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ENVIRONMENTAL ASSESSMENT OF SOLAR CELL MATERIALS

Abstract: In today's world, fossil fuels, including coal, oil, and gas, are the primary energy sources from which electricity is obtained. As they are exhaustible and their exploitation has a negative impact on the natural environment, they should be, at least partially, replaced by renewable energy sources. The implementation of this goal depends on a number of factors, including social and political, the existence of investment support programmes, and the need to lower electricity prices and ensuring energy security. One of these sources is solar energy. Each year, the Earth receives around $1 \cdot 10^{18}$ kWh of solar energy, which is more than 1000 times the current global energy demand. This is therefore a vast source of energy that can be tapped to satisfy human energy requirements. The use of solar energy releases no CO_2, SO_2, or NO_2 gases, and does not contribute to global warming. Photovoltaics is one of the technologies that makes it possible to generate electricity in an environmentally friendly manner. By using the energy of solar radiation, a photovoltaic cell converts energy without emitting harmful substances to the atmosphere, noise, and waste. Photovoltaics is the cleanest technology among all the technologies that use renewable energy. Considering the shorter and shorter times needed to generate energy equal to that required by the module production process, during its lifetime it will produce much more electricity than was used to produce it. This results in a reduction in greenhouse gas emissions. For example, during its lifetime, a 200 Wp module prevents the emission of over four tonnes ($Mg = 10^6$ g) of carbon dioxide. Although the technologies for the production of photovoltaic cells and modules entail a lower environmental burden compared to other sources of electricity, it is necessary to remember about the risks associated with the use of chemicals at the stage of module production, which threatens their release to groundwater or air, and the need to recycle modules after their disassembly. Also, the energy consumption in the production phase of PV systems significantly worsens the ecological balance. This article presents an analysis of the impact of the materials and technologies used on the result of the environmental analysis of PV installations. In the article a detailed energy balance analysis of the EPBT value has been carried out. The values of greenhouse gas emissions throughout the life cycle of the solar module were determined. Methods of limiting the impact of photovoltaic technologies on the natural environment were indicated.

Keywords: photovoltaic modules, photovoltaic materials, hazardous substances, emissions, electric energy, environmental impact

Introduction

In practice, photovoltaic devices are used as energy sources in various applications from small devices such as watches or calculators, through lighting pedestrian crossings, to large installations with a power of many megawatts, producing energy for the electricity grid from which industrial and residential buildings are supplied.

Photovoltaic modules can be applied in different systems, such as solar air heating and cooling systems, solar water heaters and solar based pumping system - an electrical pump

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system in which the electricity is provided by photovoltaic modules. All these applications are environmental-friendly solutions of the devices.

One of the most potential applications of solar energy is the supply of hot air for the drying of agricultural, textile, marine products, heating of buildings to maintain a comfortable environment. Hybrid PV/T type solar air heater shows their viability in force convection type air heating with electricity production. Solar air heaters can be equipped with thermal storage unit with phase change materials, what improves the energy balance [1].

Another interesting example is the use of photovoltaic power for storing food products at a reduced temperature. Qian et al. [2] investigated a system for cooling oysters, which is a food product, while improving water quality by filtering out sediment. The authors found that maintaining an even temperature distribution improves product quality while reducing energy consumption.

Another innovative solution is the use of photovoltaic modules to power water pumps for groundwater and groundwater for agricultural crops without access to the power grid [3].

Yishu Li [4] presented a summary of the impact of various energy generation systems, referring to the 10 major adverse impacts (Table 1). It can be seen that photovoltaic achieves the most favourable position in this ranking.

Table 1

The most significant negative impacts caused by different sources of electricity [4]

Type of impact	**Combustion based**				**Nuclear**	**Hydro**	**Wind**	**Solar**
	Coal	**Oil**	**Gas**	**Biomass**				
Resource depletion	×	×	×		×			
Land use, visual impact	×			×		×	×	×
Watercourse regulation						×		
Noise							×	
Thermal releases	×	×	×	×	×			
Radiation					×			
Air quality	×	×	×	×				
Acidification	×	×	×	×				
Eutrophication	×	×	×	×				
Greenhouse effect	×	×	×	×				

The basic material for the production of photovoltaic cells is silicon. It is used for the production of over 90 % of the modules, both mono- and multicrystalline, which are commercially available [5].

