

Emerging technologies in Solar PV: identifying and cultivating potential winners

Traversing the PV lab-to-fab “valleys of death”



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Executive summary

The rapidly declining unit cost of silicon-based photovoltaic (PV) cells over the past four decades has facilitated the advent of PV as a commercially viable energy source. However, emerging PV technologies currently in development show the potential to disrupt and replace the dominant market incumbent crystalline silicon (c-Si) technology in the future. These technologies have been used to record cell efficiencies more than three times that of typical commercial c-Si PV, and have growing academic and financial sponsorship and the prospect of value-creating cross-applicability and complementarity between materials and technology. The question now is whether the long-term viability of c-Si as the market leader has a time limit in the face of these emerging challengers.

In this article we survey the materials and technologies we think have the most potential to disrupt the PV market in the coming decade. We identify our top three potential disruptors as: perovskite, quantum-dot photovoltaics, and concentrated photovoltaics. Further, we present the policy implications of our analysis and conclude that a winning combination of financial muscle and an enlightened, patient, long-term view in which concerned actors do not cave into external demands for short-term returns are the key prerequisites for the future major sponsors of emerging PV technology. The onus is on the potential sponsors possessing these qualifications to step in and deliver the support required for these fledgling technologies, which have the potential to revolutionize the renewable energy game with sufficient backing, but may go undeveloped in the absence of this. Developing effective methods of sourcing and allocating funding is also imperative. In short, the challenge of future sponsors will be to ensure these technologies do not fall prey to the lab-to-fab “valleys of death” that have endangered promising PV technologies in the past.

1. Introduction – the rise and dominance of c-Si photovoltaics

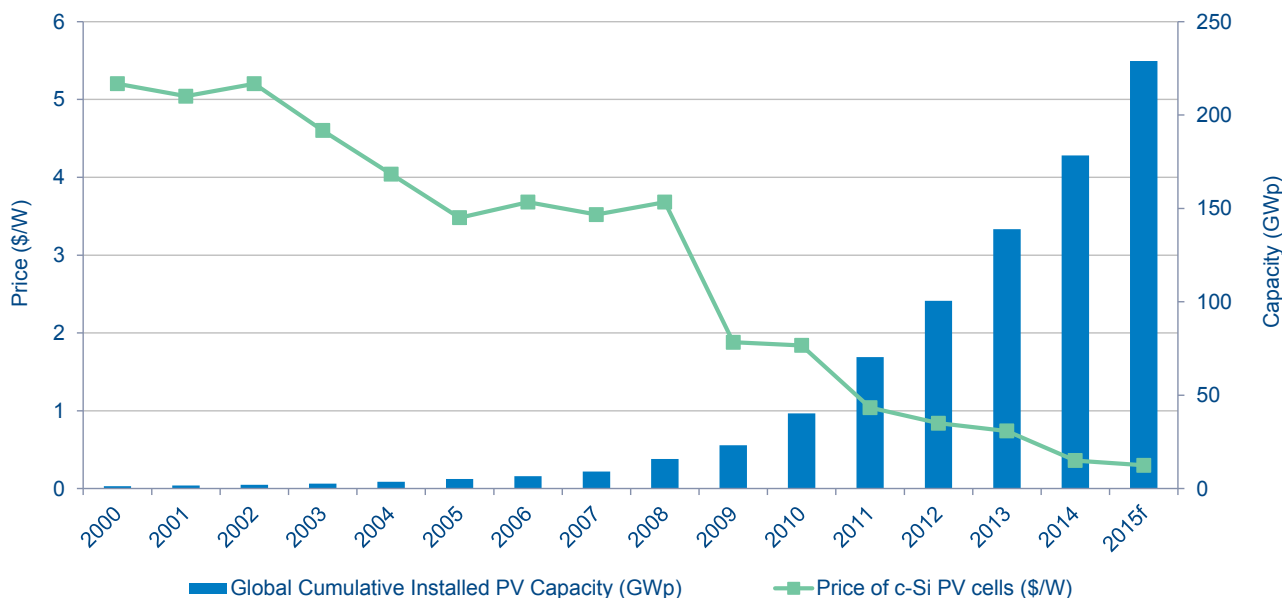
The rapid increase in overall photovoltaic (PV) electricity production has been facilitated by one key factor – the declining unit cost of silicon-based solar cells. The cost in dollars per watt (\$/W) of crystalline silicon (c-Si) PV cells has declined from a peak of over \$76 in 1977, to \$5 in 2000, to just \$0.30 in 2015 (Figure 1). This has enabled the commercial viability of PV electricity for the first time in history. PV electricity production has already reached “grid parity”¹ in close to 40 countries, and is forecasted to reach this point in over 50% of the world’s countries by 2017². Photovoltaic electricity generation is here and commercially viable today.

Representing over 90% of worldwide installed PV capacity, c-Si PV cells³ have been the vanguard to date. The affordability of such c-Si cells is driven by the economies of scale of its main ingredient, silicon, generated in the booming semi-conductor industry. Although the cost reduction of c-Si was good news for manufacturers in terms of competitiveness with conventional

energy sources, the strong competitive position of c-Si in the free market drove other promising PV technologies out to the margins.

