Clean & Green

Best Practices in **Photovoltaics**

Author

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As You Sow

As You Sow is a nonprofit organization dedicated to increasing environmental and social corporate responsibility. Founded in 1992, As You Sow envisions a safe, just, and sustainable world in which environmental health and human rights are central to corporate decision making. Its Energy, Environmental Health, Waste, and Human Rights programs create positive, industry-wide change through corporate dialogue, shareholder advocacy, coalition building, and innovative legal strategies.
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EXECUTIVE SUMMARY

The sun is the world's most abundant and cleanest source of energy. Yet our electricity and transportation systems are almost completely reliant on fossil fuels, not solar power.

Historically, the solar industry has faced challenges competing against fossil fuels on cost and the industry faces additional challenges because large-scale manufacturing of solar panels currently requires the use of numerous compounds that are toxic to humans and the environment. Over the past several years, some suppliers to major solar companies have not complied with environmental health and safety codes and improperly disposed of toxic chemicals, thus increasing concern over the production of solar panels.

In examining the challenges facing the solar industry it is important to keep in perspective the relative human and environmental impacts of different types of electricity generation. Even though there are toxic compounds used in the manufacturing of most solar panels, the generation of electricity from solar energy is significantly safer to the environment and workers than production of electricity from coal, natural gas, and nuclear fission. For example, once a solar panel is installed, it generates electricity with zero emissions whereas in 2010, coal-fired power plants in the United States emitted 1,999.6 million tons of carbon dioxide and there were 13,200 deaths in the U.S. directly attributable to particulates from coal-fired power plants.

This report highlights the best current practices that manufacturers of photovoltaics (PV) currently use and can implement to protect workers and the environment during the manufacturing of solar panels and investor considerations regarding environment, social, and governance practices for responsible management of PV companies. Company practices were obtained as responses to a survey that As You Sow sent out to over 100 PV manufacturers around the world. Best practices were determined via consultation with scientists, engineers, academics, and industry consultants.

Responses indicated that many PV manufacturers beat standards set for emissions, are reducing water use and reusing water on their own initiatives, and are participating in voluntary international programs related to worker safety. Several companies also are moving to use safer materials, rely on renewable energy to power energy-intensive processes, reduce waste by developing recycling programs that recover materials for reuse, and improve relations with workers and communities throughout their supply chains.

Best Practices in Photovoltaics Manufacturing presents practices and policies that companies use to mitigate risks from hazardous compounds, reduce environmental impact, and responsibly manage their supply chains. It highlights how companies are reducing environmental, health, and safety risks and suggests additional steps companies can take to further ensure clean production, health, safety, and fiduciary responsibility.

Findings in this report include examples of:

- Companies implementing robust protocols to ensure the safety of workers in their factories and the health of communities. For instance, First Solar has a laboratory at each manufacturing facility staffed with trained technicians that monitor treated water and allows for metals detection below permit levels.
- Companies that are siting manufacturing facilities in locations with cleaner energy inputs such as REC whose facilities in Norway are powered by hydroelectric, in Singapore by natural gas and solar, and in the U.S. by natural gas and hydroelectricity.[1] Siting has a significant impact on the footprint of PV panels, particularly in China where electricity generation is 81% from conventional thermal sources and in the U.S. where 45% is from coal.[2]

- Companies that are using ISO 14001 and EICC to monitor waste, air, and effluents in their supply chains, SA8000 and EICC for worker rights, and OHSAS18001 and EICC to monitor safe working conditions. Many of these incorporate onsite visits and should fully implement validated auditing processes for enhanced robustness.
- Companies increasingly including environmental and social criteria in selecting suppliers due, in part, to incidents related to supplier practices in the solar industry. For example, Suntech now requires its suppliers sign a document that it implements environmental management systems and meets the company's expectations for treatment of workers.[3]
- Companies that have a management system in place for audits that contain transparent criteria, corrective actions, and regular auditing cycles. REC, SunPower, Suntech, and United Solar Ovonic incorporate each of these into their auditing programs.
- Companies taking steps to reduce their water use. For example, between 2006 and 2010, Suntech reduced its water use by 51% per MW by recycling discharged water and supplying it to its HVAC systems. SunPower, Suntech, and Trina Solar clean and reuse water.
- Closed loop electronics programs that include enhanced recyclability and recycling of solar panels. First Solar has a prefunded collection and recycling program that is a stand-out in the industry and up to 95% of the semiconductor material is available for reuse in new modules. Abound Solar has a cradle-to-cradle program to reclaim both tellurium and cadmium from its modules at end-of-life. One company's panels are made from 85% recycled material and are themselves 100% recyclable and non-toxic, and Suntech uses easy to recycle, non-resource-constrained materials.
- Companies such as Abound Solar, First Solar, and Suntech stating they design their panels with end-of-life in mind.
- Executive compensation tied to environmental or safety metrics. Compensation for executives at SunPower is tied to environmental health and safety performance.
- Corporate Social Responsibility (CSR) reports. Several solar companies have begun to publish CSR reports. It is important that these reports not only describe company programs and successes, but also provide goals, milestones, and progress towards those goals and highlight current challenges, as did SunPower, and how the company is addressing them.

As demand for PV increases, it is important that companies continue to reduce the thickness of the absorber materials, reuse materials, and recycle during manufacturing. In combination, this can make marked reductions in demand for raw materials and lessen pressure for resource-constrained materials. Going forward, increasing the value of environmental and social criteria in selecting suppliers and implementing enhanced monitoring of suppliers will improve conditions for workers, protect surrounding environs, and reduce incidents throughout the industry's supply chain.

In order to transition to a cleaner source of power generation, there is a need for policy that will support the development of alternative generating sources, installation, and integration with utilities to accept and thrive with a population using intermittent and distributed generation. This policy support must also address current subsidies and tax incentives to fossil fuels that make it exceedingly difficult for solar, wind, and other renewable resources to compete on a cost-basis.

Best practices are continuously evolving — what is best of current options, may no longer be the best method in the future. It is our intention that this report be used as an introduction to the manufacturing issues and the practices as a baseline for addressing environmental, health, and safety challenges in 2012.

INTRODUCTION

The sun is the world's most abundant, cleanest source of energy. In 2009, scientists demonstrated that "solar energy has the technical, geographical, and economic potential to supply 69% of the total electricity needs and 35% of the total (electricity and fuel) energy needs of the US by 2050."[4] Today, wide-scale adoption of renewable sources of energy in the United States is limited by a lack of policy support for its development and the challenges of competing in a marketplace where its competition — fossil fuels — is given a head start with significant and on-going support in the form of subsidies and tax incentives.[5]

In comparison to fossil fuels, solar energy historically has been expensive on a cost-per-kilowatt basis. In addition, global competition, particularly from China, is changing the cost dynamics of PV manufacturing.[6] Recently, the U.S. Department of Energy has implemented an initiative, "SunShot," to reduce the cost of installed solar energy systems to $1 per watt by 2020.[7] This is not an unreasonable goal. First Solar has already broken the $1 per watt barrier for the manufacturing of its modules and Bloomberg New Energy Finance projects that solar technology costs "could fall by as much as 40 percent over 2010–20 due to experience curve effects" which occur when costs decrease due to efficiencies gained through "labor efficiency, network building, changes in the resource mix, standardization and/or method improvement."[8]

The solar industry has also faced an uphill battle because large-scale manufacturing of solar panels, at present, uses a number of compounds that are toxic to humans and the environment. The following report discusses the challenges and presents practices that photovoltaic (PV) manufacturers have adopted to protect workers, communities, and the environment in the manufacturing of this product that generates electricity with zero emissions.

PV and Fossil Fuels

Large-scale manufacturing of solar panels currently uses numerous compounds that are toxic to humans and the environment. Yet production of solar panels, even though they have toxic components, is significantly safer to workers and the environment than the extraction of raw materials and production of electricity from coal, oil, or natural gas.

> **"The solar energy that reaches the earth in one hour is about as much as the total energy used by every one on the planet for an entire year.[9]"**

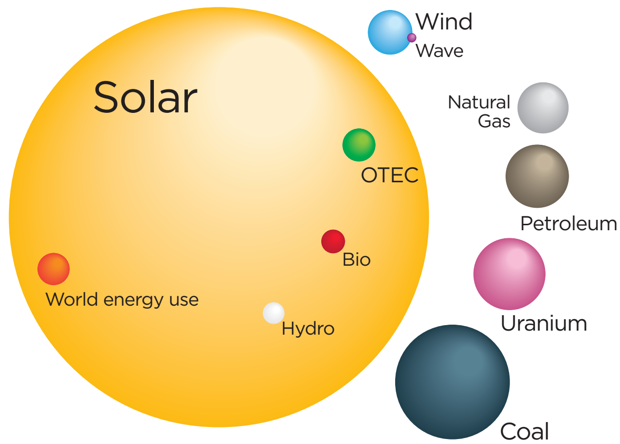
For example, the difference between injuries and deaths attributed to manufacture of PV and that attributed to mining of and generation of electricity from coal alone is orders of magnitude. Silane (SiH_4), the most widely used electronic gas, is used in crystalline silicon production and in high quantities in polysilicon production.[10] Since 1976, there have been 11 deaths attributed to silane worldwide — the most deaths attributed to any electronics specialty gas.[11] When this is compared to the 13,200 deaths attributed to fine particle pollution emitted from coal combustion for electricity generation in 2010 in the U.S. alone, the risks related to solar manufacturing begin to be put into perspective.[12]

In addition, once a solar panel is installed it generates electricity with no emissions. For comparison, in 2010 alone, coal-fired power plants in the U.S. emitted 1999.6 million tons of carbon dioxide, 5 million tons of sulfur dioxide, and 1.9 million tons of nitrous oxides.[13]

Not only are solar panels overall safer and healthier to manufacture and from which to generate electricity than fossil fuels, but also the abundance of energy from the sun makes it the world's most reliable long-term energy generating source. The U.S. Energy Information Administration states that in 2010, U.S. energy supply was 83% fossil fuels — 37% from petroleum.[14] Yet the U.S. does not have enough oil under ground to support that level of consumption. For example, based on 2010 U.S. consumption rates of oil, opening up and depleting the Arctic National Wildlife Refuge will yield 400 days of oil.[15] If we burn all of the U.S. domestic offshore oil in the moratorium, it will meet U.S. oil demand for 940 days.[16] Therefore, drilling in and extracting all of the oil in the American environmentally sensitive areas outside of the continental United States will provide oil for 3.67 years.

Fossil fuels are a finite resource. As such, there are two ways to plot our energy future — one that utilizes the least expensive resources first, and another that begins investing in new technologies now and leaves non-renewable, fossil resources in the earth for future generations. The two charts below depict resource depletion based on historical and projected rates of consumption. Note that solar and other renewables such as wind are not similarly resource constrained.

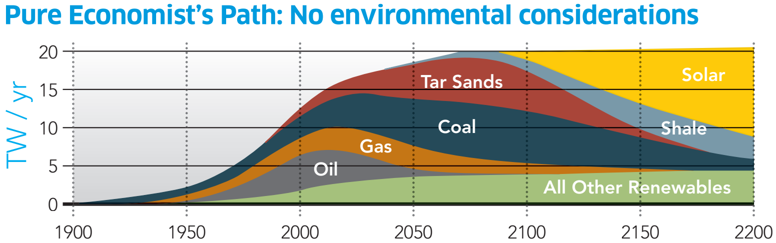
Putting the world's fossil fuel resources into perspective with the sun, we find that the energy produced from all of the crude oil currently in the earth is equivalent to the energy from approximately 15 hours of sunlight hitting the planet. All of the natural gas in the ground is approximately 24 hours of sunlight hitting the earth, and all of the coal currently in the ground has the same energy potential as 80 hours of sunlight hitting the earth.[17]



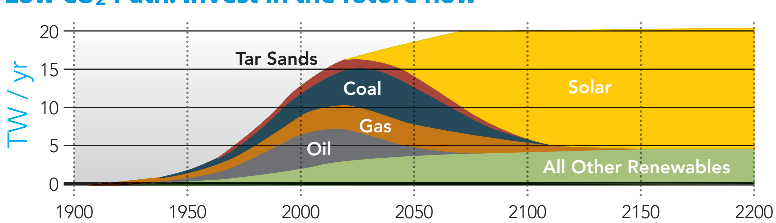
Annual potential for renewable energies. Total resources for coal, uranium, petroleum, and natural gas. Courtesy of Richard Perez, University of Albany

In addition to resource depletion, access to fresh, potable water is another concern for humanity. Wind and PV are the only deployable technologies able to generate electricity without significant water resources.[18] In each, there are minimal amounts of water used in manufacturing and in PV some water is used to clean panels.[19] In contrast, coal plants in the U.S. alone are responsible for approximately 143 billion gallons of freshwater withdrawals each day — more than 40% of all such withdrawals in the United States.[20]

Pure Economist's Path: No environmental considerations



Low CO_2 Path: Invest in the future now



[21]

Energy potential of remaining fossil reserves and renewable sources, courtesy of Brent Nelson, NREL

Currently, the U.S. Government does not put sufficient effort into supporting a renewable energy future. In 2010, the U.S. Department of Energy budget for photovoltaic research and development was $125.8 million. The same year, the budget for fossil energy research and development was $659.7 million. $393.4 million of the fossil energy research budget was given to coal-based projects, $149.9 million of which went to develop carbon sequestration – a technology that the General Accounting Office considers to be 10-15 years away from commercial deployment and could increase the cost of coal-fired electricity 30-80% above current levels.[22]

Best Practices

As You Sow fully supports the development and commercialization of clean, zero-emission technologies. At the same time, we encourage manufacturers to produce and investors and consumers to seek out the least toxic, designed for end-of-life, efficient products technologically feasible.

Investors interested in "green" portfolios have acquired holdings in solar companies often without putting those companies through the same level of environmental, social, and governance (ESG) diligence that "non-green" corporations undergo. As the industry develops, solar companies, too, will need to pass through ESG screens in order to be included in socially responsible portfolios.

This report presents investor considerations regarding ESG practices and highlights how solar companies are already addressing these issues and where there is room, across the industry, for improvement. The report also provides a snapshot of best-known methods PV manufacturers are currently using to mitigate risks in the production process as well as to use the most materials- and energy-efficient processes. These practices were obtained as responses to a survey that As You Sow sent out to over 100 solar companies around the world. Best practices were determined via consultation with scientists, engineers, academics, and industry consultants.

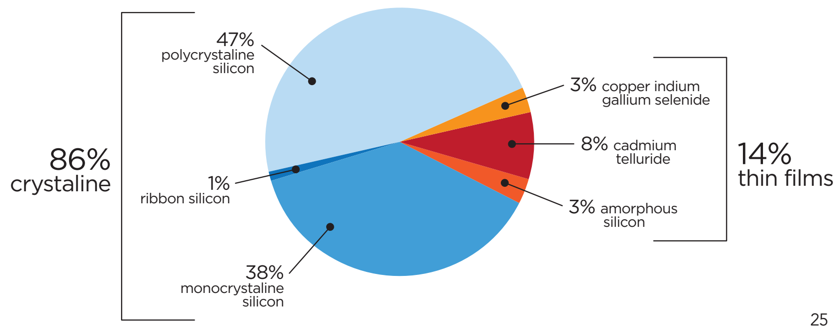
It is our intention that this report be used by investors — both public and private — as well as consumers to understand the challenges facing the solar industry in becoming both clean and green technology, and to learn how leaders in the industry are facing and surmounting these challenges in order to provide clean, abundant electricity for generations to come.