Despite extensive work carried out all over the world to replace silicon with another, cheaper material, silicon is still in the leading position due to relatively high efficiency guaranteed over the entire lifetime of the modules.

Crystalline silicon cells are classified into three groups depending on the further course of the silicon substrate production process (Fig. 1):

- monocrystalline; monocrystalline silicon is produced from molten polycrystalline silicon by the Czochralski method, who developed it in 1916, or by float-zone method [6],
- multicrystalline or polycrystalline; depending on the size of the grains with one crystallographic orientation: multicrystalline: from 1 mm to 10 cm, polycrystalline:

from 1 μm to 1 mm [7]; the process of producing multicrystalline silicon consists in the controlled melting and re-solidification of silicon in a quartz crucible,

- silicon tapes and films; obtained by the EFG method (Edge-Defined Film-Fed Growth) [8] - this is a method of removing a tape formed on a graphite matrix from a molten silicon material.

Monocrystalline silicon cells have the greatest efficiency, while being the most expensive. Slightly cheaper multicrystalline cells do not guarantee the same high efficiency, hence their market share is smaller. Research is being carried out around the world on new technologies that will reduce the price of first generation modules by reducing the consumption of semiconductor materials and electricity.

Multicrystalline cells are only slightly lagging behind in potential efficiency.

Second-generation photovoltaic technologies are thin-film cells (Fig. 1). The advantage of thin-film technologies is a significant reduction in the consumption of expensive materials, and thus an improvement in the price-to-power ratio of the cell.

There are currently three basic types of thin film cells [9]:

- amorphous silicon cells (a-Si and a-Si /μc-Si);
- cadmium telluride (CdTe) cells;
- cells made of $CuInSe_2$ (Copper-Indium-Selenide - CIS) and $CuInGaSe_2$ (Copper-Indium-Gallium-Selenide - CIGS).

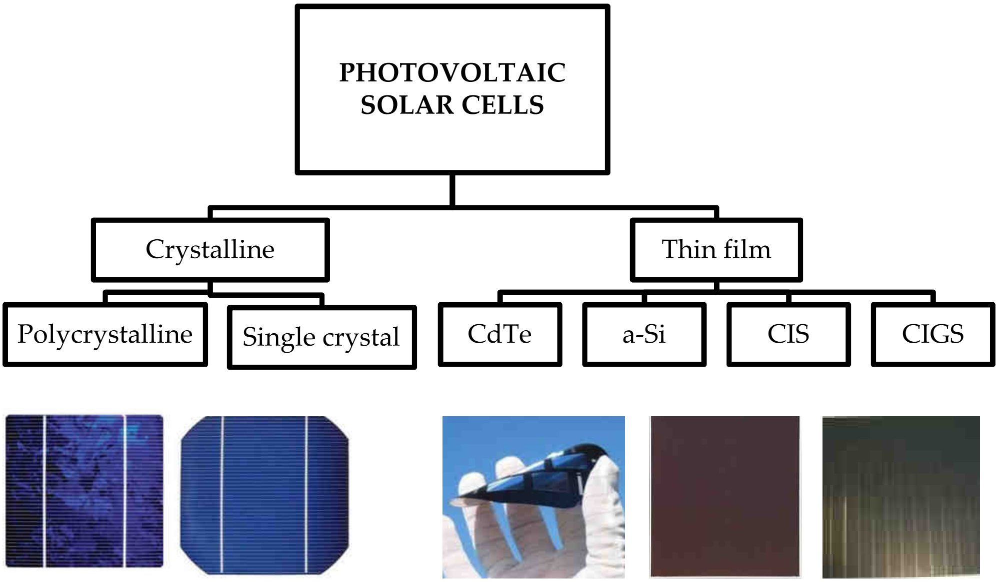

Fig. 1. Production technologies of photovoltaic cells: polycrystalline, monocrystalline, cadmium telluride (CdTe), amorphous silicon (a-Si), copper indium selenium (CIS), copper indium gallium selenide (CIGS)

The efficiency of a solar cell is measured by the percentage of the energy from the sun that actually generates electricity. The price of photovoltaic modules directly affects the cost of generating electricity.

