Technology and market perspective for indoor photovoltaic cells

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Abstract
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 is 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 the commercial challenges to be overcome for individual photovoltaic technologies to dominate this market.

I. 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, RFID tags or Bluetooth Beacons.

A significant portion of these new devices are 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 ones that allow battery replacement. Additional operation and maintenance costs are also incurred by providing replacement batteries.

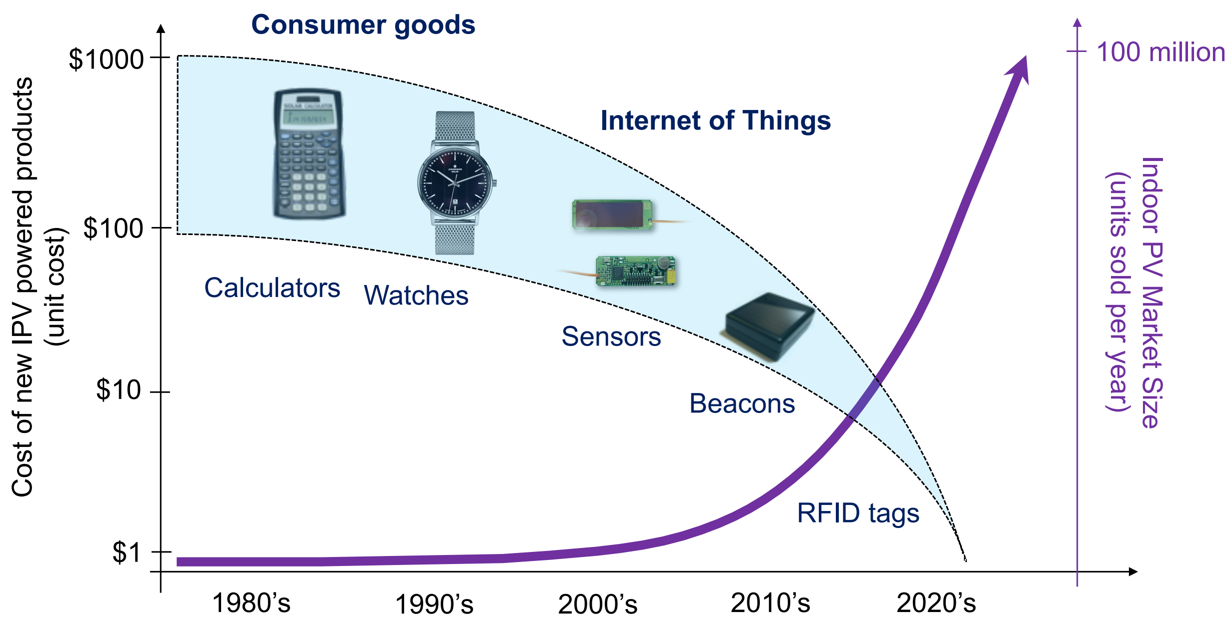
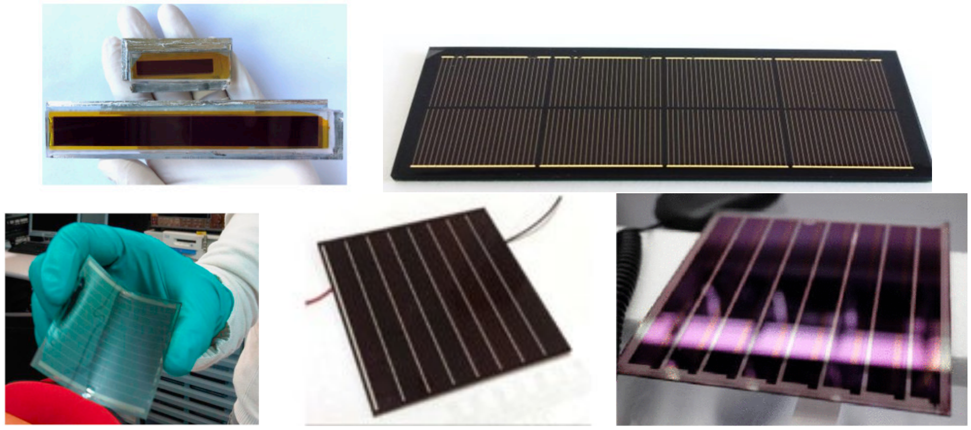


Figure 1: An overview of the cost of IPV powered devices in the past and in the future, as well as the market size for IPV cells.