The report is divided into three sections. The first section presents ESG considerations used by socially responsible investors and provides examples of how PV manufacturers are already incorporating responsible practices into their governance and operations. The second presents cross-platform technical opportunities. The final section delves into the individual technologies — presenting environmental, health, and safety (EHS) risks in manufacturing particular to each technology and the best practices that companies are using to mitigate these risks.

Best practices are continuously evolving — what is best of current options, may no longer be the best method in the future. It is our intention that this report be used as an introduction to the manufacturing issues and practices as a baseline for addressing EHS challenges in 2012. As technology develops, there will be new technologies — including more efficient modules, modules without hazardous materials, and manufacturing with more effective mitigation techniques — that will continue to transform the market.

PV Technologies

There are two primary types of PV – crystalline silicon and thin film. Within thin film, there are currently five technologies that have either reached or are soon to reach commercialization — cadmium telluride (CdTe), amorphous silicon (a-Si), copper indium gallium selenide (CIGS), organic photovoltaics (OPV), and dye-sensitized solar cells (DSSC).[23] Gallium arsenide (GaAs) cells are also in production. They are highly efficient, but currently very expensive to manufacture and used almost exclusively on satellites and concentrated solar power systems.[24]

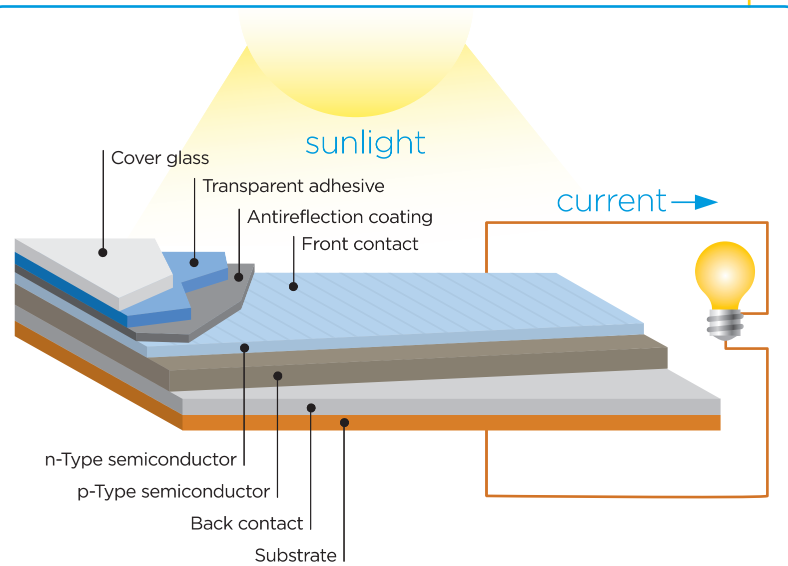


In 2010, crystalline silicon PV captured 87% of the market. Estimates for 2011 show crystalline with 86% market share. 38% is monocrystalline silicon, 47% is polycrystalline silicon, and 1% ribbon silicon. The remaining 14% of the market is held by thin films: 8% cadmium telluride; 3% amorphous silicon; and 3% copper indium gallium selenide.[26]

Silicon solar cells were the first to be produced and monocrystalline cells are, thus far, the most successful type of PV addressed in this study at transforming light into electric energy making them the most efficient cells. Pure silicon is energy intensive and expensive to produce and a relatively thick layer is needed in solar cells in order for light to be absorbed. As such, there has been much innovation in the past decades in order to reduce the thickness required for electricity production and to expand the spectrum of light that solar cells can convert into electricity.[27]

The history of PV began in 1839 when Alexandre Edmond Becquerel first observed the creation of voltage or current as a result of a material's exposure to light. Its history continued with Albert Einstein's work on the photoelectric effect, published in 1905, and Jan Czochralski's development of a process to grow purified monocrystalline silicon in 1918. In 1954, the first solar cell able to run everyday electrical equipment was developed at Bell Labs and in 1963 Sharp produced the first practical solar modules.

New inventions in PV, including new technologies, address different limitations of modules — improving materials, reducing costs of productions, and creating new applications — and increase the efficiency and usability of solar energy.



Basic components of a solar cell, courtesy of DOE

Due to the high cost of manufacturing purified silicon and the thickness required in order to create electric energy, thin film technology has developed. Thin films are less expensive to manufacture, but are currently less efficient than crystalline silicon modules. The efficiencies of thin films are increasing, but the range of efficiencies varies significantly among the technologies. Record efficiency of laboratory cells made with CIGS is 20.3%; CdTe 17.3%; a-Si 12.5%; dye-sensitized 11.1%; and OPV 8.3%, while crystalline record efficiency is 27.6%.[28]

Different spectrums of light are absorbed by different semiconductor materials

One reason that different thin film technologies exist is that each material absorbs different spectrums of light and requires different thicknesses of material to do so. Each color in the spectrum of light has a different amount of energy. The semiconductor material's band-gap matches a specific spectrum of light. If the match is correct, the light releases an electron from the material — if the light has less energy than the band-gap, no electrons are released to make electric energy. If the light has more energy than the band-gap, the electron is released but the cell also loses the surplus energy as heat. Thus, layers of materials with different band-gaps can be combined in a cell in order to convert the most light to electric energy without losing any of the energy from the sun as heat. The more light that is converted without the loss of heat, the more efficient a cell is.

Further innovations in PV are driven by the application of the solar materials. Crystalline panels are rigid, like a pane of glass. The drive to create building-integrated solar materials that are flexible with the curves of the architecture drives innovation. As does the desire to collect solar energy and create electricity on fabrics — from backpacks for mobile phones and laptops to tents to generate electricity for troops in the military. However, today's market for PV is almost all rigid modules.

Different technologies have specific strengths and challenges.

Crystalline silicon: Crystalline silicon has several advantages including silicon being the second most abundant element in the earth's crust. Sand, or quartz, consists of one silicon and two oxygen molecules and is ubiquitous on the surface of the earth. Silicon is also the most studied element in the periodic table and there is a significant base of knowledge of its industrial uses and properties from the semiconductor industry. For manufacturing, there are many vendors who provide equipment so there are relatively low barriers to entry for new companies.

A primary concern with crystalline silicon cells is the amount of energy that it takes to manufacture the silicon and that, in the production of the cells, almost half of that silicon is lost during the wafer sawing process. There is still a significant amount of reduction of the thickness of cells that is scientifically possible that has not yet been developed commercially which will reduce the energy inputs of the individual cells.

Cadmium telluride: Cadmium telluride currently has the lowest cost to manufacture of all of the thin film technologies. It has a high deposition rate, meaning that it efficiently utilizes the absorber materials in the manufacturing process. In addition, cadmium telluride panels are very tolerant to impurities.

Challenges for cadmium telluride modules are that, in general, CdTe is not as well understood as silicon and that, although cadmium toxicity is known, there are just beginning to be studies on the possible issues related to cadmium telluride. In manufacturing, one challenge has been that the industry is not standardized so each CdTe company needs to design its own manufacturing equipment. Historically, this has been a significant barrier to entry.

Copper indium gallium selenide: In the laboratory, copper indium gallium selenide cells have shown promise to have high efficiencies for thin film with laboratory efficiencies of over 20%.

A challenge for CIGS is that in order to achieve high efficiencies, there must be strict uniformity in the manufacturing process and increasing deposition rates lowers the efficiency of the cells. In addition, there is no industry standard for fabrication and there are few options for purchasing manufacturing equipment.

Amorphous silicon: Amorphous silicon is a form of silicon that exhibits no long-range order in its crystal structure. It has the benefit of using the abundant element, silicon, and the advantages of using a well-studied semiconductor, and also uses significantly smaller amounts of silicon than a crystalline cell. The conductive layers are very thin — less than one micron. Because no large crystals of silicon are grown, it requires significantly less energy to produce than a crystalline silicon cell. Amorphous silicon also has the advantage, in certain geographic locations, of working well in low light and hot temperatures. In addition, it is compatible with building-integrated photovoltaics — so it can be molded to match arched and design-driven geometric regions.

Challenges with amorphous silicon include low efficiencies and that the best materials are made at the lowest deposition rates — so time-to-manufacture increases in order to maintain quality. In addition, amorphous silicon panels are initially unstable with illumination, meaning that with early light exposure, cells become less efficient.[30] Manufacturers thus design a-Si cells for the highest stabilized efficiency rather than a more efficient cell that will degrade further over time.

Organic and Dye-sensitized: Organic cells have carbon molecules in the absorber layers. They are appealing because of the low materials cost and low-energy high-throughput processing technologies. In addition, the manufacture of organic cells does not require sub-atmospheric processes, which simplifies manufacturing. There are many potential types of organic PV, and currently the polymer-fullerene cells have the highest efficiencies.[31] OPV is highly versatile and thus has many potential applications – from systems with substrates to those without, such as solar paint and window films.

Primary challenges for organic systems are increasing efficiency and reliability. In addition, the vast number of materials that can be utilized brings both opportunities and challenges to a technology for which the physics is new in comparison to that of inorganic semiconductors.[32]

Dye-sensitized solar cells are lightweight and flexible and relatively tolerant to impurities. In addition, production is inexpensive to scale because it does not require vacuum processes and operates using low temperature and relatively common materials. The cells themselves operate at a range of temperatures and are relatively insensitive to the angle at which the light hits so that it is able to absorb more light than cells that are more sensitive.[33]

Dye-sensitized cells currently have low efficiency and do not have a long product-life.

GENERAL MANAGEMENT

This report divides general issues that are of concern to responsible investors into two sections: management systems and operations. Management systems address how the company is structured to address EHS and management disclosure on EHS issues. Operations include how the company promotes responsible manufacturing processes throughout its supply chain.

Management Systems

Management systems improve corporate performance and accountability and, in the case of environmental, health, and safety issues, can move EHS into a core business practice and elevate EHS to C-suite and board levels. Practices are often divided into governance, management, and disclosure.

Governance

How corporations are governed provides an indication of the type of company or investment that corporation is. Best practices in corporate governance are constantly shifting as beliefs on how to best manage fiduciary responsibility evolves. There are general practices that are considered to ensure transparency, fiduciary oversight, and minimize potential conflicts of interest and there are additional practices that integrate environmental and social responsibility into the core corporate structure.

General governance policies at the board level that are currently considered to protect shareholder value and best insure the integrity of management include:

- Board independence. Major stock exchanges require that listed companies have independent boards and that key board committees be fully independent within one year of listing. Investors often have higher standards for board independence that include examination of long-tenured board members and examples of boards acting independently from management.
- Few or no anti-takeover provisions. Many investors prefer that companies have few or no anti-takeover provisions — such as classified boards in which only certain directors are elected annually or poison pills in which the target company makes its stock less attractive to the purchaser. If a poison pill is proposed, it is preferred that the company requires a shareholder vote, with a simple majority being sufficient to reject adoption.
- Majority voting standard for director elections. Many investors prefer that the standard for director elections be majority, rather than plurality, voting.
- Annual elections of directors. It is preferred that all directors be elected annually.
- Advisory vote on executive compensation. After passage of the Dodd-Frank Wall Street Reform and Consumer Protection Act, publicly traded companies in the U.S. are required to submit executive compensation packages to shareholder vote, but they may choose to do so only every three years.[34] It is preferred that these compensation packages be voted upon annually.
- Simple majority voting provisions to amend the bylaws or charter. Many investors prefer that amendments to the charter or bylaws of the corporation can be made with a simple majority vote of shareholders, rather than requiring a supermajority.
- One share, one vote. Many investors prefer that companies have a single share class, rather than having multiple share classes with different voting rights. Multiple share classes with unequal voting rights can be used as an anti-takeover mechanism.

- Political spending. It is preferred that companies disclose policies on lobbying expenditures and political contributions. Direct board oversight and approval should be required for such expenditures.
- Executive compensation tied to company performance. Executive compensation should be effectively linked to company performance, including both financial and ESG performance metrics.
- Honest accounting. Companies should be in compliance with Sarbanes-Oxley section 404 and not have restatements as a result of improper accounting.[35]

Socially responsible investors and others operate within the framework that companies will only succeed in achieving sustainable shareholder value over the long term "if their focus on economic returns and their long-term strategic planning include the effective management of their relationships with stakeholders such as employees, suppliers, customers, local communities and the environment as a whole."[36] While corporate governance may not seem, at first glance, to be related to corporate environmental impacts, governance is in fact the driver of all corporate performance — whether that is financial, environmental, or social. Well-governed companies are attentive to all facets of performance that could result in a loss of brand or reputational value, litigation, or regulatory action and they take steps to avoid such problems arising.

Engaging with shareholders and stakeholders and integrating environmental and social responsibility into board structures are integral to achieving sustainable shareholder value. Board committees and structures to address ESG issues demonstrate that environmental and social concerns are taken seriously by the company.

Management

It is important that companies have accountability for environmental and social performance at both the operations/management and board of director levels.

Companies should have environmental management systems (EMS) in place and someone uniquely responsible for the EMS. It is key that there be a direct line of accountability for environmental management straight to senior executives and the board of directors. Solar companies appear to be accountable to managing these risks and have a variety of titles for the person responsible for the EMS. At SunPower, the Director of Environmental Health & Safety & Sustainability is in charge of the EMS, yet the "CEO, Board of Directors, and all employees" have responsibility for environmental performance.

In addition, for investors concerned with a company's environmental performance, a best practice is to tie executive compensation to environmental or safety metrics. Compensation for executives at SunPower is tied to EHS performance.[37]

It is also important that companies have a worker health and safety committee to identify and address health and safety challenges and act as a forum for solving challenges. Abound Solar, First Solar, REC, and SunPower all have such committees in place. Companies should implement key performance indicators (KPIs) for environmental health and safety. Suntech has EHS KPIs in place and intends to implement "a corporate social responsibility Key Performance Indicators system to improve and standardize social responsibility performance in China throughout 2011, and hope[s] to extend [its] social responsibility management system to the entire company by the beginning of 2013."[38]

Companies and their staff belong to several industry associations and professional societies that share information regarding environmental health and safety and press standards and policies including: European Photovoltaic Industry Association (EPIA), pv cycle, SEMI PV Group, Semiconductor Environmental Safety and Health Association (SESHA), and Solar Energy Industry Association (SEIA) EHS Group.

