Health and Safety Concerns of Photovoltaic Solar Panels

Introduction

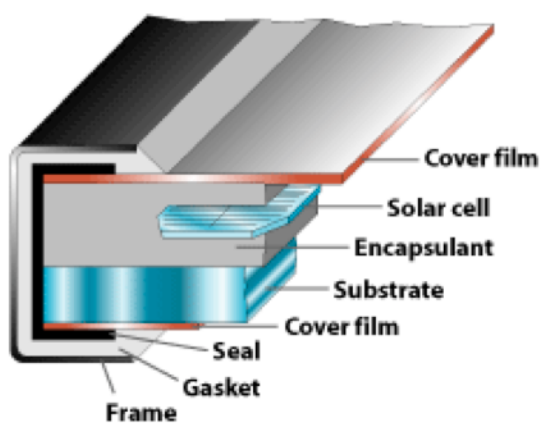
The generation of electricity from photovoltaic (PV) solar panels is safe and effective. Because PV systems do not burn fossil fuels they do not produce the toxic air or greenhouse gas emissions associated with conventional fossil fuel fired generation technologies. According to the U.S. Department of Energy, few power-generating technologies have as little environmental impact as photovoltaic solar panels.[1]

However, as with all energy sources, there are *potential* environmental, health and safety hazards associated with the full product life cycle of photovoltaics. Recent news accounts have raised public interest and concerns about those potential hazards.[2] A substantial body of research has investigated the life cycle impacts of photovoltaics including raw material production, manufacture, use and disposal. While some potentially hazardous materials are utilized in the life cycle of photovoltaic systems, none present a risk different or greater than the risks found routinely in modern society.

The most significant environmental, health and safety hazards are associated with the use of hazardous chemicals in the manufacturing phase of the solar cell. Improper disposal of solar panels at the end of their useful life also presents an environmental, health and safety concern. The extraction of raw material inputs, especially the mining of crystalline silica, can also pose an environmental, health and safety
The environmental, health and safety concerns for the life-cycle phase are minimal and limited to rare and infrequent events. With effective regulation, enforcement, and vigilance by manufacturers and operators, any danger to workers, the public and the environment can be minimized. Further, the benefits of photovoltaics tend to far outweigh risks especially when compared to conventional fossil fuel technologies. According to researchers at the Brookhaven National Laboratory, regardless of the specific technology, photovoltaics generate significantly fewer harmful air emissions (at least 89%) per kilowatt-hour (KWh) than conventional fossil fuel fired technologies.[3]

Materials used in photovoltaics solar panels

The basic building block of a photovoltaic solar system is the solar cell. Solar cells are solid state, semiconductor devices that convert sunlight into electricity. Typically a number of individual cells are connected together to form modules, or solar panels. In order to provide electrical insulation and protect against environmental corrosion, the solar cells are encased in a transparent material referred to as an encapsulant. To provide structural integrity the solar cells are mounted on top of a rigid flat surface or substrate. A transparent cover film, commonly glass, further protects these components from the elements.



Courtesy of the U.S. Department of Energy

Several types of semiconductor materials are used to manufacture solar cells but the most common material is crystalline silicon, typically from quartz or sand, capturing a 60% market share.[4] Crystalline silicon semiconductors are also utilized in the manufacture of integrated circuits and microchips used in personal computers, cellular telephones and other modern electronics.

The outer glass cover constitutes the largest share of the total mass of a finished crystalline photovoltaic module (approximately 65%), followed by the aluminum frame (~20%), the ethylene vinyl acetate encapsulant (~7.5%), the polyvinyl fluoride substrate (~2.5%), and the junction box (1%). The solar cells themselves only represent about four percent (4%) of the mass of a finished module.[5]

Oregon Department of Transportation Solar Highway photovoltaic solar panel selection
The solar panels proposed for use in the Oregon Department of Transportation's Solar Highway program feature domestically manufactured and assembled monocrystalline silicon modules. The information presented below, therefore, focuses on the life cycle environmental, health and safety hazards generally associated with this technology.

