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Economic viability of thin-film tandem solar modules in the United States

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**Tandem solar cells are more efficient but more expensive per unit area than established single-junction (SJ) solar cells. To understand when specific tandem architectures should be utilized, we evaluate the cost-effectiveness of different II–VI-based thin-film tandem solar cells and compare them to the SJ subcells. Levelized cost of electricity (LCOE) and energy yield are cal- culated for four technologies: industrial cadmium telluride and copper indium gallium selenide, and their hypothetical two-ter- minal (series-connected subcells) and four-terminal (electrically independent subcells) tandems, assuming record SJ quality subcells. Different climatic conditions and scales (residential and utility scale) are considered. We show that, for US residential systems with current balance-of-system costs, the four-terminal tandem has the lowest LCOE because of its superior energy yield, even though it has the highest US$ per watt (US$ W–1) module cost. For utility-scale systems, the lowest LCOE architec- ture is the cadmium telluride single junction, the lowest US$ W–1 module. The two-terminal tandem requires decreased subcell absorber costs to reach competitiveness over the four-terminal one.**

ower-conversion efficiency is a key driver to reduce the cost of photovoltaic (PV) electricity1. Tandem solar cells open a path to efficiencies above 30%, which exceeds the Shockley– Queisser limit of single-junction (SJ) devices by combining mul- tiple solar cell materials together2,3. However, because the higher efficiency is at least partially offset by higher fabrication costs, it is unknown whether tandems can achieve a sufficiently low levelized cost of electricity (LCOE) to compete with SJ devices in one-sun applications. To assess the cost-effectiveness of tandems requires

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coupled assessments of energy yield and cost4–9.

Prior efforts to explore the economic viability of tandems6,7,10, including cadmium telluride (CdTe)/copper indium gallium sel- enide (CIGS) and III–V-on-Si tandems, concentrate on standard testing condition (STC) efficiency and consider neither LCOE nor energy yield. These studies focus on a parallel-connected, four- terminal (4T) mechanically stacked tandem architecture in which subcells are electrically independent. This precludes a detailed comparison between the two main tandem architectures: the par- allel-connected 4T tandem and the monolithic series-connected two-terminal (2T) tandem. To determine which of those tandem architectures is preferable is a pressing question, as each architec- ture requires many months of research and development (R&D) to perfect, and thus significant investments in equipment, time and funds.

Recent energy-yield calculations for II–VI-based thin-film tan- dem solar cells examine the potential of several tandem architectures based on CdTe and CIGS, and include both 2T and 4T configura- tions11. These tandems have the advantage of leveraging known and industrially mature PV materials. Furthermore, thin-film/thin-film tandems combine subcells with similar manufacturing processes and cost structures, which favour tandems economically10. One analysis11 considers device performance in three geographical loca- tions that represent three distinct climates: dry (Albuquerque), tem- perate (Rapid City) and humid (Miami). Tandem architectures and SJ devices of different bandgaps perform differently depending on

the operating conditions and spectral variations12. Thus, location- specific energy yield is a significantly more informative metric than STC efficiency or a focus on just one location.

In this work, we explore the economic viability of thin-film tandems, and focus on the two thin-film materials that have been industrially manufactured at gigawatt scales: CdTe and CIGS. We present a bottom-up manufacturing cost model for CdTe–CIGS tandem solar modules, along with the corresponding subcells’ SJ modules, as well as location-specific energy-yield calculations for each architecture using a published model11. To motivate future development, we investigate tandems based on subcells with record efficiency quality. These tandems mark what is technologically pos- sible but go beyond what has been achieved. We then compare the economic viability using LCOE as a figure of merit. This is done using current system-installation costs in the United States, as well as a future scenario in which these costs are substantially reduced. We use parametric cost analyses to examine changing manufactur- ing and system costs to reveal what changes to technical variables are required to make tandems more cost-effective than SJ devices, the relative advantages of 2T and 4T tandems, and tandem viability in the face of declining PV balance-of-system (BOS) costs. Though we focus on industrially mature II–VI thin-film technologies, these results also apply broadly to emerging thin-film materials.

# Solar cell architectures and energy-yield calculations

From the three tandem architectures explored previously11, we selected the two highest-performing tandems: a 4T CdTe-on-CIGS tandem (Fig. 1c) and a 2T high*-E*g (1.68 eV)-top-cell-on-CIGS tandem (Fig. 1d). We use a higher-bandgap top cell for this archi- tecture because the series-connected subcells of a 2T tandem are constrained to have equal current, which causes non-ideal band- gap pairings to be more detrimental for 2T than for 4T tandems. For comparison, we additionally consider both CdTe and CIGS SJ modules. The efficiency and energy yield for each device is cal- culated using published methodology11, and is given in Table 1.

