Conversion of Radiophotoluminescence Irradiation into Electricity in Photovoltaic Cells. A Review of Theoretical Considerations and Practical Solutions

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Abstract: This review presents the current state of the knowledge regarding the use of radioactive sources to generate photonic light in scintillators as converters of ionizing radiation to electricity in photovoltaic cells. The possibility of using the phenomenon of the excitation of light photons in the scintillation materials during the interaction with particles and photons of ionizing radiation was analyzed in detail. The light photons obtained in such a way can generate an electric charge in photovoltaic cells. The whole process can be named as a nuclear cell (nuclear battery). Theoretically, the use of such physical phenomena seems to be an ideal practical solution to meet the energy needs of the modern world. However, there are many physical and technical problems that limit its widespread use in practical applications. In an ideal system, the ionizing radiation sources can emit the radiation for billions of years, and the energy of particles and photons from the radiation can be converted into photons in the scintillation material, with energy suitable to generate a photoelectric effect in a photovoltaic cell. Such a cascade sequence of different physical phenomena allows, from a theoretical point of view, for the creation of a virtually inexhaustible source of electricity. This review of historical and current literature reports aims to bring closer the idea of “energy perpetuum mobile”, which has troubled many scientists around the world for centuries.

Keywords: photovoltaic cells; conversion; nuclear battery; scintillation; radiation

1. Introduction

Photovoltaics (PV) convert the sunlight’s solar radiation energy into electricity using the photoelectric phenomenon. The solar radiation energy can be used in two main ways:

1. Direct conversion into electricity, observed in photovoltaic cells;
2. Conversion into heat, which can be used, for example, to heat domestic water, or to generate electricity.

To elaborate further, solar cells come in two basic configurations: (i) standard photovoltaic cells of various generations, and (ii) concentrated photovoltaic (CPV) cells, where the cell efficiency is increased due to the fusion of various optical systems, such as classic lenses, Fresnel lenses, mirrors (flat, concave parabolic, concave linear), linear Fresnel lenses and luminescent concentrators.

It is well known that solar radiation is an unlimited and environmentally friendly source of energy; hence, the use of photovoltaic systems to generate energy is very appealing. However, photovoltaic devices display a different level of sensitivity to various types of radiation that can be observed in nature. For this reason, the main challenge is to create a radiation-resistant photovoltaic device that lacks degradation problems both in morphology and electrical parameters. In this review, we will try to explain the influence of different radiation types on PV, taking into consideration various aspects. The other focus
will be carried out on practical aspects, such as space, underwater technology, biological sensors or implants devices autonomous and compact electrical supply source applications, where a long service life is required.

In this review, results described in articles published in years 1964–2020 are presented. Our main aim was to emphasize the new and important trends in radiation effects in various type of solar cells and scintillators, while less attention was paid to details regarding the process of radiation and the radioactive source because they were described in detail in [1–3].

The organization of this article is as follows. In Section 2, we briefly describe the radioactive sources, whereas, in Section 3, we present the various types of scintillators together with a description of the mechanisms they use in order to work. The types and architecture of solar cells are briefly described in Section 4 as an introduction to different solar cells [4–11].

In Sections 5–7, we describe the radiation effects on the main types of solar cells, such as silicon solar cells, GaAs and organic solar cells. The main goal of this review was to describe typical but not widely used and original applications of devices based on solar cells and scintillators. This information is presented in Section 8 of our review. Finally, based on all reviewed papers and our own experience, we propose five postulates about the positive effect of different radiation types as energy sources in devices based on solar cells and scintillators. To the best of our knowledge, this is the first review concerning the aforementioned subject.

2. Radioactive Sources

Radiation sources may emit various types of radiation as a result of spontaneous nuclear transformations. The sources most often used in industry and scientific research emit radiation: α, β, γ (X) and n particles. For operational reasons, sources can be classified as: short-lived, medium and long-lived. This parameter is determined by the half-life (T_{1/2}) characteristic and is constant for a given irradiation source isotope. The activity of the source can be tailored at the production stage and selected according to the needs. Based on the analysis of the literature, a group of isotopes with the highest application potential was selected to convert the ionizing radiation energy into luminescence, as presented in the article, which could then be converted into electricity in photovoltaic cells. The characteristics of the selected sources are summarized in Table 1.

| Isotope | Type of Radiation | Half-Life T_{1/2} [Years] | Specific Activity [Bq/g] | Energy E_{α} [MeV] | Energy E_{β} [MeV] | Energy E_{γ} [MeV] |
|---------|-------------------|---------------------------|--------------------------|-------------------|-------------------|-------------------|
| Co-60   | β, γ              | 5.3                       | 4.07 × 10^{13}           | -                 | 0.31              | 1.33              |
| Cs-137  | β, γ              | 30.1                      | 3.26 × 10^{12}           | -                 | 0.52              | 0.66              |
| Sr-90   | β                 | 28.8                      | 5.18 × 10^{12}           | -                 | 0.61              | -                 |
| Ni-63   | β                 | 100.1                     | 5.55 × 10^{12}           | -                 | 0.66              | -                 |
| Am-241  | α, γ              | 433                       | 1.26 × 10^{11}           | 5.49              | -                 | 0.06              |
| Ra-226  | α, β, γ           | 1600                      | 3.67 × 10^{10}           | 4.87              | 1.03              | 0.93              |

Many research described scintillation properties based on X-ray sources. The analogy to γ radiation in this case is very large. The main difference between these types of radiation is their place of their origin and the slight difference in wavelength. Both of these types of radiation cause analogous influence at the molecular level, and the scintillation (luminescence) mechanism is almost identical.

3. Scintillators—Types and Mechanism

Scintillation is a quantum process described by the probability distribution of its occurrence over time. If a charged particle (α and/or β) or an energy photon (γ and/or X) passing through the scintillation material excites a certain number of atoms, when the
atoms go to the ground state according to the stochastic relaxation, they release a number of photons, which will decrease exponentially, according to the dependence described by the formula:

$$l = e^{-t/\tau}$$  \hspace{1cm} (1)

where \( \tau \) is a parameter characteristic of the scintillation material and is called the decay time.

This is one of the key parameters when choosing a scintillator type. Usually, the response time is less than \( 10^{-8} \) s, which means that such detectors can be relatively fast. The scintillation material must have at least three energy levels in its structure: basic, excited and a third that is in between, but close to the excited level. Then, the relaxation process proceeds in two stages (according to Jabłoński’s diagram): first, to the intermediate level, without light emission, and then to the ground state, with the actual emission of the photon in the form of light. Therefore, the existence of a third level is crucial. In a configuration with only two levels, all of the emitted photons would be immediately reabsorbed; the scintillator would be opaque to its own radiation. Kallmann [13] made an attempt to determine the basic parameters of scintillation materials. A distinction has been made between the physical light power corresponding to the fraction of absorbed ionizing radiation energy that is converted into light, and the technical light output, which is the amount of light actually collected at the end of the scintillation element, taking into account all light collection and absorption factors in the medium.

The first documented research on scintillation materials was published by W.C. Röntgen in 1885, when he discovered X-rays. The further development of scintillation detection took place in the second half of the nineteenth century, when many new inorganic scintillators were developed, such as BGO (chemical formula \( \text{Bi}_4\text{Ge}_2\text{O}_{12} \)), \( \text{BaF}_2 \) or \( \text{PbWO}_4 \) (lead glass). Scintillators are of key importance in many fields of science and technology—mainly in the detection and measurement of ionizing radiation. Modern diagnostic devices use scintillation induced by the ionizing radiation, for example, for imaging diagnostics, industrial inspection, internal safety, nuclear waste testing and for oil exploration (initiation wells).

The mechanism of luminescence in scintillators is based on the excitation of light emission under the influence of ionizing radiation. Historically, it was one of the first ways to detect radiation; with its help, Rutherford made his famous discovery of the atomic nucleus. Physically, scintillation is the luminescence induced by ionizing radiation in a transparent dielectric medium. This complex sequence of phenomena characterizes the scintillation process, as opposed to the photoluminescence, which results from the direct excitation of the luminescent centers. Scintillation is the excitation of an atom, molecule or crystal lattice of a medium by the particle. Then, some of this energy is lost (to thermal excitation or the transition of an electron in the crystal lattice to the dopant level) and the remaining energy is emitted as a photon of electromagnetic radiation in or near the visible range. The scintillation process can be presented in three main steps: (i) conversion; (ii) energy transport and transfer towards luminescence; and (iii) luminescence.

The systematics of scintillation materials can have many aspects and determinants. The history of discoveries and research on scintillators dates back to the period of the first discoveries of A.H. Becquerel related to radioactivity [14]. The following scintillation materials are of the greatest practical importance in the detection and dosimetry of ionizing radiation:

- Inorganic crystals (or crystalline powders) of the alkali metal halides, sodium iodide, zinc sulphide, etc.;
- Organic crystals of the hydrocarbon, e.g., anthracene;
- Liquid solutions or plastics with dissolved hydrocarbons;
- Gas (noble gases) and glass scintillators, though they are rarely used.

