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Study the Efficiency of Thin Film Solar Cell

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ABSTRACT: Thin-film solar cells are made by depositing one or more thin layers (thin films or TFs) of photovoltaic material onto a substrate, such as glass, plastic or metal. Thin-film solar cells are typically a few nanometers (nm) to a few microns (μm) thick—much thinner than the wafers used in conventional crystalline silicon (c-Si) based solar cells, which can be up to 200 μm thick. Thin-film solar cells are commercially used in several technologies, including cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and amorphous thin-film silicon (a-Si, TF-Si).

Keywords: Thin film solar cells, photovoltaic, plastic, metal, wafers, crystalline, silicon, cadmium telluride, copper indium gallium diselenide, amorphous thin film silicon

I. INTRODUCTION

Solar cells are often classified into so-called generations based on the active (sunlight-absorbing) layers used to produce them, with the most well-established or first-generation solar cells being made of single- or multi-crystalline silicon. This is the dominant technology currently used in most solar PV systems. Most thin-film solar cells are classified as second generation, made using thin layers of well-studied materials like amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), or gallium arsenide (GaAs). Solar cells made with newer, less established materials are classified as third-generation or emerging solar cells. This includes some innovative thin-film technologies, such as perovskite, dye-sensitized, quantum dot, organic, and CZTS thin-film solar cells. Thin-film cells have several advantages over first-generation silicon solar cells, including being lighter and more flexible due to their thin construction.¹ This makes them suitable for use in building-integrated photovoltaics and as semi-transparent, photovoltaic glazing material that can be laminated onto windows. Other commercial applications use rigid thin film solar panels (interleaved between two panes of glass) in some of the world's largest photovoltaic power stations. Additionally, the materials used in thin-film solar cells are typically produced using simple and scalable methods more cost-effective than first-generation cells², leading to lower environmental impacts like greenhouse gas (GHG) emissions in many cases. Thin-film cells also typically outperform renewable and non-renewable sources for electricity generation in terms of human toxicity and heavy-metal emissions. Despite initial challenges with efficient light conversion, especially among third-generation PV materials, as of 2017 some thin-film solar cells have reached efficiencies of up to 29.1% for single-junction thin-film GaAs cells, exceeding the maximum of 26.1% efficiency for standard single-junction first-generation solar cells. Multi-junction concentrator cells incorporating thin-film³ technologies have reached efficiencies of up to 47.6% as of 2017.^[1] Still, many thin-film technologies have been found to have shorter operational lifetimes and larger degradation rates than first-generation cells in accelerated life testing, which has contributed to their somewhat limited deployment.⁴ Globally, the PV marketshare of thin-film technologies remains around 5% as of 2017.^[2] However, thin-film technology has become considerably more popular in the United States, where CdTe cells alone accounted for nearly 30% of new utility-scale deployment in 2017.^[3]

In a typical solar cell, the photovoltaic effect is used to generate electricity from sunlight. The light-absorbing or "active layer" of the solar cell is typically a semiconducting material, meaning that there is a gap in its energy spectrum between the valence band of localized electrons around host ions and the conduction band of higher-energy electrons which are free to move throughout the material. For most semiconducting materials at room temperature, electrons which have not gained extra energy from another source will exist largely in the valence band, with few or no electrons in the conduction band.⁵ When a solar photon reaches the semiconducting active layer in a solar cell, electrons in the valence band can absorb the energy of the photon and be excited into the conduction band, allowing them to move freely throughout the material. When this happens, an empty electron state (or hole) is left behind in the valence band. Together, the conduction band electron and the valence band hole are



called an electron-hole pair. Both the electron and the hole in the electron-hole pair can move freely throughout the material as electricity.^[28] However, if the electron-hole pair is not separated, the electron and hole can recombine into the lower-energy original state, releasing a photon of the corresponding energy. In thermodynamic equilibrium, the forward process (absorbing a photon to excite an electron-hole pair) and reverse process (emitting a photon to destroy an electron-hole pair) must occur at the same rate by the principle of detailed balance.⁶ Therefore, to construct a solar cell from a semiconducting material and extract current during the excitation process, the electron and hole of the electron-hole pair must be separated. This can be achieved in a variety of different ways, but the most common is with a p-n junction, where a positively doped (p-type) semiconducting layer and a negatively doped (n-type) semiconducting layer meet, creating a chemical potential difference which draws electrons one direction and holes the other, separating the electron-hole pair.^[29] This may instead be achieved using metal contacts with different work functions, as in a Schottky-junction cell.⁷