Disclosure

It is important for companies to share their efforts in environmental health and safety as well as to disclose environmental liabilities. One format that has become standard in other industries is a corporate social responsibility (CSR) report. SunPower, Suntech, and Trina Solar publish CSR reports and Q-Cells and SolarWorld publish an integrated report. It is important that these reports not only describe company programs and successes, but also provide goals, milestones, and progress towards those goals and highlight current challenges and how the company is addressing them. For example, SunPower committed to reducing its "overall carbon emissions by 50 percent by 2016 from 2007 on a carbon intensity basis measured per MW deployed" and reported that between 2007 and 2010, its "CO_2 emissions per MW of solar capacity produced fell by approximately 45%.[39] For its workforce, SunPower committed to reducing its "corporate-wide injury rate (IR) to 0.57 and lost workday case rate (LWCR) to 0.15" and has achieved this goal in Asia with "0.28 IR and 0.07 LWCR."[40] SunPower also acknowledges its challenges — such as wastewater in its Philippines facility — and states it is currently in the process of addressing the issue.[41]

In its proposal to the SEC for mandatory ESG disclosure, the Social Investment Forum and additional signatories noted that, among other things, "ESG information can inform investors of potential risks and opportunities and promote market efficiency and long-term thinking. Corporate social and environmental performance can have a material impact on portfolio performance. […] U.S. regulatory requirements and voluntary efforts have failed to produce the consistent, comparable data that a rapidly growing community of retail and institutional investors seek to make investment and proxy voting decisions. [and] Several governments and regulators outside the United States already require corporations to disclose various ESG factors. As a result, sustainability reports in these markets are generally more prevalent and substantive, placing U.S. companies and financial markets at a potential competitive disadvantage."[42]

Under SEC regulation S-K item 101, a company must describe the material effects that "compliance with federal, state and local environmental laws regulating the discharge of materials into the environment will have on earnings, capital expenditures and the competitive position of the company and its subsidiaries."[43] Item 303 of that same regulation requires that "a company report on any known trends or any known demands, commitments, events or uncertainties that the registrant reasonably expects to impact various financial aspects e.g. sales, liquidity, capital resources."[44]

Currently, companies disclose future environmental liabilities in their 10-K MD&A, annual report, corporate responsibility report, and website. An environmental liability is a "legal obligation to make a future expenditure due to the past or ongoing manufacture, use, release, or threatened release of a particular substance, or other activities that adversely affect the environment."[45]

Abound Solar, First Solar, and SunPower disclose their contingent environmental liabilities in their financial statements. A contingent liability is "the possibility of an obligation to pay certain sums dependent on future events."[46]

In addition, the SEC's February 2010 *Commission Guidance Regarding Disclosure Related to Climate Change, Exchange Act Release* should be followed. The guidance neither changed existing legal requirements nor introduced new ones, but it presented "four key categories of climate change information that companies should evaluate for materiality in order to determine whether disclosure is required: the impact of legislation and regulation; the impact of international accords; the indirect consequences of regulation or business trends; and the physical impacts of climate change."[47]

Investors prefer company-specific information to be included in the disclosures on financial statements in order to provide them with a more realistic picture of the company's risks and performance.

Operations

Managing the operations of a solar company in order to be responsible to the environment, workers, and communities along the supply chain requires a significant commitment on behalf of company management. Beginning with how a company manages and monitors its supply chain, through manufacturing, ongoing research and development, handling of toxic materials and waste including nanomaterials, and recycling both during manufacturing and at end-of-life, companies are responsible for a wide range of practices and precautionary mechanisms.

Supply Chain

It is a best practice for companies to include environmental and social criteria in selecting suppliers and to have a program for monitoring and improving manufacturing processes in addition to having standards for quality, timeliness, cost, etc. In order for a company to be sustainable it needs to be responsible to its workers not only in terms of working conditions, fair wages, and fair treatment but also environmental health and safety assurances. Trina Solar's suppliers are asked to sign an EHS declaration form and Suntech requires its suppliers sign a document that it implements environmental management systems and meets the company's expectations for treatment of workers.[48]

The most basic way that companies communicate their requirements for treatment of workers both to their suppliers as well as to company-owned factories is through a code of conduct. A code of conduct is a document that outlines the working conditions that manufacturers want upheld in their factories — "a set of principles indicating how an organization expects its members to act."[49] The further down the supply chain a company enforces its code of conduct, the better assurance the company, its investors, and its customers have that the individuals who produce the products are supported. Abound Solar, Trina Solar, and United Solar Ovonic apply their codes of conduct beyond first-tier suppliers. First Solar and Suntech's codes of conduct also apply to their recycling facilities.

There is no standard for what must be in a code of conduct, although associations such as the Electronic Industry Citizenship Coalition (EICC) promote industry-wide codes. This particularly benefits manufacturers at points in the supply chain where more than one company sources from a given facility. In December 2011, the Solar Energy Industry Association's (SEIA) board of directors endorsed a Commitment to social and environmental responsibility. This Commitment covers company and supplier requirements in the areas of labor, ethics, health and safety, environmental responsibility, and management systems. The Commitment uses the EICC code of conduct as its base and added five additional conditions including a human rights statement and the requirement to share key sustainability indicators.

Within codes of conduct, many are consistent with the International Labour Organization (ILO) core labor conventions. Countries ratify ILO conventions and apply them to their workforces. There are eight conventions that the ILO considers as priorities by all countries, regardless of economic status. These are often included in corporate codes of conduct. REC and Suntech's codes of conduct are consistent with all eight core ILO conventions.

Companies also audit supplier facilities on environmental risks and worker health and safety risks. To monitor waste, air, and effluents, companies use ISO 14001 and EICC which requires on-site visits in addition to requiring that facilities comply with local laws. To monitor safety mechanisms, companies use EICC and International Standards on Auditing (ISA) risk assessments and have Personal Protective Equipment (PPE) and Corrective and Preventative Actions (CAPA) in place. In order to best assure that workers receive fair wages, companies use SA8000 and EICC — both of which require onsite visits. To monitor safe working conditions, companies use OHSAS 18001 and EICC.[50]

Once codes are in place, companies audit suppliers to ensure that they are in compliance. Failure to comply could result in a supplier being put on probation or receiving additional training, and continued violations could result in a company disengaging a supplier. Validated audited processes by certified external auditors and NGOs are currently the best way to verify that codes are being met. Public reporting on monitoring and compliance efforts using a standardized reporting mechanism, such as the Global Reporting Initiative (GRI), is also recommended.[51] Companies should have a management system in place for audits that contain transparent criteria, corrective actions, and regular auditing cycles. REC, Suntech, and United Solar Ovonic incorporate each of these three into their auditing programs while Abound Solar and Trina Solar use third party auditors. SunPower has integrated sustainability criteria into its supplier scorecard process and evaluates suppliers quarterly on sustainability key performance indicators. It is recommended that companies also provide transparency around challenges and how they were addressed.

As the industry grows, it is also recommended that companies make siting decisions for new factories based not only on cost of production, but also on their ability to best ensure safe working conditions and environmental stewardship in their facilities. According to Verité, there is a high correlation between code of conduct violations and the country in which the factory is located, and the types of compliance violations that are uncovered in audits can often be predicted based on country of manufacture. Dan Viederman, CEO of Verité, notes that "a company that decides to site production in a place with consistent regulatory weakness must expect to face social and environmental problems, and put in place a transparent regime to uncover those problems and solve them."[52]

Oftentimes, regardless of the country of manufacture, a company can best assure its commitments to workers by engaging with local and regional governments. First Solar, REC, SunPower, Suntech, and Trina Solar all engage with local and/or regional governments. Engagement with local non-governmental organizations improves responsible practices among a company, its employees, and the local community as well as functioning as an additional level of unofficial auditing to have eyes on a facility when auditors are not present.

Engagement is essential not only during manufacturing but also in siting projects. First Solar engages with NGOs regarding the development of solar parks. One such collaboration regarding its Desert Sunlight Solar Farm "reduced the project footprint by over one-third and minimized impacts to desert tortoise." Through engagement with local officials, residents, and business and environmental groups, SunPower redesigned its 250 MW California Valley Solar Ranch project to have a smaller footprint, reuse abandoned mine areas, and permanently conserve 70% of the site and manage it to meet conservation and habitat restoration objectives.

It is important that companies respond to community concerns as well as engage communities' questions both prior to and once manufacturing is underway. In addition to charitable giving, companies engage in outreach programs, dialogues, and provide whistleblower hotlines.

Going forward, in order to preserve not only community relations, but sustainability within the communities where companies manufacture — companies could enter into agreements with communities and local governments regarding the full environmental impacts of the products — including, but not limited to, raw materials mining — and create financial agreements with the communities to transparently compensate them for their natural resources.[53]

Manufacturing

Sunlight is captured and converted to electricity using photovoltaic modules. The manufacture of the panels requires a significant amount of electricity — and depending on the location of the manufacturing facility, that electricity is derived predominantly from fossil fuels. For example, 45% of electricity generated in the U.S. is from coal and 23% from natural gas and 81% of power generation from China is from conventional thermal sources.[54] Thus, making solar panels using electricity in the U.S. or in China relies significantly on fossil fuels.

PV companies can make manufacturing-siting decisions based on the energy generation source of the region and use their panels to further reduce reliance on fossil fuels.[55] For example, REC facilities in Norway are powered by hydroelectric, in Singapore by natural gas and solar, and in the U.S. by natural gas and hydroelectricity.[56] First Solar has begun to install solar power plants on the roofs of its manufacturing facilities. It has installed 1.3MW on the roof of its Frankfurt (Oder) facility and has installed 1.7MW of a planned 2.8MW on its facility in Perrysburg, Ohio — a state where 83.7% of the electricity is generated from coal.[57] The source of electricity for consumption during module production has a significant impact upon a module's carbon footprint.[58]

Solar panels powering a manufacturing facility, courtesy of First Solar

In a PV fab, a primary concern is protection of workers and the immediate environment from exposure to materials that would have a negative impact on health. In that vein, it is important that manufacturing facilities use robust, hierarchical safety protocols. Companies that responded to our survey perform job hazard analyses, trainings, audits, and implement workplace safety internal controls and committees. In addition, facilities comply with International Building Code (IBC) and International Fire Code (IFC), and are certified ISO 14001, SA8000, OHSAS 18001, NFPA, and CGA. First Solar also has safety teams that include "a structured rotation process enabling more people to participate and includes an internal website to foster internal communications." The company also has a replication process, Copy Smart, by which it ensures that "all equipment and system changes, including those made for environmental, health, and safety reasons, are reviewed, proven, and managed at the corporate level and then systematically implemented at each site."

Inside a manufacturing facility, courtesy of SunPower

Much of the manufacturing process in a PV fab is automated within an airtight assembly line. In Abound Solar and SunPower fabs, no workers come into physical contact with the panel between loading the substrate and packaging a fully encapsulated module. At First Solar facilities, some panels have manual inspections. In facilities where there is potential exposure to toxic substances, industrial hygiene becomes a critical issue. First Solar has an industrial hygiene team that uses "globally recognized sampling and analytic methods. Only certified third party laboratories are used to provide the analysis." The industrial hygiene team also conducts air studies and "statistically analyzes the data generated from the program to identify any negative trends requiring action."

Within the manufacturing line itself, maintaining subatmospheric pressure for all non-wet processes means that if there is a breach, any compound is sucked back into the line instead of being released into the air which would pose a health risk to workers and the environment. A standard practice implemented by companies is that if there is a malfunction in the abatement system, the entire manufacturing line shuts down. Emergency scrubbers are another safety mechanism to abate toxic or highly toxic gases in case of an emergency release and at SunPower, 100% of its cell manufacturing facilities have emergency scrubbers. Companies that do not use toxic gases may not require emergency scrubbers at their facilities.

Although the water use in PV manufacturing is magnitudes less than that used in thermoelectric power plants, water is a location-specific resource susceptible to hydrogeological patterns as well as droughts.[59] Thus, reducing water use and cleaning and reusing water are important components of environmental stewardship through the PV manufacturing cycle. Companies are taking steps to reduce their water use. For example, between 2006 and 2010, Suntech reduced its water use by 51% per MW by recycling discharged water and supplying it to its HVAC systems. SunPower, Suntech, and Trina Solar clean and reuse water, and another solar company reclaims 35% of its water for reuse.

Research and Development

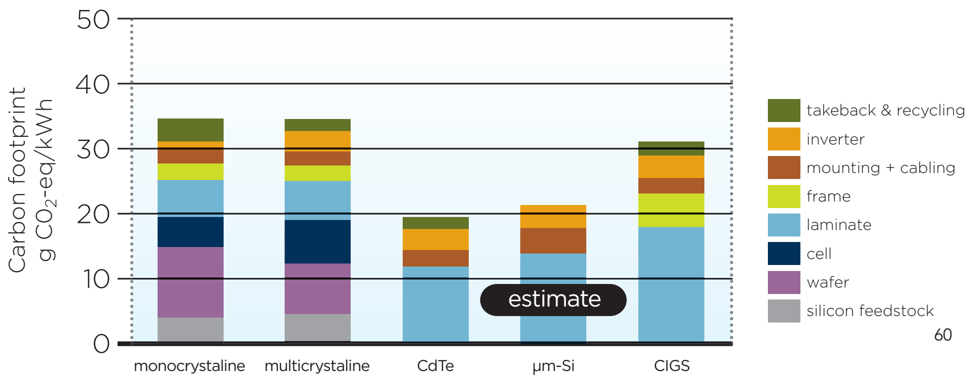
Although there is much research and development in all areas of solar technology including improving the efficiency of panels, this report focuses on EHS. Three of the most significant EHS considerations are optimizing processes to more safely work with hazardous substances, researching processes to utilize less hazardous materials, and reducing environmental impact.

Currently, many solar companies meet and exceed national and international standards for handling and abating hazardous materials. One example of optimizing processes regarding hazardous materials is First Solar's ongoing efforts on improving ventilation. At present, the company uses HEPA filters that remove 99.97% of the cadmium from gaseous streams. The company is now working to improve redundancy, monitoring, and cost efficiency in its gaseous processes and to reduce "machine down time for filter change-out." The new system will "effectively generate real-time data to confirm system performance and actual emission quality."

Companies are engaged in research to use less hazardous materials and, thus, further reduce the environmental impact of manufacturing. United Solar Ovonic is modifying its recipes to eliminate the use of hazardous gases or lessen their concentrations and switch to more environmentally friendly materials and Suntech is engaged in research to use safer chemicals. A CIGS company that uses cadmium in its cadmium sulfide (CdS) window layer is actively pursuing a cadmium-free solution but has not yet developed one with comparable energy efficiencies to the CdS layer.

Companies are using life-cycle analyses (LCA) before or during the commercialization of a new technology. LCAs can provide information as to where a company can further reduce environmental impact, and help it to set targets for future reductions in materials use, emissions, energy use, and increased efficiencies.

First Solar and REC also utilize both LCA and risk assessment studies on new chemicals.



