The Impact of Transparent Conducting Electrodes on Tandem Solar Cell Efficiency

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Introduction

Tandem solar cells have emerged as the frontier of PV science enabling the deployment of solar modules with >35% efficiency[1]. Among all technologies, monolithic two-terminal (2T) perovskite–silicon tandems show promise in extending the performance of industry-standard silicon solar cells beyond their theoretical efficiency limit near 29%[2]. For example, tandem architectures integrating wide-bandgap perovskites have now demonstrated certified efficiencies exceeding 34%[3], with ongoing laboratory efforts targeting 37–38% performance. This rapid progress is driven by the potential of lead-halide perovskite top cells to leverage high open-circuit voltages, tuneable bandgaps, and thin-film compatibility. Together with mature crystalline silicon bottom cells, tandems offer an attractive path for high-performance, cost-effective photovoltaic deployment.

To guide such development, it is critical to model the practical efficiency limits of perovskite–silicon tandems by incorporating sub-cell level recombination, absorption, and optical coupling mechanisms. Allen et al. have recently presented an integrated multi-diode circuit framework to establish the efficiency limits of perovskite–silicon tandems[4]. They use experimentally derived sub-cell parameters, realistic external quantum efficiency (EQE) spectra, and detailed balance (radiative/non-radiative recombination) models to identify a practical efficiency target of 37.8% for 2T tandems [4]. Similar efforts in the context of crystalline silicon single-junction devices have revealed the essential role of carrier-selective contacts, band alignment, and optical management in approaching the intrinsic material limit near 28.6%[5]. These modelling frameworks have proven instrumental in identifying optimal absorber bandgaps, thicknesses, and passivation schemes.

However, current modelling efforts have largely overlooked a critical loss mechanism inherent to all monolithic tandem architectures: the optical and resistive losses induced by transparent conductive electrodes (TCEs). While optical modelling typically accounts for parasitic absorption and interference from multilayer stacks, the lateral resistance of TCEs—especially in bifacial or front-illuminated configurations—remains unquantified in most system-level models. Moreover, the geometric interdependence between TCE sheet resistance, finger spacing, and metal shading introduces trade-offs that fundamentally constrain the power output but are rarely captured in practical efficiency limit calculations.

This commentary presents a unified optical-electrical modelling approach to quantify the efficiency penalties introduced by realistic TCEs in 2T tandem solar cells made up by any two absorbers. I derive closed-form expressions for lateral resistive losses from sheet resistance and geometry and integrate these into a multi-diode equivalent circuit model solved using the PySpice simulation framework. Optical transmission losses are evaluated via the transfer matrix method for various TCE stacks, including the impact of antireflection coatings and sputter buffer layers. By coupling these effects with a geometry-aware generation model, I identify the optimal finger spacing for a range of TCE conductivities and transparencies and evaluate the practical efficiency ceiling as a function of TCE parameters. I used the widely reported properties for perovskite–silicon tandems as a benchmark, but the algorithm remains valid for a variety of technologies. The resulting model elucidates the underexplored but significant role of TCEs in limiting tandem performance and provides practical guidelines for TCE optimization in future device architectures.

A table of definition and units for all variables used in this article is included in Supplementary Note 1.

Resistive losses arising from TCEs

The resistive power loss due to the lateral current flow through the TCE at one side of a tandem solar cell is given by:

$$dP = I^2 dR \qquad \text{(Equation 1)}$$

Where *dR* is the resistance contributed by a *dx* section of the TCE through which current flows laterally towards the metal finger. **Figure 1**.a illustrates the tandem solar cell domain between two fingers, illustrating carrier flow in one half of the domain (Fig 1.a), and the dimensions of the domain (w, l, d). The resistance contributed by dx is given by:

$$dR = R_{sheet}^{TCE}.\frac{dx}{w} \qquad \text{(Equation 2)}$$

The lateral current flowing (I) inside the TCE is maximum at the edge of the finger ($x = \frac{l}{2}$) and decreases linearly to zero at the midpoint between two fingers ($x = 0$). Based on the reference axis x in **Figure 1**.a, it is calculated as:

$$I = J.w.x \qquad \text{(Equation 3)}$$

Where J is the current density produced by the solar cells in the area of interest, labelled with a red dotted-line box in **Figure 1**.b, and equivalent to an area = $w.\frac{l}{2}$. The total power loss can be found by integrating the incremental resistance losses from $x = 0$ to $x = \frac{l}{2}$.