Higher efficiency also means we can install more solar panels in a smaller space.

Increasing this efficiency is the goal of all modules manufactures as they work to reduce the payback period and make the solar panels more competitive with other electricity sources like coal and wind.

Crystalline silicon modules are most often used in domestic installations, offering greater efficiency, so they occupy a smaller area for the same installed power than thin-film modules.

The development of the technology of the second generation of modules - thin-film: Cu (In, Ga) Se_2 - CIGS and CdTe solar cells, have a certain advantage compared to the first generation solar cells (made of crystalline silicon): the installed power unit is cheaper, and, in addition, they work more efficiently in diffused lighting, and they are light and flexible. Thin film has a cost advantage over crystalline material.

In direct-bandgap semiconductors, carrier momentum is the same in the conduction and valence bands. Silicon crystals have an indirect bandgap structure that makes it difficult to work efficiently. The absorption spectrum of an indirect band gap material usually has a higher dependence on temperature than that of a direct material [10].

Calculation of the width of the energy gap of semiconductor materials is possible on the basis of known models and physical equations.

The width of the energy gap can be influenced by changes in temperature, pressure, and doping [11]. In doped semiconductors, additional current carriers appear as a result of the introduction of impurities of elements from a different group of the periodic table than atoms from their home network.

The purpose of modifying the materials is to narrow the bandgap of the semiconductor and, consequently, increase its efficiency. Table 2 lists the semiconductor band gaps [12] and cell efficiencies under STC (Standard Test Conditions): the global AM 1.5 irradiance (1000 W/m^2) and at a cell temperature of 25 °C [13-19]. The width of the energy gap in semiconductors may vary ±10 % with temperature variation. This is mainly due to two reasons:

1) thermal expansion which affects the periodic potential, acting on conduction electrons,
2) electron-phonon interactions, where the concentration of phonons increases with increasing temperature.

Table 2

Semiconductor band gaps and efficiencies

Material	Band gap [eV] at 300 K [1]	STC efficiency [%]
Si	1.11	18-22 [14]
Ge	0.67	13.5 [15]
GaAs	1.43	29.1 [13]
CdS	2.42	20.3 [16]
CdTe	1.44	18 [14]
CuInSe	1.04	18.8 [18]
CIGS	1.48	22.95 [19]
a-Si:H	1.6	10.1 [17]

The efficiency of energy conversion of photovoltaic cells made in silicon technology is from 16 % to 24 % for monocrystalline cells and from 14 % - 18 % for polycrystalline cells, which gives the unit power of a cell from 75 Wp/m^2 to 155 Wp/m^2 [20]. Meanwhile, for cells made of amorphous silicon, the efficiency ranges from 4 % to 10 %. Table 3 presents comparison of the efficiency of 1st, 2nd and 3rd generation of photovoltaic cells.

The high efficiency of the cells is not only of economic but also environmental importance. Higher efficiency values compared to serial production are achieved by laboratory cells: 26.7 % for monocrystalline silicon cells, and 22.3 % for polycrystalline silicon cells. The highest efficiency of a thin film cell is 23.4 % for CIGS and 21.0 % for CdTe, and for Perovskite the highest efficiency is 21.6 % [21].

The most efficient photovoltaic modules available on the market in 2021 (Table 4) use the high purity n-type IBC (Interdigitated Back Contact) cells, manufactured by SunPower and LG. The latest Alpha series modules produced by REC use high-efficiency n-type HJT (hetero-junction solar cells) cells, achieving an efficiency similar to the level of IBC cells. The analysis of Table 4 shows that most manufacturers currently use PERC cells (PERC - Passivated Emitter and Rear Cell). The use of half-cut cells with many MBB (Multi Bus Bar) allows to increase the module efficiency above 20 %.