The continually falling cost of c-Si has made it incredibly difficult for other technologies to compete. This is despite the fact that, theoretically, silicon is not particularly well suited for photovoltaic uses because it is an indirect bandgap semi-conductor and has a low absorption coefficient. One such promising technology that suffered from competition with c-Si is copper indium gallium selenide (CIGS). Although exhibiting promise to ultimately be more cost competitive than c-Si, it was driven to near extinction due to its lesser technological maturity and yet-unproven cost advantage. As we frame it in this article, CIGS fell prey to one of the two lab-to-fab “valleys of death” (in which funding is not sustained at a sufficient level to bring the technology to commercial fruition) on the precipitous road to the consumer.

Figure 1: Cumulative installed PV capacity (GWp) vs. price of c-Si PV cells (\$/W)



Source: Price Data: Bloomberg New Energy Finance; PV Capacity Data: EPIA (European Photovoltaics Industry Association)

1 Grid parity occurs when an alternative energy source can generate power at a levelized cost that is less than or equal to the price of purchased power from the traditional electricity grid.

2 According to Deutsche Bank.

3 c-Si cells are broken down into the two groups of mono-crystalline and multi-crystalline. Mono-crystalline silicon is made from single crystals, grown in the shape of round pillars, whereas multi-crystalline silicon is made by pouring molten silicon into a cube-shaped mold and letting it cool and solidify.

2. Defining the credentials of potentially disruptive PV technologies

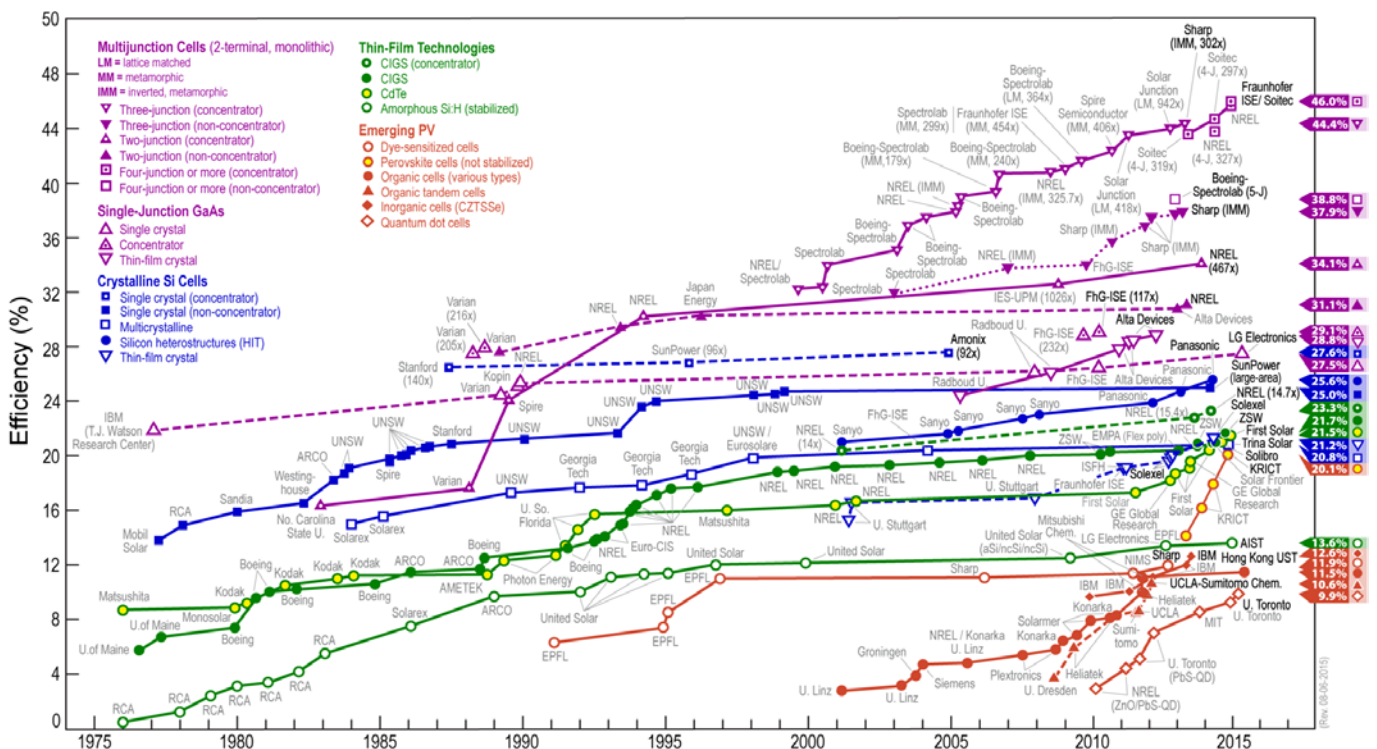
In the last 15 years, cutting-edge PV concepts including concentrated photovoltaics (CPV), multi-junction cells, organic photovoltaics (OPV), cadmium telluride (CdTe), quantum-dot cells, perovskite, and (to some extent, the exotic and not-yet-fully-understood) graphene, have all been receiving attention from both academic and financial arenas. These emerging technologies have the potential to disrupt c-Si because of their dual abilities to:

1. Beat c-Si directly in PV applications due to lower long-term \$/W potential.
2. Venture into new applications outside of PV; we call this "cross-industry applicability."

Qualifications in these two abilities, in addition to other relevant dynamics, particularly synergies and complementarities with important existing technology, are the prerequisites that certify a PV technology as potentially disruptive.

