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Technology and Market Perspective for Indoor Photovoltaic Cells

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Indoor photovoltaic cells have the potential to power the Internet of Things ecosystem, including distributed and remote sensors, actuators, and communications devices. As the power required to operate these devices continues to decrease, the type and number of nodes that can now be persistently powered by indoor photovoltaic cells are rapidly growing. This will drive significant growth in the demand for indoor photovoltaics, creating a large alternative market for existing and novel photovoltaic technologies. With the re-emergence of interest in indoor photovoltaic cells, we provide an overview of this burgeoning field focusing on the technical challenges that remain to create energy autonomous sensors at viable price points and to overcome the commercial challenges for individual photovoltaic technologies to accelerate their market adoption.

Introduction to Indoor Photovoltaics

The early years of solar-power electronic devices saw photovoltaic (PV) cells used in extremely low power but relatively expensive consumer devices, where their cost could easily be absorbed. For example, the designers of a smartwatch that sold for ~$100 could afford to incorporate a cell costing a few dollars. Figure 1 outlines how, as the number and types of low-power electronic devices have expanded over the years, their costs have reduced. At the same time, the cost of PV cells has also been reducing and the performance increasing so that now we can sensibly power a range of electronic devices including wireless sensors, radio-frequency identification (RFID) tags, or Bluetooth beacons.

A significant portion of these new devices is part of the Internet of Things (IoT) ecosystem that promises large networks of connected devices collecting the big data upon which our medical, manufacturing, infrastructure, and energy industries will be monitored and optimized. Billions of wireless sensors are expected to be installed over the coming decade, with almost half to be located inside buildings.[1] Currently, the use of batteries to power these devices places significant constraints on their power consumption, where the range and frequency of data transmission are curtailed to achieve sufficient battery life, and the range of applications is also limited to the ones that allow battery replacement. Additional operation and maintenance costs are also incurred by providing replacement batteries.

Indoor photovoltaics (IPVs) have the potential to solve these hardware issues for a future IoT ecosystem, providing greater reliability and operational lifetimes in wireless sensor networks. Persistently powering individual nodes by harvesting ambient light using small ~cm^2 PV cells is becoming possible for more and more wireless technologies and devices. Characterizing IPV cells is a growing research field with the performance of a considerable number of different PV technologies having

Context & Scale

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Indoor photovoltaics has the potential to solve these hardware issues, providing greater reliability and operational lifetimes in wireless sensor networks. Persistently powering individual nodes by harvesting ambient light using small ~cm^2 photovoltaic cells is becoming possible for more and more wireless technologies and now been measured under artificial light sources such as incandescent, compact fluorescent (CFL), halogen, and light-emitting diode (LED) bulbs, with many example modules shown in Figure 2.[2–6] Given the interest in commercializing different PV cells in this growing market, we discuss here the outstanding research questions that must be answered by the indoor PV community to enable self-powered indoor-located IoT nodes. Following this introduction section, in The Expected Market for Indoor Photovoltaics, we highlight the expected growth of the wireless sensor market and how it will drive an explosion in the IPV market. In IPV Cell Performance, we outline the measured performance of IPV cells to date. In Commercial Challenges, we discuss some non-technical barriers to commercialization of IPV technologies including a requirement for a greater understanding of the costs when manufacturing low volumes of small IPV modules, toxicity concerns, and the stability of materials.

devices. Characterizing IPV cells is a growing research field with the performance of a considerable number of different PV technologies having now been measured under ambient light sources. Given the interest in commercializing different photovoltaic cells in this growing market, we discuss here the outstanding research questions that must be answered by the indoor photovoltaic community to enable self-powered, indoor-located IoT nodes.