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**a b**

ARC glass

EVA AZO

CIGS buffer layer

CIGS absorber

Mo

Glass

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Growth direction

Growth direction

ARC glass FTO

CdTe absorber

Mo

EVA

Glass

JB

**c**

ARC glass FTO

CdTe absorber

ITO

EVA AZO

CIGS buffer layer

CIGS absorber Mo

Glass

Growth direction

JB

**d**

ARC glass FTO

High *E*g II–VI TJ

CIGS absorber Mo

EVA

Glass

Growth direction

JB

Growth direction

JB

**Fig. 1 |** Device architectures schematics. **a**–**d**, Schematic of the four device architectures, CdTe SJ (**a**), CIGS SJ (**b**), 4T tandem (**c**) and 2T tandem (**d**). EVA, ethylene-vinyl acetate; ARC, antireflection coating; FTO, fluorine-doped tin oxide; AZO, aluminium-doped zinc oxide; ITO, indium-doped tin oxide; JB, junction box; Mo, molybdenum; TJ, tunnel junction.

Methods gives more details on the device assumptions and effi- ciency calculations.

# Module manufacturing cost

We developed a bottom-up manufacturing cost model for both the 2T and 4T tandem modules and their comprising subcells, employed as SJ cells. The cost model is based on the step-by-step process flows given in Supplementary Tables 2–5. The cost breakdown for each step is given in Supplementary Tables 1–5. From the manufacturing cost, we calculate the minimum sustainable price (MSP) for each module1. Methods gives details on the development of and assump- tions used in the cost model and MSP calculations. The financial parameters used for MSP are given in Supplementary Table 6.

From the cost model, manufacturing process flows, financial parameters and calculated efficiencies in Table 1, the US$ W –1 cost and MSP for each tandem and SJ architecture are derived (Fig. 2 and Table 2). The CdTe SJ has the lowest US$ W –1 price, US$0.30 W –1, whereas the two tandems are the most expensive. The 4T tandem is the most-expensive architecture in US$ W –1, and exceeds the cost of the 2T by about US$23.32 m–2, with only a small STC efficiency advantage of 1.5% absolute. The high cost of CIGS relative to CdTe is due to the high capital expenditure (CapEx) of the CIGS absorber deposition with the current commercialized CIGS deposition process.

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# Considering LCOE

Though neither tandem architecture is cost competitive on a mod- ule level due to their significantly higher MSP than the SJ modules, tandems can still have advantages on a system level as the mod- ule costs are only part of the total PV system cost. High efficiency reduces the cost-per-watt of a system by outputting more power for a given system area. Thus, to compare fully the relative cost effec- tiveness of the tandem modules, we calculate LCOE for the four architectures in all three locations for residential- and utility-scale installed PV systems in the United Sates.

System installation costs are calculated using utility and residen- tial data13 for the 2016 US PV system costs (Supplementary Table 7). To explore how LCOE changes for the different architectures if system costs continue to fall, we include a hypothetical future sce- nario with substantially reduced system installation costs, based on a proposed US Department of Energy SunShot target scenario14 (Supplementary Table 7). We refer to this case as the ‘reduced sys- tem cost scenario’ (RSCS). Methods gives further details on the cal- culation of system costs and LCOE. The total system costs are given in Table 2.

Using the module and system costs, along with the calculated energy yields, we compute the LCOE for all four architectures for both residential- and utility-scale systems using equation (1) (Methods) for Figs. 2 and 3. We first discuss the LCOE results for

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| **Table 1 |** Module performance | | | | | | |
|  |  | Energy yield (kWh m–2 yr–1) |  |  |  |  |
| architecture | STC efficiency (%) | Dry | Temperate |  | Humid |  |
|  |  | Fixed Tracked | Fixed | Tracked | Fixed | Tracked |
| 4T tandem | 26.5 | 621.19 716.44 | 504.84 | 548.54 | 506.21 | 602.59 |
| 2T tandem | 25.0 | 569.91 658.38 | 459.45 | 500.41 | 445.31 | 539.55 |
| CdTe SJ | 19.9 | 471.52 538.55 | 381.56 | 413.31 | 397.06 | 466.46 |
| CIGS SJ | 19.8 | 464.22 536.15 | 377.76 | 411.07 | 378.53 | 451.35 |
| Efficiency under STC and calculated energy yield for each of the considered device architectures for fixed tilt (Fixed) and single-axis tracking (Tracked). Efficiencies of the tandem solar cells were calculated using subcell EQE curves and current–voltage (*I*–*V*) curve parameters (open circuit voltage, series resistance and shunt resistance) fitted from the specified cell results. The EQE curves of the bottom cells include the optical losses due to imperfect transmission and optical coupling of the top cell, which were calculated using the transfer-matrix method of optical modelling11. The fixed-axis yields are used for residential-system LCOE calculations and the single-axis tracking yields are used for utility systems exclusively. | | | | | | |