In this article we identify the main contenders that possess the potential to disrupt in the next 10–15 years as: 1) perovskite, 2) quantum-dot photovoltaics, and 3) concentrated photovoltaics.

Figure 2: Best research-cell efficiencies



Source: NREL (National Renewable Energy Laboratory, Colorado, USA)

3. The contenders

A shortlist of the most potentially disruptive emerging PV technologies over the next 10–15 years (from most to least technologically mature)

1. Cadmium Telluride (CdTe) Thin Film

Cadmium telluride is a stable crystalline compound formed from cadmium (Cd) and tellurium (Te) which has been used in research cells since the early 1970s.

Advantages and disruptive potential

Thin-film⁴ CdTe PV cells show particular disruptive potential owing to the fact that they can be manufactured quickly and relatively inexpensively compared to c-Si counterparts. The standing record research-cell efficiency for CdTe is 21.5%, achieved by Arizona-based *First Solar*. Further, the *First Solar* R&D department claims to have a clear line of sight to a 23.0% efficient thin-film cell. CdTe looks to be on the up in terms of cell efficiency, where c-Si stagnates⁵; hence, it could qualify as potentially disruptive.

Key challenges

The main drawback of CdTe technology is the highly toxic nature of one of its two main ingredients – cadmium, which is specifically listed in the European Restriction of Hazardous Substances⁶. Alongside stringent safety precautions during production, the environmental concern generated by this toxicity is somewhat mitigated by the recycling of CdTe solar modules at the end of their lifetime. Nevertheless, there are still uncertainties, and public opinion remains skeptical. The scarcity of the other main ingredient in CdTe, tellurium, is a further drawback. CdTe is very limited in its cross-industry applicability, which further limits its disruptive potential.

2. CIGS Thin Film

Copper indium gallium selenide (CIGS) is a solid solution of copper indium selenide (CuInSe) and copper gallium selenide

(CuGaSe) which has been actively researched since the mid-1970s.

Advantages and disruptive potential

This contender, which lost out to c-Si, has gained new ground and can be considered potentially disruptive once again. CIGS production has grown exponentially since 2007, and market-leading CIGS manufacturers such as *Solar Frontier* can be fairly confident about the future, given the potential for CIGS to reach c-Si levels of efficiency. They can also enjoy continued production cost reduction owing to advances such as low-temperature thin-film deposition techniques. CIGS has another advantage over c-Si (as do all such thin-film-capable PVs) in that it can be made with a high degree of physical flexibility if a plastic or flexible metal backing substrate is used. This flexibility is beneficial in terms of the diversity of applications for which these panels can be used.

Key challenges

However, although these applications are fitting when considering smaller private and highly exact commercial uses, they do not offer advantage in utility-scale PV plant applications in which features such as flexibility are all but irrelevant. If CIGS is to make it as a disruptor, it still needs to show its commercial viability in terms of cell efficiency.⁷ A further shortcoming, much like CdTe, is that CIGS has no compelling cross-industry applicability outside of solar energy.

3. Concentrated Photovoltaics (CPV)

Differing from conventional non-concentrated PV systems, concentrated PV (CPV) systems use lenses and curved mirrors to focus sunlight onto small but highly efficient solar cells.

⁴ "Thin-film" is a class of PV technologies that uses very thin depositions of semi-conductor materials compared to non-thin-film counterparts. Film thickness in thin-films varies from a few nanometers (nm) to tens of micrometers (µm) – much thinner than conventional c-Si, which uses silicon wafers of up to 200 µm.

⁵ There have been no fewer than eight world records for CdTe cell efficiency in the last five years compared to just two over the same period for standard mono- and multi-c-Si cells.

⁶ Although its use in PV panels specifically is exempted from these restrictions.

⁷ Currently CIGS lags at around ~13.0% efficiency in typical commercial applications.

Advantages and disruptive potential

Reviewing the latest *NREL*⁸ chart of the best PV research-cell efficiencies (Figure 2) to date, it is clear that CPV stands alone as the clear winner in this particular dimension. Specifically, in late 2014 a solar cell developed by the *Fraunhofer Institute for Solar Energy Systems* converted 46.0% of the sunlight hitting its surface into electricity. To contextualize, the highest recorded efficiency of a non-concentrated PV cell is 38.8%, and the industry-standard c-Si cells have only ever reached 27.6% (under concentrated sunlight) in the lab and typically operate at around 15.0% commercially (in which case the use of concentrated sunlight is currently rare).

Given how far ahead of the competition it is in terms of cell efficiency, it may be tempting to declare CPV as the PV technology of the future. Cell efficiency is a major determinant of what can be considered the optimal technology that can operate at the lowest unit-cost for a number of reasons. In the first order, the higher the cell efficiency, the less surface area you need to generate the same Wp⁹ of electricity, and hence, the smaller the quantity of solar cells that need to be manufactured. In the second order, cell efficiency indirectly reduces the costs associated with the balance of systems (BoS) and initial installation of the PV system.

Key challenges

CPV cell efficiencies were first officially recorded as early as 1983. Yet, the technology has never achieved mass commercial deployment, despite some early attempts¹⁰. Alas, this seeming super star still falls short on important cost factors, including the need for supplementary expensive accompanying components¹¹ and further added production expense, owing to greater design complexity and BoS costs. CPV also has little to zero cross-industry applicability. Further, CPV can only be used in regions with high direct normal irradiance (exposure to direct sunlight), and thus the potential market is limited. However, in regions suited to CPV¹², its extremely high proven efficiency is promising.