The Expected Market for Indoor Photovoltaics

Realizing the vision of an IoT ecosystem, where billions of sensor nodes are connected to the network, is dependent on reducing the power used by individual nodes. Recent research trends in energy-efficient hardware and low-power protocols are tackling this, improving energy utility to increase network coverage, decrease latency, minimize wasted power, and improve data reliability.[7,8] A number of low-power network protocols have recently emerged covering indoor-located IoT applications, including LoRa, Sigfox, BLE, Zigbee, ANT, and numerous backscatter approaches. Each of these technologies is based on a different energy-saving strategy and network architecture; for example, LoRa nodes save energy by communicating their data to long distance gateways through a single hop,[9] Zigbee is designed to operate an efficient mesh network supporting several different topologies,[10] BLE has been designed as a low-energy version of Bluetooth suitable for point-to-point communication with high data rates and is even supported by smartphones,[11] Sigfox uses a cellular-like system over ultra-narrow band that requires low energy,[12] and backscatter technologies avoid the use of active radios by modulating and reflecting the incoming radio-frequency (RF) signal.[13] Clearly, one protocol does not fit all applications, but there is a clear trend to reduce the power consumption of different IoT technologies, which is in turn driving the rapid growth in the wireless sensor market.[1]

Figure 3 compares the average power requirement (averaged across sensing, communicating, and sleep modes) of these IoT communications protocols to the expected average power output of 10 cm^2 PV panels under different illumination conditions both indoors and outside. It can be seen that an IPV cell operating at its Shockley-Queisser limit of efficiency of 52%[14] under 1.5 W/m^2 (~500 lux) white-LED illumination with continuous 24 h irradiance provides enough power to operate many of the available IoT protocols designed for indoor use. Reducing the expected efficiency to 30%, similar to current record IPV efficiency measurements and, assuming the same light intensity but averaging for only an 8 h illumination per day, still provides adequate power for the same set of protocols, although the range and frequency of communication would need to be reduced for BLE, ANT, and Zigbee nodes. Reducing the light intensity further to 0.6 W/m^2 (~200 lux) indicates average power outputs of tens of μWs, where only the lowest-power-consuming backscatter technologies could be powered indefinitely. The higher 10–100 mW average power consumption of standard Bluetooth, SigFox, and LoRa systems means that the reasonably sized IPV cells would not suffice, and a small solar panel located outdoors is required to power individual nodes. Those technologies that require more than 100 mW of power, e.g., Wi-Fi and 5G small cells, would need

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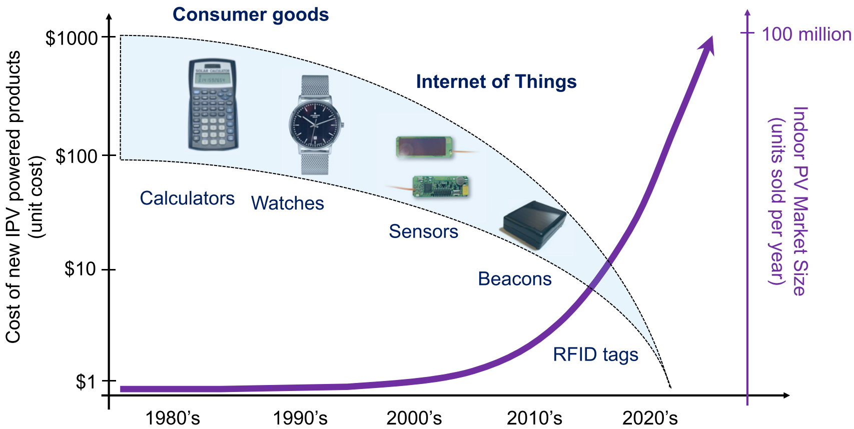

Figure 1. The History of IPV-Enabled Products

An overview of the cost of IPV-powered devices in the past and in the future taken from multiple locations including electronics purchasing websites, hobbyist websites, and catalogs as well as the market size for IPV cells.[15]

larger solar panels to power them autonomously. What is clear from the figure is that we have reached a point where the operation of multiple wireless technologies can be designed so that their average power used is less than that supplied by an indoor PV module, enabling persistent IoT nodes in buildings.

The Use of PV Cells to Power Indoor-Located Wireless Nodes Has the Potential to Drive an Explosion in the IPV Market

In 2017, the global market for IPV cells was $140 million,[15] insignificant compared to the global market for solar power modules, which was over $100 billion in the same year.[16] Still, as outlined in Figure 4A, driven by the growth of the market for IoT hardware, the annual IPV market size has the potential to be significant in its own right, reaching a predicted $850 million by 2023[15] and will likely continue to grow to a billion dollar market the following year. By 2023, the demand for PV energy harvesters is expected to reach 60 million devices per year.[15] This represents a 70% compound annual growth from today's market size, making it the fastest growing of all non-traditional PV markets as outlined in Figure 4B.