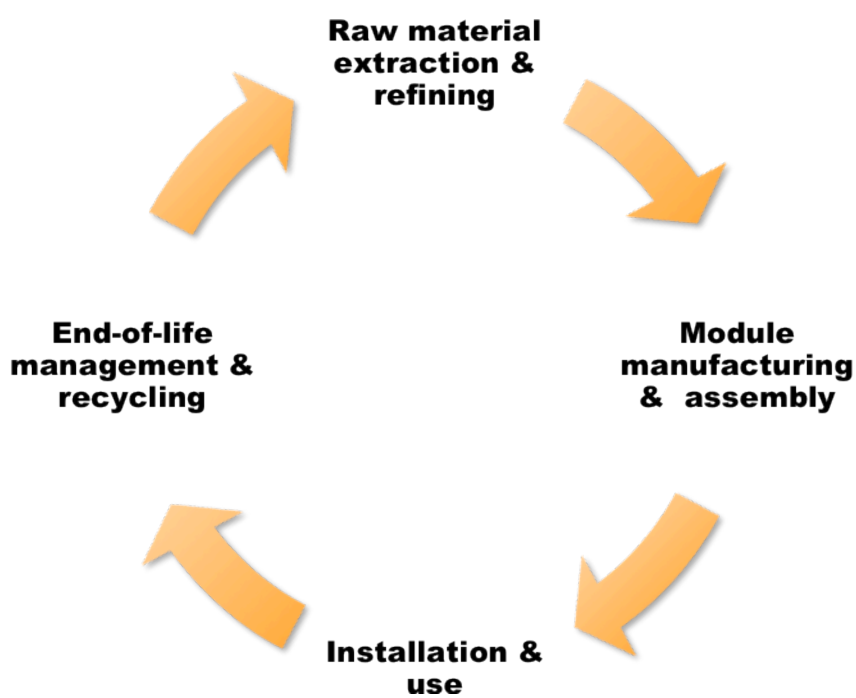
Life Cycle of Monocrystalline Silicon Solar Panels

The simplified process diagram below illustrates the basic life-cycle stages for the manufacturing of monocrystalline silicon (c-Si) solar panels.

The life cycle of a c-Si panel starts with mining of crystalline silica in the form of quartz or sand. The raw material is then refined in industrial furnaces to remove impurities to produce metallurgical grade silicon (~98% pure silicon). The metallurgical grade silicon is then further refined to produce high purity polysilicon for use in the solar and semiconductor industry. Next, the polysilicon is used to grow monocrystalline rods or ingots. These ingots are then shaped and sawn into very thin wafers. The wafers are then manufactured into solar cells and assembled into photovoltaic modules ready for installation. At the end of their useful life the materials in the panels can recycled and used as feedstock material for new panels.

The potential environmental, health and safety hazards associated with each of these steps are described on the following pages.

Figure 1: Simplified Photovoltaic Solar Panel Life Cycle



Raw material extraction and refining for solar panels

The material inputs phase consists of the extraction and processing of raw materials that are then used in the production of solar panels.

Crystalline Silica Mining

Process

Crystalline silica is the primary raw material input for the manufacture of monocrystalline solar panels. Crystalline silica is found in the environment primarily as sand or quartz. The extraction process varies by location, but typically involves some combination of earth moving, crushing, milling, washing, and screening to separate the crystalline silica particles from other minerals and impurities and to achieve the desired grain size.[6] The end product is variously referred to as silica sand, quartz silica or simply silica or quartz.

Health and Safety

A potentially harmful by-product associated with the mining and processing of silica sand is crystalline silica dust. Silica dust has been associated with silicosis, a lung disease where scar tissue forms in the lungs and reduces the ability to breath.[7] Crystalline silica dust is classified as a known human carcinogen by the International Agency for Research on Cancer.[8] Studies show increased risk of developing lung cancer through regular exposure to crystalline silica dust. Other health problems associated with regular, high exposure include chronic obstructive pulmonary disease, rheumatoid arthritis, scleroderma, Sjogern's syndrome, lupus, and renal disease.[9]

The widely recognized risk of human exposure to silica dust has resulted in the implementation of stringent health, safety, and environmental measures in the United States and across the globe. Examples of mitigation measures include monitoring air quality, automation of processes to limit human exposure, dust suppression measures and personal protective devices for workers such as respirators.[10]

It should be noted that the majority of global silica sand production (more than 80%) is used for the manufacture of glass and ceramics, metal casting and abrasives, while only 2% is utilized in the production of metallurgical grade silicon.[11]

Upgrading Silica Sand to Metallurgical Grade Silicon

Process

Metallurgical grade silicon is used in the manufacture of metal alloys such as aluminum and steel, chemical silicones for use in lubricants and epoxies as well as high purity polysilicon for the manufacture of semiconductors including solar panels. Consumption by the semiconductor industry, including photovoltaics, accounts for approximately 6% of global metallurgical grade silicon production.[12] In order to transform industrial grade silica sand into metallurgical grade silicon, the silica is combined with carbon in the form of charcoal, coal, or coke in an electric arc furnace in a process called carbothermic reduction.

Health and Safety

The primary emissions from this process are carbon dioxide and sulfur dioxide from the combustion of carbon sources. Another by-product of the process is fume silica captured via a piece of emission control technology called a bag house. If respirated, fume silica can pose the same health concerns as silica dust.[13] Additionally, there are indirect emissions of carbon dioxide from the consumption of electricity to power the electric arc furnace. The source and carbon intensity of this electricity varies by region.