3a. Multi-Junction Solar Cells

In order to unlock the full potential of CPV technology, non-conventional multi-junction (MJ) solar cells must be employed. Differing from conventional single-junction solar cells, which are constituted of one layer of a single type of photovoltaic material, MJ solar cells involve the use of several different materials stacked in multiple layers, or “junctions”:

Advantages and disruptive potential

By focusing sunlight onto the surface area of a multi-junction solar cell in a CPV system, very high cell efficiencies can be realized – far above that which has been demonstrated by any single-junction counterpart. This is because the different materials in each junction absorb a unique portion of the electromagnetic spectrum of which sunlight is constituted. The right combination of materials can therefore capture far more energy than any single-junction cell. An MJ cell¹³ was used in the 46.0% all-time cell efficiency record cited above, integrated into a CPV system. Given that the maximum efficiency achieved by a single-junction cell is 29.1%, it is patently clear that this method of stacking materials has tremendous benefits. MJ cells fare well even in the absence of concentrated sunlight. *Spectrolab*¹⁴ demonstrated an MJ cell in November 2013 with a record 38.8% efficiency, the highest-ever efficiency without sunlight concentration.

Key challenges

However, of course, there are drawbacks. In the case of MJ cells, the drawbacks are cost related. With the conventional single-junction alternative, only one material is needed, whereas in an MJ cell every layer of material comes with its associated cost. Additionally, the materials that are used in the most efficient experimental lab MJ cells are expensive relative to the commercial c-Si benchmark. For instance, one popular material for one of the junctions in a high-efficiency MJ cell is gallium arsenide (GaAs), which is approximately 1,000 times more expensive than its silicon rival¹⁵. For this reason, these gallium-based MJ cells have been relegated to exotic applications such as satellites, for which the main cost is satellite launch. Therefore, the greater cost of gallium-based MJ cells is warranted, given their weight-to-output advantage relative to single-junction counterparts.

8 The *National Renewable Energy Laboratory*, located in Colorado, US.

9 Wp = watt peak. This value specifies the output power achieved by a solar cell under full solar radiation under set standard test conditions (STC).

10 For instance, *Soltec* attempted to commercialize CPV in its early stages, but has since divested its solar system business entirely.

11 All concentrated photovoltaics (CPV) require tracking technology that orients their solar modules directly towards the sun (with accuracy of $\pm 0.1\%$ to maintain at least 90.0% of the rated power output).

12 For instance, in the Middle East, North Africa, and parts of Australia where direct normal irradiance is highest.

13 Specifically, that cell was a wafer-bonded four-junction cell constructed using gallium indium phosphide, gallium arsenide, gallium indium arsenide phosphide, and gallium indium arsenide (GaInP/GaAs/GaInAsP/GaInAs).

14 A subsidiary of *Boeing*.

15 According to Aneesh Nainani at Stanford, who lectures on the topic of semiconductor manufacturing, an eight-inch wafer of gallium arsenide costs approximately \$5,000, whereas a typical silicon eight-inch wafer costs around \$5.

4. Organic Photovoltaics (OPV)

OPV aims to provide an Earth-abundant, low-energy PV power solution using organic polymer semi-conductor components.

Advantages and disruptive potential

Because of the all-carbon nature of the polymers used, a manufacturing technique called “roll-to-roll” processing is possible with OPV solar panels, which could result in very low-cost and high-volume production-line output. This, combined with the material’s physical flexibility and potential for transparency, makes it appealing for exotic uses such as building integration.

Key challenges

Despite having been actively researched since 2001, OPV research-cell efficiencies to date are still lagging around the 11.0% mark. Hence, significant viability barriers remain. Therefore, in terms of utility-scale PV electricity production, the outlook remains bleak because of persisting higher \$/W electricity production costs.

Some cross-industry synergies do exist for OPV, owing to its existence in the context of the broader scientific field of organic electronics. If this field were to grow in importance on the back of important further breakthroughs, OPV could get an advantageous nudge in the right direction in terms of cost and effectiveness.

5. Quantum-dot Photovoltaics

Quantum-dot photovoltaics are made up of PV cell designs that use quantum dots (nanocrystals made of semiconductor materials that are small enough to exhibit quantum mechanical properties) as the absorbing PV material.

Advantages and disruptive potential

Unlike the other technologies covered here that consist of “bulk” materials and have “fixed bandgaps”, quantum-dot cells have what is called a “tunable bandgap”. In lay terms, by varying the size of the quantum dots used, the type of solar energy that can be absorbed can be altered or “tuned”. This is useful since by including quantum-dot technology as one junction in a multi-junction cell, solar energy that is usually lost as heat can be captured. This cutting-edge technique has been dubbed “multiple exciton generation” (MEG) by the NREL, which is among the pioneers of quantum-dot PV research. The prospect of engineering such tunable bandgaps means that

once quantum-dot cells reach adequate efficiency (contingent on adequate R&D support from sponsoring institutions), the technology exhibits very high potential complementarities with other emerging PV technologies, including those surveyed in this article.