Given the unique conditions of indoor ambient light harvesting and the differences in cell requirements compared to outdoor cells, the market provides an important opportunity for PV manufacturers to diversify into markets with potentially higher margins or as a beach-head market during the commercialization of novel PV materials. For example, if recently discovered PV materials are established at a lab scale,[17] this market could reduce their time to revenue, increasing a thin-film PV startup's chance of success.[18] Given the annual revenues of First Solar and SunPower in the last 3 years are in a $1–4 billion range,[19,20] it is possible the market is large enough to establish a PV manufacturing industry outside of the traditional manufacturing hubs, helping to establish greater geographical diversity in PV manufacturing in the long term.

IPV Cell Performance

When located indoors with no access to solar irradiance, IPV cells harvest the energy emitted by artificial light sources, with the illumination intensity typically 3 orders of magnitude less than sunlight. Operating PV cells at such low illumination intensities, combined with the significant differences in incandescent, CFL, LED, halogen, and

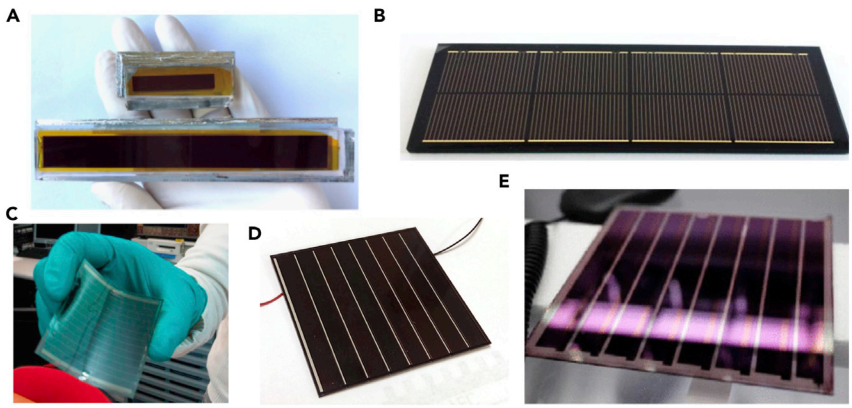

Figure 2. Examples of Recent IPV Modules
(A) Dye-sensitized IPV cells, (B) III-V IPV module, (C) flexible a-Si module, (D) an a-Si module on glass, and (E) an organic IPV module.
Reprinted with permission.[2–6]

the solar spectra, Figure 5A, have a significant impact on cell performance under indoor lighting conditions. For silicon solar cells, a practical efficiency limit of ~29% has been established, while a measured record of 26.7% under 1 sun has been achieved.[21] Estimating indoor performance is challenging because there is no universally accepted standard for indoor spectral quality and integrated irradiance (i.e., an indoor equivalent of the AM1.5G outdoor standard). Thus, it remains difficult to directly compare results given the different cell or module sizes and layouts used, the lack of masking of cells during measurements, the different illumination sources, and the use of non-calibrated power and lux meters, in essence, the lack of a standard IPV measurement practice, a challenge well summarized in Chen et al.[22]

For IPV, Rühle et al.[14] calculated theoretical maximum efficiencies for cells under 1 W/m^2 of CFL and LED illumination using the detailed balance limit of efficiency method with the results reproduced in Figure 5B. Given the narrower range of wavelengths available for conversion, the thermalization losses in an IPV cell are reduced, and they showed a ~2 eV cell is close to optimum for indoor light harvesting under both spectra with a maximum possible efficiency of 52%. In the same plot, we show the record efficiencies for IPV cells of various materials and band gaps measured under similar light sources with a clear trend shown where the majority of cells exhibit values significantly below the theoretical maximum expected for their band gap, with the leading GaAs and perovskite cells being the exceptions. Additionally, it is clear that most cells studied to date have band gaps significantly below the optimum, around 2.0 eV.