Upgrading Metallurgical Grade Silicon to Polysilicon

Process

In order to reach a purity level acceptable for use in manufacture of semiconductor devices, metallurgical grade silicon must go through two additional purification steps. The primary output from this purification process is polysilicon, the precursor to the silicon wafers used to manufacture the integrated circuits at the heart of most electronics as well as monocrystalline photovoltaic solar cells.

In the first step, pulverized metallurgical grade silicon is combined with hydrogen chloride gas and a copper catalyst in a fluid bed reactor to produce trichlorosilane. Trichlorosilane is the primary chemical feedstock for the production of polysilicon. This step also yields silicon tetrachloride, which can either be captured and further processed into trichlorosilane or utilized as a feedstock in the manufacture of fiber optics. Other byproducts from this phase include silane, dichlorosilane and chlorinated metals. Dichlorosilane is an important precursor to silicon nitride, a ceramic material used, among other applications, in the manufacture of automobile engine parts.[14,15]

To produce polysilicon, the trichlorosilane is subjected to a distillation process until the desired purity level is achieved. The purified trichlorosilane is then used to deposit very pure polysilicon in a chemical vapor deposition reactor. This process, commonly referred to as the Siemens process, accounts for as much as 98% of the world's polysilicon production.[16] Historically, polysilicon destined for photovoltaic solar cells was considered "waste" material that did not meet the purity requirement of the electronics industry and accounted for approximately 10% of polysilicon production.[17] There are indications that this trend may be changing as the size of photovoltaic markets expand.

Health and Safety

This process involves multiple potentially hazardous materials and byproducts that without proper safeguards can pose a significant risk to human and environmental health. Chlorosilanes and hydrogen chloride are toxic and highly volatile, reacting explosively with water. Chlorosilanes and silane can also spontaneously ignite and under some conditions explode.[18] Silicon tetrachloride can cause skin burns and is also an eye and respiratory irritant.[19] Silicon tetrachloride has recently gained notoriety due to news accounts of its dumping near a polysilicon plant in China.[20]

Notably, Western production facilities accounted for more 99% of global polysilicon production in 2005, the latest year for which data is available.[21] These facilities use a closed loop process that captures system byproducts for recycling and reuse within the process loop because these recovery systems are necessary for the economic operation of a facility.[22] Furthermore, any waste gasses not recoverable for recycling are led through a series of pollution control technologies (e.g. wet scrubbers) prior to any environmental releases. Environmental releases include very low levels of particulate matter, hydrogen chloride and silicon tetrachloride.[23]

Furthermore, facilities in the United States, Japan and Europe are subject to strict environmental and occupational health and safety regulation and enforcement. In contrast, production capacity is rapidly expanding in developing countries such as China and India where such safeguards may not exist or be enforced. Regardless of their location, reputable and responsible firms will have implemented beyond compliance environmental management systems (e.g. ISO 14001 certification) and adopted voluntary industry best management guidelines (e.g. Responsible Care).

Manufacturing and assembly of solar panels

From Wafer to Cell

Process

Solar cells are produced by transforming polysilicon into a cylindrical ingot of monocrystalline silicon, which is then shaped and sliced into very thin wafers. Next, a textured pattern is imparted to the surface of the wafer in order to optimize the absorption of light. The wafer is then subjected to high temperatures in the presence of phosphorous oxychloride in order to create the physical properties required to produce electricity. Next an anti-reflective coating of silicon nitride is applied to the top surface of the cell to minimize reflection and increase efficiency of light absorption. Finally, metallic electrical conductors are screen printed onto the surface wafer to facilitate the transport of electricity away from the cell. The production of solar cells is concentrated in Japan, Europe and the United States, which currently account for more than 80% of global production.[24]

Health and Safety

Many different potentially hazardous chemicals are used during the production of solar cells. The primary environmental, health and safety concerns are exposure to and inhalation of kerf dust, a byproduct of sawing the silicon ingots into wafers, and exposure to solvents, such as nitric acid, sodium hydroxide and hydrofluoric acid, used in wafer etching and cleaning as well as reactor cleaning. Many of these solvents also pose a risk of chemical burns. Other occupational hazards include the flammability of silane used in the deposition of anti-reflective coatings.[25]

The most likely exposure route for factory workers is inhalation of vapors or dusts. Secondarily, there is exposure risk for factory workers from accidental spills. Risks to surrounding communities include the release of hazardous gasses from an industrial accident or fire at the manufacturing facility.[26] These hazards are regulated by a number of occupational and environmental standards as well as industry adopted voluntary best management practices. These regulations and strategies include: extensive occupational ventilation systems, accident prevention and planning programs and emergency confinement and absorption units.[27] As a result of these safeguards, there have been no known catastrophic releases of toxic gases from photovoltaic manufacturing facilities in the United States.[28]