Indoor Photovoltaics (IPV) has 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 photovoltaic 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 now been measured under artificial light sources such as incandescent, compact fluorescent (CFL), Halogen and LED bulbs with many example modules shown in Figure 2 [2]–[6]. Given the interest in commercializing different photovoltaic cells in this growing market, we discuss here what are the outstanding research questions that must be answered by the indoor photovoltaic (IPV) community to enable self-powered indoor-located IoT nodes. Following this introduction section, in Section 2, we highlight the expected growth of the wireless sensor market and how it will drive an explosion in the IPV market. In Section 3, we outline the measured performance of IPV cells to date. In Section 4 we discuss some non-technical barriers to commercialization of IPV technologies including a requirement for greater understanding of the costs when manufacturing low volumes of small IPV modules, toxicity concerns and the stability of materials.

(a) (b)



(c) (d) (e)

Figure 2: Examples of recent IPV modules presented in the literature: (a) dye-sensitized (b) III-V (c) flexible a-Si (d) a-Si and (e) an organic device.

II. 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]. 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 [8], Zigbee is designed to operate an efficient mesh network supporting several different topologies [9], 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 [10], Sigfox uses a cellular like system over ultra-narrow band that requires low energy [11] while backscatter technologies avoid the use of active radios by modulating and reflecting the incoming RF signal [12]. Clearly, one protocol does not fit all applications, but there is a clear trend to reduce the power consumption of different IoT technologies, that is in turn driving the rapid growth in the wireless sensor market [1].

Fig. 3 compares the average power requirement of these IoT communications protocols to the expected average power output of 10 cm^2 photovoltaic 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% [13] under 1.5 W/m^2 (~500 lux) white-LED illumination with continuous 24 hours irradiance provides enough power to operate many of the available IoT protocols designed for indoor use. Reducing the expected efficiency to the record IPV cell measurement of 35% [14], and assuming the same light intensity but averaging for only 8 hours 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. 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 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 their average power used is less than that supplied by an indoor PV module; enabling persistent IoT nodes in buildings.