A historical approach to the development of scintillation materials was demonstrated by Dujardin. He presented a graphical overview of the history of discoveries and development of scintillators whose light output was greater than \( 2 \times 10^4 \) ph/MeV [15]. Moreover, it
should be stressed that, most often, the scintillators are classified according to the different criteria:

3. **Classification based on structural types of crystals**—this division covers the crystallographic structure of scintillators. This approach allowed for the prediction and production of a number of new scintillation crystals; for example, scintillators with a structure of garnet, perovskite, oxyorthosilicate, pyrosilicate doped with cerium and praseodymium ions. This is the division preferred by material scientists [16];

4. **Classification based on scintillation mechanisms**—Lempicki [17] proposed the division of scintillators into two categories: external and stoichiometric. Since cross luminescence can be observed in crystals regardless of the presence of the impurities and the stoichiometric composition, it is more complex. Nonetheless, three classes can be distinguished, namely: activated scintillators based on crystalline compounds doped with activating ions; self-activated scintillators in which the luminescence centers are ions, anionic complexes and various excited states from the matrix itself; and cross-luminescence scintillators;

5. **Classification based on user requirements**—the best scintillation material for a given application (technology). The main parameters are then: the density, photofraction, luminous efficiency in the low (E < 10 MeV) or high (E > 10 MeV) energy range and luminescence decay time;

6. **Classification based on the specific properties of the materials**—compounds with a broad band gap have been demonstrated to be considered as good scintillation materials. This is related to the development of Ce$^{3+}$-doped scintillation materials. There are also many studies confirming that the presence of a broad bandgap is not a necessary condition for scintillation to occur, and that it only increases the potential spectral domain of the scintillation, as it makes the material transparent over a wider luminescence spectrum [18];

7. **Classification based on radiation resistance**—Krech [19] showed that some scintillation materials are sensitive to the action of ionizing radiation. Some composite scintillators based on organic single crystal grains are not radiation resistant even at a dose (D) of 1 Mrad, which eliminates them from application during high dose exposure. The crystals Gd$_2$SiO$_5$:Ce (GSO) and Gd$_2$Si$_2$O$_7$:Ce (GPS) showed full resistance to a radiation dose above $2.5 \times 10^6$ Gy. The crystals Al$_2$O$_3$:Ti and Y$_2$SiO$_5$:Ce (YSO) showed even higher resistance. At a dose above $5.5 \times 10^6$ Gy, they retained full scintillation parameters.

A sodium iodide crystal doped with thallium NaI: (Tl) is often taken as a reference material for irradiance dosing—for a certain amount of ionizing radiation energy in the material, it gives the largest amount of photons of light emitted. This amount can be estimated by noting that a single energy transition triggering the scintillation process requires 7 eV. Then, 1 MeV of the energy deposited gives a maximum of approximately $1.4 \times 10^5$ photons. This value was measured in real crystals and gave $30-40 \times 10^3$ photons. The rest of the energy is dissipated through side processes other than scintillation. The very structure of energy levels also causes an energy loss of $3/7$. In order to compare the properties of different scintillation materials, the so-called light output (L$_O$ or simply L) was proposed. It defines the resolution of the detector depending on the radiation particle type. Its unit is the number of luminescence photons per 1 MeV of the deposited energy, i.e., for NaI: (Tl) it is 40,000.

The construction, process and applications of scintillators are presented in Figure 1a–e. On the other side, it should be highlighted that the scintillation process takes place in three main phases, as shown in Figure 1b: in phase I—conversion—which occurs immediately after the interaction with the ionizing particle or photon; in phase II—transport and energy transfer towards the luminescence center—where the energy of the incoming radiation is absorbed by the scintillator and high-energy electrons and holes are created in the material as a result of three basic phenomena: photoelectric effect, Compton scattering and the creation of electron–positron pairs. Due to their different nature, these processes have
different absorption coefficients, which depend mainly on the atomic number \(Z\) of atoms in the scintillator crystal and the energy \(E\) of the absorbed photons. According to Rodnyi [20], the energy absorbed by the scintillator crystal will lead to the generation of space charge carriers in the scintillator crystal in the form of electrons and holes. Their number depends mainly on the type and intensity of the radiation; and, finally, in phase III—luminescence—which involves radiation recombination in accordance with the selection rules, emitting light in the UV/Vis spectrum. The resulting charge carriers (ions or molecules) in the scintillator crystals must be selected to allow efficient radiation recombination and a fast decay time. The spatial distribution of excitation plays an important role in several quenching phenomena during the relaxation phase. The resulting UV/Vis photons emitted by the scintillator can provide a light for PV cells and convert them into electrical signals. The luminous efficiency of the scintillator depends mainly on the shape and thickness of the scintillator, and the loss mechanisms (self-abortion), which cause the reabsorption of the emitted photons in the scintillator volume.

![Figure 1](image_url)

**Figure 1.** Construction, process and applications of scintillators: (a) a scintillation detector with the main constituent parts; (b) a sketch of the scintillator process in crystal. The process is divided into three consecutive stages of (I) conversion, (II) transport and (III) luminescence, which are described in the text; (c) schematic of a detector block and ring of scintillators in a positron emission tomography scanner; (d) needle crystal scintillators used in X-ray digital flat panel detectors; (e) scintillating fibers for cosmic ray detection and high-energy physics experiments. Copyright permission from [21].

The perfect scintillator, according to [22–24], should have a certain number of properties. Firstly, it should absorb radiation with high efficiency, without the presence of other phenomena, such as the photoelectric or Compton effect. This goal is better fulfilled for the higher density materials and elements with a higher atomic number. Secondly, it should
be highly efficient in the generation of photons of light (photon yield, luminosity), which is needed to generate a large number of (visible) light quanta per kiloelectronvolt of the deposited ionization energy. In other words, these photons cannot be absorbed by the crystal itself, which must be transparent to them, and the energy of these quanta must allow for their easy use in further processing. Thirdly, it is desirable that the emission of light occurs as soon as possible after absorbing the radiation quantum; since scintillation is a very complex (and also time-related) phenomenon for many materials, the so-called decay time is distinguished, referring to the time in which (almost) all quanta are emitted.

Materials showing scintillation properties can be divided into organic (mainly liquids, but also plastic masses) and inorganic. The inorganic scintillators are crystalline substances, commonly used in nuclear medicine. The best known examples are NaI(Tl) (sodium iodide with the addition of approx. 1–4 mol per mille of thallium), CsI (Tl) (cesium iodide doped with thallium), BaF$_2$ (barium fluoride), BGO (bismuth germanium oxide, Bi$_3$Ge$_4$O$_{12}$) and LSO (Ce) (lutetium oxy-orthosilicate, Lu$_2$SiO$_4$, doped cerenon). The most commonly used is NaI (Tl); hence, certain data characterizing a given scintillator are often given as a percentage of the corresponding values for thallium-doped sodium iodide. It has a high (compared to other scintillators) light efficiency, amounting to approximately 38 quanta of light per one kiloelectronvolt of energy deposited. The decay time is approximately 230 nanoseconds and the maximum of the emitted light photons is at a wavelength of 415 nm. To produce one photon of light in NaI (Tl), approx. 30 eV is required (to generate one pair of ions in a semiconductor detector: approx. 3 eV), which means that the energy resolution is low. For the other materials mentioned above, the luminous efficiency is even lower (except for CsI (Tl)). Some plastic materials have the lowest light efficiency, with a very short decay time (even below 2 ns).

The scintillation crystal must be characterized by an appropriate size and high purity. Many of these substances are sensitive to weather conditions, including high humidity. An important disadvantage is also a high sensitivity to mechanical damage, as well as sudden changes in temperature, causing crack formation. Slightly less important from a practical point of view is the so-called radiosensitivity of the crystal; that is, deterioration of the properties, expressed mainly by the optical turbidity, following its accumulation in high doses of radiation.

The latest fields of research regarding scintillation materials are mixed and co-doped single crystalline and ceramics garnets. Their main applications are image readers of positron emission tomography (PET) scanners. They have a very beneficial cost-effective high performance. The possibility of using rare earth garnets was investigated (Gd,Lu)(3)(Al,Ga)(5)O-12:Ce, Gd-3(Al,Ga)(5)O-12:Ce and Lu$_3$Al$_5$O$_{12}$:Pr) (in brief GLuGAG) [25–28] as scintillators for PET tomography detectors. These materials have an unprecedented combination of properties, including a high stopping power (the retarding force acting on charged, attenuation length 1.3 cm at 511 keV), high light yield (~66,000 photons/MeV deposited) and a fast decay time (~40 ns), and, above all, different to most other light emitting scintillators, they are not hygroscopic.

Presented by Birowosuto et al. [29], the results of the research on scintillation properties LuI$_3$:Ce$^{3+}$ indicate a very high light output of 98.000 (±10%) photons/MeV using Cs-137 as the source of exposure. Due to its very high light output, this scintillator seems to be one of the best materials for converting ionizing radiation into photons of light, as the dopant in LuI$_3$:Ce$^{3+}$ ions allowed an excellent scintillator with an exceptionally high light output to be obtained. The high light efficiency and fairly high density make these crystals interesting for conversion applications.