Considering the performance of individual cell technologies in more detail, silicon, the dominant cell material in the solar market with record solar efficiencies over 26%,[21] demonstrates ambient light harvesting efficiencies of ~8%[23,24] because of its narrow band gap, the dominance of Shockley Read Hall (SRH) recombination at low light intensities and low shunt resistance in tested devices.[24] There are a limited number of studies that look to adapt silicon PV cells to very low-light harvesting or CFL or LED spectra, presenting an interesting opportunity for the Si PV research community. To overcome the band gap limitation of crystalline silicon, amorphous-silicon (a-Si) has gained a foothold as one of the dominant indoor PV technologies. The wider 1.6 eV

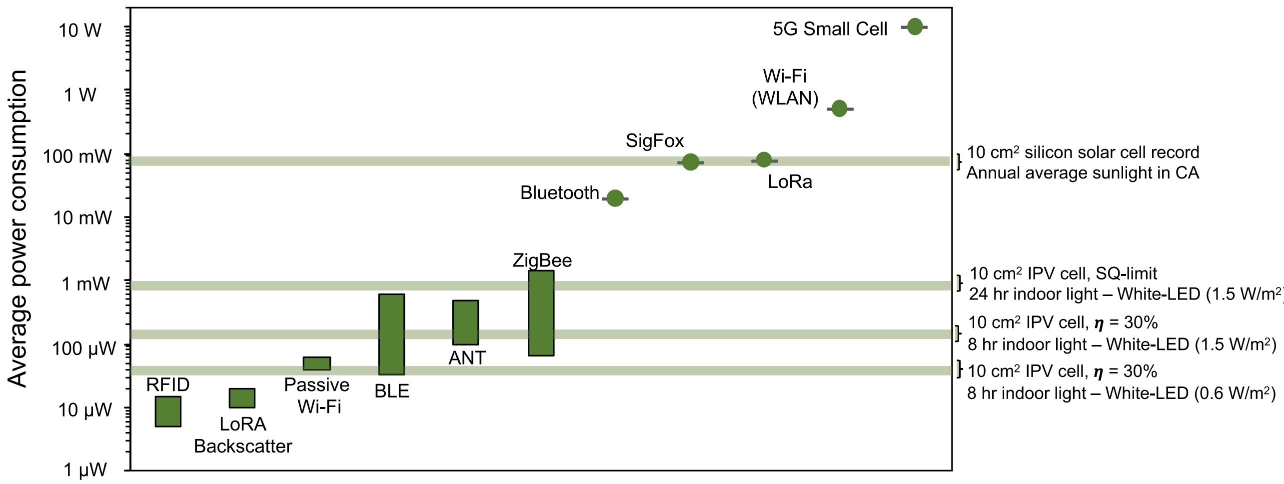

Figure 3. A Comparison between the Average Power Consumption of Wireless Protocols with the Average Power Produced by PV Cells of Different Efficiencies under Some Example Lighting Conditions

Power consumption values are taken from the measured and expected values for numerous backscatter and active radio nodes in Talla et al.[13] Measurements are taken by Dementyev et al.[49] for RFID, BLE, ANT, and ZigBee.[16] Protocols are under various communication ranges and frequencies, and the expected power requirements for future 5G small cells are as in Abrol et al.[50]

band gap is better matched to indoor light spectra and results in higher photovoltages than standard silicon cells with efficiencies closer to 10%.[24]

The most commercially successful PV technologies besides silicon are "thin-film" materials, especially CdTe and CIGS. CIGS studies under low-light conditions have shown that the devices tested suffer from low shunt resistance that significantly reduces their efficiency as light intensity decreases.[25] CdTe, however, has a band gap of 1.5 eV and is known to maintain high performance under diffuse radiation and low light.[26] Over the years, the technology itself has established a strong foothold in the PV market and is well characterized. There are, however, not many measurements available for CdTe cells illuminated by artificial spectra, with the only published result stating 10.9% power conversion efficiency (PCE) measured under 9.1 W/m^2 CFL illumination.[23] Significant progress has also been made using earth-abundant thin-film cells with efficiencies approaching 10% measured for $Cu_2ZnSn(S,Se)_4$ (CZTSSe) cells under low illuminance CFL and AM1.5G spectra.[27]

III-V light harvesters are strong contenders to power indoor wireless sensors because of the wider band-gap compositions possible and their record efficiencies under solar irradiance.[28] Under indoor light, GaAs cells have been shown to maintain their high performance with efficiencies over 20%[24] measured with cells on flexible substrates. Given that the optimum band gap for indoor light harvesting is closer to 2 eV, it would be expected that single-junction III-V cells with band gaps in the 1.8–1.9 eV range, such as $Ga_xIn_{1-x}P$ and $Al_xGa_{1-x}As$ PV cells would perform better than GaAs. In fact, studies comparing GaAs, GaInP, and/or AlGaAs cells under the CFL or LED spectra have shown very similar performance across the three cell types.[5,24,29]