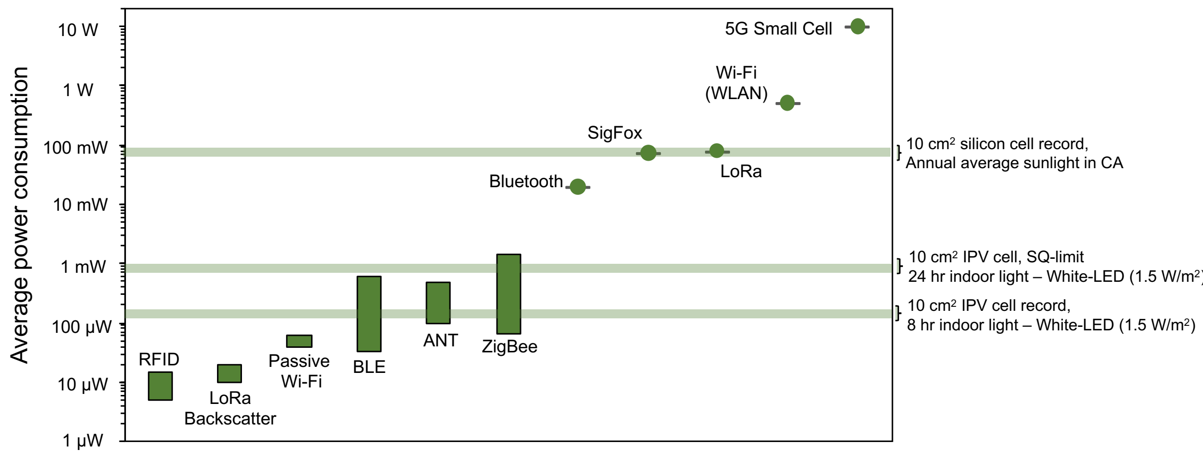
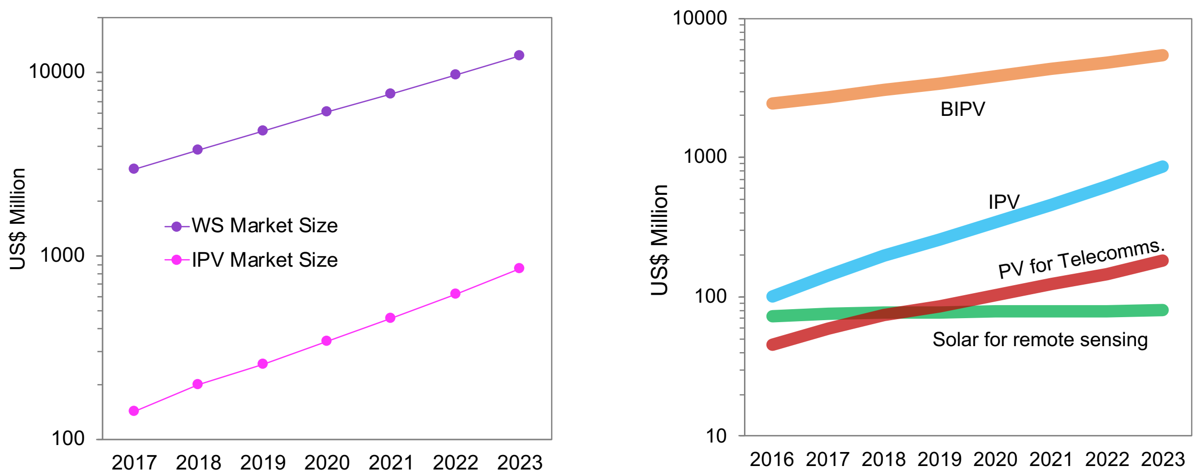


Figure 3: A comparison between the average power consumption of wireless protocols with the average power produced by PV cells of different efficiencies under some example lighting conditions. Power consumption values are taken from the measured and expected values for numerous backscatter and active radio nodes in [12], measurements taken by Dementyev et al. for RFID, BLE, ANT and ZigBee [15] protocols under various communication ranges and frequencies and the expected power requirements for future 5G small cells as in [16].

The use of PV cells to power indoor-located wireless nodes has the potential drive an explosion in the IPV market. In 2017, the global market for IPV cells was \$140 million, insignificant compared to the global market for solar power modules which was over \$100 billion in the same year [17]. Still, as outlined in Fig. 4 (a), 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 [18] and will likely continue to grow to a billion dollar market the following year. By 2023 the demand for photovoltaic energy harvesters is expected to reach 60 million devices per year. That represents a 70% compound annual growth from today's market size, making it the fasting growing of all non-traditional PV markets as outlined in Fig. 4(b).

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 photovoltaic materials. For example, if recently discovered PV materials are established at lab-scale [19], this market could reduce their time to revenue, increasing a thin-film PV startups chance of success [20]. Given the annual revenues of First Solar and Sunpower in the last 3 years are in a $1-4 Billion range [21], [22], it is possible the market is large enough to establish a PV manufacturing industry outside of the traditional manufacturing hubs in Asia, in the long-term helping to establish greater geographical diversity in PV manufacturing.