In a thin-film solar cell, the process is largely the same but the active semiconducting layer is made much thinner. This may be made possible by some intrinsic property of the semiconducting material used that allows it to convert a particularly large number of photons per thickness.⁸ For example, some thin-film materials having a direct bandgap, meaning the conduction and valence band electron states are at the same momentum instead of different momenta as in the case of an indirect bandgap semiconductor like silicon. Having a direct bandgap eliminates the need for a source⁹ or sink of momentum (typically a lattice vibration, or phonon), simplifying the two-step process of absorbing a photon into a single-step process.^[30] Other thin-film materials may be able to absorb more photons per thickness simply due to having an energy bandgap that is well-matched to the peak energy of the solar spectrum, meaning there are many solar photons of the correct energy available to excite electron-hole pairs.¹⁰

In other thin-film solar cells, the semiconducting layer may be replaced entirely with another light-absorbing material, for example an electrolyte solution and photo-active dye molecules in a dye-sensitized solar cell or by quantum dots in a quantum dot solar cell.¹¹

Thin-film technologies reduce the amount of active material in a cell. The active layer may be placed on a rigid substrate made from glass, plastic, or metal or the cell may be made with a flexible substrate like cloth. Thin-film solar cells tend to be cheaper than crystalline silicon cells and have a smaller ecological impact (determined from life cycle analysis).^[31] Their thin and flexible nature also makes them ideal for applications like building-integrated photovoltaics. The majority of film panels have 2-3 percentage points lower conversion efficiencies than crystalline silicon,^[32] though some thin-film materials outperform crystalline silicon panels in terms of efficiency. Cadmium telluride (CdTe),¹² copper indium gallium selenide (CIGS) and amorphous silicon (a-Si) are three of the most prominent thin-film technologies. Cadmium telluride (CdTe) is a chalcogenide material that is the predominant thin film technology. With about 5 percent of worldwide PV production,¹³ it accounts for more than half of the thin film market. The cell's lab efficiency has also increased significantly in recent years and is on a par with CIGS thin film and close to the efficiency of multi-crystalline silicon as of 2013.³³ Also, CdTe has the lowest energy payback time of all mass-produced PV technologies, and can be as short as eight months in favorable locations.^{[33]:31} CdTe also performs better than most other thin-film PV materials across many important environmental impact factors like global warming potential and heavy metal emissions.^[34] A prominent manufacturer is the US-company First Solar based in Tempe, Arizona, that produces CdTe-panels with an efficiency of about 18 percent.^[35]

Although the toxicity of cadmium may not be that much of an issue and environmental concerns completely resolved with the recycling of CdTe modules at the end of their life time,^[36] there are still uncertainties^[37] and the public opinion is skeptical towards this technology.^{[38][39]} The usage of rare materials may also become a limiting factor to the industrial scalability of CdTe thin film technology. The rarity of tellurium—of which telluride is the anionic form—is comparable to that of platinum in the earth's crust and contributes significantly to the module's cost.^[40]

A copper indium gallium selenide solar cell or CIGS cell uses an absorber made of copper, indium, gallium, selenide (CIGS), while gallium-free variants of the semiconductor material are abbreviated CIS. Like CdTe, CIGS/CIS is a chalcogenide material. It is one of three mainstream thin-film technologies, the other two



being cadmium telluride and amorphous silicon, with a lab-efficiency above 20 percent and a share of 0.8 percent in the overall PV market in 2018.^[41] A prominent manufacturer of cylindrical CIGS-panels was the now-bankrupt company Solyndra in Fremont, California. Traditional methods of fabrication involve vacuum processes including co-evaporation and sputtering. In 2008, IBM and Tokyo Ohka Kogyo Co., Ltd. (TOK) announced they had developed a new, non-vacuum, solution-based manufacturing process for CIGS cells and are aiming for efficiencies of 15% and beyond.^[42]