IPV cells made from organic materials are emerging as contenders for commercialization as their absorption properties and architectures are adapted for ambient lighting. A number of organic photovoltaic (OPV) cells with low-light conversion efficiencies over 16% have now been demonstrated,[30] with the best cells in the literature demonstrating efficiencies of over 28%, achieved using a material with an optical band gap of ~1.8 eV.[31] Dye-sensitized IPV cells have also shown considerable

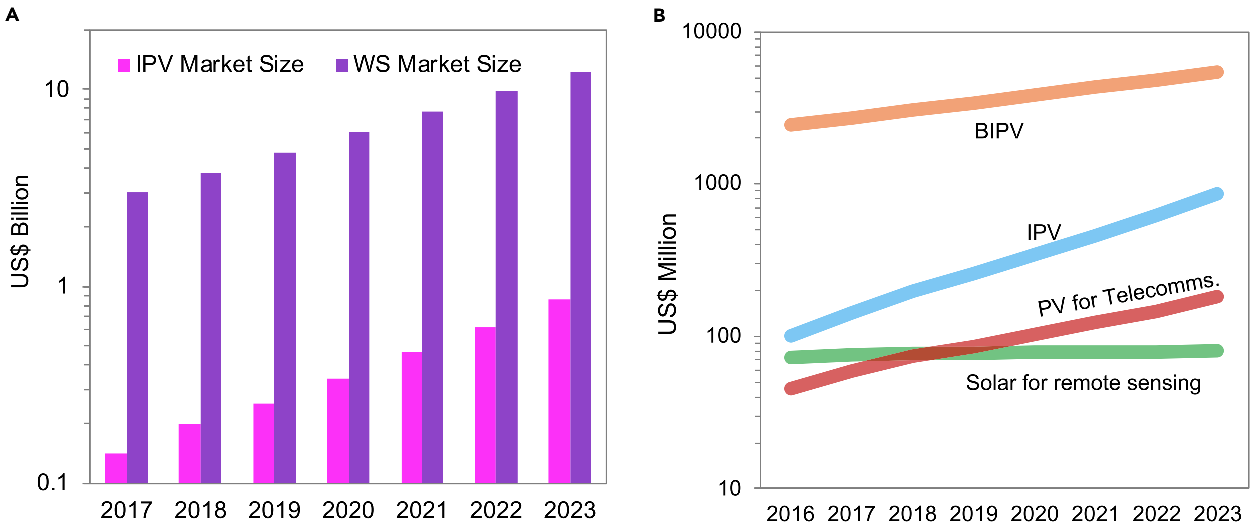

Figure 4. The Indoor Photovoltaics Market Size

(A) The projected size of the wireless sensor (WS) and indoor PV market in billions of dollars and (B) the expected size of alternative markets for photovoltaic technologies over the coming years collected from multiple market research reports.[15,16,51,52]

efficiency progress of late, with values over 27% measured under 200–1,000 lux light intensity, with one measurement of 31.8% demonstrated under 1,000 lux CFL illuminance.[2,32]

A very promising class of material with the potential to enter the PV market in the coming years is perovskite solar cells. These materials have exceptional defect tolerance[33,34] and photoluminescence quantum yields that are similar to the leading inorganic GaAs PV devices.[35] These cells have recently been tested at low light levels and exhibit performance similar to the best III-V and organic devices with multiple cell efficiencies exceeding 25%.[30,36,37] It is noticeable that while a number of perovskite PV companies have recently launched, to our knowledge, none are developing products for the IoT market and instead focus on, for example, silicon-based tandem cells (Oxford PV) or building-integrated PVs (Saule Technologies). Our market analysis in this paper makes it clear that the rapid growth of the indoor IoT market could provide an ideal jumping-off point for perovskite products, allowing a new PV company to establish customers, revenue, and credibility before establishing larger-scale solar-panel-manufacturing facilities. The lifetimes of remote sensors may be limited to less than 20 years because of the battery lifetime and communication protocol obsolescence, and indoor operating conditions are often less extreme and variable than outdoors.