$$P_{loss} = \int I^2 dR = \int_0^{\frac{l}{2}} (J.w.x)^2 R_{sheet}^{TCE}.\frac{dx}{w} \qquad \text{(Equation 4)}$$

$$P_{loss} = \frac{l^3}{24} J^2 w R_{sheet}^{TCE} = \frac{l^3}{24}\left(\frac{I}{w.\frac{l}{2}}\right)^2 w R_{sheet}^{TCE} = \frac{I^2 l}{6w} R_{sheet}^{TCE} = I^2\left(\frac{R_{sheet}^{TCE} l}{6w}\right) \qquad \text{(Equation 5)}$$

The effective series resistance loss contributed by one TCE is hence:

$$R_{s1} = \frac{R_{sheet}^{TCE} l}{6w} \qquad \text{(Equation 6)}$$

When a TCE is present at the front and rear it will contribute twice as much series resistance.

The series resistivity contributed by the TCE will be given by:

$$\rho_s = \frac{R_{sheet}^{TCE} l^2}{12} \qquad \text{(Equation 7)}$$

Optical transmission losses

The transmittance for a particular TCE was calculated using the transfer matrix method (TMM) following the implementation by Burkhard and Hooke[6], later ported to python by Mielczarek. The optical path is calculated assuming normal incidence into a stack of different materials, where transmission and reflection occur at each interface in the stack and optical absorption takes place in each layer. The theory behind this method is described in [7]. I used light incident from air (n=1), but it is also possible to account for incidence from a semi-infinite glass (pure SiO_2) or encapsulation (EVA of POE) media. A TMM approach remains valid for most perovskite devices, as they are fabricated on flat substrates, though I note that it is possible to account for a percentage of scattering by using the approach shown below for a textured silicon cell.

I first consider the TCE at the front, sun-facing side. The top perovskite sub-cell acts as the substrate and transmission is calculated through a stack comprising top-to-bottom:

1. an antireflection coating,
2. a TCE of choice,
3. a buffer layer of ALD SnO_2 traditionally required for perovskite absorbers to endure TCE sputter depositions,

4. an electron transport layer since p-i-n architectures with the electron transport layer (ETL) on the sun-facing side are the most popular in research. I use C60 as ETL following optical constants reported in [8].
5. a Cs-FA, lead, and mixed I-Br halide perovskite absorber. I choose the optical data reported in [9], and adapt it to produce an the n,k data of an arbitrary- bandgap perovskite (see Supplementary Note 2).

The AM1.5G light source originates in air and produces coherent interference in the ARC/TCE/buffer/ETL/Pvk interfaces. The weighted averaged transmittance (WAT) was calculated from the spectral light intensity transmitted (T_x) through the ARC/TCE/buffer/ETL stack as:

$$WAT = \frac{\int_0^\infty T_x(\lambda) * AM1.5G(\lambda) d\lambda}{\int_0^\infty AM1.5G(\lambda) d\lambda}$$

A circuit model accounting for optical and resistive losses

Following Anand's procedure, it is possible to lump the R_s originating from the TCE to the ideal diode model, describing the operation of the entire solar cell[10]. For a perovskite-silicon tandem solar cell, Allen *et al* have assessed the efficiency limits using a 3-diode model for both sub-cells [4]. Following their model, here I draw the complete circuit diagram as illustrated in **Figure 1**.b, lumping all contributions from TCE resistance inside the series resistance term (R_s). This circuit model leads to a system of 6 simultaneous equations (5 of which are implicit due to the diodes), describing the top and bottom circuit branches, the series resistance losses, and the perovskite defects losses (J_{0d} , R_d).

The overarching protocol of simulation has been included in supplementary figure S1. To evaluate the electrical performance of the monolithically integrated tandem solar cell, I implemented the equivalent circuit model using the PySpice simulation framework—a Python interface to the NGSpice circuit simulator[11]. The circuit was constructed using hierarchical circuit modelling, allowing flexible parametric sweeps over material properties, such as saturation current densities J_{0i}, recombination diode parameters, and resistive losses. I note here that such modelling approach is valid for any two solar absorbers, but I apply it to perovskite-silicon tandem cells due to their maturity and commercial relevance.