Hyperspectral imaging has been used to characterize these cells. Researchers from IRDEP (Institute of Research and Development in Photovoltaic Energy) in collaboration with Photon etc., were able to determine the splitting of the quasi-Fermi level³⁴ with photoluminescence mapping while the electroluminescence data were used to derive the external quantum efficiency (EQE).^{[43][44]} Also, through a light beam induced current (LBIC) cartography experiment, the EQE of a microcrystalline CIGS solar cell could be determined at any point in the field of view.^[45]

As of April 2019, current conversion efficiency record for a laboratory CIGS cell stands at 22.9%.^[46]

Amorphous silicon (a-Si) is a non-crystalline, allotropic form of silicon and the most well-developed thin film technology to-date. Thin-film silicon is an alternative to conventional wafer (or bulk) crystalline silicon. While chalcogenide-based CdTe and CIS thin films cells have been developed in the lab with great success, there is still industry interest in silicon-based thin film cells. Silicon-based devices exhibit fewer problems than their CdTe and CIS counterparts such as toxicity and humidity issues with CdTe cells and low manufacturing yields of CIS due to material complexity. Additionally, due to political resistance to the use non-"green" materials in solar energy production, there is no stigma in the use of standard silicon.²²

This type of thin-film cell is mostly fabricated by a technique called plasma-enhanced chemical vapor deposition. It uses a gaseous mixture of silane (SiH₄) and hydrogen to deposit a very thin layer of only 1 micrometre (µm) of silicon on a substrate, such as glass, plastic or metal, that has already been coated with a layer of transparent conducting oxide. Other methods used to deposit amorphous silicon on a substrate include sputtering and hot wire chemical vapor deposition techniques.^[48]

a-Si is attractive as a solar cell material because it's an abundant, non-toxic material. It requires a low processing temperature and enables a scalable production upon a flexible, low-cost substrate with little silicon material required. Due to its bandgap of 1.7 eV, amorphous silicon also absorbs a very broad range of the light spectrum, that includes infrared and even some ultraviolet and performs very well at weak light³³. This allows the cell to generate power in the early morning, or late afternoon and on cloudy and rainy days, contrary to crystalline silicon cells, that are significantly less efficient when exposed at diffuse and indirect daylight.^[44] However, the efficiency of an a-Si cell suffers a significant drop of about 10 to 30 percent during the first six months of operation. This is called the Staebler-Wronski effect (SWE) – a typical loss in electrical output due to changes in photoconductivity and dark conductivity caused by prolonged exposure to sunlight. Although this degradation is perfectly reversible upon annealing at or above 150 °C, conventional c-Si solar cells do not exhibit this effect in the first place.⁵⁵

Its basic electronic structure is the p-i-n junction. The amorphous structure of a-Si implies high inherent disorder and dangling bonds, making it a bad conductor for charge carriers. These dangling bonds act as recombination centers that severely reduce carrier lifetime. A p-i-n structure is usually used, as opposed to an n-i-p structure. This is because the mobility of electrons in a-Si:H is roughly 1 or 2 orders of magnitude larger than that of holes, and thus the collection rate of electrons moving from the n- to p-type contact is better than holes moving from p- to n-type contact. Therefore, the p-type layer should be placed at the top where the light intensity is stronger, so that the majority of the charge carriers crossing the junction are electrons.^[49] A layer of amorphous silicon can be combined with layers of other allotropic forms of silicon to produce a multi-junction solar cell. When only two layers (two p-n junctions) are combined, it is called a tandem-cell. By stacking these layers on top of one other, a broader range of the light spectra is absorbed, improving the cell's overall efficiency.⁶⁶