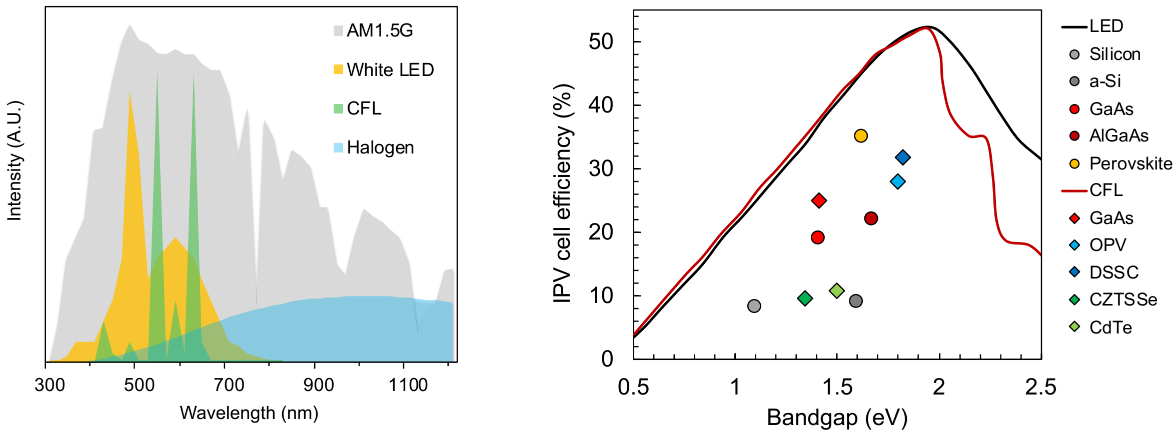
(a) (b)

Figure 4: (a) the projected size of the wireless sensor (WS) and indoor PV market in millions of dollars and numbers of IPV units sold and (b) the expected size of alternative markets for photovoltaic technologies over the coming years collected from multiple market research reports: [17], [18], [23], [24].

III. 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 3-4 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 the solar spectra, Fig. 5(a), 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 [25]. For IPV, Kasemann *et al*. [26] calculated theoretical maximum efficiencies for cells under 0.1 mW/cm^2 of CFL and LED illumination using the detailed balance limit of efficiency method with the results reproduced in Fig. 5 (b). 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 efficiency of 52% possible. In the same plot we show the record efficiencies for IPV cells of various material and bandgaps 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 bandgap, with the leading GaAs and perovskite cells being the exceptions. Additionally, it is clear that most cells studied to date have bandgaps significantly below the optimum around

2.0 eV. Below we provide a summary of these results but it remains difficult to directly compare results given the lack of a standard IPV measurement practice, a challenge well summarized in [27].



(a) (b)

Figure 5: (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 bandgap measured for indoor photovoltaic devices to date where circles represent measurements under LED bulbs and diamonds under CFL illumination [2], [14], [28]–[31]. Also shown are the maximum theoretical efficiencies calculated in [26] using the detailed balance limit of efficiency method considering an LED spectrum (black line) and a CFL spectrum (red line).

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% [25] demonstrates ambient light harvesting efficiencies under 8% [28], [29] owing to its narrow bandgap, the dominance of Shockley Read Hall (SRH) recombination at low light intensities and low shunt resistance in tested devices [32]. To overcome the bandgap limitation of crystalline silicon, amorphous-silicon (a-Si) has gained a foothold as one of the dominant indoor photovoltaic technologies. The wider 1.6 eV bandgap is better matched to indoor light spectra and results in significantly higher photocurrents than standard silicon cells with efficiencies closer to 10% [28]

The most commercially successful PV technologies besides silicon are 'thin-film' materials, especially CdTe and CIGS. CIGS studies under low-light conditions have shown the devices tested suffered from low shunt resistance that significantly reduced their efficiency as light intensity decreases [31]. CdTe, however, has a bandgap of 1.5 eV and is known to maintain high performance under diffuse radiation and low light [33]. 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 [29]. Significant progress has also been made using earth abundant thin-film cells with efficiencies approaching 10% measured for CZTSSe cells under low illuminance CFL and AM1.5G spectra [30].