The model was solved under varying illumination and load conditions using DC operating point simulations. This methodology follows the previously reported practices for SPICE-based photovoltaic modelling, but extends them to accommodate tandem architectures and geometry dependent TCE loses in the series resistance term. The detailed sub-cell representations include:

1. Detailed balance radiative efficiency limits via a diode with n=1: $J_{01}\left[\exp\left(\frac{V}{1.V_t}\right)-1\right]$, where $V_t = k_B T/q$.
2. Intrinsic Auger recombination losses via a n=2/3 diode: $J_{0,2/3}\left[\exp\left(\frac{V}{2/3.V_t}\right)-1\right]$.
3. Recombination paths via a n=1 diode in both the Pvk and Si.
4. Enhanced SRH recombination in the Pvk via an n=2 diode ($J_{02}\left[\exp\left(\frac{V}{2\,V_t}\right)-1\right]$)
5. Enhanced defect recombination and resistance in the Pvk via an n=1 diode (J_{0d}) + resistor (R_d).
6. Shunt (R_{sh}) and series resistances (R_s) losses in both subcells, both internal and TCE-originated.
7. A photogeneration current via a short circuit current source $I_{sc} = w.\frac{l}{2}J_{sc}$.

The circuit solutions were calculated for a range of cell voltages (V_{Cell}) and the point of maximum power (V_m, I_m) is found to maximise $P_{max} = V_m * I_m$.

The dark saturation currents ($J_{0,1}$) from each cell were obtained based on the detailed balance limit proposed by Shockley and Queisser considering : (1) only the photons with energy greater than the bandgap are absorbed, (2) each photon with energy greater than the band gap generates only one electron-hole pair, (3) the system is

thermal equilibration with the surroundings and only radiative recombination takes place, and (4) no losses occur from ohmic transport inside of the cell and contacts, with the contacts being perfectly selective[12].

I combined the detailed-balance formalism with realistic values of External Quantum Efficiency (EQE) based on experimentally obtained absorption coefficients and optical models for both silicon and perovskite absorbers.

The modified, detailed balance dark saturation current is obtained from the blackbody radiation photon flux density at T = 300 K as:

$$J_{01} = q.\int_0^\infty \mathrm{BB300K}(\lambda) * EQE(\lambda)d\lambda \qquad \text{(Equation 8)}$$

Where the blackbody radiation photon flux density as a function of T is found via:

$$\mathrm{BB300K}(\lambda) = \frac{2\pi c}{\lambda^4}\frac{1}{e^{\frac{hc}{\lambda kT}}-1} \qquad \text{(Equation 9)}$$

The short circuit currents are given by the proportion of photons that are absorbed at each sub-cell. For the perovskite top cell:

$$J_{scP} = q.\int_0^\infty AM1.5g(\lambda) * EQE_P(\lambda)d\lambda \qquad \text{(Equation 10)}$$

AM1.5G(λ) is the wavelength-dependent Air Mass 1.5g spectral photon flux density, calculated from the spectral irradiance reported on standard ASTM G173-03, divided by the energy of photons at each wavelength.

Due to the nanometre scale thickness of the perovskite top cell, its EQE is calculated using the transfer matrix method as implemented in [6], with the absorption coefficient (α) calculated from empirically obtained ellipsometry data for perovskite solar cells, and let the perovskite cell thickness (W) be an independent variable.

All losses from light reflection or parasitic absorption can be lumped into a transmission ratio (T_x) that reduces the AM1.5g photon flux entering the perovskite top cell or silicon bottom cell. This makes it possible to calculate the cell efficiency from optical modelling of the antireflection and transparent conductor layers in different locations of the cell.

Similarly, for the silicon bottom cell, the short circuit current density is given by:

$$J_{scSi} = q.\int_0^\infty T_{x,front} * AM1.5G(\lambda) * \left(1 - EQE_P(\lambda)\right) * EQE_{Si}(\lambda)d\lambda \qquad \text{(Equation 11)}$$

Where reflection losses are again lumped into the percentage transmission ($T_{x,front}$), and the silicon sub-cell receives a filtered spectrum after absorption in the perovskite: $AM1.5G(\lambda)\left(1 - EQE_P(\lambda)\right)$.

