufacturing step. As such, it reduces the risk of missing any important cost factors. It also allows for levels of uncertainty in each input datum that allows the analysis to be completed without requiring high accuracy in every input datum, thus significantly reducing the resources required to complete the analysis. In that work, we analysed a perovskite on glass (POG) sequence that had been demonstrated to produce a 100 cm$^2$ module [5]. This particular sequence used evaporated gold as the rear metal layer, and used a mask lift-off process to pattern a compact TiO$_2$ layer. The projected manufacturing cost of this sequence was very high at over \$300/m$^2$ because of the expensive gold rear layer. But with two projected process improvements, being the replacement of the rear evaporated gold layer with evaporated silver, and the replacement of the mask lift-off patterning process with a laser process, a much lower median cost of \$107/m$^2$ was expected.

Cai et al. [6] analysed two POG structures that had been demonstrated on single small area cells. The first demonstration reported by Chen et al. [7] was a low cost structure using TiO$_2$ and ZrO$_2$ and carbon as the rear contact, which addresses the issue of an expensive rear metal layer commonly used in perovskite cell fabrication. Chen et al. reported a peak efficiency over 13% on single cells of area 0.5 cm$^2$. In the cost estimate, Cai et al. assumed that this process could be scaled up to large modules with series interconnected cells as has been demonstrated with Dye Sensitised Solar Cells, and by making allowances for the different perovskite specific processes. They calculated a manufacturing cost of \$30/m$^2$. The second demonstration, reported by Wu et al. [8] was a higher cost process using PEDOT: PSS, PCBM and a vacuum deposited rear aluminium layer. Wu et al. reported a peak 18% efficiency with a single 0.1 cm$^2$ cell. Cai et al. assumed that this process could be scaled up to large modules of series interconnected cells using processes from thin film silicon production. Again, with adjustments to allow for the different perovskite steps, the manufacturing cost was estimated at \$41/m$^2$. These costs are much lower than that estimated by Chang

et al., due partially to the different processes chosen, but also, as pointed out by Song et al. [9], this analysis neglected some important material costs in the module fabrication.

Song et al. [9] examined the cost of manufacturing a POG module using a p-i-n structure, with low cost materials NiO and ZnO as the HTM and ETM, and sputtered Al as the rear metal. The selection of this structure was based on lab demonstration described by You et al. [10], showing a peak efficiency of 16% for an 0.1 cm$^2$ cell. Song et al. assumed that this sequence could be scaled up to large modules with interconnected cells using a similar process sequence to that used in other thin film photovoltaic module production. Some processes were changed to be more production compatible, in particular the replacement of spin-casting with screen printing which has much higher material utilisation, and the use of Al sputtering instead of evaporation. A manufacturing cost estimate of \$31.7/m$^2$ was obtained.

These previous cost analysis all considered perovskite cells produced on a rigid glass substrate. In this work, we apply the cost methodology outlined by Chang et al. to the state of the art R2R perovskite processing sequences. Consistent with previous work, we focus firstly on calculating the costs of the process as closely as possible to the demonstrated sequences, and then consider a number of potential improvements to address key cost drivers. We then consider the potential market niche for this technology and identify efficiency targets to be competitive with existing products.

## 2. Scope and method

### 2.1. Sequence definitions

A number of R2R processes for fabricating perovskite solar cells compatible with flexible substrates have been reported. A selection of these, with their processing details, are summarised in Table S1 in the Supplementary Material. From these, we have selected three initial sequences for analysis.

Heo et al. [11] of the CSIRO, report the demonstration of a high efficiency perovskite solar cell using R2R processing on an Indium Tin