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0.50

0.40

**a**

12.5

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 4T 2T CdTe SJ CIGS SJ

**b**



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5.5

0.30

Cost and MSP (US$ W–1)

0.20

0.10

Maintenance and overhead

Labour Utilities Materials Depreciation

US$0.43

US$0.36

US$0.36

US$0.30

Estimated MSP

11.5 

10.5

LCOE (UScents kWh–1)

9.5

5

4.5

4

0.00

**Fig. 2 |** Module costs. Module cost and MSP for each architecture output from our module manufacturing cost model. The MSP is calculated such that the cash flow has an IRR equal to the weight average cost of capital (WACC), assuming a WACC of 14%.

the 2016 scenario (Fig. 3). The 4T tandem has an LCOE advantage for residential-scale systems over both the 2T and the SJ modules. It has the lowest LCOE in all three locations, that is, 8.0%, 8.4% and 4.9% lower than the next cheapest SJ module in the dry, temperate and humid locations, respectively. This advantage exists due to the high BOS and installation costs for residential systems in the United States, relative to the PV modules, which make up 72–78% of the total system cost for these four architectures. This creates a signifi- cant premium on maximizing the energy generated per area of a system, and so causes residential systems to favour high-efficiency and high-yield modules. Additionally, the 4T tandem continues to have the lowest LCOE if the optical transmission to the bottom cell is worse than modelled. The power from the bottom cell can drop by up to 30% in a humid climate and 40% in dry and temperate climates and still remain the lowest LCOE residential architecture.

Furthermore, the 4T tandem LCOEs are 2.0%, 2.7% and 6.0% lower than the 2T tandem LCOEs for residential systems for dry, temperate and humid locations, respectively. Despite having a lower manufacturing cost, the 2T tandem’s lower performance ratio due

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| **Table 2 |** Total module and system costs | | | | |
| architecture | Module | Module | Total | Total installation **+** |
|  | Cost | MSP | installation | BOS costs, Utility |
|  |  |  | **+** BOS costs, |  |
|  |  |  | residential |  |
|  | (US$/ | (US$/ | (US$) (US$/ | (US$) (US$/ |
|  | m2) | m2) | Wp) | Wp) |
| 4T Tandem | 76.44 | 111.17 | 12,140 1.77 | 77,557,623 0.98 |
| 2T Tandem | 61.13 | 90.16 | 12,019 1.76 | 76,617,691 0.93 |
| CdTe SJ | 42.44 | 58.84 | 11,609 1.97 | 73,417,333 0.96 |
| CIGS SJ | 49.42 | 71.18 | 11,601 2.05 | 73,398,925 1.04 |
| Total calculated module manufacturing cost and minimum sustainable price (MSP) for each architecture, and the total cost of installation (excluding module costs) for each architecture in a residential (area = 35.9 m2) and utility (area = 0.6 km2) system based on the 2016 system cost scenario. Wp refers to the module power output, in watts, at peak power equal to nameplate capacity. | | | | |

**Fig. 3 |** 2016 system-cost scenario LCOE values. **a**,**b**, Calculated LCOEs for residential-scale (**a**) and utility-scale (**b**) systems in each of the three specified dry, temperate and humid locations for each architecture, using the 2016 system and installation costs.

to current mismatch in realistic climates and the slightly lower effi- ciency (−1.5%) mean the 2T tandem is a more expensive tandem configuration, on a system level, than the 4T architecture. The 2T

tandem performs best in dry and temperate locations where it has the second-lowest LCOE, whereas it performs worst, comparatively, in the humid location, with a higher LCOE than both the 2T and the CdTe SJ, because water vapour causes a significant spectral shift that results in current mismatch, and so reduces energy yield. Furthermore, the absorption edge of CdTe is above the absorption peaks of water vapour, which makes the CdTe SJ energy yield par- ticularly robust to humid climates. As a result, the added cost for the 2T module is not justified compared to a CdTe SJ.

Utility-scale systems, alternatively, show no advantage for tan- dems. The CdTe SJ module is associated with the lowest LCOE in a utility system for all three locations, though the 2T LCOE is equal in the dry location. This is a result of the significantly lower installa- tion and BOS costs, which diminish the value of high efficiency and cause utility-scale systems to favour the cheapest module.

The LCOE results produced using the RSCS (Fig. 4) show that to reduce the non-module system costs makes tandems less favour- able. The 4T tandem loses its advantage over the CdTe SJ for resi- dential systems in humid climates, with a 2% higher LCOE in this case. Tandems remain the lowest LCOE option for dry and temper- ate locations: the 4T LCOE is still the lowest in the temperate loca- tion and the 2T and 4T LCOEs are almost equal in the dry location, with the 2T providing the lowest LCOE. The relative advantage of tandems compared to SJ architectures for these locations, however, is reduced for this RSCS to just 1.4% and 1.8% for dry and temperate locations, respectively. The utility-scale results are similar to those for the 2016 case, with the CdTe SJ having the lowest LCOE for all locations; the benefit of the CdTe SJ over the tandem architectures has increased.