III-V light harvesters are strong contenders to power indoor wireless sensors owing to the wider bandgap compositions possible and their record efficiencies under solar irradiance [34]. Under indoor light, GaAs cells have been shown to maintain their high performance with efficiency measurements over 20% [28]. Given the optimum bandgap for indoor light harvesting is closer to 2 eV, it would be expected that single-junction III-V cells with bandgaps in the 1.8-1.9 eV range like $Ga_xIn_{1-x}P$ and $Al_xGa_{1-x}As$ PV cells would perform better than GaAs. In fact, studies comparing GaAs, GaInP and/or AlGaAs cells under CFL or LED spectra have shown very similar performance across the three cell types [28], [35].

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 OPV cells with low-light conversion efficiencies over 16% have now been demonstrated with one cell with an optical band gap around ~1.8eV achieving 28% [36]. Dye-sensitized devices have shown considerable progress in recent years, in terms of IPV efficiency, with remarkably high efficiencies over 28% under 200-1000 lux light intensity and a record of 31.8% recently demonstrated under 1000 lux CFL illuminance [2], [37].

The most promising class of material with the potential to enter the photovoltaic market in the coming years are perovskite solar cells. What makes these materials stand out are their tolerance to defects and optoelectronic properties that are similar to the leading inorganic GaAs photovoltaic devices. 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% and a remarkable record of 35.2% recently demonstrated [14], [36].

While great progress is being made, there is clearly room to improve the efficiency of IPV cells to reach their theoretical maximum, however, it should be noted that to create autonomous sensors, the power supplied by the energy harvester is just one of many parameters that must be considered, with the supply voltage of similar importance to minimize losses or remove the need for power management electronics [38].

IV. COMMERCIAL CHALLENGES

Here we discuss the non-technical barriers to commercialization of IPV technologies including a requirement for greater understanding of the costs when manufacturing low volumes of small IPV modules, cell stability, toxicity concerns and market dynamics.

i. Manufacturing costs

As well as system-level energy benefits, the economic cost of using indoor photovoltaic cells to power wireless sensors must be considered. In the literature to date, technoeconomic studies for photovoltaic cell technologies concentrate on manufacturing scales compatible with the production of large solar power modules (> $1m^2$) for the utility scale or residential markets. Figure 6 summaries 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 [18] 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%). Amorphous-silicon IPV cells are available in low volumes from electronic suppliers and currently sell at ~ 0.2 \$/cm^2 [39]. Given 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 are 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 are above the expected market price for IPV cells.

Economically, no clear technology winner emerges 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, low-capex manufacturing processes will be required []. Otherwise the \$/m^2 of IPV technologies will be dominated by capital expenditure as these fixed costs are recuperated across a relatively small volume of module sales. 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.

