

15. Environmental Impacts of Photovoltaic Systems

Emmanouil Fylladitakis Brunel University UK

Learning Outcomes

After completing this chapter, the readers should be able to:

- List the major environmental impacts of solar power.
- Understand the area required by such system and assess the suitability of the installation site.
- Realize the impacts on hydrological resources.
- Gain knowledge on the most important hazardous materials that are being used to produce photovoltaics and associated equipment.
- Comprehend the level of energy required for the production of photovoltaic systems equipment and their impact on global warming.
- Realize the visual impact photovoltaic systems may have and comment on the suitability of each application.
- Empirically assess all of the aforementioned impacts.

Introduction

Undoubtedly, the sun is an incredible energy resource, allowing the generation of electricity seemingly without toxic pollutants or an effect on global warming. Some argue that photovoltaics are the cleanest form of electricity generation and few go as far as to claim that it is the only form with no effect on the environment at all. This notion however is flawed, as solar power does have significant and multidimensional environmental impacts, during the construction, operation and decommissioning phase.

The major environmental impacts of solar power are associated with:

1. The use of land
2. The use of water
3. The use of natural resources
4. The use of hazardous materials
5. The life-cycle global warming emissions
6. The visual impact

The scale and technology of the photovoltaic system has a direct effect on the level of each aforementioned impact. For example, building-integrated

photovoltaics (BIPV) may require zero or nearly zero land use but may adversely affect the aesthetics of the site.

Land Use

Larger utility-scale photovoltaic electricity generation plants raise concerns about land degradation, loss of cultivable land, even that of habitat loss. Depending on the technology, site topography and location, estimates indicate that the generation of utility scale PV systems requires 12.000 m² to 40.000 m² per MW. Wind turbines require similarly large areas but there is greater opportunity to share land with other facilities, such as for agricultural use.

Studies suggest that the impact that utility scale PV systems have on land use may be minimized by placing them at location where the land quality is very low [1]. These sites may be brownfields, abandoned mines or existing transportation/transmission corridors [2]. Large-scale PV systems are generally suitable for use in isolated, deserted or other low land quality areas (Fig. 1).



Figure 1 - Utility-scale PV installation situated on barren land of very low value.

Medium-scale installations can also be integrated on large commercial buildings or as sound insulation barriers near sites of interest, such as hospitals, or between highways and residential/commercial areas (Fig. 2).



Figure 2 - Medium-scale PV installation acting as a highway sound barrier. Brenner Motorway, outside the town of Marano, Italy.

Small scale and building integrated PV arrays are usually installed on existing man-made structures and thus have minimal impact on the use of land. It is interesting to note that the net area of land made unavailable for other uses by PV power plants may be significantly less than for coal or nuclear energy, when all associated land uses, including mining, processing, etc. are taken into account [16].

Water Use

The use of water becomes a problematic issue with concentrating solar thermal plants that, like any thermal energy generation plant, requires water for cooling. As the sites that have the highest potential for such plants usually are those with dry climates, careful evaluation of the trade-offs is essential [1, 3, 4].

Photovoltaic panels however seemingly do not use water for the generation of electricity. However, water is required for their maintenance, in order for the systems to maintain their maximum performance. Specifically, water is necessary for the cleaning of the panels, the amount of which greatly varies depending on the location of the system [5]. Furthermore, as with most manufacturing processes, water is also required during the manufacture of photovoltaic panels and other components that a photovoltaic system requires [6].



Figure 3 - Cleaning of a small-scale PV installation by jetting water.

Although it is not direct use of water, large utility-scale PV installations may have a severe impact on the hydrological resources at the installation site. They may reduce the rate of groundwater recharge, the filtration of the air and rainwater from pollutants and even increase the likelihood of flooding [7]. This is especially likely if the installation forced the removal of trees on a sloping hillside. Still, if they are to be compared to any conventional form of energy, the effect of PV systems on these impacts is greatly beneficial [7].

Natural Resources Use

Aside from the production of current photovoltaic panels being an energy intensive process, it also requires very large quantities of bulk materials. Very large quantities of common minerals are required for the production of PV panels, such as iron, copper and aluminum. Aluminum and copper ores are not used by coal, petroleum or gas-fired energy generation stations at all, or are used in insignificant quantities. Iron is used in relatively large quantities by all conventional energy stations but still PV systems are estimated to require far greater quantities per produced kWh compared to all conventional forms of energy, including even coal-fired installations [8].

Even though these materials are recyclable, the immense mineral depletion numbers should not be ignored. Studies report that 3.3 gr and 1.2 gr of iron and aluminum (Bauxite) ore are necessary per produced kWh [9]. Such figures command the establishment of effective recycling programs if PV systems are to become a major energy contributor.

Also, even though the required quantities are small, scarce materials such as Telluride, Indium, Cadmium and Gallium. Some, such as Cadmium, are toxic as well. Acquiring these materials can be a costly and difficult process, especially when those are toxic.