Key challenges

However, coming in with the lowest research-cell efficiency record to date (having been posting records since 2010), quantum-dot PV cells have much distance to cover before they can compete¹⁶. Nevertheless, this technology should by no means be written off or cast aside. Efficiency is but one of the determinants of \$/W potential, as well as other important factors, such as the ability of the material to play a complementary role with important existing technology. In this regard, quantum-dot technology shows high potential. Researchers have discovered potential applications for quantum dots, including in transistors, LEDs, LCD TV displays¹⁷, diode lasers, medical imaging, and quantum computing. As with silicon, if economies of scale arise for quantum-dot technologies in other industries, the associated cost reductions would greatly benefit the PV aspect of quantum-dot opportunities.

6. Perovskite

Perovskite cells, which are primarily lead-halide based, lend their name to the class of compounds which have the same type of crystal structure as calcium titanate, known as the “perovskite structure”.

Advantages and disruptive potential

Having been in very early stages of development throughout the 2000s, by 2009 this highly exotic material was only achieving efficiency levels of around 3.8%. This performance is paltry even compared to commercial c-Si average of around 15.0%. However, recent advances have resulted in significant step-improvements in performance, such that the best recorded efficiency in the lab now stands at 20.1%. This is a faster rate-of-efficiency increase than any of the other emerging PV technologies, as can be seen on the *NREL* efficiencies chart in Figure 2. The journal *Nature* validated the unprecedented character of this rapid improvement by hailing one of the perovskite pioneers, Henry J. Snaith, as one of 2013’s “ten people who mattered”.

If perovskite continues its rapid ascent up the efficiency records table, the material could turn out to be truly revolutionary. Given the importance of reaching efficiency levels of around 25.0%

¹⁶ Quantum-dot cells have yet to break through the 10.0% efficiency barrier, even in the lab.

¹⁷ The first commercial release of a product utilizing quantum dots was the Sony XBR X900A series of flat-screen TVs released in 2013. Sony used quantum dots to increase the color gamut of its LCD displays.

for commercial viability, this continued momentum is a key factor for success. However, perovskite fanatics should heed the cautionary tale of the CIGS story told in the introduction to this article, making sure they are sufficiently sensitive to the risky nature of presuming recurrent efficiency gains under technological uncertainty.

Key challenges

A considerable challenge for perovskite is its instability. Because it degrades quickly due to its high sensitivity to moisture, it must be enclosed in a watertight seal. Some cells fabricated in this way have performed stably for more than 1,000 hours, and experimental results suggest that perovskite cells can generate stable power for more than 2,000 hours under full sunlight. However, with the industry-standard 25-year warranty for solar panels (equating to ~54,000 hours under full sunlight), it is clear that finding an effective, inexpensive moisture barrier to counter this instability is crucial for perovskite PV commercial viability. Further, the cross-industry synergies of perovskite, if any exist, have yet to emerge. The only minor discovery made so far was a demonstration in 2014 showing that perovskite could generate laser light from visible light with 70% efficiency. If perovskite is to successfully rise to dominance in the PV market, it appears that it may need to do so without the external economies-of-scale advantage enjoyed by c-Si.

7. Graphene

Graphene is a highly exotic material at the cutting edge of development. It is made of a single layer of carbon atoms that are bonded together in a repeating pattern of hexagons.

Advantages and disruptive potential

Much excitement has arisen recently in the academic and corporate world concerning graphene and its plethora of potential applications, which include, but are not by any means limited to, PV. In terms of PV-specific applications, MIT researchers announced in June 2013 their aim to develop a new solar cell made from graphene in combination with molybdenum disulfide, which they say has the potential to achieve the absolute maximum power conversion possible by a PV cell¹⁸. In 2014 a different group at MIT developed a flexible transparent graphene-based electrode for graphene polymer solar cells, reporting it as the most efficient such electrode ever developed.

Outside of PV-specific applications, graphene has the potential to solve another major challenge in the PV business – energy

storage. Currently, due to the necessarily cyclical nature of PV electricity generation throughout the day and year, problems have emerged which are rooted in the constantly changing difference in the amount of energy output from that demanded of any PV plant. Consequently, reliable, efficient, and inexpensive storage capabilities are crucial to PV viability as a dependable major utility. In response to this distinctive problem, a Canadian renewable energy company, Sunvault Energy, has formed a joint venture to develop UCLA-patented graphene super-capacitor technology. This, it says, when incorporated with its own currently existing PV technology, will result in the creation of a device capable of generating, transferring, and storing energy in one unit, all because of the super-capacitating capabilities of graphene. If efficient-enough graphene PV cells can be developed, this means that PV plants constituted entirely of graphene-based components (i.e. both the generation and storage elements of a PV plant could be graphene-based) are possible in the future.

Elsewhere, in the corporate world, Apple and Samsung have both launched themselves into the graphene battle by doing what they know and do best, racing for patents. As a transparent material that conducts electricity (it can be stretched across the glass surfaces of phone screens to make them into touchscreens) and is thinner, stronger, and more flexible than any current material, graphene is ideal for futuristic gadgets such as bendable smartwatches or tablets that fold up into smartphones. Consequently, the two tech giants have been amassing arsenals of graphene-related patents, in part because sales of so-called “wearable computing devices” are predicted to rise 14-fold in the next five years (according to Bloomberg).

As a material with the potential of extremely high cross-industry applicability, graphene naturally invites comparison with silicon and its functional and industrial revolution over the past 40 years. The importance of this comparability should not be taken lightly. As emphasized earlier, technologies which exhibit cross-industry applicability and a high degree of complementarity with important existing technologies have additional inherent value magnitudes of difference beyond single-application technologies. If graphene as a PV technology can “piggy-back” on the growth of graphene as a material applied in other areas, it will experience a huge competitive advantage by free-riding its way down to and beyond the grid-parity tipping point of PV commercial viability, just as silicon did.