These results show the impact of system costs in determining whether tandems are favourable. There is significant potential for installation costs to change over time or across different locations. The costs used in the RSCS, however, are aggressive and other sce- narios are possible. To have a fuller understanding of the effect of system costs, we varied the total installation cost, the area-dependent cost and the per-project cost to look at how the lowest LCOE

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**a b**



4T 2T CdTe SJ CIGS SJ

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8.5

# 5

8



LCOE (UScents kWh–1)

The modelled CIGS absorber price is too high for a tandem sub-cell, given how much added energy-yield a CIGS bottom cell generates. If the MSP of the CIGS absorber comes down by about 10% or if we are overestimating the cost, tandems are much more viable. The high MSP for CIGS is due to the high CapEx associated with the CIGS absorber deposition. This is based on current commercialized manufacturing processes and tools. CIGS has only recently been commercialized, so there is potential for the CapEx to come down

7.5

7 

6.5



4.5



4

as the technology matures or sees innovation and so reduces the cost and MSP of the CIGS absorber and enables a cost-competitive tandem. Additionally, the 2T is favoured over the 4T in utility scale because the modules are cheaper per watt, other than in the humid location, because the 2T suffers considerably from spectral mis- match, as discussed previously.

Generally, if the price of both subcells decreases, tandems become cost competitive, which shows the advantage of tandems for very-low-cost absorbers. This is because those module compo- nents that are not doubled when going from a SJ to a tandem, such as glass and the junction box, as well as many aspects of the instal- lation costs, are a larger fraction of the total system cost. Tandems

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**Fig. 4 |** reduced system cost scenario LCOE values. **a**,**b**, Calculated LCOEs for residential-scale (**a**) and utility-scale (**b**) systems in each of the three specified locations for each architecture for the hypothetical future reduced system and installation cost scenario.

architecture changes with each. Fig. 5 shows the stability of the cheapest architecture remaining the cheapest and how much each type of cost would need to change to alter the outcome.

As expected, as the system costs, especially the area- and project- dependent costs, decrease, tandems become less favourable. In other words, the economic window of opportunity for tandems narrows as the trend of system cost reduction continues. The total 2016 system costs have to come down substantially (over 50%) for a SJ device to have a lower LCOE than a tandem one in residential systems in temperate and dry locations, and the 4T architecture has a fairly stable financial preference over fluctuations in system costs. The SJ cannot become cheaper than the 4T tandem without substan- tially reducing the project costs, such as permitting, interconnection fees and overheads. In the dry location, there is a narrow range, at 46–52% total system-cost reduction, in which the 2T tandem has the lowest LCOE. As the system costs drop more, the advantage of the 2T tandem does not last and the CdTe SJ quickly becomes the lowest LCOE architecture. The 4T LCOE remains lower than CdTe until the system costs drop by 52%.

Finally, we explore the effect of absorber MSP on the lowest LCOE architecture, as this is one of the most impactful parameters on the viability of tandems compared to their SJ counterparts. We co-varied the MSP of the CdTe and CIGS absorbers and mapped which architecture has the lowest LCOE for both the 2016 scenario (Fig. 6a) and RSCS (Fig. 6b), which allows us to explore the effect of potential future changes in absorber costs, uncertainties in our model’s absorber costs and different deposition methods. The latter is particularly interesting as it gives the opportunity to evaluate the value, or lack thereof, of very-low-cost deposition methods, such as solution-based coating15,16.

From this analysis, for 2016 residential systems, the 4T tandem has a stable advantage and remains the cheapest option over a wide range of absorber MSPs. For all three climates, even as subcells become cheap, the 4T is always preferred over the 2T tandem. This, again, shows the value of high-energy yield for rooftop solar.

For 2016 utility-scale systems, as the cost of the absorbers decrease, the 2T tandem becomes the lowest LCOE architecture in dry and temperate locations (Fig. 6a, red) and the 4T tandem in the humid location (Fig. 6a, blue). This shows that the price of CIGS needs to drop for a tandem in a utility-scale system to be favoured.

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then provide an increase in efficiency with only a small percent increase in price.

We then perform the same analysis of varying the absorber MSP but for the RSCS (Fig. 6b). This shows us that, for signifi- cantly reduced system costs, whereas tandems are the lowest resi- dential LCOE option for dry and temperate locations, the CIGS absorber MSP would need to drop by about 25% for a tandem to have the lowest residential LCOE in the humid location. In this scenario, the differences in relative energy yield between the 2T and 4T tandems among locations becomes more relevant, as the tandem architecture that has the lower LCOE varies across loca- tions. The 2T tandem dominates the majority of the parameter space in which tandems have the lowest LCOE in the dry location and both architectures are somewhat equally represented for the temperate location, whereas the 4T architecture is always cheaper than the 2T architecture in the humid location. As the lower sys- tem cost diminishes the premium on a high energy yield, the 2T tandem is much more competitive in residential systems in this scenario than in the 2016 scenario. In the residential RSCS, every- where that the 2T tandem has the lowest LCOE in this parameter space, the 4T tandem has the second-lowest LCOE, lower than either SJ architecture.