It is worth noting the performance of flexible IPV cells and modules, as flexible formats are more adaptable and could allow easier integration with sensors or other IoT nodes while they could enable rapid prototyping if facile manufacturing methods such as printing are used. While some decrease in performance is seen for flexible cells, a-Si, perovskite, and dye-sensitized IPV cells on plastic have all demonstrated efficiencies of ∼10% and higher.[4,38–40] Additionally, the leading GaAs IPV cell results are all measured on flexible cells showing how >20% is possible for flexible indoor PV cells.

Commercial Challenges

Here, we discuss the non-technical barriers to commercialization of IPV technologies, including a requirement for a greater understanding of the costs when manufacturing

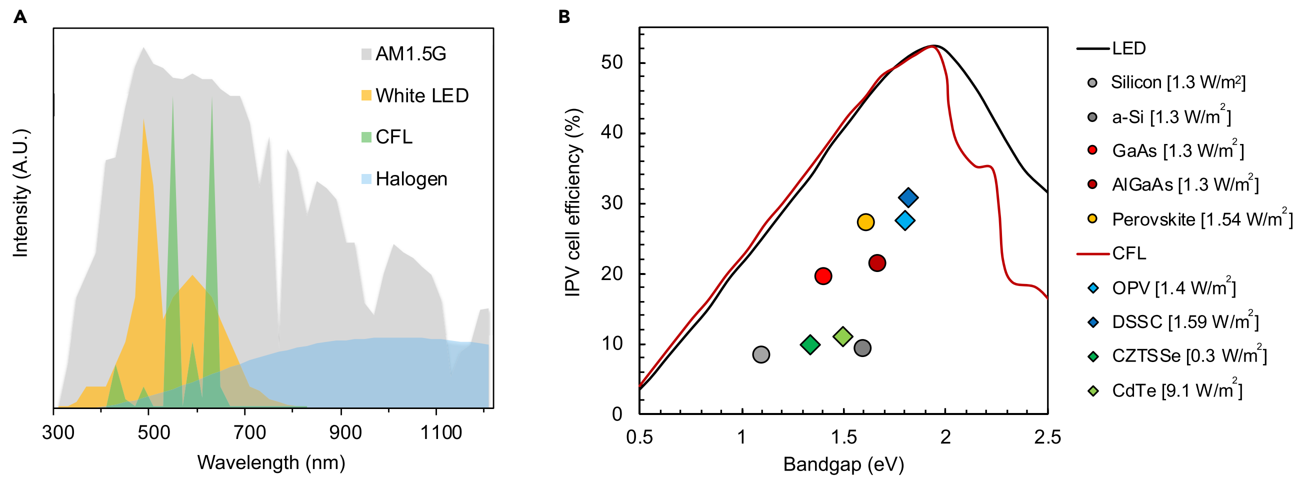

Figure 5. The Testing of Indoor Photovoltaic Cells

(A) Outline of the different light spectra under which photovoltaic device efficiency is evaluated including the standard solar spectrum (AM1.5G) and typical spectra from White LED, CFL, and Halogen sources.

(B) The maximum efficiencies versus band gap measured for indoor photovoltaic devices to date where circles represent measurements under LED bulbs and diamonds under CFL illumination.[2,23,24,27,31,36] We show only results measured at ~500 lux and provide the light intensity in W/m^2 in the legend for easy comparison. For the thin-film technologies, CZTSSe and CdTe, only measurements under CFL bulbs at light intensities much lower or higher than ~500 lux exist, and we provide these for completeness. Also shown are the maximum theoretical efficiencies calculated in Rühle et al.[14] using the detailed balance limit of efficiency method considering an LED spectrum (black line) and a CFL spectrum (red line) of 1 W/m^2.

low volumes of small IPV modules, cell stability, toxicity concerns, and market dynamics.

Manufacturing Costs

As well as system-level energy benefits, the economic cost of using indoor PV cells to power wireless sensors must be considered. In the literature to date, technoeconomic studies for PV cell technologies concentrate on manufacturing scales compatible with the production of large solar power modules (>1 m^2) for the utility scale or residential markets. Figure 6 summarizes relevant studies on the cost of manufacturing various solar power modules or cells, \$/cm^2, versus the volume of product produced per year, m^2/year. Also, on this plot, we show in the shaded region, the expected volume of this market over the next 5 years versus the price per unit as predicted by BCC Research[15] where, in summary, the market demand is expected to grow from ~100 m^2/year to 100,000 m^2/year with an almost order-of-magnitude drop in market price over the same period.