¹⁸ However, the unofficial record of graphene-based cell efficiencies to date is still down at the ~15.0% mark and not yet officially verified.

Key challenges

As it is currently in very early stages of development, it is really too early to say with certainty whether graphene will live up to the high expectations. However, if the world’s largest and most successful technology corporations, such as Apple, IBM, and Samsung, are spending serious amounts of time and money filing graphene-related patent applications (by 2013 Samsung, the purported leader, had filed over 400 graphene-related patents worldwide), the intimation of the huge potential of graphene is somewhat validated. If the material does live up to its hype, then PV graphene stands to benefit tremendously from the economies-of-scale advantage generated by the rapidly growing future graphene-manufacturing business.

The most important scientific developments in history often do not come as a result of actively pursuing a previously defined target, but serendipitously, in so-called “eureka” moments. The eureka moment for graphene came when UCLA PhD student Maher El-Kady attached a small light bulb to a graphene solar cell for two to three seconds under intense brightness, and the bulb continued to emit light for over five minutes after the external energy source had been switched off. This demonstrated for the first time the super-capacitor qualities of graphene. This discovery may prove to change the world significantly.

Figure 3: Short-listed emerging PV technologies and their disruptive potential

	Record cell efficiency to date	Theoretical maximum efficiency	Ability to beat c-Si in PV applications	Cross-industry applicability	Overall disruptive potential
Perovskite	20.1%	33.0%			
Quantum-dot	9.9%	66.0%			
CPV	46.0%	86.0%			
CdTe	21.5%	33.0%			
CIGS	21.7%	33.0%			
OPV	11.5%	24.0%			
Graphene	<i>Not yet officially proven</i>	60.0%	<i>Unclear</i>		<i>Unclear</i>
(Commercial c-Si)	20.8%	33.0%	N/A		

Source: Arthur D. Little analysis

4. The top-three emerging PV technologies of tomorrow

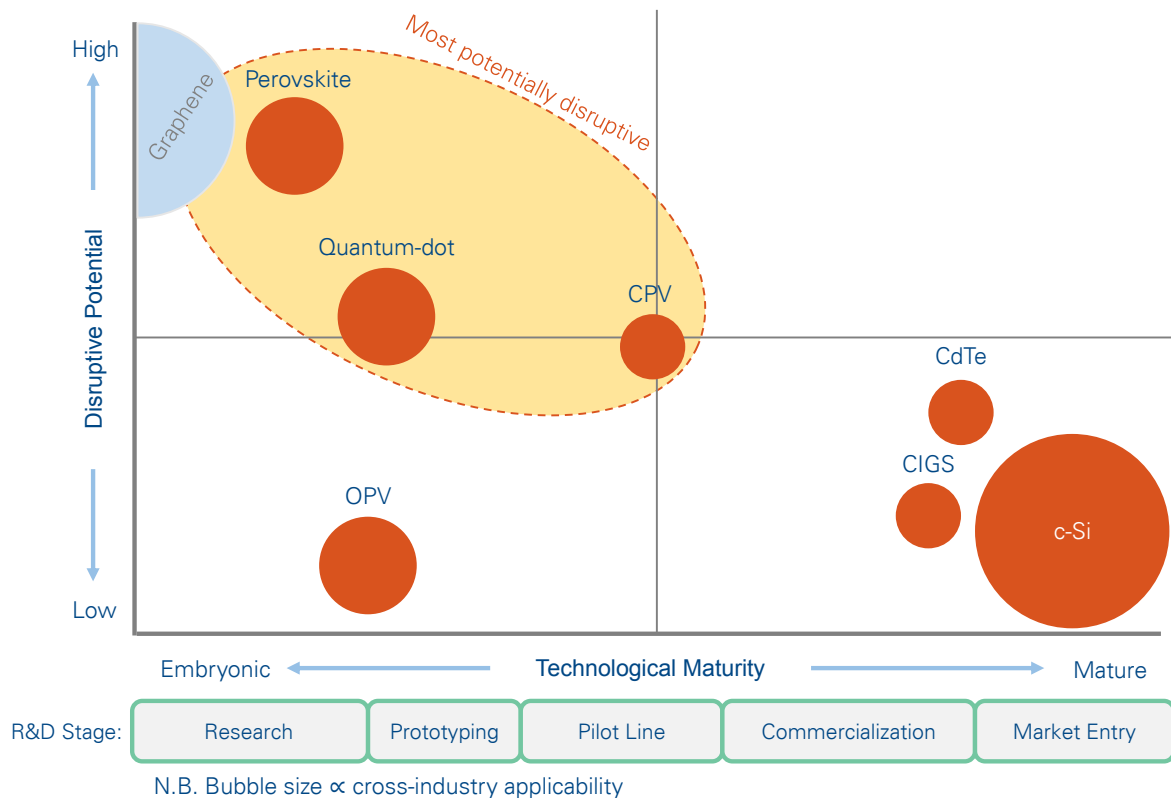
To recapitulate, we scrutinized each of seven selected emerging PV technologies in consideration of their ability to:

1. Compete with c-Si within PV applications
2. Venture successfully into new applications outside of the reach of c-Si.

Subsequently, our analysis suggests that: perovskite, quantum-dot photovoltaics and concentrated photovoltaics are the most potentially disruptive PV technologies in the coming 10–15

years.¹⁹ This is neither to undermine the daunting challenge of beating c-Si (as it continues to break new records for higher efficiencies), nor to say that these technologies are the ones that we expect to see rising rapidly up the PV installed capacity rankings in the next decade or so. Rather, these three, if given sufficient R&D attention, have the highest potential to change the PV game in the long term. They are all still in relatively early lab stages (perovskite and quantum-dot more so than concentrated photovoltaics), and require further dedicated attention to bring them to mass production (Figure 3 and 4).