Module components and assembly

Process

A typical solar module consists of several individual cells wired together and enclosed in protective material called an encapsulant, commonly made of ethylene vinyl acetate. To provide structural integrity the encapsulated cells are mounted on a substrate frequently made of polyvinyl fluoride. Both ethylene vinyl acetate and polyvinyl fluoride are widely considered to be environmentally preferable to other chlorinated plastic resins. A transparent cover, commonly glass, further protects these components from weather when in place for electrical generation. The entire module is held together in an aluminum frame. Most modules also feature an on board electrical junction box.[29]

Health and Safety

Individual solar cells are typically soldered together with copper wire coated with tin. Some solar panel manufacturers utilize solders that contain lead and other metals that if released into the environment can pose environmental and human health risks. Module assembly is not a likely pathway for human exposure to these metals as this step in the assembly process is typically automated. For more discussion regarding the end-of-life product phase risks of lead containing solders, see the discussion in the decommissioning and recycling section below.

Installation and use of solar panels

Installed silicon-based cells pose minimal risks to human health or the environment according to reviews conducted by the Brookhaven National Lab and the Electric Power Research Institute.[30]

Health and Safety

Because solar panels are encased in heavy-duty glass or plastic, there is little risk that the small amounts of semiconductor material present can be released into the environment.

In the event of a fire, it is theoretically possible for hazardous fumes to be released and inhalation of these fumes could pose a risk to human health.[31] However, researchers do not generally believe these risks to be substantial given the short-duration of fires and the relatively high melting point of the materials present in the solar modules. [32] Moreover, the risk of fire at ground-mounted solar installations is remote because of the precautions taken during site preparation including the removal of fuels and the lack of burnable materials – mostly glass and aluminum – contained in a solar panel.

A greater potential risk associated with photovoltaic systems and fire is the potential for shock or electrocution if a fire-fighter or emergency responder comes in contact with a high voltage conductor. These concerns are almost entirely related to roof mounted residential and commercial solar arrays. The Oregon Building Code Division is currently considering new rules to increase public safety for structures equipped with solar photovoltaic systems. The proposed rules are inspired by a model code adopted by the California Department of Forestry & Fire Protection. As it applies to ground mounted photovoltaic arrays, the California model code calls for a clear marking of system components in order to provide emergency responders with appropriate warnings.[33]

The strength of electromagnetic fields produced by photovoltaic systems do not approach levels considered harmful to human health established by the International Commission on Non-Ionizing Radiation Protection. Moreover the small electromagnetic fields produced by photovoltaic systems rapidly diminish with distance and would be indistinguishable from normal background levels within several yards. For a detailed discussion of electromagnetic fields and solar arrays read the *Scaling Public Concerns of Electromagnetic Fields Produced by Solar Photovoltaic Arrays* paper at http://www.oregonsolarhighway.com.

End-of-life management and recycling of solar panels

Process

While the solar cell is the heart of a photovoltaic system, on a mass basis it accounts for only a small fraction of the total materials required to produce a solar panel. The outer glass cover constitutes the largest share of the total mass of a finished crystalline photovoltaic module (approximately 65%), followed by the aluminum frame (~20%), the ethylene vinyl acetate encapsulant (~7.5%), the polyvinyl fluoride substrate (~2.5%), and the junction box (1%). The solar cells themselves only represent about four percent (4%) of the mass of a finished module.[34]

Proper decommissioning and recycling of solar panels both ensures that potentially harmful materials are not released into the environment and reduces the need for virgin raw materials. In recognition of these facts, the photovoltaic industry is acting voluntarily to implement product take-back and recycling programs at the manufacturing level. Collectively, the industry recently launched PV Cycle – a trade association to develop an industry-wide take back program in Europe.[35] In the United States, product take-back and recycling programs vary by manufacturer; SolarWorld, the supplier selected for the three Oregon Solar Highway projects, is one of the manufacturers which fully supports the entire life cycle of their product.

While recycling methods and take-back policies vary by manufacturer, the most frequently recycled components are the cover glass, aluminum frame, and solar cells. Small quantities of valuable metals including copper and steel are also recoverable. The ethylene vinyl acetate encapsulant and polyvinyl fluoride substrate are typically not recoverable and are removed through a thermal process with strict emission controls and the by-product ash land-filled. Following this process, the glass and aluminum frame are separated and typically sold to industrial recyclers. The solar cells are then reprocessed into silicon wafers with valuable metals recovered and sold. Depending on the condition, the wafer can then either be remade into a functioning cell or granulated to serve as feedstock for new polysilicon.[36]

Health and Safety

If not properly decommissioned, the greatest end of life health risk from crystalline solar modules arises from lead containing solders. Under the right conditions it is possible for the lead to leach into landfill soils and eventually into water bodies. Notably total lead solder use accounts for only approximately 0.5% of lead use in the United States.

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