The dry and temperate residential cases in this scenario also illustrate how absorber cost affects the comparison of 2T and 4T tandems. Cheap subcells favour 2T tandems, which makes them more cost-effective relative to 4T, as demonstrated by the lowest LCOE changing from 4T to 2T moving towards the bottom-left cor- ner (Fig. 6b); however, in the humid location, the 2T disadvantage is too large for this effect to make 2T tandems have the lowest LCOE. For utility-scale systems, the CIGS absorber cost needs to be about 20% lower for tandems to have a chance of succeeding in dry and temperate locations for this hypothetical future scenario. This seems feasible, as it is likely that module manufacturing costs will come down in the time needed for system and installation costs to drop, and thus offset some of the impact of the lower installation costs on tandem viability. In the humid location, the CIGS absorber price would need to fall by about 70%, which appears improbable

given current technology and material costs.

Finally, we expect the R&D needed to bring tandem technology to market to be less for 4T than for 2T technology. The 4T archi- tecture comprises two mature materials and can be manufactured using their currently preferred processes. The 2T tandem, on the contrary, requires the development of a tunnel junction, the devel- opment of a high-*E*g top cell and potentially optimizing the super- strate deposition of CIGS. This is a vital consideration that is not directly accounted for in these results. Additionally, the advantage

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**a** System- cost type

Project Area Total

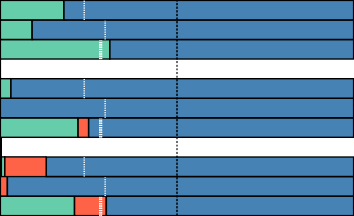
Dry Temperate Humid location location location

Project Area Total

Project Area Total

4T 2T CIGS CdTe

**b** System- cost type

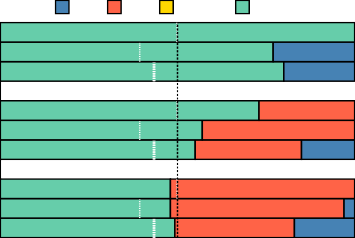
Project Area Total

Dry Temperate Humid location location location

Project Area Total

Project Area Total

4T 2T CIGS CdTe

–100

–50

0

% change (cost)

+50

+100

–100

–50

0

% change (cost)

+50

+100

**Fig. 5 |** analysis of the impact of system-cost variability. **a**,**b**, Maps of which architecture has the lowest LCOE as various system-cost parameters are varied relative to their 2016 scenario reference value (given in Supplementary Table 7) for residential-scale (**a**) and utility-scale (**b**) systems in each location. The colour in each bar represents the architecture with the lowest LCOE for the relative value given on the *x* axis of the specified parameter (project- dependent, area-dependent or total system cost) given along the *y* axis. The blue region represents the conditions for which the 4T tandem LCOE is lowest, the red correspondingly for the 2T tandem, the yellow for the CIGS SJ and the green for the CdTe SJ. The dotted white lines mark the values for the RSCS.

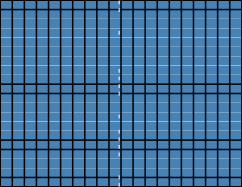
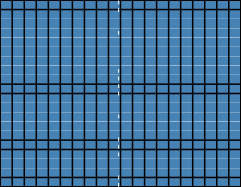
1. Dry

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| 20 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 20 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 20 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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| 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

Temperate

Humid

CIGS

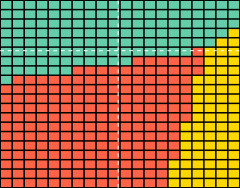
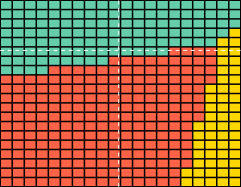
0 0

Residential

CIGS absorber MSP (US$ m–2)

CdTe

0 10 20 30 40 0

40 40

30 30

20 20

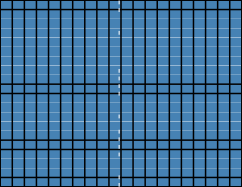
Utility

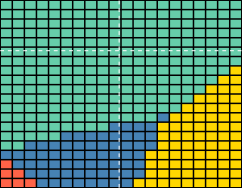
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0 0