In micromorphous silicon, a layer of microcrystalline silicon (µc-Si) is combined with amorphous silicon, creating a tandem cell. The top a-Si layer absorbs the visible light, leaving the infrared part to the bottom µc-Si layer. The micromorph stacked-cell concept was pioneered and patented at the Institute of Microtechnology (IMT) of the



Neuchâtel University in Switzerland,^[50] and was licensed to TEL Solar. A new world record PV module based on the micromorph concept with 12.24% module efficiency was independently certified in July 2014.^[51]

Because all layers are made of silicon, they can be manufactured using PECVD. The band gap of a-Si is 1.7 eV and that of c-Si is 1.1 eV. The c-Si layer can absorb red and infrared light. The best efficiency can be achieved at transition between a-Si and c-Si. As nanocrystalline silicon (nc-Si) has about the same bandgap as c-Si, nc-Si can replace c-Si.^[52]

A new attempt to fuse the advantages of bulk silicon with those of thin-film devices is thin film polycrystalline silicon on glass. These modules are produced by depositing an antireflection coating and doped silicon onto textured glass substrates using plasma-enhanced chemical vapor deposition (PECVD). The texture in the glass enhances the efficiency of the cell by approximately 3% by reducing the amount of incident light reflecting from the solar cell and trapping light inside the solar cell. The silicon film is crystallized by an annealing step, temperatures of 400–600 Celsius, resulting in polycrystalline silicon.⁷⁷

These new devices show energy conversion efficiencies of 8% and high manufacturing yields of >90%. Crystalline silicon on glass (CSG), where the polycrystalline silicon is 1–2 micrometres, is noted for its stability and durability; the use of thin film techniques also contributes to a cost savings over bulk photovoltaics. These modules do not require the presence of a transparent conducting oxide layer. This simplifies the production process twofold; not only can this step be skipped, but the absence of this layer makes the process of constructing a contact scheme much simpler. Both of these simplifications further reduce the cost of production. Despite the numerous advantages over alternative design, production cost estimations on a per unit area basis show that these devices are comparable in cost to single-junction amorphous thin film cells.^[47]

III. DISCUSSION

The efficiency of a solar cell quantifies the percentage of incident light on the solar cell that is converted into usable electricity. There are many factors that affect the efficiency of a solar cell, so the efficiency may be further parametrized by additional numerical quantities including the short-circuit current, open-circuit voltage, maximum power point, fill factor, and quantum efficiency.⁸⁸ The short-circuit current is the maximum current the cell can flow with no voltage load. Similarly, the open-circuit voltage is the voltage across the device with no current or, alternatively, the voltage required for no current to flow. On a current vs. voltage (IV) curve, the open-circuit voltage is the horizontal intercept of the curve with the voltage axis and the short-circuit current is the vertical intercept of the curve with the current axis. The maximum power point is the point along the curve where the maximum power output of the solar cell is achieved and the area of the rectangle with side lengths equal to the current and voltage coordinates of the maximum power point is called the fill factor.⁹⁹ The fill factor is a measure of how much power the solar cell achieves at this maximum power point. Intuitively, IV curves with a more square shape and a flatter top and side will have a larger fill factor and therefore a higher efficiency.^[82] Whereas these parameters characterize the efficiency of the solar cell based mostly on its macroscopic electrical properties,²² the quantum efficiency measures either the ratio of the number of photons incident on the cell to the number of charge carriers extracted (external quantum efficiency) or the ratio of the number of photons absorbed by the cell to the number of charge carriers extracted (internal quantum efficiency). Either way, the quantum efficiency is a more direct probe of the microscopic structure of the solar cell.^[83] Some third-generation solar cells boost efficiency through the integration of concentrator and/or multi-junction device geometry.^[61] This can lead to efficiencies larger than the Shockley–Queisser limit of approximately 42% efficiency for a single-junction semiconductor solar cell under one-sun illumination.^[84]