Table 3

Comparison of the efficiency of 1st, 2nd and 3rd generation of photovoltaic cells [22]

Technology	**1st generation**		**2nd generation**			**3rd generation**		
	sc-Si	**mc-Si, pc-Si**	**a-Si**	**CIS/CIGS**	**CdTe**	**hetero-junction/CPV**	**DSSC**	**Organics/ polymer**
STC efficiency [%]	20-24	14-18	6-8	10-12	8-10	36-41	8.8	8.3

Table 4

The most efficient solar modules (residential 60-66 cell size modules only) - as of the beginning of 2021 [23]

	Manufacturer	**Module**	**Rated power [W]**	**STC efficiency [%]**
1	SunPower	Maxeon 3	400	22.6
2	LG	Neon R	380	22.0
3	REC	Alpha	380	21.7
4	FuturaSun	FU M Zebra	360	21.3
5	Panasonic	EverVolt	370	21.2
6	Trina Solar	Vertex S	405	21.1
7	Jinko Solar	Tiger Pro 6Rl3	390	20.7
8	Q cells	Q.Peak DUO G9	360	20.6
9	Winaico	WST-375MG	375	20.6
10	Longi Solar	Hi-Mo 4	375	20.6

Materials used in the PV cells and modules production processes

A number of materials and chemicals are used in the production of photovoltaic modules that may have an adverse effect on human health and the environment.

Both the amount and type of substances used vary depending on the technology. For example, for silicon cells, the process begins with the extraction of the raw material, i.e., quartz sand, and for CdTe, modules of Zn and Cu ores. Then they are processed and cleaned.

Silicon is one of the elements that are very common on Earth. In the earth's crust, it is the second most abundant element, right after oxygen. Its content reaches about 27% by weight. The silica contained in the quartz sand is reduced in a furnace to metallurgical grade silicon, which is further purified to electronic grade (PV-grade) silicon in a Siemens furnace [24].

Due to the constant development of thin-film technologies, their commercial market share, currently amounting to approximately 10 %, is expected to increase in the future. Thin-film modules have the unquestionable advantage of lower prices of generated energy. In the near future an increase in the production of modules from CdTe and CIS, as well as amorphous silicon and CIGS, is expected.

Table 5 presents a list of basic chemicals and materials used in the production process of thin-film photovoltaic cells. The amount of chemical compounds used may be different in the production processes of photovoltaic cells and modules of the same type, depending on the manufacturer and the technology used.

Pure semiconductor materials are used in small amounts due to the small thickness of the substrate layers.

Table 5

Materials used in the manufacturing process in different thin-film photovoltaic technologies [25]

CIS	**CIGS**	**GaAs**	**CdTe**	**Cu_2S**	**a-Si**
Cadmium	Cadmium	Arsenic	Cadmium chloride	Ammonium chloride	Acetone
Copper	Copper	Arsine	Cadmium	Ammonium fluoroborate	Aluminium
Hydride gas	Gallium	Gallium	Molybdenum	Cadmium sulphide	Chloro-silanes
Hydrogen sulphide	Indium	Hydrochloric acid	Nickel	Chromate coating	Diborane
Hydrogen selenide	Molybdenum	Methane	Sulphur	Copper	Hydrochloric acid
Indium	Selenium	Phosphine	Tellurium	Cuprous chloride	Hydrofluoric acid
Molybdenum	Zinc	Trichloro-ethylene	Thiourea	Gold	Hydrogen
Selenium		Triethyl gallium	Tin	Hydrochloric acid	Isopropanol
Zinc		Trimethyl gallium		Hydrogen sulfide	Nitrogen
				Methanol	Phosphine
				Nickel	Phosphoric acid
				Nitrogen	Silane
				Polyvinyl butyral	Silicon tetrafluoride
				Silicon monoxide	Silicon
				Sodium chloride	Sodium hydroxide
				Tantalum pentoxide	Tin
				Zinc	
				Zinc fluoroborate	

Table 6 summarises the amount of metals used in the production process of various types of cells.