Carbon footprint of components of five PV technologies

Manufacturing crystalline silicon cells is, collectively, the most energy intensive process in producing a solar panel. Thus, any efforts to reduce the thickness of wafers, reduce and reuse waste from sawing and etching processes, or develop new technologies to grow silicon ingots will have a significant impact on reducing a company's energy and carbon footprint. Crystalline silicon companies are working to reduce the thickness of their wafers and REC has recently started full scale manufacturing of silicon using a new process that reduces electricity consumption by approximately 90%. Suntech is also returning broken wafers to its suppliers for reuse. During manufacturing, companies are recycling wafer and scrap materials, and SunPower states that over 90% of the nonproduct in its manufacturing is reused and that the company is striving for cradle-to-cradle waste management.

As demand for PV increases, it is important that companies continue to reduce the thickness of the absorber materials, reuse materials, and recycle during manufacturing. In combination, this can make marked reductions in demand for raw materials and lessen pressure for resource-constrained materials. For example, crystalline silicon wafers are typically approximately 200 microns thick. SunPower has developed a crystalline wafer that is thinner than 145 microns. This has enabled the company to "drive significant polysilicon efficiencies as [its] grams per watt use has been reduced to an industry leading 5.5 grams/watt."

At present, companies are not seeing major challenges in materials use in scaling production to meet future demand. OneSun states there are no limits for its materials. Yet other companies do note market fluctuations for commodities, silicon supply, and the availability of silver as minor challenges. First Solar discloses these challenges in its 10-K, noting that tellurium is dependent on copper demand, but that the company has secured its supply for the years ahead. There has been much discussion regarding tellurium as a resource constrained substance. In a 2010 article in *Science*, Ken Zweibel writes that "the concerns about Te [tellurium] availability limiting CdTe PV module production assume that the layer thickness will be maintained at 3µm. Projections of maximum market share attainable are shown based on modest increases in Te production (from 1% growth per year in copper production, its main supply route) and module efficiency (15%), but substantial decreases in CdTe active-layer thickness."[61] Disclosing materials reduction and tactics for managing future materials constraints is a practice that we would like to see more companies undertake.

Companies are also evaluated on the energy payback time (EPBT) of their panels. EPBT is the amount of time a system must operate to recover the energy that went into making the system. It became a point of discussion in the 1970s, when people were wondering if it was "worth it" to create solar panels based on the amount of energy it took to manufacture them. As such, EPBT represents the embedded energy of a product. It depends upon the PV technology, insolation — or the amount of sunlight in the location, and the balance of system used.[62] Balance of system has a relatively high EPBT.[63] Companies self-reported the EPBT for their panels: REC's is 8 months; First Solar and Abound Solar is 6 months; and early-stage technologies claim even lower EPBT such as Konarka's 3 months. Companies engage in R&D to reduce the EPBT of the systems, as once EPBT has been accounted for, the panel, still, has a lifetime production of energy.[64]

Nanotechnology

Nanotechnology is the science of manipulating matter at the molecular scale to build structures, tools, or products, known as nanomaterials. Nanomaterials are those whose small scale imparts unique physical properties. Nanotechnology offers advantages to solar technology — particularly in its potential for enhanced optics and to reduce raw materials needed for conductive layers in the panels.

One concern regarding the use of nanomaterials is that either during manufacturing, usage, or end-of-life the nanomatierals will escape into the air or water and cause damage either to the environment or to human life. One company has a patent pending on a technique that prevents the nanomaterials from dispersing as nanoparticles.

As You Sow encourages companies to participate in voluntary environmental programs and report the nanomaterials they are using or emitting either in manufacturing or in final products to appropriate organizations including the U.S. Environmental Protection Agency (EPA), UK Department for Environment, Food, and Rural Affairs (DEFRA), or the Project on Emerging Nanotechnologies/Woodrow Wilson International Center for Scholars (PEN). In addition, companies that use nanomaterials should follow guidance to best protect workers, the environment, and communities such as those from the Department of Energy (DOE), International Council on Nanotechnology (ICON), and National Institute for Occupational Safety and Health (NIOSH).

Companies should obtain from their suppliers and provide to their stakeholders information on the materials, risks from migration, toxicology and ecotoxicology studies, as well as data on end-of-life and recycling of nanomaterials in or used in the manufacturing of their products. The risks should be disclosed in either a CSR report, annual report, 10-K MD&A, or website.

Recycling

The recyclability and recycling of solar panels is an important element to a closed loop electronics program. The Organization for Economic Co-operation and Development (OECD) found electronic waste (e-waste) to be one of the fastest growing waste streams, and it is the fastest growing sector of waste in the U.S.[65] Electronic waste and the growth of e-waste is a concern both because electronics contain toxic compounds that can be released into the environment or be exposed to humans at a product's end-of-life and because these and other compounds are economically valuable and can be reused in other products. Reuse of metals and compounds is an important part of corporate sustainability because reusing metals has significantly less environmental impact than virgin materials and it provides a level of security for products, health, and safety when compounds are resource constrained or toxic.

As You Sow supports design for end-of-life as a best practice in manufacturing. The idea behind this is that the product is designed so that its components can be disassembled and reused in new products. The components are recyclable — such as the company that makes its panels from 85% recycled material and are themselves 100% recyclable and non-toxic, or Suntech which uses easy to recycle, non-resource-constrained materials. Abound Solar, First Solar, and Suntech all state that they design their panels with end-of-life in mind. Over 90% of Abound Solar's components are recycled at end-of-life and both Abound Solar and First Solar reclaim and recycle the semiconductor materials from their modules. SolarWorld recently established a joint venture, SolarCycle, that generates metals from secondary sources and treats compound materials from recycled solar modules.[66]

Implementing an extended producer responsibility (EPR) program can best ensure that companies reduce waste during manufacturing, modules are recovered at the end of their useful life, that there is accountability for safe and proper dismantling of modules, and that the component parts are reused either in new modules or in different products. As part of their EPR programs, Abound Solar and First Solar include the cost of recovery of the module at end-of-life as part of the purchase price.

First Solar has a prefunded collection and recycling program that is a stand-out in the industry. A trust structure has been set up to guarantee funds available for recovery and recycling regardless of the financial status of First Solar. The owner of the panel requests collection of the modules at end-of-life and the company provides the packing materials and transportation for recovery and manages their recycling in order to form a closed loop for the semiconductor materials.[67]

CROSS-PLATFORM TECHNICAL OPPORTUNITIES

Depending on the semiconductor employed, photovoltaic technologies vary greatly – but there are four broad technical considerations affecting environmental health and worker safety that are common to the five technologies addressed in this report.

The first is system-wide improvements to increase efficiency of the final module. Companies are usually more invested in one or several stages of the PV value chain, but, for the most part, are not fully vertically integrated from raw materials through manufacturing, installation, and recycling. Yet communication during the design phases of components in each stage in the value chain can improve the efficiency of the final PV system. Attending to the potential for improving efficiencies and reducing the footprint and cost of the final modules is something that all cell manufacturers should be looking towards.

Companies of all technologies can make system-wide improvements to integrate the module prior to installation that would boost efficiency of the final system, reduce costs, or both. This would include improvements in integrating the cells with the module, inverter, electrical, and racking systems — the balance of system [for an illustration and description of balance of system, see Appendix A]. For example, Abound Solar is examining DC-DC converters and microinverters to improve efficiency and Trina Solar is exploring building smart microinverter technology directly in to the panel to manage shading and other environmental conditions. SunPower is mitigating shading loss at the module level by putting the metal grid on the back of the cell to reduce shadow loss.

Another way to improve efficiency is at the system level via tracking. When a system tracks the sun, the panels turn throughout the day in order to maintain the most exposure to the sun. This enables the module to produce significantly more energy per year than a fixed tilt system. For example, in San Francisco, a 4kW array on a tracking system produces $200.88 more electricity per year than does a fixed system.[68]

All companies can also improve the corrosion protection and electrical insulation of the modules that will extend the useful life of the modules and overall operating safety. Encapsulants can trap compounds in the panels that cause corrosion. Tests have shown that "constructions with breathable backsheets allow higher rates of moisture ingress, but also allow egress of deleterious substances that can result in decreased corrosion."[69]

As responsible manufacturers, companies can also work to improve efficiencies in the module manufacturing process and reduce the overall cost of the module. For example, Suntech optimized its cell manufacturing process and reused wastewater for air conditioning in its Wuxi production facility that resulted in a reduction of wastewater of approximately 50% per MW of production.[70] REC owns its full value chain in some regions — from silicon manufacture through installation. Its innovation throughout the value chain has reduced the company's energy payback time for complete systems from 1.4 years in 2007 to 1 year in 2011.[71]

A second technical consideration facing all manufacturers is the encapsulation materials. Encapsulation is the process to contain the module in a moisture-impermeable material in order to protect the module and enable it to function most efficiently. Key concerns are the component's ability to provide enhanced optical transmission and electrical safety. The nature of the cell material has a direct impact on the requirements for an encapsulant. For example, if a cell is made of amorphous-silicon, the conductive material is relatively stable in the face of weather and can use a wider range of encapsulants than CIGS, which is more sensitive to moisture. Most modules are encapsulated with polyvinyl fluoride (PVF)/Tedlar® or ethyl vinyl acetate (EVA), and polyethylene terephthalate (PET) and many companies also have a glass layer. Although glass does not have many of the environmental concerns of components generated from petrochemicals and fluoropolymers, it is heavier and more difficult to laminate two glass layers. First Solar cells are deposited on glass, have an encapsulant layer and a glass backsheet, and do not use either PET or Tedlar®.

The different encapsulants serve different purposes. For example, EVA acts as an adhesive and optically couples front glass to cells. EVA flexes easily, but does not insulate the electronics sufficiently. PET provides good electrical insulation, but is not particularly durable. Some companies use PVF or Tedlar®, which is both physically durable and protects PET from ultraviolet (UV) radiation. Ethyl tetrafluoroethylene (ETFE) is both durable and non-polar, meaning that the material does not soil and dust does not stick to it. ETFE is very transparent and has good electrical insulation properties so it is used on the front (sun-facing) side of a module. Fluoropolymers such as PVF/ Tedlar® and ETFE are claimed to be environmentally stable in modules, but create a supply chain challenge as their manufacture involves hazardous materials and are also expensive. BP Solar does not use Tedlar® in its modules and instead uses a stabilized PET.

A third technical challenge that all companies face is how to reduce the use of and protect the environment from hazardous compounds. All companies can reduce the amount of hazardous materials in their module and many of these materials can be, or with technological advancements will be able to be, eliminated. The publicly-available GreenScreen™ is used by electronics companies, state governments, and the EPA to identify chemicals of concern and to make informed substitutions of safer chemicals.[72]

Solar manufacturing currently uses toxic and hazardous substances, but some companies have made efforts to use less hazardous materials. For example, lead was initially used as a solder to connect crystalline silicon cells into modules. Currently, SunPower uses a lead-free solder to connect its cells and thereby increase the voltage in its modules. Thin-film modules use laser scribing to isolate individual cells within the modules.

When using toxic and other materials, companies can use a hierarchy of procedures in order to treat liquid effluents from operations. The least desirable from an environmental health and safety perspective is to collect the effluents and dispose of them as hazardous waste, followed by dilution. Dilution is a process by which more water is added to the fluid in order to make the parts of hazardous material less concentrated in the water. As a result, the fluid becomes less toxic by unit, but the same overall amount of compounds is being released into the environment.

For many technologies that do not use heavy metals, pH adjustment and flocculants can be sufficient to treat the effluents. These processes neutralize the water and aggregate the particles, respectively. For manufacturing processes that use heavy metals, precipitate removal and ion exchange are recommended to separate out the particles and remove any electric charge.

The final technical consideration that affects all PV manufacturers is calculating their environmental footprint and managing operations to reduce that footprint. Life-cycle analyses in which companies calculate their carbon footprint for both carbon dioxide (CO_2), as well as for greenhouse and fluorinated gases, and disclose the energy payback time for each product are preferred.[73] It is important that the calculations use process-based data and cradle-to-grave production stages. Companies should calculate the carbon footprint of each of its panels, and report this information in its corporate reports as well as the company's overall carbon footprint to the Carbon Disclosure Project (CDP). At the time of this publication, more than ten solar companies have reported in the CDP.[74]

In 2012 it will be mandatory for solar manufacturers that emit 25,000 or more metric tons of carbon dioxide equivalent (CO_2-e) to also report fluorinated greenhouse gas emissions to the EPA.[75] Companies will need to calculate the CO_2-e of their fluorinated gases including hydrofluorocarbons (e.g. CHF_3), perfluorocarbons (e.g. C_2F_6), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6).[76] REC currently calculates the CO_2-e for each of the fluorinated gases it uses.

EHS AND PV TECHNOLOGIES

Crystalline Silicon (x-Si)

Crystalline Silicon (crystalline, or x-Si) panels currently dominate the PV market. As a technology, crystalline has the advantage of being based on silicon — the second most abundant element on the earth's crust — as well as being able to build off of the engineering and technical advancements of the semiconductor and integrated chip industries with which it has much in common.

The general process for manufacturing a crystalline wafer is described in Appendix B. There are two basic types of crystalline silicon wafers — monocrystalline and poly- or multicrystalline. Monocrystalline wafers are made from a single crystal, while polycrystalline wafers have many crystals in one wafer. Monocrystalline wafers have higher efficiency. This is due to the fact that, in a polycrystalline wafer, any impurities in the silicon are drawn to the grain boundaries between the individual crystals. The

Monocrystalline wafer

Multicrystalline wafer

boundaries provide opportunities for electrons to get trapped. These electrons do not move through the wafer and thus are not available to provide the maximum amount of electricity. Because a monocrystalline wafer crystal lattice is continuous, this does not occur and the maximum number of electrons moves through the wafer and produces electricity. As a result, multicrystalline is less efficient than monocrystalline wafers but it is both less expensive and faster to produce than monocrystalline.


Monocrystalline ingot

Manufacturing purified polysilicon, from which monocrystalline and multicrystalline silicon ingots are grown, is an energy intensive process that uses hazardous gases and liquids such as silane (SiH_4), hydrochloric acid (HCl), hydrofluoric acid (HF), silicon chloride hydride ($SiCl_3$), and silicon tetrachloride ($SiCl_4$). Due to the large volumes of these that are necessary for production, the best practice is to utilize a closed system to protect the environment. In the cases of gases such as SiH_4 that are pyrophoric and cannot be exposed to the air, closed systems are a basic requirement in order to protect the health and safety of workers. Recovery of materials is both economical and protects the environment from additional waste.

It is important that companies engage with and audit their suppliers on the processes and safeguards they have in place to ensure the safe handling of the gases used in the silicon manufacturing process. Abatement processes are dependent on concentrations and flows of gases, and if they are single gases or mixed with other gases in the manufacturing process.