A multi-junction cell is one that incorporates multiple semiconducting active layers with different bandgaps. In a typical solar cell, a single absorber with a bandgap near the peak of the solar spectrum is used, and any photons with energy greater than or equal to the bandgap can excite valence-band electrons into the conduction band to create electron-hole pairs. However, any excess energy above the Fermi²⁶ energy will be quickly dissipated due to thermalization, leading to voltage losses from the inability to efficiently extract the energy of high-energy photons. Multi-junction cells are able to recoup some of this energy lost to thermalization by stacking multiple absorber layers on top of each other with the top layer absorbing the highest-energy photons and letting the lower energy



photons pass through to the lower layers with smaller bandgaps, and so on. This not only allows the cells to capture energy from photons in a larger range of energies, but also extracts more energy per photon from the higher-energy photons.^[85]

Concentrator photovoltaics use an optical system of lenses that sit on top of the cell to focus light from a larger area onto the device, similar to a funnel for sunlight. In addition to creating more electron-hole pairs simply by increasing the number of photons available for absorption, having a higher concentration of charge carriers can increase the efficiency of the solar cell by increasing the conductivity. The addition of a concentrator to a solar cell can not only increase efficiency, but can also reduce the space, materials, and cost needed to produce the cell.^[86]

Both of these techniques are employed in the highest-efficiency solar cell as of 2017, which is a four-junction concentrator cell with 47.6% efficiency.^[1]

One of the significant drawbacks of thin-film solar cells as compared to mono crystalline modules is their shorter lifetime, though to extent to which this is an issue varies by material with the more established thin-film materials generally having longer lifetimes. The standard lifetime of mono crystalline silicon panels is typically taken to be 30 years^[77] with performance degradation rates of around 0.5% per year.^[122] Amorphous silicon thin-films tend to have comparable cell lifetimes^[77] with slightly higher performance degradation rates around 1% per year.^[122] Chalcogenide technologies like CIGS and CIS tend to have similar lifetimes of 20–30 years^{[34][61]} and performance degradation rates just over 1% per year.^[122] Emerging technologies tend to have lower lifetimes. Organic photovoltaics had a maximum reported lifetime of 7 years and an average of 5 years in 2016,^[65] but typical lifetimes have increased to the range of 15–20 years as of 2019.^[123] Similarly, dye-sensitized cells had a maximum reported lifetime of 10 years in 2007,^[34] but typical lifetimes have increased to 15–30 years as of 2019.^[123] Perovskite cells tend to have short lifetimes, with 5 years being a typical lifetime as of 2016.^[66] The lifetime of quantum dot solar cells is unclear due to their developing nature, with some predicting lifetimes to reach 25 years^[34] and others setting a realistic lifetime as somewhere between 1 and 10 years.^[123]

Some thin-film modules also have issues with degradation under various conditions. Nearly all solar cells experience performance decreases with increasing temperature over a reasonable range of operating temperatures. Established thin-film materials may experience smaller temperature-dependent performance decreases, with amorphous silicon being slightly more resistant than mono crystalline silicon, CIGS more resistant than amorphous silicon, and CdTe displaying the best resistance to performance degradation with temperature.^[78] Dye-sensitized solar cells are particularly sensitive to operating temperature, as high temperatures may cause the electrolyte solution to leak and low temperatures may cause it to freeze, leaving the cell inoperable. Perovskite cells also tend to be unstable at high temperatures and may even undergo structural changes that impact the operation of the devices.^[62] Beyond temperature-induced degradation, amorphous silicon panels additionally experience light-induced degradation, as do organic photovoltaic cells to an even larger extent.^{[122][62]} Quantum dot cells degrade when exposed to moisture or UV radiation. Similarly, perovskite cells are chemically unstable and degrade when exposed to high temperatures, light, moisture, or UV radiation.^[62] Organic cells are also generally considered somewhat unstable,^[62] though improvement has been made on the durability organic cells and as of 2017, flexible organic cells have been developed that can be unrolled 500 times without significant performance losses.^[124] Unlike other thin-film materials, CdTe tends to be fairly resilient to environmental conditions like temperature and moisture, but flexible CdTe panels may experience performance degradation under applied stresses or strains.^[62]