Lutet oksyorthosilicate (LSO)—Lu$_2$O$_5$Si—is often used with a scintillator to detect $\gamma$ radiation in PET and other similar techniques. LSO is usually doped with Ce$^{3+}$ in the proportion of 0.05 ÷ 0.5%. In the publication [30], it was shown that a small addition of Ca$^{2+}$ ions significantly improved the luminescence efficiency. Loef et al. [31] obtained a new class of inorganic scintillators based on rare earth elements and iodine. It mainly concerned chemical compounds, such as LuI$_3$YI$_3$ and GdI$_3$, doped with trivalent cerium.
ions. Monocrystals of LuI$_3$:Ce$^{3+}$, Y$_3$:Ce$^{3+}$, and GdI$_3$:Ce$^{3+}$ were obtained by the vertical Bridgman technique in evacuated silica ampoules. Owing to Ce$^{3+}$, a wide spectrum of luminescence in the range of 500–550 nm, high light efficiency up to 100,000 photons/MeV and fast base decay time constants <40 ns were obtained.

There was a large progress in radically reducing the hygroscopicity issue by Hawrami et al. [32] in the cesium cerium bromide—Cs$_2$CeBr(CeBr)$_5$—and cerium potassium bromide—K$_2$CeBr(CeBr)$_5$—crystals. These crystals were grown from the alloy using the Bridgman–Stockbarger vertical technique. These new materials (exposed to Cs-137) show very good scintillation properties for use in gamma and X-ray detectors. From the point of view of the application of the converters described in this article, the potassium content (β emission) is an additional factor that stimulates self-activation (autoluminescence). It is a favorable and expected phenomenon. Table 2 lists the basic features and parameters of various scintillation materials in terms of their usefulness in the device (converter) discussed in the article.

Table 2. Selected scintillation materials and their essential properties. Source: own study based on selected papers.

| Substance Consistency | Effective Charge * $\bar{n}$ | Decay Time [ns] | Scintillation Yield [ph/MeV] | Refs. |
|-----------------------|-----------------------------|-----------------|-------------------------------|-------|
| NaI (Tl) (reference)  | 51/0.06/2.6                 | 230             | 43,000                        | [33]  |
| **Fluorides**         |                             |                 |                               |       |
| Cross-luminescent materials |                     |                 |                               |       |
| BaF$_2$               | 53/0.085/2.0                | 620             | 9950                          | [34]  |
| Activated materials   |                             |                 |                               |       |
| CaF$_2$:Eu            | 16/0.045/3.7                | 940             | 21,500                        | [35]  |
| LuF$_3$:Ce            | 61/0.31/1.1                 | 23              | 8000                          | [36]  |
| Self-activated materials |                         |                 |                               |       |
| CeF$_3$               | 53/0.11/1.8                 | 30              | 4500                          | [37]  |
| **Chlorides**         |                             |                 |                               |       |
| Cross-luminescent materials |                     |                 |                               |       |
| BaCl$_2$              | 48/0.06/2.7                 | 35              | 6000                          | [38]  |
| Self-activated materials |                         |                 |                               |       |
| Cs$_2$HfCl$_6$        | 54/0.09/2.5                 | 70              | 54,000                        | [39]  |
| LaCl$_3$              | 46/0.05/2.9                 | 3480            | 34,000                        | [40]  |
| Activated materials   |                             |                 |                               |       |
| LiGdCl$_4$:Ce         | 49/0.07/3.0                 | 33              | 64,600                        | [41]  |
| RbGd$_3$Cl$_2$:Ce     | 54/0.07/2.8                 | 1000            | 43,000                        | [42]  |
| **Bromides**          |                             |                 |                               |       |
| Self-activated materials |                         |                 |                               |       |
| CeBr$_3$              | 46/0.06/1.9                 | 21              | 58,000                        | [43]  |
| K$_2$CeBr$_5$         | 41/0.03/3.8                 | 74              | 50,000                        | [32]  |
Table 2. Cont.

| Substance Consistency | Effective Charge * $Z_{\text{eff}}$ | Decay Time [ns] | Scintillation Yield [ph/MeV] | Refs. |
|-----------------------|---------------------------------|----------------|----------------------------|-------|
| **Activated materials** |                                 |                |                           |       |
| CsBa$_2$Br$_5$:Eu     | 47/0.06/2.2                     | 1260           | 92,000                     | [44]  |
| LaBr$_3$:Ce           | 47/0.07/1.6                     | 30             | 73,000                     | [45]  |
| Cs$_2$LiLaBr$_6$:Ce   | 46/0.05/2.4                     | 55             | 60,000                     | [46]  |
| RbGd$_2$Br$_7$:Ce     | 51/0.07/2.1                     | 66             | 54,700                     | [42]  |
| **Sulfides**          |                                 |                |                           |       |
| **Activated materials** |                                 |                |                           |       |
| ZnS:Ag                | 27/0.06/1.9                     | 105            | 73,000                     | [47]  |
| **Iodides**           |                                 |                |                           |       |
| **Self-activated materials** |                                 |                |                           |       |
| CaI$_2$               | 51/0.07/2.3                     | 550            | 86,000                     | [48]  |
| **Activated materials** |                                 |                |                           |       |
| SrI$_2$:Eu            | 49/0.07/2.0                     | 1200           | 115,000                    | [49]  |
| CsBa$_2$I$_5$:Eu      | 54/0.1/1.75                     | 14,000         | 102,000                    | [50]  |
| YI$_3$:Ce             | 51/0.08/2.0                     | 34             | 98,600                     | [51]  |
| CaI$_2$:Eu            | 51/0.07/2.3                     | 790            | 86,000                     | [48]  |
| **Materials with mixed anions** |                                 |                |                           |       |
| **Activated materials** |                                 |                |                           |       |
| BaBrI:Eu              | 51/0.09/1.8                     | 714            | 89,000                     | [52]  |
| **Sulfides&Selenides&Tellurides** |                                 |                |                           |       |
| **Activated materials** |                                 |                |                           |       |
| ZnSe:O                | 32/0.02/2.3                     | 12,000         | 71,500                     | [53]  |
| **Oxides**            |                                 |                |                           |       |
| **Self-activated materials** |                                 |                |                           |       |
| Lu$_3$(Al-Se)$_5$O$_{12}$ | 63/0.20/1.4                      | 610            | 22,500                     | [54]  |
| ZnWO$_4$              | 63/0.27/1.2                     | 22,000         | 21,500                     | [55]  |
| **Activated materials** |                                 |                |                           |       |
| (Gd-Y)$_3$(Al-Ga)$_5$O$_{12}$:Ce | 45/0.08/2.0                      | 600            | 60,000                     | [56]  |
| K$_3$Lu(PO$_4$)$_2$:Ce | 51/0.07/3.1                     | 37             | 50,000                     | [57]  |
| Gd$_3$Al$_2$Ga$_3$O$_{12}$:Ce | 51/0.12/1.6                      | 800            | 46,000                     | [58]  |

* effective charge $Z_{\text{eff}}$, the photo-absorption coefficient for 511 keV, cm$^{-1}$/X$_0$, cm and the radiation length X$_0$.

Remark: The parameters of the scintillation materials presented in the table relate to room temperature.

The activated iodides SrI$_2$:Eu and CsBa$_2$I$_5$:Eu definitely have the best luminescent parameters. The CsBa$_2$Br$_5$:Eu and LaBr$_3$:Ce activated bromides also show useful properties suitable for a converter. The analysis of literature reports prompts the search for the best solutions.

The ideal scintillator according to Knoll [59] should have a high light output, short response time, high radiation holding capacity, radiation resistance, low hygroscopicity and good energy resolution. Many materials have been tested for scintillation applications, but, so far, no single material has proven to be useful under a wider range of measuring conditions [60–62]. Based on the conducted literature research, it can be observed that the most frequently developed scintillators are dedicated for specific technologies.
A new view of the radiation resistance of scintillators was demonstrated by Boyarintsev in [63]. They investigated the possible processes and mechanisms of radiation changes occurring in composite scintillators containing inorganic dopants (activators) for Al₂O₃:Ti, GSO:Ce, GPS:Ce, YSO:Ce and YAG:Ce during irradiation. The results indicate that all crystalline scintillation materials contain defects that may act as luminescence centers or as quenching centers. Irradiation destroys and changes not only the basic material but also these centers. As a result, the luminescence intensity can increase for some time. In this case, the scintillator luminescence spectrum does not change its form at different doses (D), since new luminescence centers are not generated. Potentially useful scintillators (for example, CsBa₂I₅:Eu or SrI₂:Eu) for the converter discussed in this article should exhibit a strong scintillation (scintillation yield), short pulse rise time followed by a single exponential decay, which is the signature of the radiative relaxation of the luminescent center, and a long bleaching time. For the standardization of the division criteria, the parameter values presented in Table 2 take into account exposure to photons γ with an energy of 511. The α and β radiation have a much higher ionization density $\rho_{\alpha, \beta}$; therefore, the luminescence parameters will be much higher.