The silicon EQE is calculated following the ideal expressions derived by Green for Lambertian light trapping with an ideal rear reflector in the bottom cell[13] , and an optical pathlength enhancement factor $Z_{(\lambda)}$:

$$Z_{(\lambda)} = \frac{2 + a\cdot(\alpha_{Si}.W_{Si})^b}{1 + a\cdot(\alpha_{Si}.W_{Si})^b} \qquad \text{(Equation 12)}$$

$$A_x = T_{x,mid}\frac{1-\exp\left(-2.Z_{(\lambda)}.\alpha_{Si}.W_{Si}\right)}{1-\left[\left(1-\frac{1}{n_{Si}^2}\right).\exp\left(-2.Z_{(\lambda)}.\alpha_{Si}.W_{Si}\right)\right]} \qquad \text{(Equation 13)}$$

Where A_x is the net absorption in the silicon substrate, n_{Si} is the real part of silicon's refractive index, α_{Si} is the wavelength-dependent absorption coefficient, taken here as a=0.935 and b=0.67 following Green's model, and W_{Si} the wafer thickness.

Equation 13 models light absorption accounting for ideal Lambertian surfaces at both the top and bottom, where light angle is randomized after each surface interaction. The numerator describes the fraction of light absorbed over an enhanced average path length of $2 \cdot Z_{(\lambda)}$ accounting for two Lambertian surfaces, top and bottom. The denominator accounts for light that might escape the cell after internal scattering: $1-1/n^2$ represents the escape probability based on statistical optics, reflecting the chance that a randomized ray falls within the escape cone defined by total internal reflection. The denominator thus reduces absorptance depending on how likely light is

to exit the cell before being absorbed. Overall, this treatment assumes perfect scattering at the front and rear surfaces of the silicon cell, which approximates the behaviour of pyramidal texturing in real devices.

The efficiency limit of a silicon sub-cell

I start by obtaining the 3-diode parameters that describe the ultimate efficiency limit that a silicon solar cell might be able to achieve using advance device processing a large scale. I use the formalism proposed by Black and McDonald[14], where a pseudo I-V curve can be drawn from knowledge of the implied open-circuit voltage vs implied current density (iV_{OC} vs iJ). These account for transport, intrinsic and extrinsic recombination losses as:

$$iV_{OC} = \frac{kT}{q}\ln\left(\frac{\Delta n*(N+\Delta n)}{n_{i,eff}^2}\right) \qquad \text{(Equation 14)}$$

$$iJ = J_{sc} - \frac{qW\Delta n}{\tau_{eff}(\Delta n)} \qquad \text{(Equation 15)}$$

$$\tau_{eff} = \frac{1}{\frac{1}{\tau_{int}} + J_0\frac{(N+\Delta n)}{W.q.n_{i,eff}^2}} \qquad \text{(Equation 16)}$$

where k is the Boltzmann constant, T is temperature, q is the electron charge, Δn is the excess carrier concentration, N is the dopant concentration, and $n_{i,eff}$ is the effective intrinsic carrier concentration (including bandgap narrowing), τ_{eff} is the effective lifetime, and J_{sc} is the optical generation current calculated as stated in Section 3.1. By varying Δn, it is possible to generate an implied curve of current density vs voltage, and find the maximum power point.

Following Black's calculation, I use the J_{sc} calculated with a full AM1.5g spectrum without perovskite filtering, reflection or parasitic absorption losses, using a measured silicon absorption coefficient [15]. The cell thickness (W) can be optimised by finding the trade-off between enhanced J_{sc} and increased R_{ser} originating from thicker cells. Supplementary Note 3 includes a description of how to account for the internal series resistance in the silicon using the excess carrier concentration. The intrinsic carrier concentration including bandgap narrowing $n_{i,eff}$ = 9.65 × 10^9 cm^{-3} and the intrinsic lifetime τ_{int} accounting for radiative and Auger recombination is calculated following the parameterisation and models in [16]. I choose a realistic defect-assisted J_0 parameter following the lowest reported for a silicon cell, e.g. in LONGI's world-record solar cell[17], $J_{01,d}$ = 2 fA/cm^2, accounting for all non-radiative recombination losses.