IV. RESULTS

In order to meet international renewable energy goals, the worldwide solar capacity must increase significantly. For example, to keep up with the International Energy Agency's goal of 4674 GW of solar capacity installed globally by future, significant expansion is required from the 1185 GW installed globally as of 2017.^[125] As thin-film solar cells have become more efficient and commercially-viable, it has become clear that they will play an important role in meeting these goals. As such, it's become increasingly important to understand their cumulative environmental impact, both to compare between existing technologies and to identify key areas for improvement in developing technologies. For instance, to evaluate the effect of relatively shorter device lifetimes as compared to established solar modules, and to see whether increasing efficiencies or increasing device lifetimes is has a large influence on



the total environmental impact of the technologies.⁴⁵ Beyond key factors like greenhouse gas (GHG) emissions, questions have been raised about the environmental and health impacts of potentially toxic materials like cadmium that are used in many solar cell technologies. Many scientists and environmentalists have used life cycle analysis as a way to address these questions.^[75] Using established first-generation mono crystalline silicon solar cells as a benchmark, some thin-film solar cells tend to have lower environmental impacts across most impact factors, however low efficiencies and short lifetimes can increase the environmental impacts of emerging technologies above those of first-generation cells.⁷⁸ A standardized measure of greenhouse gas emissions, is displayed in the chart in units of grams of CO₂ equivalent emissions per kiloWatt-hour of electricity production for a variety of thin-film materials.^{[34][77][123]} Crystalline silicon is also included for comparison.

In terms of greenhouse gas emissions only, the two most ubiquitous thin-film technologies, amorphous silicon and CdTe, both have significantly lower global warming potential (GWP) than mono crystalline silicon solar cells, with amorphous silicon panels having GWP around 1/3 lower and CdTe nearly 1/2 lower.^{[66][77]} Organic photovoltaics have the smallest GWP of all thin-film PV technologies, with over 60% lower GWP than mono crystalline silicon.^[65]

However, this is not the case for all thin-film materials. For many emerging technologies, low efficiencies and short device lifetimes may cause significant increases in environmental impact. Both emerging chalcogenide technologies and established chalcogenide technologies like CIS and CIGS have higher Global warming potential than mono crystalline silicon, as do dye-sensitized and quantum dot solar cells.⁵⁶ For antimony-based chalcogenide cells, favorable for their use of less-toxic materials in the manufacturing process, low efficiencies and therefore larger area requirements for solar cells are the driving factor in the increased environmental impact, and cells with modestly improved efficiencies have the potential to outperform mono crystalline silicon in all relevant environmental impact factors. Improving efficiencies for these and other emerging chalcogenide cells is therefore a priority.^[61] Low realized efficiencies are also the driving factor behind the relatively large GWP of quantum dot solar cells, despite the potential for these materials to exhibit multiple³⁴ exciton generation (MEG) from a single photon. Higher efficiencies would also allow for the use of a thinner active layer, reducing both materials costs for the quantum dots themselves and saving on materials and emissions related to encapsulation material. Realizing this potential and thereby increasing efficiency is also a priority for reducing the environmental impact of these cells.^[34]