Finally, we would like to mention scintillators that are based on very popular at-the-last-period materials, such as perovskite, which is also widely used in photovoltaics. The scintillator converts ionizing radiation into photons of light, each of which has energy close to the material’s band gap or energy gap between the substrate and the activator’s excited states. The photons produced are captured by PV cells and converted into electrical signals [64–66].

These articles discuss scintillation technologies, with a particular emphasis on perovskite materials. The scintillation materials have small band gaps between 3 and 4 eV and large exciton-binding energy. The detection threshold of the perovskite detectors is very low. It is around a dozen nGy × s⁻¹. An undoubted advantage is also low-temperature mass production (see Figure 2).

A number of research works were conducted aiming at a search for new scintillator materials. The perovskite halide single crystals are particularly promising for such use [67]. The crystal production (culturing) process can be successfully carried out at temperatures lower than 100 °C. Another advantage of perovskites is their small band gap, high effective atomic number and high mass density, which increases the luminescence efficiency during γ and X radiation absorption. Another important feature of the perovskites is also their high resistance to the radiation damage.

An important element, apart from the light efficiency of scintillation materials, is the appropriate wavelength, which can be chemically tuned depending on the type of anionic component of the perovskite. Although their light efficiency is lower than, for example, SrI₂:Eu or CsBa₂I₅:Eu, the economic and technological aspects are very advantageous.
4. Type and Architecture of Solar Cells

4.1. Inorganic Solar Cells

The solar cells can be broadly divided into inorganic and organic. In the silicon-based solar cells, electrons and holes are created during the absorption of the light by the silicon (Si) semiconductor. Due to the large dielectric constant Si, electrons (e\(^-\)) and holes (h\(^+\)) are quickly separated from each other, without interacting. Inorganic solar cells form the first and the second generation of cells. The first generation solar cells include solar cells based on monocrystalline (mono c-Si) and polycrystalline silicon (poly c-Si). Generally, crystalline silicon cells are made of a semiconductor as a base material,
p-n junction and metal electrodes. In addition, the cell contains an emitter and both passivating and antireflection layers. A typical crystalline silicon photovoltaic cell contains: the area of the base material: -p-type silicon, the dopant layer on the front surface: -n-type silicon, front and back metal electrodes, most often made of screen printing pastes, an anti-reflection and passivating layer, e.g., SiN$_x$, and a BSF layer (back surface field). It should be stressed that scientists modify the typical architecture of silicon solar cells in different ways: the cells based on crystalline silicon with a modified structure are HIT cells (heterojunction with intrinsic thin layer), IBC cells (integrated back contact) and BF cells (bifacial). Moreover, taking into account the location of the electrodes in a crystalline silicon photovoltaic cell, we distinguish:

1. Silicon photovoltaic cells in which the electrodes, positive and negative once, are on opposite sides of the silicon wafer;
2. Silicon photovoltaic cells in which both electrodes are located on the back side of the silicon wafer (BC, back contact).

The basic classification of solar cells based on crystalline silicon is as follows: heterojunction technology (HJT), back contact (BC) and passivated emitter and rear cell (PERC). HJT and BC solar cells are considered high efficiency cells and are now in mass production. In turn, PERC-type cells are currently the most promising type of solar cells, so we distinguish their modifications, such as: passivated emitter rear directly contacted (PERD), passivated emitter rear locally doped (PERL), passivated emitter rear totally diffused (PERT) and passivated emitter rear floating-junction (PERF).

In order to eliminate the phenomenon of recombination on the back and front surfaces, the production technology of PERC silicon photovoltaic cells was developed, where the base material is p-type silicon. In addition to PERC cells, HJT cells are manufactured, based on the high-quality n-type silicon, and the passivating layer on the front and the back surfaces is made of amorphous silicon. The electrodes are located on the front and back sides of the cell. Another type of crystalline silicon-based solar cells are BC cells based on high-quality n-type silicon, with no front electrode. As a result, the surface recombination on the cell front side is reduced to a minimum. Both electrodes are located on the back of the cell.

Apart from silicon cells, we can also distinguish other inorganic cells, such as: (i) CIGS solar cells (compounds of copper, indium, gallium and selenium), (ii) gallium arsenide (GaAs) solar cells and (iii) kesterite solar cells (Cu$_2$ZnSnS$_4$) [68,69]. The advantages and disadvantages of selected inorganic solar cells are shown in Table 3.

| Type of Inorganic Solar Cells | Advantages and Disadvantages |
|------------------------------|-----------------------------|
| Cells based on monocrystalline silicon | high efficiency (25.6%), durability of up to 25 years, small amount of space in relation to efficiency, high cell price related to the costly technology, decrease in efficiency in diffused light. |
| Cells based on polycrystalline silicon | lower price than monocrystalline cells, no loss of efficiency in diffused light, lower efficiency than for monocrystalline cells (21%) |
| Cells based on amorphous silicon | up to 25 years of durability, low production costs (due to lower silicon consumption), low price, no toxic heavy metals, can be applied to the substrate at a temperature of approximately 75 °C, lower efficiency (12%) than for monocrystalline Si (25%), relatively large amount of occupied space in relation to the efficiency. |
Table 3. Cont.

| Type of Inorganic Solar Cells | Advantages and Disadvantages |
|------------------------------|-----------------------------|
| CIGS cells                   | high efficiency (22%),      |
|                              | low weight,                 |
|                              | the ability to absorb light from different directions, |
|                              | complicated and difficult technological process, |
|                              | the presence of cadmium.    |
| GaAs cells                   | highest efficiency (32%),   |
|                              | excellent durability (due to resistance to moisture and UV radiation), |
|                              | excellent light absorption (due to the wide band gap), |
|                              | flexibility, lightness,      |
|                              | high price,                 |
|                              | the toxicity of chemical reagents used in production (which limits the scope of applications for powering ships and space probes). |
| Kesterite solar cells (Cu$_2$ZnSnS$_4$) | they are made of cheaper, more accessible and more environmentally friendly materials than in the case of CIGS or CdTe cells. |
|                              | still exhibited low efficiency (~10%). |

4.2. Organic Solar Cells

Organic solar cells are the third generation of solar cells. The working principle of organic solar cells is not exactly the same as inorganic solar cells. In the case of the organic photovoltaics, the following stages of the sunlight conversion process into electricity are distinguished:

1. The generation of an exciton (electron–hole pair) under the influence of absorbed light;
2. The exciton dissociation;
3. The charge diffusion towards the electrodes;
4. The electron accumulation at the cathode and the anode holes.

Many key parameters allowing organic solar cells with a high efficiency and stability to be obtained are still not sufficiently explained. Regardless, the reduction (limitation) in the charge carrier recombination process plays a key role in obtaining efficient solar cells. In addition, it is necessary to distinguish losses related to reflection and transmission, the existence of barriers at the electrodes or processes related to the spontaneous disappearance of excitons or the transmission of exciton energy to the defect. All of these limitations and losses observed in organic solar cells are the reason for intensive scientific research towards eliminating these drawbacks. There is extensive research on the modification of the architecture of organic solar cells. The division of organic photovoltaic cells due to the architecture of the cell’s active layer includes:

1. Layer cells, where the active layer is composed of separate donor and acceptor layers, e.g., P3HT/PCBM, where P3HT: (poly (3-hexylthiophene) and PCBM: [6,6]-phenyl-C61-butyric acid methyl ester;
2. Bulk heterojunction, the so-called BHJ, where the active layer is a mixture of materials of donor (D) and acceptor (A) nature, e.g., P3HT:PCBM;
3. So-called combed cells, where the donor layer has a comb-like arrangement, separated with the acceptor layer with a complementary comb-like structure, which should eliminate the effect of recombination in the cell.

Presently, the organic solar cells can be divided into: (i) solar cells based on low molecular weight compounds in the active layer called organic solar cells [70–75], (ii) polymer solar cells [76,77], (iii) dye-sensitized solar cells (DSSC) [78,79], (iv) perovskite solar cells [80–82] and solar cells 3rd generation with nano-compounds, called the 4th generation of solar cells [83–95]. The fourth generation of the photovoltaic cells (organic solar cells with nano-compounds) includes various types of the third-generation solar cells enriched with
various types of nanocompounds, such as: metallic nanocompounds (Ag, Au, Pt), chemically modified graphene and carbon nanotubes, MoO$_x$, TiO$_x$ or ZnO, located in different places in the cell to improve photovoltaic parameters, including solar cell efficiency [96].

In the organic photovoltaics, P3HT (poly(3-hexylthiophene), PCDTBT (poly[N-9'-heptadecanyl-2,7-carbazole-alt-5,5-(4',7'-di-2-thienyl-2',1',3'-benzo[4,5-b:2,1,6-b']thiadiazole)]) and PTB7 (poly[(4,8-bis[(2-ethylhexyl)oxy]benzo[1,2-b:4,5-b']dithiophene-2,6-diyl][3-fluoro-2-[(2-ethylhexyl)carbonyl]thieno[3,4-b]thiophenediy]]) polymers are most often used as the donor materials, whereas PCBM or PC$_{71}$BM fullerenes are used as the acceptor materials [96–100].

A typical architecture of the BHJ organic photovoltaic cell consists of: ITO/PEDOT:PPS (as hole transporting layer)/active layer (donor–acceptor pair)/cathode buffer layer/Al.