Figure 4: Disruptive potential vs. technological maturity of candidate disruptors



Source: Arthur D. Little analysis

¹⁹ Although we think graphene is a very exciting material and definitely one to watch in the future given the multitude of applications which it can supposedly dominate, we concluded that at present the highly embryonic stages of its development, and the associated technological uncertainty, mean it cannot truly be said to be one of the most potentially disruptive as yet.

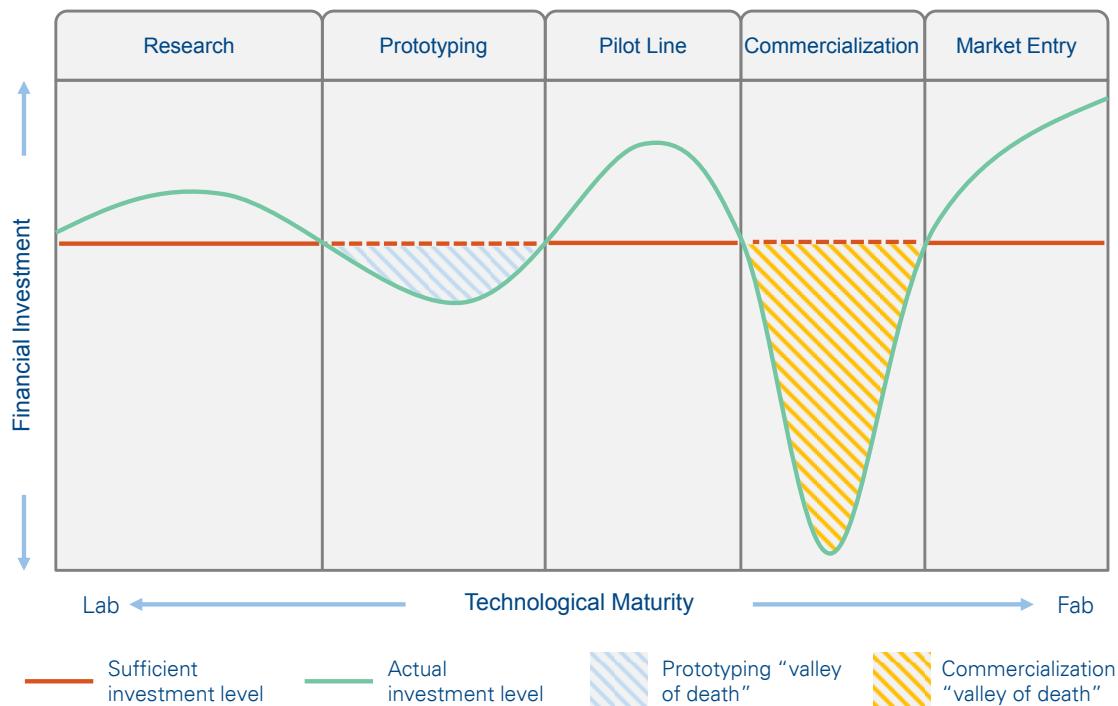
5. Cultivating potential winners – avoiding the valleys of death

Defining and sizing the two valleys

A graphic put out by the US Department of Energy's *SunShot Initiative* (Figure 5) demonstrates the implications of the belief that PV technologies with high disruptive potential have been identified. The graphic shows the typical path that PV technologies take from laboratory to fabrication, from high to low technological risks, and the magnitude of related necessary financial investments. Two zones of danger, or “valleys of death”, are highlighted.

1. The first is the *prototyping valley of death*:
 - Here, previously conceptual technology has made it to the prototyping stage and government funding starts to tail off as projects no longer qualify for conceptual R&D grants. However, venture capitalists have yet to be satisfied by the risk-return profile of the technology to jump in and provide financial support.
2. The second, and much more foreboding, valley of death comes after the technology has been through the pilot line but has yet to hit the production line. This is the *commercialization valley of death*:
 - *SunShot* suggests that this particular shortfall amounts to ~\$20mn for most PV technology development.
 - *SunShot* estimates this shortfall to be in the realm of \$50–100mn per PV technology.
 - It is where, for instance, CIGS nearly became extinct.
 - In order to traverse this chasm and to ensure that promising technologies make it from “lab to fab”, governments and other potential financial donors must exert more support to bring the technological potential to market and convert pipeline dreams into mainline reality.

Figure 5: PV technology “lab-to-fab” pathway and “valleys of death”



Source: US Department of Energy – SunShot Initiative (Adapted simplification)

6. Traversing the valleys of death

In order to traverse the valleys of death, besides providing financial muscle to develop the technologies, an enlightened, patient, long-term view is required in which concerned actors do not cave in to external demands for short-term returns. Doing so would result in the abandonment of fledgling, but potentially game-changing, emerging PV technologies. Scientific advancements of this scale often happen incrementally, so a time horizon of five years or greater is necessary.