Heavy metals can be emitted directly in the production processes of photovoltaic cells and modules and for example, the annual production volume of 2,000 tonnes of photovoltaic modules with a capacity of 10 MWp consumes about 20 tonnes of semiconductor material, the rest is mainly glass [26].

Table 6

Amounts of metals in various types of PV cells [27]

Cell type	**Material requirements [g/m^2]**
Amorphous-Si/Ge	
Sn	3.3
Ge	0.22
Si	0.54
Al	2.7
CdTe	
Sn	0.66
Cd	4.9
Te	4.7
Mo	10.0
CIGS	
Zn	9.1
Cu	1.8
In	2.9
Ga	0.53
Se	4.8
Cd	0.19
Mo	10.0

Heavy metals can be emitted directly in the production processes of photovoltaic cells and modules, and indirectly through the use of electricity. From this point of view, CdTe modules look the best despite the emission of cadmium. This is due to the fact that these types of cells require much less electricity from the grid in the production process.

Cadmium is present in cells made in the thin-film technology. Its compounds are used in CdTe cells and - in small amounts - in CIS and CIGS cells. Cadmium can be released to the environment through leaching to wastewater and emission of fumes and dusts.

The cadmium content in the CdTe module is 125 times greater than in the CIS module. It also strongly depends on the thickness of the layers, from 5.5 g/m^2 in a 2 μm layer to as little as 0.55 g/m^2 in a 0.2 μm layer. In fact, about 25 % to 50 % more cadmium input is needed than is fed to the final product due to losses during the production process [28].

Lead is found in contacts with busbars. A typical photovoltaic module contains up to 12 grams of lead. This metal is mainly found in the busbar shell and solder paste used to connect photovoltaic cells. Most of the busbar is made of copper with tin (67 %), and the lead in the coating is 37 %. Lead is mainly used because it lowers the melting point but also improves many alloy properties, while zinc is used as the back contact layer.

Energy Payback Time

The most frequently used parameter to determine the environmental impact of the production technology of energy conversion devices is Energy Payback Time (EPBT).

The production of raw materials, in particular pure silicon, and the production of PV cells and modules requires significant energy expenditure. Electricity needed for these processes most often comes from traditional power plants powered by fossil fuels, which is a significant environmental burden. During the first period of operation of a PV module, it produces electricity, which, in a way, is returned to the environment as debt.

The time needed for the photovoltaic module to generate the same amount of electricity (converted into equivalent primary energy) that was needed to produce it is known as Energy Payback Time (EPBT) - (Table 7).

The EPBT value is calculated as follows:

$$\mathrm{EPBT} = \frac{primary\ energy\ demand\ \left[\frac{kWh}{m^2}\right]}{annual\ energy\ generated\ \left[\frac{kWh}{m^2 year}\right]}\ [year] \tag{1}$$

Primary energy consumption is the sum of the energy contained in the materials and the energy consumed during the production of the module. Due to the indicator related to the generated energy, EPBT depends directly on the location where the module will be installed, therefore it is not an objective parameter. Yearly sums of solar radiation in European countries differ almost twice for different localisation, which significantly affects the value of EPBT (Fig. 2).