Selected advantages and disadvantages of the main organic solar cells are presented in Table 4.

| Type of Organic Solar Cells | Advantages and Disadvantages |
|----------------------------|-------------------------------|
| Small molecular/polymer solar cells | lower toxicity, flexibility, lightness, large-scale production easier and cheaper than cells constructed on the basis of inorganic materials, a variety of chemical compounds used (polymers, dendrimers, oligomers or liquid crystals), short life, lack of sufficient stability in the air atmosphere, the problem with rescaling technology from a laboratory scale to a semi-technological or technological scale. |
| DSSC | high efficiency (15%), low manufacturing cost, low consumption of organic materials, transparency (they can act as panes), low sensitivity to the angle of incidence of solar radiation (they can work effectively both under the influence of reflected and refracted radiation, as well as with partial shading), less CO$_2$ produced during the production of a dye cell than a silicon cell, short payback period of energy used to produce a single DSSC module (energy payback time), problems with liquid electrolyte (work is underway to replace it with gel or solid electrolyte), high cost of platinum and ruthenium (searching for cheaper materials), problem with long-term stability (work is underway to replace the iodine in the cell with, for example, cobalt). |
| Perovskite cells | the ability to absorb light with a very wide wavelength spectrum, high efficiency (22%), low production cost, flexibility, low weight, possibility of application on various surfaces, the presence of lead in the perovskite (CH$_3$NH$_3$PbI$_3$), which pollutes the environment and is hazardous to human and animal health (work is underway to replace lead in perovskites, e.g., with tin), problem with stability in the air atmosphere (they decompose under the influence of moisture). |
Examples of the applications of the first to fourth generation of solar cells are presented in Table 5.

Table 5. Examples of the applications of the first to fourth generation of solar cells.

| Generation of Solar Cells                                                                 | Application                                                                 |
|------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|
| First generation cells                                                                    | power plants, solar farms.                                                 |
| Cells based on amorphous silicon (2nd generation)                                         | for the production of solar lamps or calculators, as well as modules.      |
| CIGS cells (2nd generation)                                                              | modules on roofs, portable power plants and powering vehicles.             |
| GaAs (2nd generation)                                                                     | chargers for phones, laptops, automotive and aviation.                     |
| DSSC cells (3rd generation)                                                               | glass, glass or facade elements, cell phone chargers, photovoltaic modules.|
| Organic solar cells (3rd and 4th generation)                                             | as covers for backpacks, bags, cell phone chargers, a photovoltaic system integrated with the construction industry BIOPV (building integrated organic photovoltaic).|

The use of photovoltaics is multifaceted and includes optoelectronics, microelectronics, computer science and telecommunications. The current trend, which is very important, is the construction of interconnected systems, including devices for the production and storage of electricity, i.e., a solar cell–supercapacitor or solar cell–lithium-ion battery [100,101].

Currently, an increasing trend is observed in the number of manufactured and installed photovoltaic modules, which is beneficial for environmental protection and the development of renewable energy sources (RES). However, such trends also bring issues regarding the management of damaged and worn-out modules. Unfortunately, at the present moment, the process of solar cell recycling is not economically viable, although the technology in this area is slowly changing. The French company Veolia has launched the first plant in Europe in which only used solar modules will be recycled. Apart from glass and aluminum, this plant will also recover silicon, copper, silver and plastics [102–104].

To summarize this chapter, it has becomes of key importance to include in photovoltaics a multi-faceted approach in the cell construction (from material synthesis to solar cell recycling), leading to alternative technologies. These subjects are related to the principles of green chemistry and broadly understood sustainable development and they include economic, environmental, economic and social aspects.

5. Radiation Effects on Silicon Solar Cells

Currently, energy generation using silicon solar cells is the most commonly used technology worldwide. Critical to the applicability of silicon photovoltaics is the influence of external factors having an impact on the cell, including the temperature and availability of solar irradiation. The influence of different irradiation types on the energy conversion in Si solar cells becomes more relevant concerning outer space use in particular [105]. It has become a very important aspect and can have different influences, depending on the size of the particles, on different parts of the p-n junction. Since that moment, researchers have focused their work on testing various optoelectronic devices both theoretically and experimentally [106–112]. Considering the possible influence of the radiation on the solar cell, two main types of damages can occur in the solid-state: displacement damage and an ionization effect. Regarding displacement damage, we can understand defects in the lattice caused by the movement of atoms from their regular position. The second one influences the generation of hole–electron pairs in the material. It is also expected that, due to the low atomic number of silicon, which is equal to 14, the possible response of the silicon solar cells would be less affected by the incident photon energy compared to the other photovoltaic devices [113,114].
It is widely known that conventional solar cells work in a limited light wavelength region, which is mostly in the visible range. Therefore, in this part, we will focus on the radiation damage of silicon solar cells and the possible use of such irradiation to generate the electric current.

Scharf [115] is one of the first to present the influence of X-ray and gamma irradiation on the performance of solar cells based on silicon. It was noticed that the silicon solar cells showed a better energy dependence than other solid-state devices used for the measurement of high-energy radiation, such as cadmium sulfide. It was noticed that both the open circuit voltage and photocurrent generated in the cell after the irradiation strongly depend on the exposure dose, and drops of even 15–20% for 150 r/min are observed. It was also detected that, due to the strong temperature influence on the open circuit voltage, it is suggested to use the photocurrent as the analytical value for irradiation influence. The author suggested using solar cells as the radiation level detectors, especially by stacking cells, which would increase their sensitivity to high-energy irradiation.

In many developed countries, nuclear power plants are important in their electricity generation. They also generate large amounts of nuclear waste (spend fuel) every year that needs to be stored for 20–30 years before it can be further processed. The gamma irradiation is one of the by-products released from uranium and plutonium nuclear fuels [116].

Nikolić et al. [117] studied permanent damage in the crystalline structure of the silicone in the solar cells driven by the collisions of the incident radiation particles. They found that the defect formation, including vacancies, self-interstitials, impurities and dopants, interacts with Si atoms in the lattice, resulting in the formation of undesirable phenomena, such as recombination and compensator centers. This strongly affects the performance of the solar cells. As reported, the gamma irradiation is reduced by approx. 5% when irradiated with a Co60 gamma source with a dose of 2000 Gy, an energy 1.25 MeV, and a half-life period of 5.27 years (this energy is sufficient for the creation of the electron–hole pairs), as is presented in Figure 3. The dose rate was 100 Gy/h at a distance of 150 mm away from the radioactive source. It is worth mentioning that the authors used annealing to restore the initial parameters of the solar cells.

![Figure 3](image_url)  
**Figure 3.** I-V characteristics of the solar panels before and after gamma irradiation. Reproduced with permission from [117].

Another aspect was studied by Tobnaghi et al. [113] and included changes in the electrical parameters of the silicon solar cells (commercially available) while changing the doses of the gamma radiation. A deterioration of the electric properties was noticed upon an increase in the gamma dose in a range of 1 to 20 kGy for all solar cells. The only exception was noticed for the fill factor, whose value either increased or was relatively...
steady. Regarding the other parameters, a significant reduction in the values was observed (Figure 4a). The authors explained such results by the sensitivity of the charge carriers’ lifetime and the undesired recombination. The life time of minority carriers is sensitive to the radiation-induced defects that mostly act as recombination points, and the decrease in the minority carrier life time reduces the solar cells parameters. The analysis of the spectral photocurrent results highlights the idea that the gamma irradiation, in the case of most of the cells, reduces their performance in the low wavelength of the spectrum. This means that gamma radiation causes defect production near the cell surface (Figure 4b).

Figure 4. I-V characteristics of silicon-based solar cell under gamma irradiation (a) and normalized PV parameters as a function of gamma irradiation dose (b). Reproduced with permission from [113].
Other aspects regarding gamma radiation in the field of solar cells were presented by Vasić-Milovanović [118]. Her work investigated how the performance of the solar cells, such as the photovoltaic generators, would change under a high temperature and radiation for samples with a layered architecture of TiN/Ti/Si. For such samples irradiated at two different light intensities, 38 W/m² and 58 W/m², it was noticed that both the efficiency and the maximum power diminishes by approximately 10 to 15% for a dose close to 500 mGy (Figure 5).

Figure 5. Dependence of the maximum power (a) and efficiency (b) on doses of gamma irradiation. Reproduced with permission from [118].
Author also observed that it is crucial to control the temperature level of the solar cells in order to not increase the noise level due to the degradation of their electrical and optical characteristics. Therefore, the permanent monitoring of the working conditions is a must in order to maintain the PV performance on a stable level, which increases the cell lifetime.