Firstly, it can be seen that the majority of cost models in the literature consider large annual productions over 100,000 m^2/year, which are typical production rates expected in solar panel factories (for example, 1,000,000 m^2/year is 180 MW/year for a module level efficiency of 18%). a-Si IPV cells are available in low volumes from electronic suppliers and currently sell at ~ 0.2 \$/cm^2.[41] Given that this technology currently dominates the market, it suggests that the actual price, when selling in large volumes to wireless sensor manufacturers, etc., are lower than the price available more generally. CdTe, as an established technology, and potential perovskite manufacturing costs are the range expected for IPV. The large variation in OPV costs is a result of the assumption of very low cost R2R manufacturing in some studies, while some studies do exist for lower volumes (10,000 m^2/year). Despite including some studies that look at lower-cost III-V cell manufacturing, for example, on silicon substrates or combining epitaxial-lift-off and substrate re-use, the cost of these cells is above the expected market price for IPV cells.

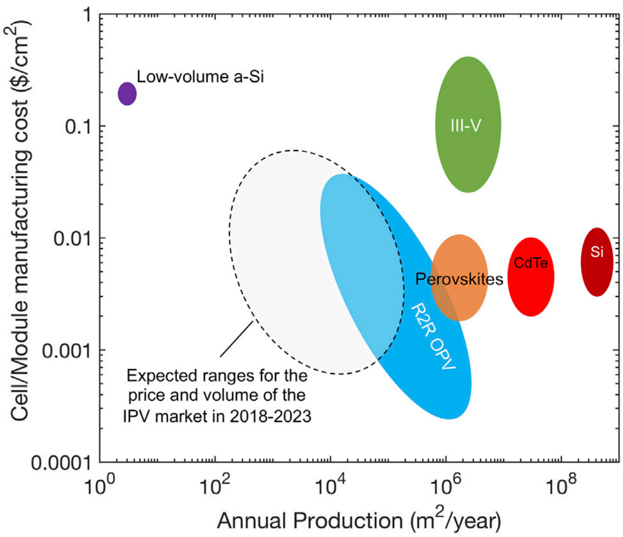

Figure 6. The Manufacturing Costs of Photovoltaic Cells and Modules

Predicted (III-V, OPV, and perovskite) and actual (a-Si, CdTe, and Si) PV module manufacturing cost versus the annual production (m^2/year) for multiple cell types and manufacturing processes.[53–65] Also indicated by the shaded region are the expected volume and maximum price point for the indoor PV market in 2018 and 2023, respectively (the maximum volume and price are found by assuming the typical module size in the market will be 1–20 cm^2 and using the 2.4 million and 60 million units sold and 0.06 and 0.014 $/unit prices given by BCC Research for 2018 and 2023, respectively).[15]

Economically, no clear technology emerges as the winner, as the benefits of economies of scale are present in the majority of technoeconomic cost models. For the low costs predicted in technoeconomic studies to translate to smaller production volumes, manufacturing processes with low factory capital expenditure (capex,[42]) will be required. Otherwise, the $\$/m^2$ of IPV technologies will be dominated by capex, as these fixed costs are recuperated across a relatively small volume of module sales.[43] The impact of capex warrants further attention from researchers to ensure their materials and methods used will result in low-cost IPV modules at low volumes.

Stability

Another consideration for indoor PV cells is their ability to provide power over the multi-year lifetime of the wireless sensor. The environment within which the system will be deployed can be expected to include office spaces, unheated warehouses, cold rooms, etc. Wireless sensing products deployed in these environments can expect to witness high and/or low temperatures and relative humidity throughout their deployment. For any technology that has been commercialized in the solar market, the degradation rate of the technology has been well established according to the standards of that industry with over 20-year lifetimes expected. It can be taken, therefore, that silicon, CdTe, and CIGS PV cells fabricated for indoor applications will maintain high performance throughout their life powering a wireless sensor indoors. Similarly, III-V solar cells have been used to power satellites in space for decades and can be considered to degrade at very low rates indoors. a-Si cells degrade because of the Staebler-Wronski effect losing up to 20% of their rated power output in the first few weeks of operation.[44] PV cells made from organic and perovskite materials are known to have higher degradation rates. Despite their low cost, organic cells have failed to achieve significant market penetration, as their low stability inhibits their widespread use in the large utility and residential-scale PV markets.[45] Perovskites, as a more recent breakthrough, have already achieved impressive efficiency results in a short space of time. Perovskite solar cell stability remains a concern, however, that could prevent successful commercialization if not addressed,[46] although indoor IoT requirements are less stringent than for outdoor power production.