Multicrystalline ingots

Once the ingots of monocrystalline and polycrystalline silicon are grown, they are cut down to the desired size and shape and sliced into wafers using wire saws. In cutting monocrystalline ingots, the "tops and tails" are removed and can be reused in silicon production. In order to slice with the wire, a slurry of abrasive materials are added to enhance the efficacy of the wire. Cutting with wire saws produces a significant amount of non-product — between 35-40% of the ingot is lost as kerf during the sawing process.[77] As such, it is a best practice for companies to recover the silicon from the wafer-cutting process as well as to reuse the slurry. REC recovers the silicon carbide and polyethyleneglycol from the cutting process and reuses the slurry. Kerf loss can be reduced by using other sawing processes, such as wire electrical discharge machining, which uses a significantly smaller wire than traditional wire sawing and new kerf-free processes are being developed.[78]

Wafers are then etched in order to remove the hard oxide layer and enable a good junction to electrically join them together into modules. Hydrofluoric acid (HF) is used to etch silicon wafers. HF is a common commercial acid, but is highly toxic and a significant safety concern as the acid penetrates the skin, affects the nervous system, and can cause cardiac arrest. As such, best practice is to use a minimum amount of the acid to avoid exposure and to process excessive waste. For processing waste, best practice to abate HF is to neutralize the acid and precipitate to collect the fluorine. SunPower neutralizes the acids in the etching formula and diverts and concentrates the solids for chemical oxygen demand and biochemical oxygen demand oxidation.

Cadmium Telluride (CdTe)

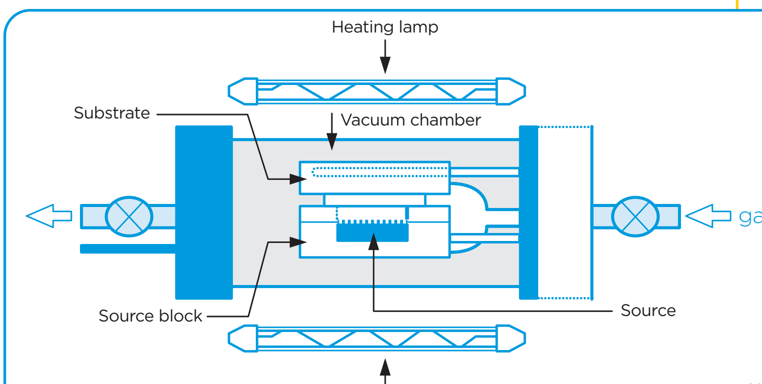
Cadmium telluride (CdTe) solar cells use a CdTe compound as the solar absorber layer. First Solar's CdTe modules have attained 14.4% efficiency and the company has a verified laboratory cell efficiency of 17.3%.[79] Even so, there has been much concern because cadmium is a highly toxic material and a carcinogen.[80] Interestingly, there is less cadmium in a residential solar array than usually found in batteries inside the house. A one square meter CdTe panel contains, on average, 7 grams of cadmium. One nickel-cadmium (NiCd) C-battery contains 10.5 g of cadmium and a D-battery has 21 g.[81] 10 C-batteries has the same amount of cadmium (70 g) as there is in a 1 kW array.[82] Nevertheless, due to its toxicity, there has been much attention to safety in CdTe production and recycling.

It is important to note that when cadmium is bound into a compound with tellurium (telluride), it is much more stable and less water-soluble than cadmium.[83] 63.3% of cadmium exposure in humans has been attributed to food consumption via plants' uptake of fertilizers (42.3%) and burning fossil fuels (21%).[84] Exposure due to production, use, and disposal of cadmium products is 2.4%.[85] It has been argued that using cadmium in CdTe, a relatively inert compound, has net environmental benefits both in terms of sequestering cadmium as well as, in the case of photovoltaics, reducing the amount of coal burned for electricity which releases, "a minimum of 2 g of Cd in gaseous emissions and about 140 g of Cd in ash form for each GWh of electricity produced."[86] Power plants with less efficient emissions controls and those without emissions controls will produce more cadmium. As for risks related to operating a CdTe PV system, studies have shown that for CdTe modules, "emissions of cadmium during fires in central PV systems are considered to be essentially zero."[87]

A best practice is for CdTe companies to follow the precautionary principle, apply life-cycle management tools, and make all efforts to protect their workers and the environment from cadmium and other toxic compounds used in the production of PV modules. Companies use both HEPA filters and baghouses to abate cadmium compounds from the air. It is preferred that both manufacturers and suppliers recycle cadmium compounds from solid waste streams. Companies use both precipitation and ion exchange to abate cadmium compounds from water streams. For example, First Solar "operates wastewater treatment facilities at each of [its] global manufacturing sites (Perrysburg, Ohio; Frankfurt Oder, Germany; and Kulim, Malaysia). The treatment protocol consists of traditional metals precipitation, followed by filtration and a final ion exchange (IEX) separation step. After completion of IEX, the clean effluent is collected in one of multiple, parallel batch tanks. A sample of the clean water is taken from each batch tank and analyzed for cadmium. If the clean effluent meets the environmental permit limits in the specific geography, only then is the water discharged. If the water does not meet requirements, it is sent to the front of the process for further treatment. Each manufacturing location is equipped with a laboratory, staffed with trained technicians. The laboratory contains an ICP [inductively coupled plasma mass spectrometry] which will allow metals detection below permit limits."

On site, manufacturing is highly automated and companies put in HEPA filters and perform processes in enclosures with personal protective equipment and under negative pressure in order to protect workers from exposure to cadmium compounds. A best practice used by First Solar is the ongoing monitoring of the efficacy of its ventilation systems.

Currently, both the absorber and window layers in a CdTe module contain cadmium, CdTe, and cadmium sulfide (CdS), respectively. The CdTe layer is deposited through close space sublimation or vapor transport deposition. In close space sublimation, the CdTe goes directly from a



Close space sublimation [88]

solid to a gas and is deposited on a substrate positioned very close to the sublimating material. In vapor transport deposition, a type of physical vapor deposition, the cadmium and tellurium are also in vapor form when they are deposited on the substrate. Both processes benefit from a very high material utilization rate and localized materials. The CdS is also deposited via physical vapor deposition. For both CdTe and CdS deposition, vapors that do not become part of the active module layers condense into solid form within the deposition chamber and can be reclaimed.

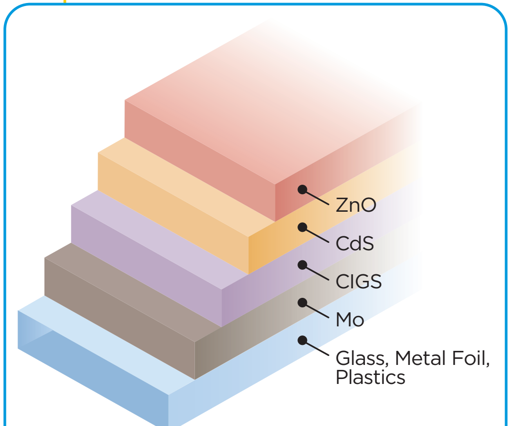
CdTe cells are laser scribed in order to allow the module to operate at higher voltage and lower current, thereby limiting losses due to electrical resistance. A similar process is used to remove an amount of CdTe near the edge of the module to facilitate a moisture seal. Yet scribing creates dust from the CdTe and CdS layers and thus it is a best practice to have HEPA filters in place during the laser scribing process, as do Abound Solar and First Solar.

Tellurium (Te) is a resource-constrained substance. Abound Solar and First Solar use recycled tellurium in their panels. Reclaiming tellurium at end of life and using recycled tellurium are significant in order to have sustainable production and scalability of CdTe technology.[89] An added benefit to Te remaining valuable is that it increases the likelihood that Cd will also be recycled from the module. Due to the toxicity of cadmium and the constraints of tellurium, CdTe photovoltaic companies have become leaders in semiconductor materials recycling. Abound Solar has a cradle-to-cradle program to reclaim both tellurium and cadmium from its modules at end-of-life and First Solar's recycling program recycles "up to 95% of the semiconductor material for reuse in new modules." Both module and chemical companies continue to invest in research and development to improve their recycling technology.

Copper Indium Gallium Selenide (CIGS)

Copper indium gallium selenide (CIGS) has the highest laboratory efficiency of the thin film technologies and thus holds the promise of a high efficiency thin film module. Currently there is no prevalent method for creating the CIGS layer within a module because the high efficiency techniques are difficult to manufacture and the faster the layer is grown, the quality of the material declines. CIGS cells are deposited by co-evaporation, sputtering, precursor mixing, chemical bath deposition, and printing techniques. A standard process will depend upon which company using which technology emerges as a sector leader.

At present, the best performance in a CIGS cell is achieved by a structure of a glass substrate, molybdenum (Mo), CIGS deposited in a vacuum via co-evaporation, cadmium sulfide (CdS), and a zinc oxide (ZnO) transparent contact layer. The CdS is deposited via chemical bath deposition, which helps achieve the highest efficiency in cells but takes a disproportionately larger volume of liquid material to deposit the layer that, in turn, means more material to be processed, recovered, and managed. The CdS layer is quite thin and a CIGS cell contains much less Cd per area than a CdTe cell, but due to the toxicity of Cd, research is being conducted to make the cells cadmium free. In the lab, research is being done to replace the CdS buffer layer with zinc sulfide (ZnS), with the ultimate goal of being able to replace ZnS with zinc oxide (ZnO) as both the absorber and transparent contact.



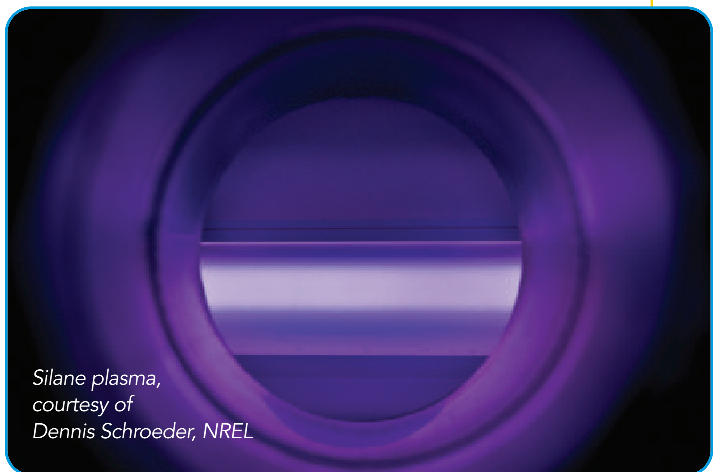
CIGS, courtesy of NREL

In addition to cadmium, CIGS manufacturers must carefully manage selenium and/or hydrogen selenide, depending on the deposition process used. Selenium is a hazardous material and needs be treated. Most companies use solid selenium sources, but a risk persists during the cleaning of the chamber. If the chamber is opened while still hot, the selenium will react with the water vapor in the air to form hydrogen selenide (H2Se), a highly toxic gas. Best practices to abate hydrogen selenide are gas-fired heat oxidation or gas-fired heat oxidation with wet scrubbing.

Due to the presence of cadmium and selenium in the modules, it is important that CIGS manufacturers have HEPA filters in place during the laser scribing and reactor cleaning processes.

Indium is a resource-constrained substance.[90] Best practice is to use recycled indium and to reclaim it at the end-of-life of the panel.

Amorphous Silicon (a-Si)



Silane plasma, courtesy of Dennis Schroeder, NREL

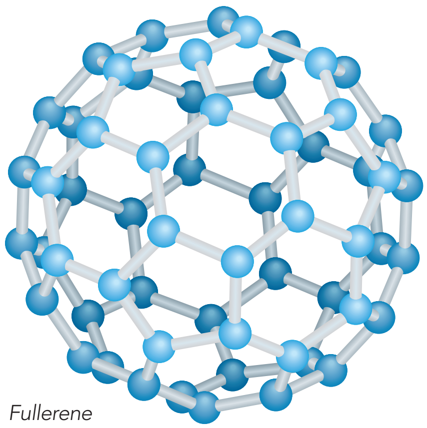
Amorphous silicon (a-Si) is deposited onto a substrate using a chemical vapor deposition (CVD) process from a plasma of ionized silane (SiH_4).

Environmental challenges inherent in a-Si manufacturing stem largely from the gases used in the silicon production, doping, and production chamber cleaning. A-Si production can require silane (SiH_4), hydrogen (H_2), germane (GeH_4), and methane (CH_4). Silane, the source-gas for a-Si, can spontaneously combust if not managed properly.[91] As such, silane delivery systems need contain well-designed and well-maintained valves and be safely handled in order to insure worker safety. After use, each of these gases can be abated, for instance with gas-fired heat oxidation and wet scrubbing.

To go from an inert layer of semiconductor to a functional solar cell, elements known as dopants must be introduced to the material. For a-Si, the most common dopant elements are phosphorous and boron, which are delivered to the substrate in the form of gaseous compounds. Dopants used in a-Si production, including phosphine (PH_3), diborane ($B2H_6$), trimethylboron ($B(CH_3)_3$), and boron trifluoride (BF_3), are highly toxic and pyrophoric. Responsible usage of these compounds requires well-maintained process equipment and abatement systems, specifics of which depend on the flow, concentration, and combination of gases.

United Solar Ovonic uses dry vacuum and solvent wipes for cleaning the deposition chambers. The advantage of this method is that it does not introduce any additional gases into the manufacturing process. In other systems, additional gases are used to clean the deposition chambers. Two options for cleaning deposition chambers with gas are on-site generated fluorine (F_2) and nitrogen trifluoride (NF_3). Nitrogen trifluoride has low toxicity but is a potent greenhouse gas with a global warming potential of 17,200 times that of carbon dioxide.[92] New technology enables fluorine to be generated on-site from hydrogen fluoride (HF). The advantages to this technology are that neither fluorine nor HF have climate effects, and the system generates only the amount of fluorine necessary at any given time, reducing the risks from storage.[93] The disadvantage is that both hydrogen fluoride and fluorine are highly toxic. Best practice is determined by the factory's ability to manage either the greenhouse gas or toxicity risk.

Organic (OPV) and Dye-sensitized (DSSC)



Fullerene

Organic photovoltaics (OPV) have organic (carbon-based) compounds in the absorber layer. In the United States, OPV manufacturers often use absorber layers that consist of conjugated polymers and fullerenes.

Polymers are large molecules with a repeating structure. The electron clouds of the conjugated polymers join to form a tube through which electrons pass to the fullerene. The basic structure of a fullerene consists of 60 carbon molecules with an atomic arrangement similar to that of a soccer ball. Due to their small size, fullerenes could pose potential risks in different situations. The US Department of Energy (DOE) states that fullerenes are "unknown" as per hazards. DOE has classified fullerenes as nanomaterials and, as such, manufacturers of OPV should follow guidelines for safe use and handling of nanomaterials. Best practices include maintaining negative air pressure in the ink-making facilities so that the fullerenes in powder form can not escape into the air. Konarka's facilities have a solvent hood so that workers are not exposed and the company states that there is no risk to human health when fullerenes are in the ink and in the dried, sealed product.

The polymer is an electron donor and the fullerene is an electron receptor. In OPV, they are blended together by deposition from a common solvent. Once deposited on the substrate, the process yields a composite film with fullerenes bound together with the conjugated polymer. This blended, or mixed, structure is required to separate and transport charges in the absorber layer. The construction can be physically robust and, as such, in the future will function independently as a paint or film.