0 10 20 30 40 0

0

10 20 30 40 0

40

30

20

10

0

10 20 30 40 0

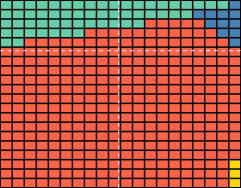
10 20 30 40

10 20 30 40

4T

2T

1. Dry

40

30

Residential

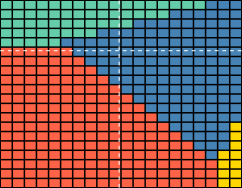
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CIGS absorber MSP (US$ m–2)

10

CdTe absorber MSP (US$ m–2)

Temperate

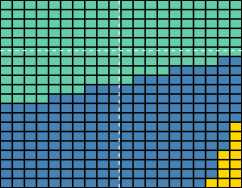
40

30

20

10

Humid

40

30

CIGS

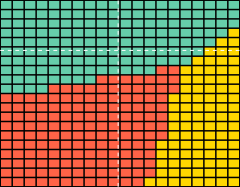
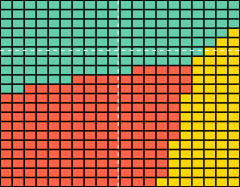
20

10

CdTe

0 0

0 10 20 30 40 0

40 40

30 30

20 20

Utility

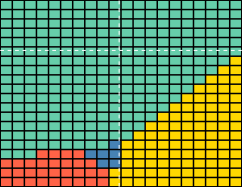
10 10

0 0

0 10 20 30 40 0

0

10 20 30 40 0

40

30

20

10

0

10 20 30 40 0

10 20 30 40

10 20 30 40

4T

2T

CdTe absorber MSP (US$ m–2)

**Fig. 6 |** analysis of the impact of the absorber price. **a**,**b**, Maps of the architecture with the lowest LCOE over varied MSP for the CdTe and CIGS absorber for residential-scale (top row) and utility-scale (bottom row) systems in the dry, temperate and humid locations assuming the 2016 scenario (**a**) and the hypothetical RSCS installation costs (**b**). The blue region represents where the 4T tandem LCOE is lowest, the red is where the 2T tandem LCOE is lowest, the yellow where the CIGS SJ LCOE is lowest and the green is where the CdTe SJ LCOE is lowest. The white dashed lines correspond to the absorber cost specified by the cost model.

of 4T tandems is even more significant when considering land scar- city; rooftop PV systems have limited space, which makes efficiency more valuable.

Though some of the costs used in this model may vary or have some uncertainty, because we frame our analysis as a comparison between architectures and focus on the relative LCOE values rather

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than their magnitude, the effect of error has significantly less impact on our conclusions. This is because many of the process steps are used in multiple or all architectures.

Though the efficiencies used in this work are relatively high compared to commercially available modules, we do not expect this to have a significant impact on our results. High efficiencies have been shown to have diminishing returns on reducing the cost of system installation17. Thus, we expect lower efficiencies to show the same result, but for the relative benefit of the lowest LCOE architec- ture to increase.

# Beyond CdTe–CIgS tandems

The results demonstrated provide knowledge and have implica- tions for examining the cost-effectiveness of tandems that comprise other materials systems. For thin-film tandems with absorber costs similar to CdTe and CIGS, the best avenue for a cost-competitive tandem is a 4T tandem architecture, used in residential systems in dry and temperate locations. This has the advantage that areas with significant residential solar markets tend to have primarily cooler, dryer climates. To pursue a cost-competitive 2T tandem, low-cost subcells should be used, such as solution-processed perovskite-on- perovskite tandems18–20 (assuming similar contact and module costs can be achieved).

Perovskite-on-silicon marks another popular tandem pair- ing21–23. Though the fabrication process of silicon is quite different from those described in this paper, we expect the key trends and findings to hold. Though the cost of the two absorbers are prob- ably unequal, the analysis in this paper (Fig. 6a) suggests that it may be possible for the 4T perovskite-on-silicon tandem to have a lower LCOE than either SJ module, provided a similar SJ-to-tandem efficiency boost to that of CdTe–CIGS is achieved. As system costs come down (Fig. 6b), however, the unequal absorber costs make it quite difficult for the tandem to have a lower LCOE than a low-cost perovskite solar cell by itself.

Perovskite-on-CIGS tandems have also been explored24–26. Similar to CdTe–CIGS, a perovskite–CIGS tandem may be viable in residential systems, even as system costs decrease, if the absorber cost of CIGS falls, again assuming similar device performances. A larger reduction in CIGS cost is needed for a lower-cost top cell, however, and the 2T configuration may then be favoured.

# Conclusions

In this paper, we evaluate the financial viability of CdTe- and CIGS- based thin-film tandem solar cells using a detailed bottom-up cost model and energy-yield calculations.

We find that for residential systems, the 4T tandem, hav- ing the highest efficiency, features the lowest LCOE given 2016 system costs. In utility-scale systems, tandems have no LCOE advantage, and the lowest LCOE is achieved by the technology with the lowest US$ W–1 cost, the CdTe SJ. As installation costs come down, tandems have less of an advantage as the importance of energy yield is reduced; however, the total system cost must come down by almost 50% for residential systems before the 4T tandem no longer has the lowest LCOE. In other words, the eco- nomic window of opportunity for tandems shrinks when the BOS costs decline.