Toxicity

The regulation of materials used to manufacture IoT products will fall under the restrictions on the use of certain hazardous substances (RoHS) legislation enacted in multiple jurisdictions. The regulations governing the use of hazardous materials differs across the world, and while a comprehensive analysis of all relevant regulations is not possible here, they could prevent the commercialization of certain IPV technologies. Lead, for example, is widely used in solder for silicon module stringing to provide reliable interconnects, where reliability critically impacts the levelized cost of solar electricity.[47] While it may not be necessary to use lead-based solders in smaller IPV modules, lead is also a principal component in the standard recipe for perovskite PV cells.[48] The use of Cd in thin-film solar modules has already led to the creation of recycling programs for panels at the end of their life. Deploying electronic devices containing arsenic, as in GaAs IPV cells, may not even be possible in some regions. For more information on this topic, we recommend readers start by referring to the EU's RoHS directive (ec.europa.eu/environment/waste/rohs_eee) and similar legislation in California (https://www.dtsc.ca.gov/HazardousWaste/rohs.cfm) as starting points.

Market Entry

Currently, multiple companies are commercializing IPV products including a-Si modules available from Panasonic, Solems (www.solems.com), and Powerfilm (www.powerfilmsolar.com), dye-sensitized IPV modules from GCell (www.gcell.com), and III-V products from Alta Devices (www.altadevices.com) and Lightricity (www.lightricity.co.uk). There is not, to our knowledge, any company providing thin-film or perovskite products despite their potential. As a final consideration for companies thinking to launch products using these or other material systems, we summarize our own findings on the role of timing in the commercialization of new IPV technologies. For entry into the IoT market, any sustainable company needs to innovate within a rapid timeframe. The IoT market is fragmented with many technological options across multiple application spaces. While a novel IPV module technology may initially be envisaged to target one application, it is likely that, within a short time frame, it will need adapting to ensure the combined market size of its addressable applications is large enough to support an early-stage company. Some form of modular approach that ensures the energy harvester and potential storage options can be rapidly adapted for trials with different communication protocols across different applications is required. By default, this requires an IPV-cell-manufacturing process that is easily configurable to new formats and can produce high efficiency and robust modules within a very short time frame.

Conclusions

By providing power persistence for a future IoT ecosystem, the use of PV cells to power indoor-located wireless nodes will drive significant growth in the IPV market over the coming years. As the power required to operate wireless devices continues to decline, the type and number of nodes that can now be persistently powered by indoor PV cells are rapidly growing. While smaller than the traditional solar power market, the 70% annual growth rate in the number of required devices, combined with the unique conditions of ambient light harvesting, can provide an important testing ground for less established or novel PV materials to test their commercialization potential.

Our specific recommendations to accelerate the development of IPV for IoT are as follows:

(1) To develop universally accepted standards for measuring IPV efficiency and also the energy requirements of wireless devices and communications protocols; that way, both technical communities can work independently today, and intersect down the road.
(2) To continue to develop IPV device and system architectures better suited for indoor energy yield. To date, the majority of measured IPV cells have exhibited efficiencies far below the theoretical maximum of 52% under 1 W/m^2 CFL or LED illumination, with leading results around 30%. One avenue to higher efficiency is to design and fabricate cells with wider band gaps, closer to the $\sim$2 eV optimum.
(3) To develop cost and business models for low-volume PV device manufacturing for the IoT end market, taking capex into consideration. For many new PV technologies, thin-film manufacturing costs should be low enough to enter this market, although the impact of capex on manufacturing costs at low volumes needs to be studied further.

A number of technologies have the potential to be utilized cost effectively in this growing market, providing an opportunity for new PV technologies to be commercialized, providing greater material diversity in the PV marketplace, and increasing the number of successfully commercialized energy technologies to help tackle climate change.

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