For organic photovoltaics, short lifetimes are instead the driving factor behind GWP. Despite overall impressive performance of OPV relative to other solar technologies, when considering cradle-to-gate rather than cradle-to-grave (i.e. looking only at the material extraction and production processes, discounting the useful lifetime of the solar cells) GWP, OPV constitute a 97% reduction in GHG emissions compared to mono crystalline silicon and 92% reduction relative to amorphous silicon thin-films. This is significantly better than the 60% reduction compared to mono crystalline silicon currently realized, and therefore improving OPV cell lifetimes is a priority for decreasing overall environmental impact.^[65] For Perovskite solar cells, with short lifetimes of only around 5 years,²³ this effect may be even more significant. Perovskite solar cells (not included in the chart) typically have significantly larger global warming potential than other thin-film materials in cradle-to-grave LCA, around 5-8x worse than mono crystalline silicon at 150g CO_{2-eq}/kWh. However, in grade-to-gate LCA¹², Perovskite cells perform 10-30% lower than mono-crystalline silicon, highlighting the importance of the increased environmental impact associated with the need to produce and dispose of multiple Perovskite panels to generate the same amount of electricity as a single mono crystalline silicon panel due to this short lifetime. Increasing the lifetime of Perovskite solar modules is therefore a top priority for decreasing their environmental impact.^[66] Other renewable energy sources like wind, nuclear, and hydropower may achieve smaller GWP than some PV technologies.^[34]

It's important to note that although emerging thin-film materials don't outperform mono crystalline silicon cells in terms of global warming potential, they still constitute far lower carbon emissions than non-renewable energy sources which have global warming potentials ranging from comparatively clean natural gas with 517g CO_{2-eq}/kWh to the worst polluter lignite with over 1100g CO_{2-eq}/kWh. Thin-film cells also significantly outperform the typical energy mix, which is often in the range of 400-800g CO_{2-eq}/kWh.^[77]

Though material selection and extraction does not play a large role in global warming potential, where electricity usage in the manufacturing process is near universally the largest contributor, it often has a significant impact on



other important environmental impact factors, including human toxicity, heavy-metal emissions, acidification potential, and metal and ozone depletion.³³

Human toxicity and heavy-metal emissions are particularly important impact factors for thin-film solar cell production, as the potential environmental and health effect of cadmium use has been a particular concern since the introduction of CdTe cells to the commercial market in the 1990s, when the hazards of cadmium-containing compounds were not well-understood.^[126] Public concern over CdTe solar cells has continued as they have become more common.^[127] Cadmium is a highly hazardous material^[128] that causes kidney, bone, and lung damage and is thought to increase the risk of developing cancer.^[129] Initially, all cadmium-containing compounds were classified as hazardous, although we now know that despite both Cd and Te being hazardous separately, the combination CdTe is very chemically stable^[25] with a low solubility and presents minimal risk to human health.^[126]

Feedstock Cd presents a larger risk, as do pre-cursor materials like CdS, and cadmium acetate, which are frequently used in other photovoltaic cells as well, and often contribute significantly to environmental impact factors such as human toxicity and heavy metal emission.^[61] These effects may be more pronounced for nanofabrication processes that produce Cd ions in solution, like the manufacture of quantum dots for QDPV.^[34] Due to these effects, CdTe solar cell production is actually seen to have lower heavy-metal emissions than other thin-film solar manufacturing. In fact, CdTe production has lower cadmium emission than ribbon silicon, multi-crystalline silicon, mono-crystalline silicon, or quantum dot PV manufacturing, as well as lower emission of nickel, mercury, arsenic, chromium, and lead.^[34] In terms of total heavy metal emissions, quantum dot PV has the highest emissions of PV materials with approximately 0.01 mg/kWh, but still has lower total heavy metal emission than any other renewable or non-renewable electricity source⁶⁶

V. CONCLUSIONS

The desire to alleviate safety concerns around cadmium and CdTe solar cells specifically has sparked the development of other chalcogenide PV materials that are non-toxic or less toxic, particularly antimony-based chalcogenides.⁷⁷ In these emerging chalcogenide cells, the use of CdS is the largest contribution to impact factors like human toxicity and metal depletion, though stainless steel also contributes significantly to the impact of these and other PV materials. In CIGS cells, for example, stainless steel accounts for 80% of the total toxicity associated with cell production and also contributes significantly to ozone depletion.^[61] Another potential impact factor of interest for PV manufacturing is the acidification potential, which quantifies the emission of sulfur and nitrogen oxides which contribute to the acidification of soil, freshwater, and the ocean and their negative environmental effects. In this respect, QDPV has the lowest emissions, with CdTe being a close second⁸⁸