Tandems become financially more favourable as the price of both subcells decreases. As absorbers become cheap, 2T tandems become more favourable relative to 4T tandems and SJs; however, whether 2T tandems have a lower LCOE than 4T tandems depends on location and system costs. Furthermore, the 2T tandem currently requires significant R&D to achieve an effective tunnel junction and high-bandgap top cell material to enable this device architecture, which potentially results in a more expensive fabrication process than anticipated. For tandems to succeed on the utility scale, the absorber costs need to be substantially lower.

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Finally, this analysis shows the importance of using energy yield when tandem viability is assessed, as using STC efficiency alone results in the 2T tandem having the lowest LCOE in both system sizes for both system cost scenarios.

# Methods

**Device efficiency and yield calculations.** Due to the 2T tandem’s series-connected configuration, the subcells are forced to generate equal current, a constraint known as current matching. If there is a mismatch in current generation, the device is limited by the cell with the least current. This causes 2T devices to be more sensitive to subcell bandgap pairings and can additionally cause significant losses in the harvesting efficiency of the tandem under a naturally varying solar spectrum27,28. As a result, a CdTe-on-CIGS 2T tandem is not viable due to the degree of current mismatch with such a bandgap pairing. We therefore, instead, consider a high-*E*g CdTe alloy, such as CdZnTe, with a bandgap of 1.68 eV (ref. 11) as a top cell on a CIGS bottom cell. We assume a top-cell device performance similar to that of current CdTe devices, despite current alloys such as CdZnTe being much less mature and having not yet reached comparable efficiencies.

Currently, the record CdZnTe efficiency is 16.4%, and a 16.8% CdZnTe 2T tandem on silicon has been demonstrated29.

The 4T tandem configuration, however, has no current matching constraint, as the subcells are electrically independent, each with their own set of contacts and an insulating layer between the top and bottom cell. This allows more flexibility

in bandgap pairings of subcells and decreases the sensitivity to spectral changes. Thus, we can leverage two mature materials as subcells in the 4T tandem, CdTe (1.48 eV bandgap) and CIGS (1.04 eV bandgap). Though the higher bandgap CdTe alloy (1.68 eV bandgap) is a better bandgap pairing, the difference in absolute efficiency is small: 1.6%, assuming detailed balance-efficiency limits, and 0.4% for the parameters used in this work.

The efficiency and energy yield for each device is calculated using published methodology11 for each location. We have updated the calculations to reflect recent advances in device performance. The CdTe quantum-efficiency curve used previously11 was replaced with that of the most-recent record CdTe cell from First Solar30, and we also used the quantum-efficiency curve from a recent CIGS solar cell, based on device results from Solar Frontier31, as this device is fabricated by sputtering and sulfurization after selenization (SAS). We then added cell-to-

module losses with increased series resistance, reflection and inactive area between the cells (Supplementary Table 8 and Supplementary Methods give details). The new *I*–*V* curve parameters and the external quantum efficiency (EQE) were then used to calculate the STC efficiency (Table 1). Our choice to use record-level efficiency solar cell results was motivated by the aim to address the next-generation PV modules in this work and to anticipate the rapid progress of PV development.

Energy yield was calculated using a published approach11 that utilizes time-resolved spectra for each location generated with the Simple Model for

Atmospheric Radiative Transfer of Sunshine (SMARTS) from National Renewable Energy Laboratory32,33. As previously11, the efficiency for each architecture was calculated using the one-diode model. The input parameters were determined by the experimental open-circuit voltages, the EQE for each device and fitting the series and shunt to the published *I*–*V* curves30,31. As SMARTS does not account for cloud coverage, thus overestimating annual insolation, the yields for each location were scaled by the ratio of the local average insolation34 and the modelled insolation (Supplementary Table 9). The resulting energy yields for all four architectures are shown in Table 1.

**Module manufacturing cost model.** In this section, we describe our bottom-up manufacturing cost models for the two tandem modules and their comprising subcells, employed as SJ cells. The assumed step-by-step manufacturing process flows for all four architectures are listed in Supplementary Tables 2–5. In the described process, CdTe is deposited in a superstrate configuration by vapour transport35,36 and CIGS is deposited in a substrate configuration by sputtering plus SAS, as these are the predominant commercial methods of fabrication and the method by which the quoted devices were deposited31.