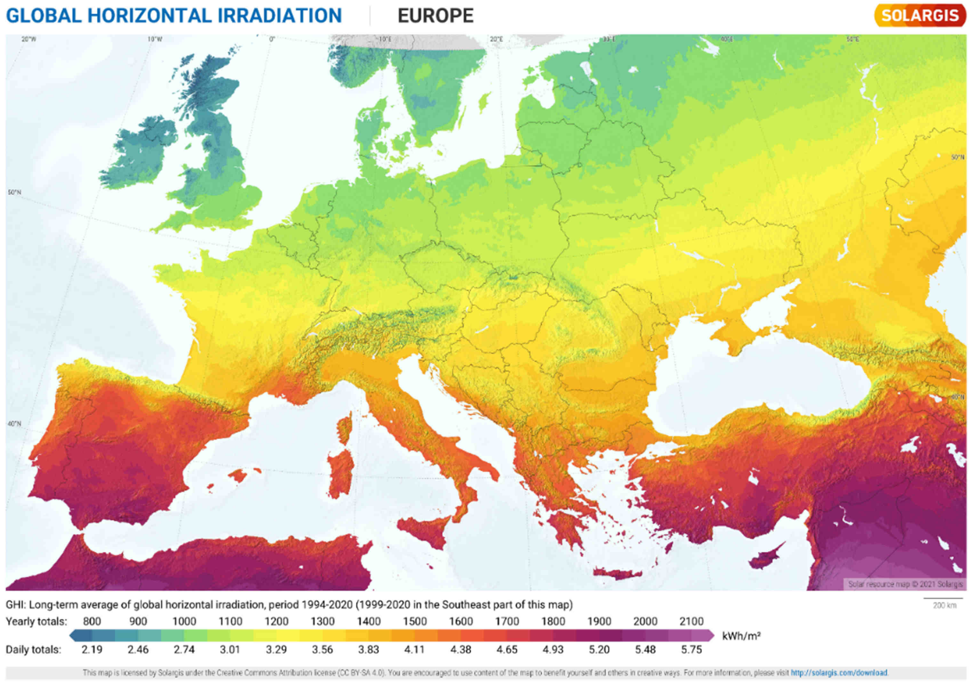

Fig. 2. Average of global horizontal irradiation in Europe [29]

Also, better grid efficiency of modules produced in Europe may typically decrease the EPBT by 9.5 % compared to PV modules produced in China.

Photovoltaic modules made in the monocrystalline silicon technology burden the environment mainly due to the production of silicon in Siemens reactors and the Czochralski process, which results in a long energy return period. Therefore, although monocrystalline silicon has a higher conversion efficiency than polycrystalline silicon, EPBT for single crystals is lower.

Table 7

Energy requirements in different processes for production of PV module [30]

Process	**Energy requirements**
Silicon purification and processing	
- Czochralski silicon (Cz-Si) production from EG-Si	290 kWh kg^{-1} of EG-Si
- Electronic grade silicon (EG-Si) production form MG-Si	100 kWh kg^{-1} of EG-Si
- Metallurgical grade silicon (MG-Si) production from silicon dioxide (quartz, sand)	20 kWh kg^{-1} of MG-Si
Fabrication of solar cell	120 kWh m^{-2} of silicon cell
Assembly of PV module	190 kWh m^{-2} of PV module
Roof top integrated PV system	200 kWh m^{-2} of PV module

A detailed energy balance analysis shows that the EPBT value is on average 2 years to 3.2 years for installations located on the roof of a building in areas with medium to high irradiation (1,700 kWh/m^2/year to 2,200 kWh/m^2/year), and 4 years to 5 years in locations with low irradiation (1,100 kWh/m^2/year) [31].

Figure 3 and Table 8 present a review of EPBT results of different types of PV modules.