A best practice is to deposit the active layer from a solvent onto a roll-to-roll substrate through a slot-die. This method yields little material losses. At the end of the process the solvents are heated out. This offers a more uniform application and higher materials utilization than spraying or spin coating. Konarka uses several ink-printing methods, including slot die applied to a PET substrate. Another method is to have organic dyes that are thermally evaporated in a closed chamber. This process is not used as frequently in the U.S. but is being explored more in Europe.

Konarka uses silver for its top electrodes. The silver is in an ink that is printed on to the cells. The company is currently looking in to ways to recycle the panel that will reclaim the silver as it is harmful to plant life and a valuable metal.

Dye-sensitized solar cells (DSSC) often employ organic metal-containing molecules of dye as the light-absorbing medium. Such dye molecules are metal-organic compounds that most often have a ruthenium (Ru) core (in contrast, OPV systems generally do not employ metal-organic complexes). Ruthenium is a rare metal and toxic. As such, more abundant elements such as zinc (Zn) or titanium (Ti) are preferred from both health and sustainability perspectives.

The hazardous and potentially hazardous substances in DSSC and OPV are bound to other molecules in the active material of the cells. Companies should therefore make plans for end-of-life of the modules and address not only the recycling of modules but also how the compounds break down in various scenarios. During production, manufacturers also need to properly manage the inks and solvents such as orthodichlorobenzene (C_6H_5Cl). In order to reduce hazardous materials in production processes, xylene, toluene, and other solvents can be used. At production levels, solvents should be recovered and recycled.

CONCLUSION

Photovoltaics provide the most long-term, abundant, sustainable source of electricity generation available. It is critical that government policy, funds for research, and customer incentives to support PV penetration are increased as companies continue to invest and participate in research and development to improve efficiencies, reduce costs, reduce reliance on harmful materials, and continuously improve mitigation of presently unavoidable materials.

This report presents a snapshot of where the PV industry is today in terms of addressing environment, health, and safety risks and provides best practices in EHS, recycling, as well as general management in order to continuously improve the sustainability of the PV industry.

It found that companies are often not only meeting but outperforming standards set for emissions, are reducing water use and reusing water on their own initiatives, and are participating in voluntary international programs related to worker safety. As companies and the industry continue to grow, there will be more milestones regarding environmental health and safety as "best" possible practices continuously improve.

Going forward, increasing the value of environmental and social criteria in selecting suppliers and implementing enhanced monitoring of suppliers will improve conditions for workers, protect surrounding environs, and reduce incidents throughout the industry's supply chain.

In addition, companies have the opportunity to use safer materials, rely on renewable energy to power energy-intensive processes, reduce waste by developing recycling programs that recover materials for reuse, and improve relations with workers and communities throughout their supply chains. Increased disclosure — on financial statements, in CSR reports, and in stakeholder engagements — will continue to build confidence among investors and consumers in a company's performance, products, and future.

As we move, inevitably, to an electricity-generating system based on renewable resources, the PV industry and others will continue to be encouraged to be green while providing clean energy solutions.

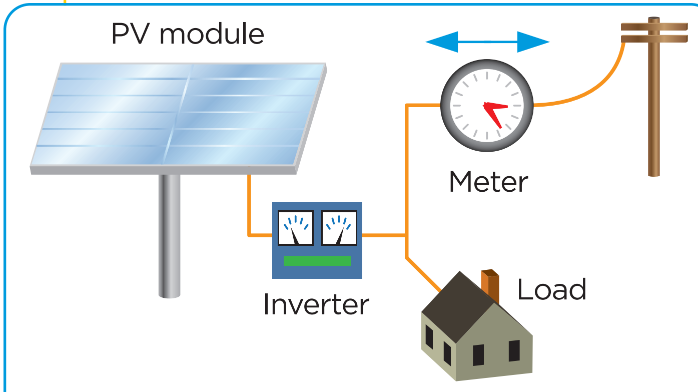
APPENDIX A: BALANCE OF SYSTEM

The balance of system (BOS) is the physical support for the panels and the electronics that connect the modules to the electricity system (either grid-tied or off-grid).

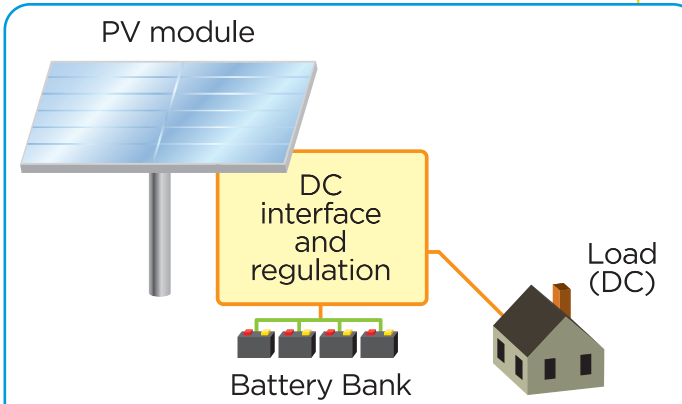
In the U.S., the BOS represents a significant percentage of the total cost of a solar installation. The Rocky Mountain Institute found that BOS costs can account for almost half of the installed cost of a commercial or utility PV system.[94] This is a function both of the costs of system materials and labor to install the modules as well as the costs of permitting. As PV manufacturers work throughout their supply chains to better integrate the BOS to improve efficiencies and encourage suppliers to reduce costs, an equal attention needs be paid to the policies that will reduce permitting costs and thereby increase the competitiveness of solar as an electricity generating solution.

BOS also contributes to energy payback time and carbon footprint. Systems with lower sunlight-to-electricity efficiency generally need more balance of systems per watt of installed cells, thus worsening the EPBT and carbon footprint of the balance of systems.

The general components of BOS are: mounting racks, wiring, inverters, charge-controllers, net meters (for grid-tied installations), and batteries (for systems using storage).



Grid-tied BOS, courtesy of DOE



BOS with battery storage, courtesy of DOE

Mounting racks: Mounting racks provide stability for the modules and the frame. The mounting racks position the modules so that they are properly aligned to the sun. Frames and mounts are often made of aluminum, a material that is highly energy intensive and valuable in the recycling stream.

Wiring: The electricity produced in the cells is moved through and out of the modules via wires. Wiring is needed both to string modules together in an array as well as to take the electricity produced in an array to an inverter or storage (if used), point-of-use, or to the grid connection.

Inverters: Solar modules produce power that is direct current (DC). Inverters convert DC power into alternating current (AC) power to be either transmitted back into the grid or to power the appliances, lights, equipment, etc. in a home or building. There are two basic types of inverters, those that work directly from the module without storage batteries and those that convert energy that has been stored in batteries.

Charge-controllers: Charge-controllers are used in PV systems with batteries. They prevent the batteries from being overcharged. Some charge-controllers also monitor the power in such a way as to increase the power obtained from an array.

Net meters: Meters track the amount of electricity generated in the solar array, the amount that is utilized, and the amount that is "outflow" back to the electric grid. They calculate when there is unused (net) electricity that can be sold back to the grid, or when additional electricity needs be purchased.

Batteries: Batteries are utilized to store the electricity produced by a solar array. Batteries enable the electricity to be used on-demand and not solely when the array is producing electricity. Most of today's PV systems connect directly to the grid and do not use battery storage.

The components of the BOS contain metals that are valuable at end-of-life. In addition, components such as batteries contain substances that should be recycled in order to both reuse materials and to reduce the risk of potential exposure from hazardous and toxic materials in the battery.

APPENDIX B: SILICON

The production of pure silicon is the largest single energy input into the PV manufacturing lifecycle. Although silicon is the second most abundant element on the earth's crust, it is in the form of quartz (SiO2) and must undergo several energy-intensive processes in order for it to be pure enough to use in crystalline silicon panels.

The following is a general flow for silicon production.

The first stage creates silicon that is 98% pure by carbothermic reaction. The quartz is placed in a barrel and carbon rods are heated to 1600^0 C. The heat separates the silicon from the oxygen and the carbon combines with oxygen. Carbon dioxide and carbon monoxide are released, and the solid silicon collects at the bottom of the vessel. Currently, there are no zero-greenhouse gas emission technologies, but the CO_2 per kWh of silicon production is low relative to both coal and natural gas.

The next stage is a purification stage. Hydrochloric acid is added to the silicon. This creates a gas, trichlorosilane, which has purity of over 99%.

Following, the silicon must be removed from the trichlorosilane gas and returned to a solid form. The silicon generated at this phase will be used as feedstock for growing silicon ingots. There are three primary ways to do this:

1. **Siemens Process:** In the Siemens Process, long, very thin square rods of silicon are heated to 1000^0 C in a chamber. The trichlorosilane is pumped in. When the gas hits the rods, it splits into chlorine, hydrogen, and silicon. The silicon sticks to the rod and the hydrogen and chlorine are removed as gas. As the silicon gas attaches itself to the rods (in solid form) the rods become very thick "poles" of silicon — almost as thick as a telephone pole.

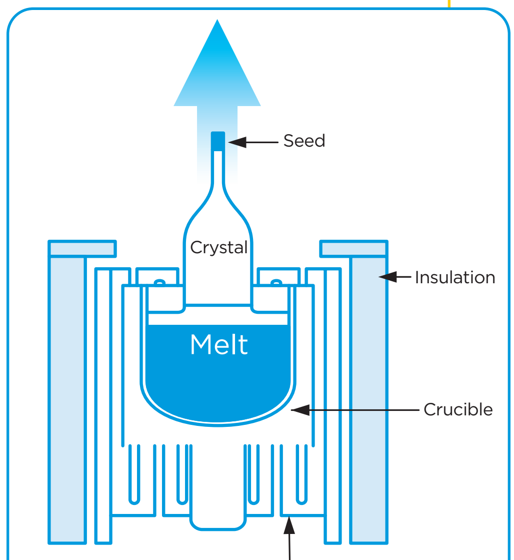
2. Modified Siemens Process: The Modified Siemens Process is similar to the Siemens Process. The main difference between the two is the manner in which the hydrogen and chlorine gases are recovered.

3. Fluidized Bed Process: In the Fluidized Bed Process, a fluidized bed of pure silicon powder (the silicon is in powder form, but behaves like a fluid, not a gas) is floated in a chamber heated to 1000^0 C. Trichlorosilane is pumped in, splits into hydrogen, chlorine, and silicon, and the silicon attaches to the powder and creates beads of pure solid silicon.

A fourth way to manufacture pure silicon is Upgraded Metallurgical Grade (UMG). This process is similar to the Siemens Process, but either uses additives in order to further purify the silicon, or takes the output from the Siemens Process and repeats the process to get the silicon more pure.

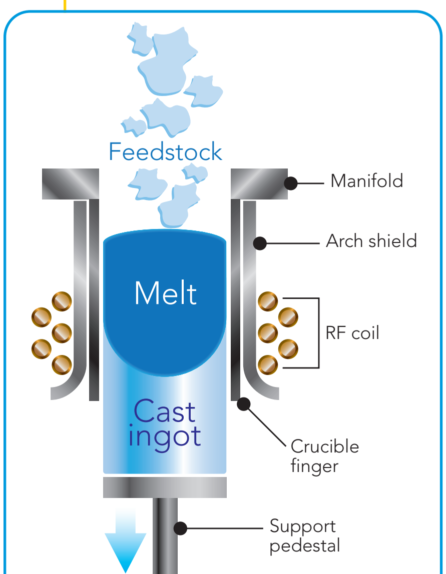
In the next stage, silicon crystals are grown from the feedstock. Either single crystals (monocrystalline) or multiple crystals (multicrystalline) are grown. There are three primary ways to do this.

The most common way to grow monocrystalline silicon is the Czochralski Process (Cz Process). Chunks of purified silicon created in the above processes are placed into a graphite bowl inside a chamber that is heated to 1450^0 C (usually beads are not used at the start due to the high surface area). The silicon feedstock melts and no longer has a crystalline structure. A silicon seed-crystal is lowered into the liquid silicon and is slowly raised, pulling the liquid silicon with it. As the seed-crystal moves further from the bowl, the liquid cools and solidifies — replicating the crystal structure of the seed. As the bottom of the bowl is reached, the ingot is tapered off into a "tail."



Monocrystalline

Prior to sawing into wafers, the "tops" and "tails" of the monocrystalline ingot are removed and the outside of the ingot is ground to the desired diameter.

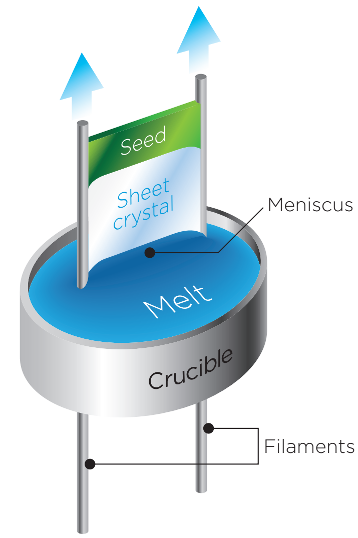


Multicrystalline

Casting is used to manufacture multicrystalline silicon ingots. In order to cast multicrystalline, chunks of the feedstock are placed into a rectangular crucible. As the crucible is heated, the chunks melt and beads of silicon are also added. The crucible is then lowered. As it moves below the heating elements, the liquid silicon cools from the bottom up and the ingot grows to fill the crucible. This makes multicrystalline ingots because the silicon on the bottom of the crucible make individual crystals juxtaposed to one another. As additional silicon cools, it takes on the crystal structure of the solid silicon below it, yielding a multitude of single crystals next to one another.

A third way to fabricate silicon for cells is by ribbon. In this process, 1-2 kg of silicon beads are melted (versus hundreds of kg of silicon in other processes). Because less silicon is used, the process requires less energy than others. Two strings are pulled through the liquid silicon. As the strings are lifted, a meniscus forms and eventually there is a ribbon of multicrystalline silicon between the strings. Once the silicon

solidifies, the ribbon is wrapped around a wheel for storage.
A monocrystalline ribbon can also be manufactured. This is called "dendritic web" and is produced by inserting a monocrystal into the liquid to start the crystalline process. Ribbon silicon is slow to manufacture but yields significantly less waste in the balance of the wafer production process. Even so, it has not been as successful in the marketplace as silicon ingots.



Ribbon

Prior to wafer cutting, the crystalline silicon is a commodity — yet there are functional differences between monocrystalline and multicrystalline silicon. Monocrystalline silicon is of similar quality to that used in the microelectronics industry. It yields the highest efficiency crystalline cells yet is the most expensive and energy intensive to produce of the three. Multicrystalline is less energy intensive to produce than monocrystalline — but it yields cells with slightly lower efficiencies. It is currently the largest segment of the crystalline PV market.