Role of emerging countries in overcoming valleys of death

Until now, developed countries such as the US, Germany and Japan have carried the bulk of the burden in developing emerging PV technologies. That said, the current situation offers a unique opportunity to emerging countries such as China, India and the GCC (Gulf Co-operation Council) region, among others, to share efforts towards the development of these promising technologies. The emerging nations could play a pivotal role in their R&D efforts in developing these technologies alongside the increased investments earmarked for solar infrastructure development. There is plenty of strong recent evidence establishing the positive relationship between R&D activities and the growth of total factor productivity of economies, specifically for the ones in the GCC region.²⁰ The knowledge “spillovers” from engaging in high-tech R&D can greatly assist the productivity of human capital and other assets, ultimately driving growth of technologically intensive, “future proof”, and high value-added sectors of the economy. A prime example of this is, of course, the development of silicon as a semiconductor material, which has had tremendous impact on the computer and electronics industry.

R&D collaboration towards developing an innovation ecosystem

Moving beyond a single-country model of PV R&D to a model in which many countries pool resources into central, elite developmental laboratories may be a route to more rapid PV advancement. The benefits of such an international resource-pooling framework would diversify the technological and financial risk for any given country and foster synergies. Examples of existing international collaborative research projects are 1) *SERIIUS* (The Solar Energy Research Institute for India and the United States), led by the *Indian Institute of Science* and the *NREL*, and 2) *EUREC* (The Association of European Renewable

Energy Research Centers), an association of 43 renewable energy R&D groups across Europe. The combination of such borderless collaboration, with a competitive funding process as adopted by the US Department of Energy, could prove to be a powerful combination as the number of responding research organizations increases, resulting in better-quality research output and more rapid advancement.

An obvious candidate region for such a collaborative framework or “innovation ecosystem” for R&D efforts is the GCC. The fact that the Gulf countries not only are geographically clustered, but also exhibit economic and social homogeneity and have similar technical issues in deployment of solar energy (e.g. reduction of module efficiencies due to dust and heat in the desert climate) means that such cross-border collaboration should come with relative ease. Furthermore, local research infrastructure already exists in the field of solar energy, such as *Masdar*, *KAUST*, *KACST*, and the *Qatar Foundation*. Considering also the immense financial muscle of the region and recent intimations of a hankering for scientific prowess,²¹ the GCC emerges as a well-suited candidate for a central regional institute of PV research, a network of PV-based research clusters, or a combination thereof.

However, two key barriers exist to establishing the envisaged “innovation ecosystem” in the GCC. Firstly, notwithstanding the presence of research and academic institutions, the GCC is not known for its venture capital and private equity establishments – a key ingredient in the innovation ecosystem, a source of efficient funding and an agent of entrepreneurship. Secondly, an innovation ecosystem works well only when there is a strong demand for its products and services. In this regard, the GCC’s solar energy demand is limited compared to some other developed and emerging markets, such as India and China.

Other options to develop an innovation ecosystem include:

- Partnerships with R&D wings of major global technology companies and conglomerates (such as Samsung, GE, Siemens, Sharp, Panasonic)
- Relocation of major research institutes to the GCC through appropriate incentive mechanisms (such as Fraunhofer, NREL, or major universities).

All such options and many more should be carefully explored and pursued.

Summary and conclusions

In summary, although c-Si is the dominant Solar PV technology today, it may not remain so forever. Instead, the emerging PV technologies surveyed in this article could potentially disrupt and replace c-Si in the long term, depending on their ability to beat c-Si within PV applications and their cross-industry applicability. We believe the most promising of these emerging technologies are perovskite, quantum-dot photovoltaics, and concentrated photovoltaics.

However, there exist “valleys of death” (funding shortfalls) that imperil these emerging technologies. Although efforts such as the *SunShot* initiative in the US are attempting to traverse these valleys of death by sponsoring, developing, and patenting the leading PV technologies, further support from emerging markets that have the financial capacity would be extremely constructive. The GCC, for example, is well positioned to become such a center for solar PV innovation.

There are different options for the funding of these research efforts, and we believe that one which utilizes 1) incentive-compatible, technologically neutral funding methods (such as competitive funding opportunity announcements) and 2) cross-collaborative synergies across research organizations (whether academic or industrial) are most effective.

The goal of mitigating a CIGS-style near-extinction of these other technologies represents a challenging but highly praiseworthy goal for any willing and able sponsor. The stakes are too high; the world cannot afford to let emerging PV technologies go undeveloped. The time to act is now.

²⁰ Numerous recent scholarly articles address and confirm the positive relationship between R&D and total factor productivity. They include: “The impact of research and development on economic growth: The case of the MENA countries” (2015) by Lamia Ben Amor and Naceur Ben Zina of the University of Economics and Management of Sfax, Tunisia, “The modern drivers of productivity” (2014) by Francesco Venturini of the National Institute of Economic and Social Research, London, and “The Impacts of Research and Development Expenditures” (2011) by John J. Wetter of the University of Maryland.

²¹ For example, “Mission Hope” in the UAE, which aims to send an unmanned space probe to Mars by 2020. Further, KAUST (King Abdullah University of Science and Technology) in Saudi Arabia has one of the fastest-growing research and citation records of any university in the world, and the “Manama” project in Qatar aims to develop a cutting-edge, secure computer model that could allow the use of sensitive data on untrusted platforms without any security risk.

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