Horiuchi and co-workers [119,120] presented the influence of gamma radiation on the characteristics of solar cells towards gamma cells that could generate current. For this purpose, amorphous and crystal-type solar cells equipped with scintillation crystals of CsI(Tl) and NaI(Tl) and plastic scintillators were coupled. They observed that amorphous solar cells were insensitive to direct gamma rays, even after using a scintillator that changes the spectral wavelength of the gamma rays to the region of the visible light. The difference between both cell types was of an order of 100 times in the case of the generated voltage. Moreover, the amorphous solar cells present a linear response to the high-intensity gamma irradiation. The electric power generated by a single solar cell after exposure to gamma radiation was very small, but a large amount of electric power can be obtained by arranging many solar cells in stacks and by combining their induced current or voltage and by operating the cells all day, as they are not greatly affected by weather conditions. It was noticed that, by stacking just three solar cells, it was possible to obtain a very similar level of conversion rate for all devices. Furthermore, the crystal-type solar cells are very sensitive to the gamma radiation; the cell conversion efficiency can be drastically improved by coupling with the scintillator. It was concluded that gamma cells using the gamma radiation of the nuclear spent fuel can be expected to be useful for electric power generation in the future.

Lee and Yim [121,122] developed a trend of using a scintillator as an active layer, transforming the gamma irradiation and shifting it to the visible range. In their work, they examined the possibility of using electricity generation in a spent fuel storage pool at a nuclear reactor via computational modelling from residual gamma irradiation. In their model, they used CsWO4 in addition to the above mentioned CsI. From the analysis of the energy distribution of gamma radiation per one spent fuel assembly over spent fuel storage time, the changes in the gamma activity of one spent fuel storage assembly do not change significantly between 0 and 18 months of the storage. However, the drop in the activity is evident when the storage period increases to 10 years (Figure 6). This demonstrates that the gamma electricity generators could work up to 10 years using waste nuclear fuel. In their model, they also included a stacking of cells in order to improve the effectiveness of the whole system.

![Figure 6](image_url)

*Figure 6.* The energy distribution of gamma radiation generated by a single spent fuel assembly. Reproduced with permission from [121].
Presented by authors [122], data indicated that the use of the CdWO$_4$ scintillator for the energy conversion system is appropriate, as the system’s performance, including the radiation damage effect, becomes comparable to that of the non-irradiated CsI(Tl) system. However, the energy generated from the system containing CsI would be approximately four times greater. It was mentioned by the authors that this technology requires further development and a series of practical trials in real conditions.

Other concepts include the use of solar cells as an energy harvester of beta particles. This includes the capturing of beta particles from specific radioisotopes and their conversion into electrical energy. Such designed betavoltaic batteries would possess unique features, such as a long service life (even to several decades) and small size, being an attractive power source for fulfilling the requirements of the future generation of electronic devices [123–125]. This type of influence is not as destructive as the previously described gamma irradiation and requires only the modification of the silicon structure to adapt to the beta particles.

Alam et al. [123] observed an important factor while constructing the betavoltaic harvester; namely, the thickness of the beta active layer. The issue is related to the penetration of such a big particle into the semiconductor.

Uhm and co-workers [124] focused on the deposition of the beta particle source in order to obtain a better battery performance. The difference in the short-circuit current between the p-n junctions with and without radioactive $^{63}$Ni (16.5 MBq) was found to be 5.03 nA. The power output was found to be 0.8 pW and the power density was found to be 5 pW/cm$^2$. A relatively enhanced power output was achieved from a very weak power source due to the p-n junction without a seed layer. Although the power output was enhanced, a very low current ranging from nano- to microamperes was generated in the devices (Figure 7).

![Figure 7. Planar battery performance characteristic of magnified I-V curves. Reproduced with permission from [124].](image-url)
Kasanov and others [125] in theoretical work suggested to technologically develop a three-dimensional (3D) Si structure. The betavoltaic converter containing such a modified silicon layer was evaluated for the p-n junction with the Ni contact layer formed by the reducing reaction across the strongly developed Si microchannel surface in the electron irradiation modes. The authors calculated that this approach would improve the performance of the betavoltaic battery, as can be seen in Figure 8.

![Figure 8. The I-V characteristics of an experimental 3D BVC structure. Reproduced with permission from [125].](image)

6. Radiation Effects on GaAs Solar Cells

It is interesting to note that the effects of the electron and the proton irradiation on thin film solar cells, such as silicon, GaAs, CdS and CdTe solar cells, were the subject of investigation in 1966 by Joseph J. Loferski. The New York Times called him “a pioneer in the development of solar cells” [126]. It was concluded that only protons have been shown to produce damage in the cells, and depended only on the kind of encapsulant used. For example, the samples with 0.6, 1.0 and 2.5 MeV electrons up to a maximum dose of approximately $10^{17}$ electrons/cm$^2$ encapsulated in Tedlar and H-Film did not exhibit any degradation, whereas the cells encapsulated in Mylar decayed (the rate was independent of electron energy). Meanwhile, the same devices were irradiated by protons (2, 5, 7 and 10 meV), for a dose of approximately $10^{14}$ per cm$^2$ decreasing by 10% photovoltaic parameters, such as $J_{sc}$ and $V_{oc}$, independently from the type of encapsulation used.

In 1964, Flicker et al. [127] created the so called “atomic battery” by combining the $\beta$-emitting radioisotope Promethium-147 and a semiconductor based on the p-n junction in GaAs and silicon cells. It was shown that a long-life and a small-power source can be constructed by combining Pm$^{147}$ with n/p silicon cells. Such batteries would have a half-life (1.6 years) shorter than that of Pm$^{147}$ and could generate a few milliwatts of power from a volume of approximately 2 cubic inches, including shielding. On the other hand, GaAs cells do not exhibit radiation damage from Pm$^{147}$ beta particles.

In all created devices, one of the main issues was the stability of the device when under radiation, raising the question about whether degradation is still important.

Orlova et al. [128] studied the degradation of photovoltaic cell with an architecture of Ge/GaAs/GaInP/AlInP under ionizing radiation. All of the radiation (radiation belts...
and solar and cosmic radiation) can deteriorate the electric parameters of the constructed devices. The authors investigated a single-degradation characteristic of the solar cells in depth by irradiation devices with fast neutrons and electrons also at different fluences. The GaAs cells are far less susceptible to destruction by high-energy protons and electrons than silicon cells due to the high light absorption by GaAs and low mandatory lifetime and diffusion length of minority carriers. The authors observed that the fast electron and neutron irradiation shifts the J-V characteristics towards lower values of current and voltage, and that the power conversion efficiency (PCE) decreased from 21.1% to 16.3% and to 17.8% after the fast neutron and electron irradiation, respectively. This effect can be explained by the decrease in the lifetime and the diffusion length due to the formation of recombination centers in the devices.

Interesting work was carried out by Khvostikov et al. [129] where an electrical supply source based on AlxGa1-xAs/n-GaAs p-n heterostructures with various band gaps and tritium radioluminescent lamps with blue and green glow were investigated. A constructed photovoltaic converter with an area of 0.12 cm² upon irradiation at 550 nm exhibited a short-circuit current density of 180 nA/cm² and output electrical power of >100 nW/cm². In the authors’ opinion, an electrical supply source based on the radiation of electroluminescent lamps is less effective than the direct use of the β-decay of isotopes, where the generation of the electron–hole pairs happens not only in the narrow-gap active region but also in the wide-gap passivating layer of the investigated heterostructures, which also unfortunately negatively affects the direct β-radiation conversion efficiency.

Very interesting work was described by Russo et al. [130], where an approach to increasing the power density in a β-photovoltaic nuclear battery was described in detail. Nickel-63 in a chloride solution was integrated in a phosphor film (ZnS:Cu,Al) and the β⁻ energy was converted into optical energy via an InGaP photovoltaic cell. The authors constructed and investigated two β-photovoltaic cells based on ⁶³Ni/ZnS:Cu,Al/InGaP with a planar (on 15 mCi ⁶³Ni foil) and volumetric (with film thickness from 50 to 565 μm) configuration. As an example, the constructed volumetric β-photovoltaic cells are presented in Figure 9.

![Figure 9](image_url)

**Figure 9.** Illustrations and images of the volumetric β-PV cell experiment: 3D configuration for 200 μm phosphor sample (a), 63NiCl₂-loaded phosphor sample after solution integration and drying procedure (b) and sample placed on top of InGaP PV cell in a light-tight enclosure (c). Copyright permission from [130].

The authors found that the planar configuration at a thickness of 50 μm with 15 mCi activity reached the highest (however, still very low) PCE = 0.0638% on the ⁶³Ni metal foil. It was found by the authors that the electrical parameters depend on the phosphor thickness (the highest values were found for thickness 10–15 μm). In the case of the volumetric architecture, the highest PCE = 0.289% was found for the cell with a phosphor film thickness of 200 μm at the 15 mCi ⁶³Ni set. The authors concluded that using the volumetric configuration resulted in the β⁻ source being able to be surrounded by the nuclear and
optical converter, which means the phosphor and photovoltaic cell, respectively. Of course, it should be highlighted that, in the case of the volumetric devices, the limiting factor was the dispensing method applied to create the $\beta^+$ source, which was inhomogeneity. For future work, the authors suggested using $^{147}$Pm in a form of a foil and a solution in order to increase the nuclear battery power limit from microwatts to milliwatts per 1000 cm$^3$.