Hazardous materials

The manufacturing process of photovoltaic panels and associated components (e.g. inverters) contains a number of hazardous materials. The release of these hazardous materials to the environment is frequently considered to be the most critical negative environmental impact of both large and small PV systems [10]. Most are used to clean and purify the semiconductor surface of photovoltaic cells. These chemicals are similar to those used in the general semiconductor industry and usually include:

- Hydrochloric acid
- Sulfuric acid
- Nitric acid
- Hydrogen fluoride
- 1,1,1-trichloroethane
- Acetone

The amount and type of chemicals used depends on the type of cell, the amount of cleaning that is needed, and the size of silicon wafer [1]. More advanced technologies also tend to broaden the list of hazardous materials present during their manufacture. For example, thin-film photovoltaics contain more toxic materials than traditional silicon-based cells, including gallium arsenide [11, 12], copper indium gallium diselenide (CIGS) [13, 14], and cadmium telluride [15, 16]. In normal operation, cadmium telluride cells do not pose any environmental risk. Nevertheless, in a fire, and only in a fire, poisonous gases can be produced [17]. Copper indium diselenide cells are considered less potentially hazardous than cadmium telluride cells [17]. If not handled and disposed of properly, these materials could pose serious environmental or public health threats. However, manufacturers have a strong financial incentive to ensure that these highly valuable and often rare materials are recycled rather than thrown away.

Still, if compared to conventional forms of energy, the life-cycle of PV systems involves far less hazardous materials. For example, Cadmium emissions are nearly 300 times greater in the case of coal-fired energy stations [18, 19]. The emissions of common pollutants which are dangerous for the well-being of humans, such as NO_x and SO_2 , are orders of magnitude lower than any conventional form of energy, with the exception of nuclear energy [19]. The combustion emissions of conventional fuel-fired power stations also include pollutants that are associated

with cancer, reproductive, and cardiovascular effects [20]. In that respect, PV systems are greatly superior to any combustion-driven power station.

The manufacturing process of photovoltaic cells is also a known health hazard for workers, who face the risk of inhaling silicon dust [21-23].

Life-cycle global warming emissions

Undoubtedly, there are virtually zero global warming emissions during the operation of photovoltaic systems. However, emissions are generated through almost every other stage of the photovoltaic life cycle. Some of these stages include the manufacturing of the photovoltaic panels and other associated parts, their transportation, the installation and site alteration procedures, maintenance processes, even the recycling and decommissioning of defunct installations.

Primary energy consumption for the manufacturing of photovoltaic panels has been one of the most serious concerns of researchers for decades. An earlier review paper summarized many of these studies and the author specifically noted the significant disagreement between researchers [24]. As the author reports, there were studies indicating that the energy consumption required for the production of one m² of multicrystalline silicon (mc-Si) modules may be as low as 667 kWh or as high as 2115 kWh. Similarly, the reported energy consumption for monocrystalline silicon (mn-Si) panels was between 1470 kWh and 4580 kWh per m². Thin-film technologies are much less energy-intensive, generally requiring about a quarter of the energy required to make an equivalent mc-Si panel. The review however covered older studies, before 2000. As such, they were based on assumptions involving older manufacturing methods and silicon processing. In addition, it should be noted that all similar studies have to assume the estimated production of the PV system, which obviously differs from site to site. As such, studies that were performed for areas with low solar irradiation obviously report less optimistic results [8].

Most estimates of life-cycle emissions for photovoltaic systems are between 30 and 80 grams of carbon dioxide equivalent per generated kWh, depending on the energy generation mix of the area/country [25]. There are studies indicating that newer photovoltaic technologies, such as Cadmium Telluride (Cd-Te) panels, can go as low as 24 grams/kWh, rivalling the nuclear energy baseline [26-28]. These emissions are almost entirely associated with the production and transportation of the materials required for a photovoltaic installation, i.e. the panels and the power electronics. The emissions associated with the materials of conventional power plants are a very low percentage of their total emissions per generated kWh, as the bulk of their greenhouse gas (GHG) emissions come from their operation [28]. Still, even if their operation emissions are not accounted at all, solely the production and the transportation of their fuel greatly surpasses the GHG emissions of photovoltaic panels per kWh [29].

Visual Impact

Another important environmental impact is the visual impact that PV systems may have on buildings and areas. The visual intrusion of a building-integrated PV system can be very high but can also be addressed with relative ease. Careful architectural designing and materials can introduce the photovoltaic panels as architectural elements, complementing the appearance of the building instead of degrading it. It is not necessary for the architect to hide panels and components entirely, only to implement them as part of the overall building design. From the side of PV panel manufacturers, modern designs can easily be developed specifically for their installation in populated areas and on buildings, with colored versions already in the market for the few years. Colored PV panels are frequently used to simulate the appearance of ceramic roof tiles or typical glass. Retrofitting PV systems on roofs and large surfaces of older buildings usually is a viable solution as well, with the exception of buildings that cannot be visually altered, i.e. those which are of historical or cultural importance. Furthermore, thin film panels could easily replace the mirrors and glass surfaces of large buildings. As thin film panels have a lower solar transmittance than glass, they could also be used as a means to reduce the cooling load of buildings, offering shading or even heat extraction [30]. However, the architect always has to consider the effects of glare as well. The replacement of glass surfaces may very well be the only method applicable to historical buildings and buildings with high cultural value, where visual modifications of the structure itself are impossible.



Figure 4 - Pfizer-University of Granada-Junta de Andalucía Center for Genomic and Oncologic Research (GENyO) ventilated photovoltaic façade designed by Onyx Solar. It generates about 32 MWh/annum.

Utility-scale installations are a more complicated matter. The installation of a utility-scale installation at or near areas of natural beauty, tourist attractions, archeological sites, ecological areas and other similar locations is problematic and should be avoided. Large installations need to be properly sited, usually outside

residential and commercial areas as well. Abandoned areas and low-quality land usually are the most suitable sites for such installations.



Figure 5 - Polycrystalline PV panels retrofitted to cover the facade of a commercial building. They were used to replace mirrors.

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