It is possible to use the bottom branch for the silicon 3-diode circuit model in **Figure 1**.b to find the parameters that best reproduce the pseudo-efficiency from Black's formalism. A minimum-least-squares algorithm has been used to extract the parameters that produce the best fit of 3-diode circuit model. The optimal properties are included in the table in **Figure 2**.a. **Figure 2**.b and c illustrate the J-V plot for the ultimate efficiency that can be obtained from a silicon solar cell with maximum recombination of $J_{01,d}$ = 2 fA/cm^2, both in a linear and a logarithmic current density y-scale.

The efficiency limit of a perovskite sub-cell

To establish the practical maximum efficiency of the perovskite sub-cell, I isolate the top branch of the circuit model in **Figure 1**.b, and follow the modified detailed-balance formalism of Shockley and Queisser. I find the radiative dark current $J_{01,Rad}$ from a black-body integral Equation (8), and the short-circuit current density as stated in Equation (10). Crucially, the perovskite film absorptance was evaluated using a measured absorption-coefficient spectra as per ref [9] and an explicit film thickness (W=800 nm – optimal for current matching in a Pvk-Si tandem cell). Similar to Allen et al, I use the external radiative efficiency (ERE) defined as:

$$ERE = \frac{e^{\frac{V_{OC}}{V_t}} J_{0,rad}}{J_{sc}} \qquad \text{(Equation 17)}$$

to quantify non-radiative recombination losses in the perovskite, providing a convenient metric to translate material quality into voltage penalties. Following recent high efficiency lead-halide single junction perovskite cell

results, I expect ERE to approach 10% in industrial practice in the foreseeable future. I therefore adjusted the parameters reported by Allen et al to obtain a 10% ERE leading to a 22.9 % efficient cell for a 1.70 eV bandgap absorber, including a thickness W=800 nm, for optimal for 2J Pvk-Si tandem current matching[4]. The resulting J-V behaviour extracted from the three-diode circuit is illustrated in **Figure 2**.d, including all parameter values.

The interplay between active area, resistance, and metal shading

Elucidating the practical limits for perovskite-silicon tandems must account for inevitable metallisation grids. There is an interplay between the generation current and the finger pitch (l) since smaller pitch leads to higher shading losses, from light reflected by the metal contacts. Recent generations of metal printing technology have enabled very thin silver and copper fingers , yet they still impose a constrain on how much shading losses are tolerable. I assume that fingers as thin as $f = 20\ \mu$m are possible and scale the generation current such that the light injected in the active area including the metallised shaded faction (SF) is:

$$J'_{sc} = J_{sc} \cdot (1 - SF) = J_{sc}\left(1 - \frac{f}{l}\right) \qquad \text{(Equation 18)}$$

The series resistance from the TCE comes into play as it depends on l via Equation 7. When l becomes larger the series resistance losses from charge flow in the TCE become intolerable, so an optimal finger pitch l must be found as the trade-off between resistance and shading losses, for every choice of TCE. I have achieved this by executing a subroutine that identifies the optimal finger pitch by calculating efficiency as a function pitch l, including the resistance contribution from the selected TCE. I illustrate this algorithm in the supporting information, where is clear that variations in TCE sheet resistance change the optimal pinger pitch, making spaces as large as 4 mm possible, when very high TCE conductivities are achievable without substantial J_{sc} losses.

Efficiency limits imposed by TCEs

I now assemble the entire model to predict the efficiency penalties that changing a TCE (resistivity or optical properties) or its thickness have on the practical efficiency of a perovskite-silicon tandem solar cells. **Figure 3**.a Illustrates a tandem efficiency map as a function of the percentage of light that can be transmitted through the TCE, both due to parasitic absorption and refractive index matching, and the material sheet resistance. To evaluate the performance achievable via standard ITO, I use the optical data provided in [18] and assume a thickness independent resistivity to calculate the efficiency potential. A single layer ITO can be placed it the front surface just above the perovskite absorber layer. **Figure 3**.b shows that regardless of the thickness of the ITO, coherent interference and refractive index mismatch lead to a weighted average transmittance of 86%. On the contrary, when a magnesium fluoride antireflection layer is added on top of the ITO and its thickness optimised, the transmittance can be increased up to 96%. At such point, an optimal 40-50 nm ITO provides the best combination between light injection and lateral resistance losses leading to an efficiency of 35.13%, down from a maximum practical limit of c. 37%.