Another interesting concept was proposed by Guo et al. [131], where a dual-effect multilevel isotope battery based on a $\gamma$ radioisotope source was studied for two types of energy conversion mechanisms: radio-voltaic and radio-photovoltaic effects under a $^{60}$Co source at dose rates of 103 kGy/h and 0.68 kGy/h. Authors found that the thickness of the scintillator strongly influences the obtained electrical results. A schematic of the dual-effect multi-level isotope battery is shown in Figure 10.

The authors suggested that, by the use of a multi-level conversion module based on an LYSO scintillator and a GaAs photovoltaic cell, the $\gamma$ ray source can be applied step by step with so-called dual effects, and the isotope battery can produce an extension, as presented below, for batteries in series and parallel configurations ($I_{sc}$, $V_{oc}$, FF and $P_{max}$):

- 0.103 kGy/h-series: 0.084 $\mu$A, 0.46 V, 0.47 and 0.018 $\mu$W;
- 0.68 kGy/h-series: 0.74 $\mu$A, 0.76 V, 0.58 and 0.326 $\mu$W;
- 0.103 kGy/h-parallel: 0.12 $\mu$A, 0.19 V, 0.45 and 0.0103 $\mu$W;
- 0.68 kGy/h-parallel: 1.38 $\mu$A, 0.36 V, 0.54 and 0.268 $\mu$W.

The energy conversion efficiency (PCE) of the multi-level isotope battery was found to be in the range of 0.0193 to 0.0235% for 0.68 kGy/h-parallel and 0.68 kGy/h-series, respectively. The lowest values of PCE was found for 0.103 kGy/h experimental conditions. In conclusion, it can be said that the battery with multi-level conversion modules in the series exhibited better output power than that in the parallel. A theoretical simulation showed that the electrical performance increased and then decreased, along with an increase in the thickness of the scintillator, and reached the highest values of $I_{sc}$, $V_{oc}$ and $P_{max}$ for the 1.5 cm thickness of the used scintillator.

Xu et al. [132] also investigated a dual-effect nuclear battery based on a radio-voltaic and radioluminescence effect and additionally on a ZnS:Cu radio-luminescence layer to a Cd-109 X-ray radioactive source and GaAs radio-voltaic layer. The authors discovered that the dual-effect nuclear battery is more effective than the single radio-voltaic nuclear battery, where its PCE increased from 0.079% to 0.119%. It is well known that the penetration power of an X-ray or $\gamma$-ray is stronger and more destructive than $\alpha$ and $\beta$ radiation, and, consequently, the corresponding self-absorption effect is very weak. However, it should be stressed that the infrequent use of mentioned sources (X and $\gamma$) in the device’s construction is due to radiation protection consideration. One of the solutions is to use it as an outer space environment [133,134]. The schematic of the Cd-109 dual-effect nuclear battery is presented in Figure 11.
The authors analyzed the subject theoretically using a Monte Carlo simulation optimization and experimentally, where, as an example, the selected electrical performance parameters of the nuclear batteries are shown in Table 6 and presented in Figure 12.

| Electrical Properties | Value     | Single Radio-Voltaic Nuclear Battery | Dual-Effect Nuclear Battery |
|-----------------------|-----------|--------------------------------------|-----------------------------|
| \( I_{oc} \) (\( \mu \text{A} \)) | theoretical | 6.14 | 12.76 |
| \( V_{oc} \) (V)    | theoretical | 0.51 | 0.54 |
| \( I_{sc} \) (\( \mu \text{A} \)) | experimental | 4.25 | 6.26 |
| \( V_{oc} \) (V)    | experimental | 0.42 | 0.43 |
| \( P_{\text{max}} \) (\( \mu \text{W} \)) | experimental | 1.04 | 1.59 |
| \( \text{PCE}_{\text{total}} \) (%) | experimental | 0.079 | 0.119 |

Figure 11. The schematic of Cd-109 dual-effect nuclear battery. Copyright permission from [132].

Figure 12. (A) Nuclear battery samples and structure schematic; (B) I–V and P–V characteristic curves of nuclear battery before and after performance enhancement. Copyright permission from [132].
The authors investigated constructed devices in depth in order to optimize the energy utilization and improve the battery conversion efficiency, focusing on spectral response matching, radio-luminescent layer thickness optimization and reflective layer design. The authors discovered that the application of the ZnS:Cu radio-luminescent layer and the aluminum reflective film increases the maximum output power of the nuclear battery from 1.04 μW to 1.59 μW. Finally, it should be stressed that the authors proposed a remarkably interesting and perceptive solution, replacing the single radio-voltaic nuclear battery with the dual-effect nuclear battery, which can increase the output power and prolong the service life.

7. Radiation Effects on Organic Solar Cells

At the beginning of this section, we want to emphasize that, in the organic photovoltaics, the heart of every cell is an organic compound: a polymer with conductive properties. Unfortunately, the polymer in the solar cell is also one of the weakest elements of the cell, and is sensitive to atmospheric factors, such as moisture, oxygen from the air and ionizing radiation. Therefore, scientists are conducting extensive research into the encapsulation of the organic solar cells. The effect of the ionizing radiation on infrared polarizers based on polypyrrole with a 100 S/cm conductivity was shown by Boye et al. [135]. Authors discovered that, unfortunately, the ionizing radiation would decrease the conductivity of polypyrrole. These results are in contrast to their previous results for polyaniline (PANI), where both high and low energy protons did not affect the conductivity. However, other scientists are in contrast to these results, and it was shown that gamma ray irradiation cases increase the conductivity in PANI [136] and in poly(3-methylthiophene) [137]. Obtained results showed the influence of the morphology of created films but also the thickness of the film and the experimental conditions.

Kumar et al. [138] showed that the polymer solar cells with an ITO/PEDOT:PSS/P3HT:PCBM/In/Al architecture were degraded under X-rays as an effect of the charge accumulation at the interface, and were dependent on the w/w ratio of the donor to acceptor (10:1, 4:1, 1:1 and 1:2) and the various dose rate. The authors discovered that, at a dose rate of 300 Krad SiO₂, a less than 1% loss in the transmission of the polymer film was found; similar results were obtained for all of the w/w ratios of P3HT:PCBM. The effect of the X-ray dose on the normalized short-circuit current (Iₛₒ) for various dose rates of P3HT:PCBM in the ratio 1:1 and for the different w/w ratios of P3HT:PCBM at a fixed rate of 6.4 Krad/min are presented in Figure 13.

![Figure 13. Effect of X-ray dose on normalized short-circuit current (Iₛₒ) for (a) various dose rates of P3HT:PCBM in the ratio 1:1 and (b) for different w/w ratios of P3HT:PCBM at a fixed rate of 6.4 Krad/min. Copyright permission from [138].](image-url)
The authors noticed that charge accumulation can be a simple problem resulting in a temporary degradation in the solar cell performance. It is interesting to note the fact that, when the amount of the acceptor is higher in the active layer, the device is more stable to radiation, as presented schematically in Figure 14.

![Figure 14](image-url)

**Figure 14.** Physical model of the effect of X-rays on polymer solar cells: (a) scheme of electronic levels and transitions in a molecule: 1: excitation, 2: internal deactivation, 3: transition to the ground state, 4: dissociation from higher excited states and 5: dissociation from the first excited level; (b) a low PCBM % bulk P3HT:PCBM film showing isolated PCBM domains; (c) a high PCBM% bulk P3HT:PCBM film showing well connected PCBM network, resulting in good charge transport. Copyright permission from [138].

Similar work was carried out by Kouhestani et al. [139], where the ionizing radiation effect in the polymer solar cells with an architecture of glass/ITO/PEDOT:PSS/P3HT:PCBM (1:1)/Ca/Al/encapsulated glass for total accumulated doses of up to 300 krad (SiO$_2$) was examined in detail. The authors, based on the obtained results, concluded that only the open circuit voltage varies with the accumulation of irradiation, whereas the other investigated parameters (relaxation time, short circuit current, charge carrier density) maintain the first order constant. Moreover, the authors revealed that, regarding post-irradiation, the relaxation time saturation regime is shorter with Voc.

It is known that the polymer solar cells are sensitive to the action of moisture or oxygen from the air. In addition, scientists are modifying the cell architecture by introducing additional cathode and anode blocking layers in order to limit Al or In migration to the active layer and thus reduce contamination of the active layer.

Thomas et al. [140] investigated the morphology of the active layer in depth based on P3HT:PCBM before and after ionizing radiation exposure of up to 1 Mrad with X-rays (10–60 keV), as presented in Figure 15. The authors created various active layers by con-
trolling the film processing conditions, such as the type of the solvent and the thermal annealing of the active layer, and finally used chlorobenzene as the solvent and a temperature of 110 °C at 6 min for the thermal annealing of the active layer. A total of 36 annealed and 22 as-cast devices with an architecture of ITO/PEDOT:PSS/P3HT:PCBM/Al were investigated by the authors.

![Graph](image_url)

**Figure 15.** (a) J-V curves of typical P3HT/PCBM devices before (black) and after (red) exposure to X-rays; (b) responses of several devices with accumulated radiation dosage illustrating the effect of device-to-device variation. Copyright permission from [140].