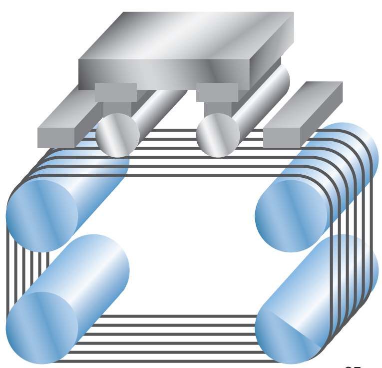

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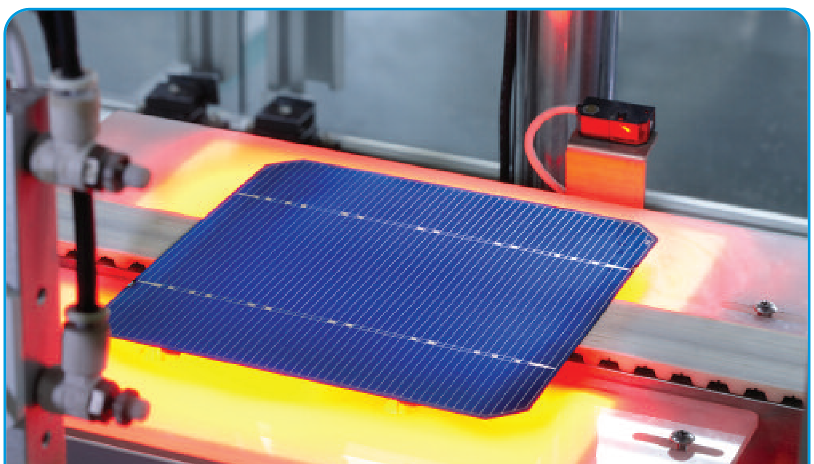
Diagram of a wire saw

Silicon ingots are sliced into wafers using wire saws. The saws use a long wire, wrapped around the ingot that moves both forward and backwards. The wire saws through the silicon at carefully spaced intervals simultaneously. In order to cut through the silicon, an abrasive — or slurry – is used. This slicing creates a silicon dust, or kerf. The amount of kerf is significant — as the amount of kerf can be half of the material of the original ingot. A challenge is to reclaim the energy-intensive purified silicon dust from this process.

Ribbon silicon does not have the same percentage of waste, as the ribbons are already wafer-thin and only need to be sized.

Silicon wafers then need to be processed in order that the electrons pass in one direction and the silicon conducts electricity. The manner by which silicon wafers are treated to generate and conduct electricity ("defect engineering") is the differentiating technology among crystalline silicon PV cells. Wafers are typically treated with phosphorous and boron compounds the first of which makes one side negatively charged (has extra electrons) and the latter positively charged (in need of an electron).


Solar cell, courtesy of Suntech

GLOSSARY

Abatement systems remove materials from air or water. There are several types of abatement systems used in PV manufacturing including: heat oxidation, precipitation, ion exchange, reaction or adsorption using resin or packed beds, and passive air addition.

Absorber materials are the semiconductors in a photovolatic cell that enable the device to convert sunlight to electricity. These materials lend their names to the different types of solar panels, e.g. silicon, cadmium telluride, copper indium gallium diselenide (CIGS), gallium arsenide, etc. The properties of the absorber materials play a large role in determining the efficiency of a solar cell.

AC is alternating current. It is the form in which electricity is currently transmitted and used by consumers.

Alloy is a mix of materials. In PV, alloys are added to a substance to change its properties. Alloys are >1% concentrations.

Ammonia (NH_3) is a common industrial chemical used for cleaning applications and chemical processes. In crystalline silicon PV, it also can be used in manufacturing the anti-reflective coating. Exposure to elevated concentrations of ammonia can result in lung damage, blindness, and, in extreme cases, death.

Anti-reflective coating increases the cell efficiency by maximizing the amount of light trapped in the cell and minimizing the amount of light that gets reflected off and out of the cell. This increases the photo-generated current.

Anti-takeover provisions are measures taken by a company to prevent or deter takeovers.

Automation is the use of robots and machinery in lieu of workers in the production line. In PV manufacturing, automation serves to reduce cost and the need for human contact with toxic and hazardous substances used in some manufacturing processes. Automation and redundant computerized mechanical safety mechanisms improve the economic performance of the fab and technical performance of the modules by increasing manufacturing precision, throughput, and reproducibility and decreasing the likelihood of routine environmental and health hazards.

Baghouses use fabric tubes, envelopes, and/or cartridges to capture particles from being released into the atmosphere.

Band-gap is the amount of energy required to free an electron in a semiconductor. Depending on a material's band-gap, light (photons) of different energy match the band-gap, are absorbed, and release electrons in the material. Multi-junction devices use materials with different band-gaps to better utilize light across the solar spectrum.

Biochemical oxygen demand oxidation provides liquid oxygen to biological organisms to break down the organic material in water.

Boron compounds are used to create p-type silicon-based semiconductors. It has three electrons whereas silicon has four.

Boron trifluoride (BF_3) is used to dope silicon and create a p-type semiconductor using boron. BF_3 is highly toxic and can cause burns if it comes in contact with skin or eyes. If inhaled, BF_3 can lead to death. There are a number of other chemicals that can be used to dope a semiconductor with boron, but none are perfectly interchangeable and each comes with its own environmental and health safety risks. BF_3 is also known as boron fluoride and trifluoroborane.

Building-integrated photovoltaics (BIPV) are PV systems integrated into the envelope of the building including: curtain walls, glazings, tiles, shingles, and skylights.

Cadmium is a metal used in cadmium telluride (CdTe) panels and in the cadmium sulfide layer of CdTe and CIGS panels. It is highly toxic and a known carcinogen.

Cadmium sulfide (CdS) is used as an emitter layer in both CdTe and CIGS panels.

CAPA is corrective action and preventative action. It is used to investigate and prevent violations.

Carbothermic reaction uses carbon and heat to transform a metal oxide to the pure metal.

Cell is the smallest building block of a PV module. It is self-contained, converts sunlight into electricity, and delivers the electricity for use. Cells are connected together to make modules.

CGA (Compressed Gas Association) develops and promotes safety standards and safe practices for industrial gases.

Chemical bath deposition is a technique for depositing materials as a thin film. In chemical bath deposition, the material to be deposited begins in a liquid state and the substrate is immersed into the liquid. It has a relatively low materials efficiency. The precise hazards are defined by the chemicals employed.

Chemical oxygen demand oxidation uses chemicals to oxidize organic material in water.

Chemical vapor deposition (CVD) is a technique for depositing materials as a thin film. In chemical vapor deposition, the material to be deposited begins in a gaseous state. Types of chemical vapor deposition include: plasma-enhanced, hot wire, and thermal vapor deposition.

Chlorobenzene is a solvent. It is used in inks in both organic and dye-sensitized processes.

Close space sublimation (CSS) is a physical vapor deposition technique in which the substance transitions directly from a solid to a gas without going through a liquid state. The solid source of the material is placed close to the substrate where the material is to be deposited. It is used in CdTe because of the material efficiencies and its scalability.

Co-deposition is the simultaneous deposition of substances which allows them to be juxtaposed on the substrate. Repeated co-deposition steps can be used to precisely tune the composition of the solar cell.

Compound is a chemical substance of two or more elements in a particular ratio.

Concentrating Photovoltaics (CPV) is the use of mirrors or lenses to focus light onto photovoltaic cells to directly convert sunlight to electricity.

Concentrating Solar Power (CSP) uses mirrors or lenses to direct sunlight either to a tower or pipes where water is converted to steam. The steam turns turnbines that drive electric generators.

Conductive layer is a layer in an electronic device that conducts electricity. In PV cells the conductive layer allows the current to flow out of the cell into an external circuit.

Conductor is a medium in which an electric current can freely flow. Conductors are typically metals.

Conjugated polymer is a string of carbon atoms each arranged in a hexagon. They are used in organic photovoltaics because the electron cloud above the string of carbon atoms acts as a tube through which electrons can pass to a fullerene.

Cradle-to-cradle is the concept that products contain materials which, at the end of life of the product, either biodegrade or are recycled into new products.

Current is the flow of electricity through a wire. The symbol for current is "I".

Czochralski Process (Cz Process) is the most common way to manufacture a monocrystalline silicon ingot. In Cz Process, a single crystal is lowered into liquid silicon. As it is raised, a monocrystalline ingot is formed.

DC is direct current. PV cells create direct current. Inverters are installed with panels to change the direct current to alternating current.

Deposition is the settling or growth of particles or atoms onto a surface.

Deposition rate is the rate at which particles or atoms settle onto a surface.

Design for end-of-life is the concept that designers, engineers, etc. create products in such a way that, at end-of-life, components of the products can be easily separated and reused in new products.

Diborane (B_2H_6) is used to dope silicon and create a p-type semiconductor using boron. Diborane is a toxic gas when inhaled and can cause respiratory problems and headaches at low concentrations. At high concentrations or repeated exposure, diborane can cause damage to the nervous system, liver, or kidneys, or even death. Diborane is pyrophoric and also known as boron hydride, diboron hexahydride, and boroethane.

Diffusion is the passive movement of molecules from a region of higher concentration to one of lower concentration. In PV it is a method for doping a semiconductor.

Dilution is a process whereby a chemical's concentration is reduced by increasing the amount of other substances (liquid or gas). It is used in PV to reduce the concentration of toxic chemicals in liquids or gases after their use in manufacturing.

Dopant is an impurity added to a substance to change its electrical charge. Dopants are in <1% concentrations.

Doping chamber is the chamber in which substances are doped.

Dry abatement is a method of gas abatement where emissions are passed through a bed of materials and bond with the materials. There are two primary methods: hot bed and resin bed. Hot bed systems operate at elevated temperatures and resin bed systems rely on more complex media. The abatement happens by gradually deactivating the media by clogging it with the target compound (usually something extremely hazardous like arsine that cannot be flushed with water).

Efficiency is the percentage of the light energy that shines on the cell or module that is converted to electrical energy.

Effluent is the outflow of water or gas. It is important that effluents from manufacturing facilities do not contain elements that are toxic to the environment or human health.

EHS is the abbreviation for environmental health and safety.

EICC is the Electronics Industry Citizenship Coalition. It provides a code of conduct for managing global supply chains in the electronics and information communication technology industries. The code addresses both environmental and worker issues.

Electric heat oxidation is a method of gas abatement where electric heaters heat undesirable emissions to temperatures at which they become inert.

Electrodeposition is a process by which an electric current is put into a solution of dissolved metals. When the current becomes active, the metals become deposited onto a substrate. Its EHS performance is dependent on the electricity consumed in the process and the sources, management, and end-of-life treatment of the solution and the metals in the solution. It is also called electroplating.

Electrolytic purification separates a metal from its impurities using electrolysis.

Electronic waste (e-waste) is discarded electric or electronic equipment. Electronic waste (or e-waste) can be detrimental to both human and environmental health as improper treatment of e-waste can expose people to hazardous materials and, when left in landfills, release toxins into the environment.

Electroplating *see **electrodeposition***.

Emergency scrubber is a safety mechanism to abate toxic or highly toxic gases in case of an emergency release.

Emissions are gases or particles that are put into the air.

Emitter layer is the layer that releases electrons into the solar cell.

Encapsulant contains the components of a panel and protects them from moisture and dirt.

Enclosures are the exhausted and filtered containers or areas for handling hazardous materials and processes.

Energy Payback Time (EPBT) is the amount of time time a system must operate to produce the energy that went into making the system.

Environmental Management System is a formal system in a company to manage the environmental impacts of production.

Epitaxial growth is a process by which a gas deposits onto a substrate in the exact crystal lattice of the substrate. It is used to grow high purity semiconductors.

ESG is environment, social, and governance. It refers to an approach to investing where a company's environmental, social, and governance performance are considered in addition to financial performance when making investment decisions.

Etching is the use of acid, ions, sputtering, or vapors to cut into a surface to remove unwanted material.

Ethyl tetrafluoroethylene (ETFE) is used as a flexible backsheet for PV modules. It is a fluorinated polymer and thus has significant risks to both workers and the environment during its manufacture.

Ethylene vinyl acetate (EVA) is a clear durable material used as an encapsulant to protect the PV module. It is made from ethylene (C_2H_4) and vinyl acetate ($CH_3COOCH{=}CH_2$). The vinyls used in EVA are carcinogenic.

Evaporation is a process by which molecules go from a liquid to a gaseous state. Some CIGS processes use evaporation to deposit the material on the substrate.

Extended producer responsibility (EPR) is a strategy to decrease the environmental impact from a product by making the manufacturer of the product responsible for the entire life-cycle of the product and its packaging, particularly take-back, recycling, and disposal.

Fab is the term used for a cell fabrication facility.

Flocculants are chemicals that cause small particles floating in a solution to aggregate, easing a cleaning process. They are used to clean liquid effluents before releasing fluids from a facility.

Fluidized Bed Process is used to create polysilicon. Trichlorosilane is added to a pure silicon powder at a controlled density so that it behaves like a fluid. The trichlorosilane attaches to the powder and creates beads of polysilicon.

Fluorine is a strong oxidizing agent. It is used to clean doping chambers. It has a relatively low environmental impact but is highly reactive and introduces worker-safety issues.

Fullerene is 60 carbon molecules with a structure similar to a soccerball. It is used in organic photovoltaics. Cylindrical fullerenes are known as carbon nanotubes.

Gas-fired heat oxidation is an abatement technique powered by the burning of natural gas. Emissions are heated and oxidized, which breaks the chemicals apart. The resulting atoms bond with the oxygen, rendering them harmless. This process results in carbon dioxide emissions from the burning of the natural gas.

Germane (GeH_4) is used in silicon production as a source of germanium. Germane gas is toxic, flammable, and potentially pyrophoric. There are a number of liquid and solid phase germanium complexes such as iso-butyl germane ([C4H7]GeH3) that have been investigated to replace germane gas, although as with any of these emerging technology alternatives, there are potentially life-cycle or process issues that have significant EHS risks themselves.

Germanium is a semiconductor and is used to alloy amorphous silicon. It is toxic to the blood and kidneys.

Global warming potential (GWP) is a measurement of the contribution of a given compound to global warming. The global warming potential of one kilogram of carbon dioxide is unity (one). The GWP of other gases are calculated from the atmospheric lifetime and radiative efficiency of the compound and discussed as a multiple of the GWP of carbon dioxide.

Grätzel cell is a type of dye-sensitized solar cell invented by Michael Grätzel and Brian O'Regan.

HEPA filter stands for high efficiency particulate air filter. It is an air filter used to capture very small pollutants so they do not escape into the air.

High Voltage DC (HVDC) transmission lines move DC (versus AC) current. Many have recommended HVDC be added to the electricity infrastructure in order to better incorporate widescale adoption of PV and other distant sources of energy, such as wind, into the grid.

Hot bed abatement is a process whereby gases are trapped in a solid material at high temperatures.

Hydrochloric Acid (HCl) is a powerful and caustic cleaning chemical. It is corrosive and exposure can affect respiration, eyes, and intestines.

Hydrofluoric acid (HF) is used to etch silicon wafers. It is a common commercial acid, but is highly toxic. A small amount of HF can penetrate the skin, and can affect the nervous system or cause cardiac arrest.