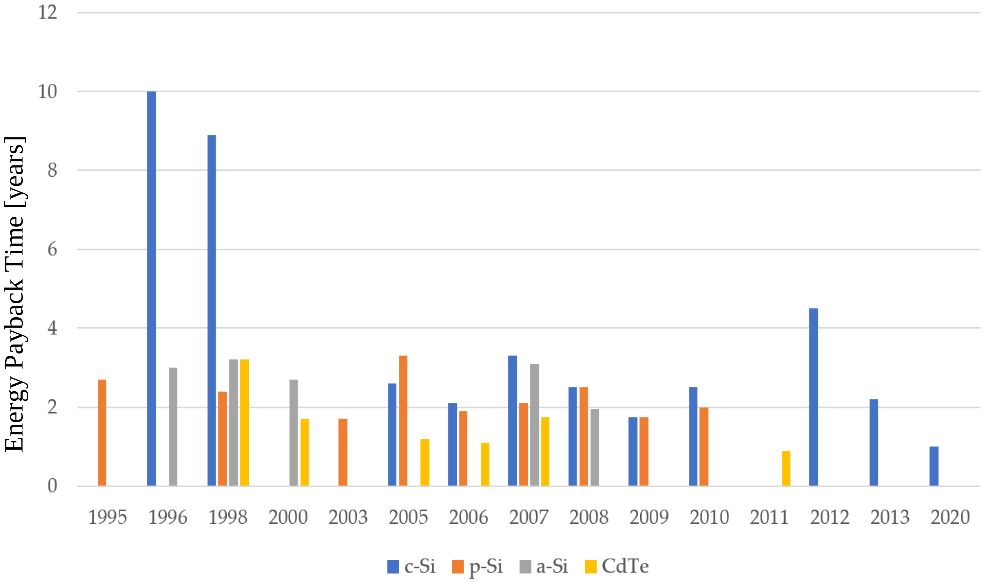

Fig. 3. EPBT for different PV technologies during the period 1995-2020 (based on [32] and [21])

Currently produced modules show EPBT values of about 1 year (for irradiation of 1700 kWh/m²/year and optimally inclined module).

Table 8

EPBT for different PV technologies considering recycling process [33]

	m-Si	p-Si	a-Si	CIS
EPBT [year]	3.03	2.3	1.95	2.47
EPBT [year]*	1.39	1.07	-	-

* Considering recycling process - the modules made from recycled wafers save 30 % of energy compared with those produced using new materials

Photovoltaic wastes and releases

Most manufacturers today advertise a guaranteed lifetime of 25 years, while the industry standard for a photovoltaic module’s productive lifetime is 25-30 years. The oldest operating solar power plant is over 60 years old.

The photovoltaic industry generates wastes similar to that generated by the rest of the semiconductor industry, but its amount is generally less (especially for the silicon technology).

The estimated cumulative waste volumes of end-of-life PV modules around the world were calculated. In the regular-loss scenario, PV module projected waste amounts is about 1,7 million tonnes by 2030. An even more drastic rise to approximately 60 million tonnes can be expected by 2050. The early-loss scenario projection estimates much higher total PV waste streams, with 8 million tonnes by 2030 and 78 million tonnes by 2050, as the early-loss scenario assumes a higher percentage of early PV module failures than the regular-loss scenario [34].

The disposal of large amounts of photovoltaic modules in a single landfill may constitute a threat to the natural environment. Leaching chemicals into groundwater and surface water can be hazardous.

From a legal point of view, waste from solar PV modules in the world falls under the general classification of waste. The only exception is at EU level, where PV panels are defined as e-waste in Directive 2012/19/EU on Waste from Electrical and Electronic Equipment (WEEE) [35]. It defines photovoltaic panels as electronic devices and requires 85 % efficiency in the recovery of secondary raw materials for them. At least 80 % of this must be recycled or further produced. According to EU recommendations, producers of solar modules installed in the EU should cover the costs of their collection and recycling.

The emissions of harmful substances from PV installations to the air are both emissions from chimneys and emissions related to the use of chemicals used for cleaning and etching. Among the chemical compounds that are released in the greatest amounts are: 1,1,1-trichloroethane, isopropyl alcohol, acetone, ammonia, and methanol.

Greenhouse gas emissions throughout the life cycle of a solar module are closely related to the Energy Payback Time (EPBT). These emissions are mainly due to the energy consumption in the module production process.

For the same photovoltaic module, the emission level may vary depending on the energy mix used to generate electricity in the production plant.