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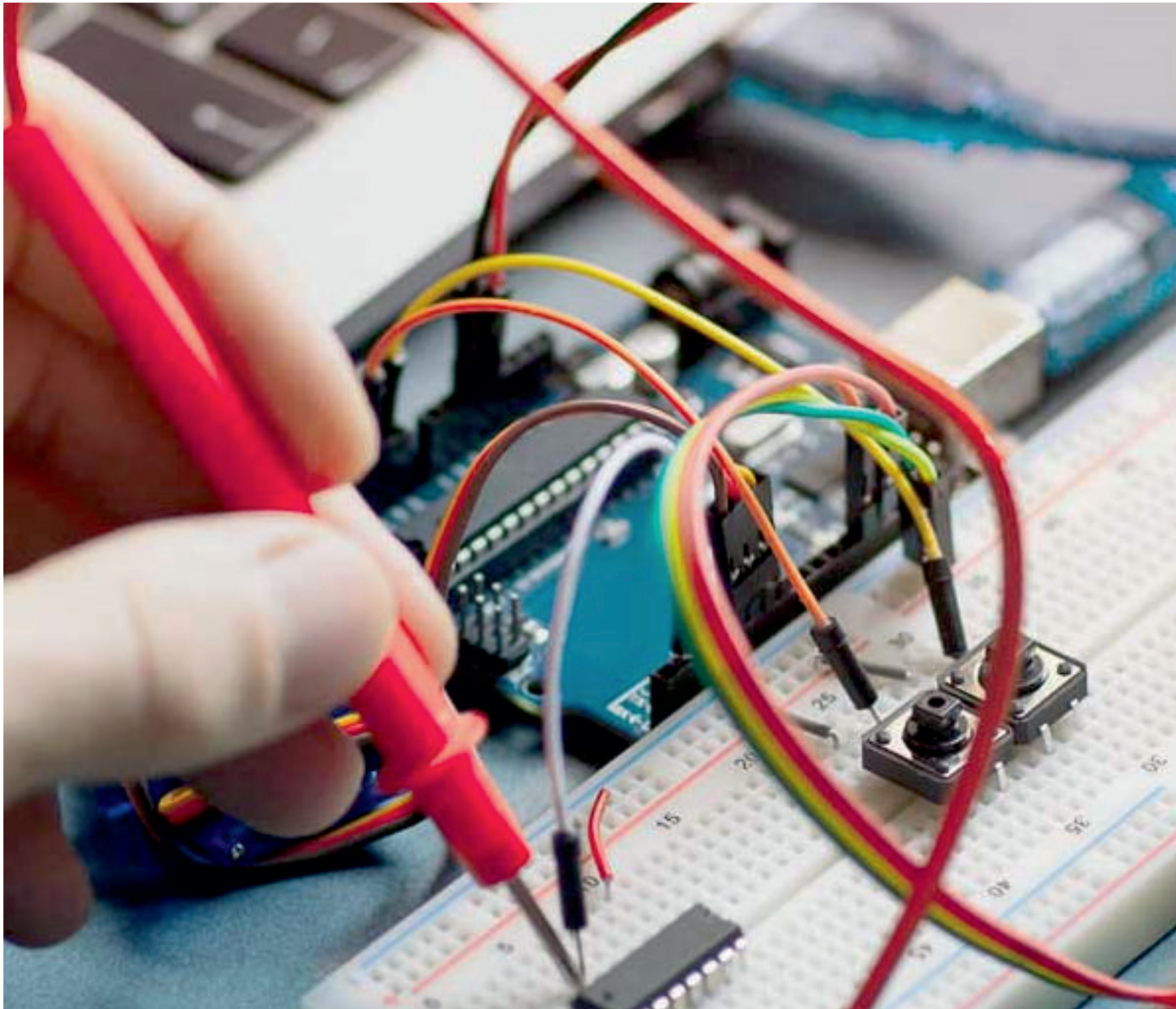
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