Analysis and Implications

I now consider the implications of this model in the context of recent advances in perovskite–silicon tandems. TCEs have been shown to constitute a fundamental constraint on device efficiency, alongside recombination and optical management. While conventional modelling frameworks often assume ideal contacts, this work enables a direct calculation of the penalties that lateral resistance and optical loss have on the efficiency of tandem solar cell. The model presented hence provides a missing link by quantifying the electro-optical trade-offs of TCEs and their geometric interplay with grid design. Practical efficiency limits were established for both the perovskite and silicon sub-cells using detailed-balance-based dark saturation currents and realistic recombination parameters, yielding practical sub-cell efficiencies of 22.8% and 28.9%, respectively. By

combining these limits and incorporating geometry-dependent TCE losses, the tandem cell efficiency was found to reach a practical maximum of 37%, with typical TCEs (e.g. 50 nm ITO combined with an antireflection coating) reducing this down to 35.13% efficiency when only one TCE is used. This means that, for a perovskite-silicon tandem, an efficiency penalty in the range of >2 %abs is imposed by just one TCE. Tandems normally require mid- and rear-TCEs further decreasing the efficiency. Such losses align well with experimental reports showing that small changes in ITO/IZO deposition conditions, antireflection coatings, or ALD barrier layers directly translate into measurable performance gains in state-of-the-art tandems. These results highlight the critical role of TCE selection, thickness, and optical design in determining the realistic performance potential of monolithic tandem architectures.

The implications for device design are clear. First, TCEs must be co-optimized with antireflection layers and transport barriers as a unified optical stack, with deposition strategies tailored to avoid sputter damage. Second, future tandems will require diversification beyond indium-based TCEs, both to relieve resource constraints and to sustain optical and electrical performance. Third, grid architectures must be treated as a first-order design variable, where the balance between resistive and shading losses is re-evaluated for every new TCE recipe. Finally, as interface passivation and recombination junctions approach their practical limits, the TCE will emerge as the decisive element governing whether tandems can bridge the final gap from today's 34% to the projected 37–38% efficiency frontier.

In summary, this work reframes TCEs from auxiliary layers into co-limiting elements in tandem photovoltaics, offering a unified modelling framework that couples material choice, optical design, and metallisation layout. By doing so, it establishes practical guidelines for navigating the electro-optical landscape of future tandem architectures and provides a forward-looking path toward sustainable, high-efficiency photovoltaic deployment.

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Data Availability

The Python models used to calculate the efficiency limits in this work are all provide open access on a CC BY license via https://github.com/OxfordInterfacesLab/TandEx

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Figure 1. Schematic representation of the simulation domain for a double-junction tandem solar cell. (a) Unit domain of a two-terminal tandem solar cell with d representing the finger width, and l the finger pitch, w representing the cell width and dx an infinitesimal change in the x direction (perpendicular to the cell width w). (b) Multi-diode model of a 2-terminal perovskite-silicon tandem solar cell including photogeneration, diode dark and loss currents, and resistive loss terms

Figure 2. The parameters and J-V characteristics of single junction solar cell at its practical efficiency limit. (a) Parameters table and (b) Current-Voltage (J-V) curve from a pseudo J-V model and the three-diode simulation of a silicon solar cell with minimised losses. (c) Parameters table and (d) J-V curve a three-diode

simulations for a 1.70 eV perovskite solar cell with parameters enabling an external recombination efficiency near 10%.

Figure 3: Variation in tandem efficiency as a function of TCE WAT and R_{sh}
Panel (a) illustrates the practial limits for arbitrary combinaitons of TCE transmittance and sheet resistance. In panel (b) I evaluate an ITO film with and without a thickness-optimised antireflection coating. The colour map scale applies to both panel (a) and (b).