Assuming that amounts of GHG emitted during the production of electricity from coal-fired power stations are:

- 960 Mg CO_2 /1 GWh
- 7 Mg SO_2/1 GWh
- 3 Mg NO_x/1 GWh
- 0.19 Mg dust emissions/1 GWh,

a 1-kW PV system being installed in a region with medium insolation (1700 kWh/m^2/yr) will contribute emission reductions of:

- CO_2: 1600 kg per year
- SO_2: 12 kg per year
- NO_x: 5 kg per year
- dust: 0.34 kg per year [34].

The average carbon dioxide emissions at the production stage of a photovoltaic installation are significantly lower than those of conventional coal-fired power plants producing the same amount of electricity, considering that the photovoltaic modules are used for a period of 20-30 years.

In the *Union for the Coordination of Transmission of Electricity* (UCTE) energy mix, CO_2 emissions range from 21 g CO_2 equiv./kWh for CdTe, to 43 g CO_2 equiv./kWh for c-Si technology.

The best results are obtained for CdTe modules, however the differences between PV technologies are insignificant compared to the difference between PV systems and conventional fossil fuel energy. The average CO_2 emissions for electricity generation of is equal to 750g CO_2 equiv./kWh in Poland and 275g CO_2 equiv./kWh in the Europe [36]. There are a number of options for reducing waste and releases in the PV industry:

- the use of material-saving technologies (reduction of the necessary amounts of silicon, cadmium, and others); for example, silicon wafer thickness decreased from 400 μm in 1990 to 160 μm in 2019, while silicon usage decreased from 16 g/Wp to 6.5 g/Wp over the same period [21],
- reducing water consumption and reducing the amount of wastewater; use of a closed water circuit,
- reducing the consumption of chemicals, especially hazardous chemicals,
- process changes (for example using less-toxic chemicals instead of hazardous ones),
- recycling and reuse of semiconductor substances and solvents.

In our previous work, we have shown that the Life Cycle Analysis of crystalline silicon photovoltaic cell production using recovered semiconductor materials from the recycling of spent modules shows the environmental impact of cell production was reduced by half compared to production from virgin material [30].

Life Cycle Analysis is a tool that allows you to quantitatively assess to what extent individual technologies fit into the implementation of the idea of a circular economy.

The circular economy is characterised by resource conservation, recycling, coordination, low development, high utilisation and low emissions. All material and energy use is reasonable, and sustainable land use minimises the influence of economic activities on the natural environment [37].

Conclusion

Electricity production with the use of PV modules is undoubtedly the most environmentally friendly solution and is currently popular all over the world. PV installations do not emit any radiation or noise and do not generate waste during the operation stage. However, the period of production and waste management puts a burden on the natural environment. This load depends on the technology (semiconductor materials and chemicals used) and the efficiency of the cells, which affects the Energy Payback Time, significantly influencing the result of the Life Cycle Analysis.

To make the PV technology environmentally friendly for the whole lifetime (from cradle to grave) we should:

- define the types of chemicals used in the production process of photovoltaic cells and modules and their potential for release into the environment,
- identify environmental threats related to the production and disposal processes of modules, including the potential possibility of infiltration into the air and groundwater,
- indicate the existing or developing technologies for the production of photovoltaic modules, which pose a lower threat to the natural environment,
- recycle up to 80 % - 95 % of old PV modules.

The greatest threat to the environment is posed by the use of hazardous substances, although it is much lower than in other industrial processes, and high energy consumption at the production stage of pure semiconductor materials. It should be remembered that the impact of hazardous substances on living organisms depends not only on their toxicity and carcinogenic effect, but also on a sufficiently high concentration (dose) and the distance of the organism from the place of occurrence of the substance. Thus, merely identifying a hazardous substance without obtaining information on the extent of exposure should not explicitly disqualify a given process.

Photovoltaics is considered an energy source responsible for relatively small waste streams, as no waste is generated during the lifetime of the photovoltaic modules. However, one should not forget about the waste streams generated during the production period, as a result of quality control, as a result of damage arising at the stage of operation of the installation, and at the end of life of photovoltaic systems.

The negative impact on the environment can be significantly reduced by increasing the efficiency and extending the lifetime of both the modules and the entire photovoltaic system.

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