For the 4T tandems (Fig. 1c), modification of the process flow for each subcell is straightforward, as the superstrate top-cell and substrate bottom-cell fabrication are naturally compatible with integration in the tandem structure. The top- and bottom-cell processes are assumed to flow in parallel until each subcell has the final contact deposited. The two subcells, each integrated onto a glass sheet, are then laminated together, assuming similar loading and encapsulation costs to those of standard SJ glass–glass module encapsulation. We assume no added module circuitry or installation cost for the 4T tandem, as subcells would connect in parallel voltage-matched strings37. If additional circuitry is needed, however, the 4T module can cost up to an additional US$8.87 m–2, US$12.54 m–2 or US$23.06 m–2 and remain the cheapest residential LCOE in the dry, temperate and humid locations, respectively, as is the case in Fig. 3.

Despite the significant R&D barriers for the 2T tandem (Fig. 1d), we assume that the cost of the high-*E*g II–VI top-cell absorber is equivalent to that of CdTe. We consider a superstrate configuration (front-to-back process) for the 2T tandem. First, the CdTe alloy top cell is deposited by vapour transport deposition on the

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front contact, followed by the tunnel junction, which is deposited by sputtering, and, last, the rest of the CIGS absorber and back contact are deposited, front-

to-back, on to the CdTe–tunnel junction stack. This requires four primary R&D challenges: the development of the high-*E*g CdTe alloy top cell, a polycrystalline tunnel junction, a process flow that prevents copper diffusion and a high-efficiency superstrate deposition method for CIGS.

We have derived the cost for each step through supplier quotes, discussions with contacts in industry and other academic and non-academic sources35,38–43, conscious of recent changes in manufacturing costs. The costs associated with each process step for module manufacturing are given in Supplementary Table 1. From the process costs and manufacturing process flows, we compute the manufacturing cost-per-area for each of the four architectures. From these costs, we then compute the MSP using an iterative goal-seek algorithm assuming straight-line depreciation. The MSP is defined as the minimum price for which the internal rate of return (IRR) is equal to the weighted average cost of capital (WACC), a metric used to define a price that will sustain a manufacturer1. All the financial parameters used in these calculations are given in Supplementary Table 6.

**LCOE.** The LCOE is computed with the equation44:

total lifetime cost

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LCOE =

total lifetime electricity production

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*I* + Σ*N* OM

(1)

Technology advances needed for photovoltaics to achieve widespread grid

*i*=0 (1 + *r*)*i N E* (1 − *d*)*i*

Σ

=

*i*=0 (1 + *r*)*i*

where *I* is the total initial investment to install the PV system (including cost of PV modules, racking, interconnects, labour, permits and so on), OM is the annual cost for operation and maintenance, *E* is the annual energy output by the system as electricity in the first year (Table 1), *N* is the system lifetime in years, *d* is the

annual module degradation rate and *r* is the nominal discount rate for the customer (Supplementary Table 6). We use an annual relative degradation rate of 0.5% yr–1 for both CdTe and CIGS45 in all locations. We assume both tandems’ subcells degrade at the same rate as in SJ devices, so we use the same 0.5% yr degradation rate for both tandems.

To calculate the total installation cost of a system, we use data13 for the 2016 US PV system costs for utility- and residential-scale systems. The costs are broken down into those that scale with system area and system power, and those that are fixed per project17 (Supplementary Table 7). These include all costs of installing

a PV array (excluding the PV modules), such as BOS, racking, inverters, labour, permitting and so on. To calculate the installation costs for each type of module, we assume a constant area of 35.9 m2 for residential systems and 0.6 km2 for utility- scale systems. The total module cost to the customer is calculated from the module MSP and an installer markup (Supplementary Table 7).

The hypothetical future RSCS with substantially reduced system installation costs is based on the US Department of Energy SunShot target scenario14 (Supplementary Table 7). We use the US$ W–1 costs from this source14 and break them into area-, power- and project-dependent costs based on a published breakdown17. A few of the costs in this SunShot scenario14 were higher than the 2016 costs, as they fell faster than anticipated between 2015 and 2016. In these few cases, the 2016 cost13 was used instead.

**Code availability.** The cost model and parametric analyses from this paper are available online at <http://pv.mit.edu/tma/>in an excel document. Additional analysis code is available upon reasonable request.

**Data availability.** The data that support the plots within this paper and other findings of this study are available on pv.mit.edu or from the corresponding authors upon reasonable request.

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The CdTe cost model was made independently, without contribution from or corroboration by First Solar. The CIGS cost model was made independently, without contribution from or corroboration by Siva Power.

# author contributions

S.E.S. compiled cost data and developed the cost model and analysis tools, with cost inputs and feedback contributed by D.N.W., B.J.S., I.M.P. and T.B. J.P.M. and S.E.S. performed energy-yield calculations. S.E.S. performed analysis and data visualization. I.M.P., T.B. and D.N.W. conceptualized the initial project. The manuscript was written by

S.E.S. and edited by all the co-authors. I.M.P. provided lead mentorship. All the authors reviewed and approved the manuscript.

# Competing interests

The authors declare no competing interests.

# additional information

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T.B. or I.M.P.

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