Hydrofluorocarbons (HFCs) are used in the cleaning and etching of cells. They are powerful global warming gases with global warming potentials ranging from from 140 (HFC-152a) to 11,700 (HFC-23). They need be abated in order to prevent escape into the atmosphere.

Hydrogen is used in amorphous silicon production. It is a non-toxic, highly flammable gas.

Hydrogen fluoride (HF) is a gaseous source of fluorine. The gas itself can cause blindness and, when it comes in contact with tissue, forms hydrofluoric acid.

Hydrogen selenide (H_2Se) is a toxic gas. It can be used as a precursor for selenium, and is formed when selenium mixes with the water vapor in the air.

ICP (Inductively Coupled Plasma) is a process that detects trace elements in a solution.

***In situ* chamber cleaning** is a process in which a fluorinated chamber cleaning gas is injected directly into the process chamber to be cleaned. The gas etches the residue on the inside of the apparatus. This effectively removes residue but does not fully utilize the cleaning gas as upwards of 50% of the input gas passes through unaffected.

Indium is a resource-constrained elemental metal used in CIGS.

Industrial hygiene is the science that addresses conditions in the workplace that may cause injury or illness to workers.

Inert is a term used to describe a substance that is not chemically reactive.

Ingot is, in PV, a mass of silicon that is shaped and from which wafers are sawed.

Inks are used to deposit metals, semiconductors, and/or transparent conducting oxides by directly "printing" onto the substrate. The desired materials are usually suspended in a liquid that is then evaporated, leaving the desired materal. Inks have a high materials efficiency but often contain nanoparticles or potentially toxic organic compounds. Inks offer a manufacturing process that is simpler than vacuum-based processes.

Insolation is the amount of solar radiation a location recieves in a given time.

International Standards on Auditing are standards for financial audits issued by the International Auditing and Assurance Standards Board of the International Federation of Accountants.

Inverters convert the DC output of a solar cell or module to AC so that the electricity can be used.

Ion is an atom or molecule with a positive or negative electrical charge.

Ion-exchange is a method of removing charged particles (ions) from a solution, for instance cadmium dissolved in water. The contaminated water is passed through an ion exchange medium, like a resin or functionalized beads, where the ions are bound to the medium.

ISO 14001 is a voluntary environmental management standard developed by the International Organization for Standardization in Geneva, Switzerland.

Junction is where two materials with different electrical properties come in contact.

Kerf is the silicon dust created during the wafer sawing process. Due to the high cost of the feedstock it is important to reduce the quantity of kerf and to recycle it.

Laser scribing is used in thin films to divide large areas into sub-cells that can be interconnected. Doing so reduces the distance the current must travel (and thus reduces losses) in getting the current out of the module and maximizes the voltage while keeping current low in the module.

Laser stands for light amplification and stimulated emission of radiation. A laser is a focused beam of light.

Life-cycle analysis (LCA) is a method for calculating the environmental impacts associated with the sourcing, manufacture, distribution, use, and disposal of a product.

Liquid bath deposition is a general term for deposition methods whereby a substrate is immersed in a solution containing the precursors to thin films. Chemical bath deposition and electrodeposition are examples of liquid bath deposition.

Metal organic compound are organic (carbon-based) molecules that include inorganic atoms (metals). They are precursors for reactions that create the desired compound, such as in the deposition of gallium arsenide. Typically the organic consituients are removed from the final PV product during the thermal processing of the device.

Methane (CH_4) is the primary component of natural gas. It is used in PV manufacturing for various thermal processes including abatement.

Microcrystalline silicon is tiny (on the nanoscale) crystals of silicon. It is used in thin film technology. It is lower bandgap than amorphous silicon (a-Si) and is used in multi-junction a-Si cells to increase the response to the red end of the solar spectrum. It is also called nanocrystalline silicon.

Modified Siemens Process is a modification of the Siemens Process that utilizes a different process to recover the gases left over after the silicon is deposited. It has a similar energy use and produces less waste.

Module is a grouping of individual cells, which are either separated by scribing or joined together, that provides packaging for the cells such that they are protected from the elements and can be easily installed into arrays.

Molybdenum (Mo) is a highly conductive elemental metal. It is used as the back contact in a CIGS cell (directly deposited onto the substrate).

Monocrystalline silicon is a single crystal of silicon, regardless of the size of the ingot. It is very energy intensive to manufacture, but produces the highest efficency silicon cells.

Multicrystalline silicon is an ingot consisting of many different crystals of silicon that can be seen with the naked eye. It is less efficient than monocrystalline silicon but less expensive to produce.

Multiple share classes of stock are common stocks with different voting rights assigned to each class of shares in the company.

Mutagens are substances that damage or change the genetic material of an organism, which, in turn, cause higher than normal occurrence of genetic mutation. Well-known chemical mutagens include benzene and vinyl chloride.

N-type is a semiconductor with an excess of electrons, or a negative charge. It is an electron donor.

Nanomaterial is a compound at the nanoscale (from 1-1,000 nm or billionths of one meter). They are often "intentionally engineered" to take advantage of unique properties at the nanoscale including conductivity and permeability but can also occur during cell fabrication and modification. Nanoscale materials in PV can allow for significant reduction in raw materials use.

Negative pressure is less than atmospheric pressure. Keeping process lines at negative pressure is a safety precaution because, if the line is compromised, air from the outside is sucked into the line (because it was at negative pressure). This prevents gases from escaping.

NFPA (National Fire Protection Association) provides code and standards to reduce the risk of fire and other hazards.

Nitric Acid (HNO_3) can be used to etch and texture silicon wafers for higher absorption of incident sunlight and is also sometimes used to strip excess tin, tin-lead, or nickel deposits on the industrial belts that cells pass over as the front and back contacts are being deposited. It is a highly toxic and corrosive acid.

Nitrogen Trifluoride (NF_3) is used to clean doping chambers. It is a highly effective cleaner, but has a significant global warming potential: 17,200.

Off-line wet cleaning is the oldest chamber cleaning technology. It involves taking the process chamber off-line, opening it up, and cleaning it manually with acids and other cleaning chemicals. The solvents and other cleaning substances have health risks, and the technique has been phased out because on-line alternatives allow for much higher process efficiency.

OHSAS 18001 is designed to help facilities mitigate occupational health and safety risks. It is an assessment series for occupational health and safety.

On-site generated fluorine is a technology to produce fluorine (F_2) onsite thereby reducing health and safety risks associated with transporting F_2.

Oxide is a chemical compound that contains oxygen (e.g. SiO_2, commonly known as quartz and a feedstock for silicon production).

P-type is a semiconductor with a deficiency of electrons. It has a positive charge and is, therefore, an electron receptor.

Passive air addition adds air to gasses in order to provide a safe venue for reaction or to dilute contaminant concentrations before they are released to the environment. Passive air addition is one of five types of point of use (POU) oxidation systems commonly used in the semiconductor industry.

Perfluorocarbons (PFCs) are used in cleaning and etching applications for semiconductor manufacturing. PFCs are powerful greenhouse gases, with global warming potentials ranging from 7,390 to 12,200. They are also known as poly-fluorinated compounds.

pH adjustment is used to abate very acidic or alkaline compounds by neutralizing them.

Phosphine (PH_3) is a gas used to dope silicon wafers with phosphorous creating an n-type semiconductor. Phosphine is both flammable and toxic and is also known as hydrogen phosphide, phosphorus hydride, and phosphorus trihydride.

Phosphoros is a dopant used to create n-type silicon-based semiconductors. It has five electrons, whereas silicon has four.

Phosphoryl Chloride ($POCl_3$) is used to dope silicon wafers with phosphorous creating an n-type semiconductor. Phosphoryl chloride is a highly toxic and corrosive compound.

Photovoltaic effect is the creation of voltage or current in a material as a result of its exposure to light.

Photovoltaics (PV) is the conversion of light to electricity.

Physical Vapor Deposition (PVD) is a general term for depositing materials where the material to be deposited begins as a solid. Thermal evaporation, e-beam evaporation, sputtering, and laser ablation are all types of PVD.

Plasma is ionized gas. It contains electrons and positively charged atoms. Plasmas are used to deposit semiconductor layers and some transparent conducting oxides to a substrate.

Plurality voting elects the individual who has the most votes, as opposed to a majority vote.

Polycrystalline is many different crystals that can not, normally, be detected by the naked eye. There are polycrystalline thin films such as CdTe and CIGS. In polycrystalline silicon you can see the crystals with the naked eye, but it differs from multicrystalline silicon where the grain boundaries are visible.

Polyglycol is a category of chemical compounds that can be used as lubricants in the wafer sawing process.

Polysilicon is a material consisting of very small silicon crystals.

Polyvinyl chloride (PVC) is plastic used as an encapsulant in PV modules. PVC production releases compounds that cause cancer, endocrine disruption, birth defects, and other diseases. PVC is a major source of volatile organic compounds and leaches phthalates and other chemicals into the air that have been linked to asthma. At its end-of-life, incineration of PVC creates dioxin and other toxins.

Polyvinyl fluoride (PVF) is used as an encapsulant for PV modules, where it reduces flammability. It is more commonly known by its DuPont brand name Tedlar™.

Power is the rate at which energy is converted. In a solar array, power (P) = voltage (V) x current (I)

PPE is personal protective equipment. It is required by the Occupational Safety and Health Administration (OSHA) to reduce worker exposure to hazards.

Precipitate is to separate out solids from a solution.

Precipitation is when compounds in a waste stream are separated out from the solution.

Precursors are materials that produce other desired materials. For example, phosphine gas is a precursor for phosphorous. The phosphine undergoes a reaction that releases phosphorous which is desired to dope silicon in crystalline silicon cells.

Pyrophorics are materials and substances that spontaneously ignite when in contact with air. Pyrophorics used in PV manufacturing include arsine, diborane, phosphine, and silane, underscoring the importance of reliable, redundant safety systems in fabs.

Remote plasma source (RPS) is a microwave device used to produce a plasma outside of the target process chamber. The plasma is then pumped to the chamber for use.

Resin bed abatement is a process by which gases are trapped in a resin bed, where they are chemically transformed into non-volatile compounds.

Ribbon silicon, or "string ribbon" silicon, is manufactured by pulling a ribbon of crystalline silicon from a bed of liquid silicon. It uses less energy to produce than other processes to manufacture silicon and has the benefit of not needing to be sawed so material is not wasted as kerf.

Ruthenium is a toxic rare metal that is often used in dye-sensitized solar cells.

SA8000 is a standard for working conditions. SA8000 certified facilities should meet standards of health and safety, working hours, child labor, forced labor, discrimination, freedom of association and collective bargaining, wages, and discipline. It is administered by Social Accountability International (SAI).

Scrubbing removes particulates or gases from air exhaust.

Selenization is a process of introducing selenium to a metallic precursor, often a copper-indium alloy. Often it uses hazardous precursors, such as hydrogen selenide (H_2Se).

Semiconductor is a material that conducts electricity, but its rate of conductivity is between that of an insulator (doesn't conduct) and a metal (conducts). By engineering the material in various devices the conductivity can be controlled to perform specific functions. In PV devices, it is exploited to directly convert sunlight into electricity.

Shading loss is the reduction of electricity produced by a PV system due to reduced exposure to light. Within the cell this could be due to metal contacts or grids, outside it could be due to other structures, trees, etc.

Siemens Process is a process of growing polycrystalline silicon by decomposing trichlorosilane at high temperatures so it deposits silicon on an existing silicon rod.

Silane (SiH_4) is used to manufacture both crystalline and amorphous silicon. It is toxic and pyrophoric.

Silicon chloride hydride ($SiHCl_3$) is used in the purifcation of silicon and in the Siemens and Modified Siemens Processes to make silicon. It is also called trichlorosilane.

Silicon is the basis of the most common technology currently used in PV. It is the second most abundant element on the earth's crust. Silicon has been widely studied as it is also the basis for the semiconductor and integrated chip industries.

Silicon tetrachloride ($SiCl_4$) is a source gas for making silicon. It is an environmental hazard and should be recovered after use and properly managed.

Slot dye is a process by which a solution is pumped through a slot onto the substrate. It is used in organic PV and is being explored for other technologies where inks can be employed due to its manufacturability (low loss, uniform coating, and non-clogging nature).

Slurry is abrasive materials in liquid used to enhance the efficacy of wire in wire-cutting silicon wafers.

Solvent dissolves a substance into a solution.

Spectrum is a range. Each PV material absorbs specific spectrums of light.

Sputtering is used to deposit thin films by shooting ions into a source material, called the "target." When the target is released, small pieces shoot off and land onto a substrate.

Subatmospheric pressure, *see* ***negative pressure***.

Substrate is the material onto which thin films are deposited. A substrate is further from the sun than the semiconductor material.

Substrate rinsing operations are necessary to clean the substrate on which thin films are deposited. Cleanliness is paramount in semiconductor and PV manufacturing since performance depends on very precise compositions and conformations of materials. The compounds used to clean the substrates, however, are often toxic and require abatement.

Sulfur hexafluoride (SF_6) is an industrial etchant and cleaning gas. SF_6 is the most powerful greenhouse gas known, with a GWP of 23,900. Only a portion of the SF_6 used in a cleaning operation is destroyed in process, requiring substantial post-cleaning emission management. There are effective methods of capturing, purifying, and recycling unused SF_6.

Supermajority vote requires a large majority (67-90%), specified by a company's charter.

Superstrate is the material onto which thin films are deposited. A superstrate is closer to the sun than the semiconductor material.

Tails, *see* ***tops and tails***.

Thermoelectric power plant is a plant where steam spins a turbine that drives an electric generator.

Thin film is a type of solar cell characterized by its thickness and it being deposited, as a film, on a substrate (versus a free-standing wafer). A cell less than 10 microns is considered "thin."

Tops, *see* ***tops and tails***.

Tops and tails are cone-like forms at the top and bottom of a crystalline silicon ingot. Tops and tails are not sliced into wafers. They are removed and should be recycled.

Transparent conducting oxide is a metal oxide where the transparent properties of oxides are combined with the conduction properties of metals. It is used on the layer of the PV device closest to the sun to both complete the electrical circuit of the cell and to let light pass to the active layers to generate electricity.

Trimethylboron ($B(CH_3)_3$) is a pyrophoric, toxic gas and source of boron which creates p-type semiconductors.

Upgraded Metallurgical Grade (UMG) is solar-grade silicon made directly from metallurgical-grade silicon. The process is significantly less energy intensive than the Siemens' Process, but typically produces lower quality material.

Vacuum distillation is a process by which substances evaporate in a vacuum. It is used to purify materials.

Vapor transport is a deposition technique in which substances are in vapor form when they are deposited on a substrate.

Voltage moves current. The symbol for voltage is "V."

Wafer is the slice of silicon that forms the foundation for a crystalline silicon solar cell.

Wet scrubbing is a process that uses liquid to remove pollutants from a gas.

Window layer is the top layer in a PV cell that lets light pass through, while also aiding the flow of electricity.

Wire sawing is used to saw silicon ingots into wafers. Wires cut both ways and are aided by slurry. Wire sawing creates a significant percentage of waste silicon, or kerf, that should be recycled.

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