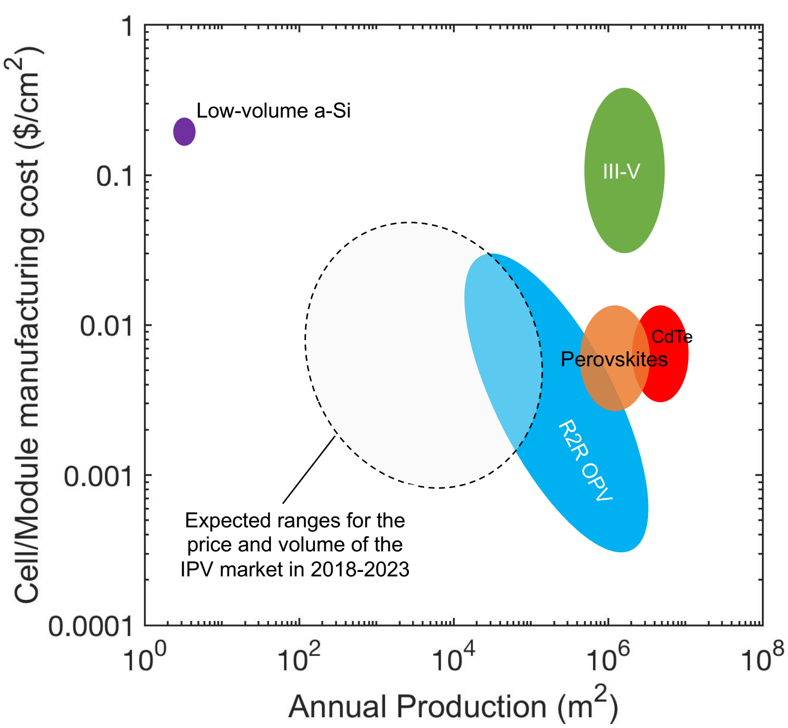


Figure 6: Predicted solar module manufacturing cost versus the scale of production (m^2/year) for multiple cell types and manufacturing processes [40]–[52]. Also indicated by the shaded region is the expected volume and maximum price point for

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).

ii. Stability

Another consideration for indoor photovoltaic 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 photovoltaic 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. Amorphous-silicon cells degrade due the Staebler-Wronski effect losing up to 20% of their rated power output in the first few weeks of operation [53]. The technologies known to exhibit lower resistance to degradation are organic and perovskite materials. While both technologies promise extremely low cost, organic cells have been on the market for a number of years but have failed to achieve significant market penetration as their low degradation rates inhibit commercialization [54]. Perovskites, as a more recent breakthrough, have already achieved impressive efficiency results in a short space of time while recently there has been a recognition that the inherent instability of these materials needs to be investigated and reduced [55].

iii. Toxicity

Electronics products in buildings will be subject to restrictions on hazardous substances that vary depending on the region of the world where the technology will be deployed. While a comprehensive analysis of global regulations is not possible here, it is a constraint worth considering for a number of PV technologies. For example, for silicon solar panels, lead-based solders are still used in module stringing as they provide more reliable interconnects, where reliability critically impacts the levelized cost of electricity [56]. While it may not be necessary to use lead-based solders in smaller IPV modules, lead is also present in the standard perovskite solar cell recipe although lead-free alternatives remain an active area of research [57]. Additional toxic materials found in photovoltaic materials include Cadmium in CdTe and Arsenic in GaAs. Therefore, the use of toxic materials in IPV cells and the regulations that restrict them need to be well understood in each geographic market segment.

iv. Market entry

As a final consideration 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 very rapid timeframe (perhaps as short as one-week) for two primary reasons: (1) commoditization-proofing and (2) customers can have rapidly moving goal posts in early-stage markets with various requests for different communications protocols and sensing standards. The IoT market itself is fragmented with many technology 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 are 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 communications 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.

V. Conclusion

By solving hardware issues 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 photovoltaic cells is rapidly growing. While small compared to 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. To date the majority of measured IPV cells have exhibited efficiencies far below the theoretical maximum of 52% under 0.1 mW/cm^2 CFL or LED illumination, with a maximum of 35% measured using a perovskite IPV cell. It is clear, higher efficiency will be achieved by designing and fabricating cells with wider bandgaps. While the record efficiency was measured in a device with a 1.6 eV bandgap, the optimum for CFL and LED illuminance is closer to 2 eV but measurements of such wide bandgap PV cells under ambient lighting are currently lacking. Additionally, 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. Nevertheless, a number of technologies can potentially be utilized in this growing market; providing an opportunity for new PV technologies to be commercialized, providing greater materials diversity in the PV marketplace, and giving us a larger number of successfully commercialized energy technologies to help tackle climate change.

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