As-cast polymer solar cells with a large fraction of a well-mixed P3HT:PCBM phase showed enhancements in performance upon the post-irradiation annealing treatments. For the devices annealed prior to the irradiation, authors observed an irreversible performance degradation that cannot be investigated further. The authors obtained a large amount of information based on resonance Raman and photocurrent/photovoltage modulation spectroscopy and imaging. As was shown by Raman spectroscopy analyses of the investigated
devices, an irradiation of up to 1 Mrad did not influence the P3HT structural and packing integrity for both types of devices. On the other hand, by using intensity modulated photocurrent/photovoltage spectroscopy, the authors confirmed the known fact that the charge transfer from the aluminum cathode leads to the formation of a space charge zone that becomes more pronounced in devices with greater phase purification, and, consequently, degradation occurs. For example, larger PCBM crystallites are created in the vicinity of the cathode. A great morphology of the active layer with optimum donor to acceptor ratio is required in order to create perfect polymer solar cells with good thermal stability that are stable under ionizing radiation exposure. Finally, authors concluded that, for constructed polymer solar cells, radiation-induced damage to the polymer is small even for doses of up to 1 Mrad, which is good news for the practical application of organic devices.

In addition to intensive research on the influence of ionizing radiation on the active layer, scientists are also working on modifying the PEDOT:PSS hole transporting layer in order to improve its resistance to ionizing radiation. For example, Ghazy et al. [141] proposed silver nanoparticles (NPs) to be added to PEDOT:PSS by an applied chemical and radiochemical reduction in order to obtain NPs with various sizes. In the chemical reduction of silver ions, the authors used, in the first case, sodium borohydride, and compared it with the reduction using gamma radiation towards defined sizes of NPs, which was found to be smaller in the case of the chemical reduction. The mechanism of silver ion reduction by gamma radiation is shown in Figure 16.

\[
\begin{align*}
H_2O \xrightarrow{\text{GammaRay}} & \quad e_{aq}^- + H_3O^+ + H^0 + H_2 + OH^- + H_2O_2 + \ldots \\
Ag^+ + e_{aq}^- \xrightarrow{\text{Reduction}} & \quad Ag^{0} \\
Ag^{0} + Ag^+ & \rightarrow Ag_2^+ \\
Ag^{0} + Ag_2^+ & \rightarrow Ag_3^+ \\
(Ag)_n^+ + e_{aq}^- & \rightarrow (Ag)_n
\end{align*}
\]

**Figure 16.** Mechanism of silver ion reduction by gamma radiation. Copyright permission from [141].

In the second case, Ag NPs were prepared in a polyvinyl pyrrolidone solution using gamma irradiation and then were added to the PEDOT:PSS dispersion. The obtained PEDOT:PSS:Ag NPs layer exhibited various morphologies depending on the particle size and amount (1, 2, 4, 6, 8, 10%), and a smooth morphology was found for PEDOT:PSS layers containing Ag NPs of up to concentrations of 4%. Gamma radiation was proposed as a simple and clean method for the reduction of metal ions e.g., Ag or Au.

Currently, the main focus for the organic photovoltaics is on improving their performance and finding the optimal working conditions in Earth’s environment [142]. However, the possibility of being applied in other conditions, such as the stratosphere or cosmic conditions, would require resistance to almost completely different environmental conditions. The possibility of using organic photovoltaics for the space industry would open a completely new era for this class of devices.

In order to change the focus to this new application area, it is important to identify what the weak sides of this technology are and to identify additional impacts that could affect the solar cell stability. Currently, all research regarding the organic PV technology focuses on testing in standard earthly conditions, without taking into account other factors,
such as other types of irradiation, such as protons, electrons or electromagnetic rays that are scarcely observed on Earth.

These unknown questions concerning how organic solar cells would perform in different conditions gave rise to the OSCAR (Optical Sensors based on CARbon materials) mission [143, 144]. This mission included the testing of 256 solar cells of various types during a stratospheric balloon flight. The experiment intended to last 5 h and, in which, the balloon reached an altitude of 32 km, while registering the performance of all cells. As can be seen in Figure 17, the altitude in which the organic photovoltaics were sent was almost three times higher than the commercial aviation [145].

![Schematic illustration of the experimental setup and selected experimental details.](image)

**Figure 17.** Schematic illustration of the experimental setup and selected experimental details. Copyright permission from [142].

Table 7 contains the data of $I_{sc}$, $V_{oc}$, PCE and FF for cells containing MAPbI$_3$, PBDTTPD:PC$_{71}$BM, PCPDTQx(2F):PC$_{71}$BM, F4-ZnPc:C$_{60}$, DCV5T:C$_{60}$ and a flexible module. In general, comparing the photovoltaic parameters before and after the flight, the four types of solar cells (MAPbI$_3$, PBDTTPD:PC$_{71}$BM, PCPDTQx(2F):PC$_{71}$BM and the flexible module) resulted in a drop in the PCE, mostly due to the FF decrease, mainly for the perovskite solar cell. In the case of PBDTTPD:PC$_{71}$BM, it was argued that the result of the decay was mostly due to encapsulation defects, or, for the flexible modules, it was most likely the mechanical stress [146].
Table 7. Summary of different solar cells and their average performance parameters before and after flight, as measured under an AM1.5G simulated solar spectrum with an irradiance of 1000 W/m² (only working devices were re-measured: the number of devices included in the statistics is lower for the after flight measurements than for the before flight measurements). Since measurements were carried out in different laboratories, testing conditions might slightly vary. Due to both the lack of solar simulators at the launch site and the need for early shipment of the samples, the measurements correspond to a few months before flight and a few weeks after flight. Copyright permission from [142].

| Solar Cell Type | Before/After Flight | Jsc [mA/cm²] | Voc [V] | FF [%] | PCE [%] |
|----------------|---------------------|--------------|---------|--------|--------|
|                |                     | Av. St.Dev.  | Av. St.Dev. | Av. St.Dev. | Av. St.Dev. |
| MAPbI₃         | 32                  | 21.4/19.3    | 0.6/4.9  | 1.0/0.9 | 69.7/49.4 | 3.3/20.6 | 14.6/9.3 | 1.1/5.4 |
| PBDTTT-Pc70:BM | 32                  | 10.4/9.4     | 0.9/1.1  | 0.8/0.8 | 57.0/49.8 | 9.3/13.0 | 4.6/3.7  | 1.4/1.3 |
| PCPDTQ(2F):Pc70:BM | 32                | 12.7/11.9    | 0.6/1.3  | 0.7/0.7 | 48.6/46.2 | 4.2/2.2  | 4.1/3.7  | 0.8/0.5 |
| F4-ZnPc:C60    | 96                  | 10.6/11.5    | 0.2/0.2  | 0.7/0.7 | 57.7/54.7 | 1.0/5.5  | 4.4/4.5  | 0.1/0.5 |
| DCV5T:C48      | 48                  | 10.7/11.7    | 0.1/0.1  | 0.9/0.9 | 57.1/56.7 | 1.8/0.5  | 5.4/5.9  | 0.1/0.1 |
| Flexible module| 16                  | 5.0/4.1      | 0.6/0.2  | 6.0/6.0 | 53.8/47.6 | 0.6/2.0  | 1.6/1.2  | 0.2/0.1 |
| total          | 256                 |              |          |        |         |         |         |        |

A further investigation of the perovskite solar cells revealed small bubbles in the perovskite film due to the thermal degradation of the material for the closed cell, whereas the open cell bleaching of the color suggested that a degradation of the perovskite phase was evident. SEM images of the samples showed a small protuberance in the area of active materials and the bare hole transporting layer. The presence of the gold electrode, working as an additional encapsulation, seems to better protect the organic components. Additional studies of 3D profiling with the time of flight, such as secondary ion mass spectroscopy, gave evidence toward encapsulation failure during the flight. Losing the integrity of the sealing resulted in strong intermixing between each layer in the solar cell. In addition, current atomic force microscopy showed visible eaters formed by the ion bombardment, which was very strong at high altitude. However, the results presented in the work [142] do not offer a full understanding and conclusive evidence of a long-term operation in the stratosphere or outer space: they present the first insight into what the weak points of organic solar cells are. The study raised some interesting aspects of the general stability of different semiconducting materials and their integrity versus harsh conditions. This work is an indicator as to where future studies should explore.

8. Solar Cells Connected with Scintillators—Review and Our Point of View

In 1913, Henry Moseley invented the first energy generator based on radioactive decay. His nuclear battery consisted of a silver-plated glass ball on the inside with a radium emitter mounted in the center on an insulated electrode. Electrons from the beta decay of radium made a potential difference between the silver foil and the center electrode. However, the wide voltage of the device was too high—tens of kilovolts—and the current was too low for practical applications. However, it gave rise to the search for various solutions for a nuclear battery. References in this regard are very scattered. Several attempts were made to systematize these issues in a comprehensive manner. Kavetsky et al. [147] described techniques and methods of converting ionizing radiation energy into electricity using luminescent and semiconductor techniques. Likewise, Kaminski and Akulov [148], for the conversion of radiation into electricity, presented phenomena and materials for potential use. Kumar [149] made a synthetic review of techniques for obtaining electricity from radioactive sources using various techniques and technologies. Among the various methods of obtaining energy, he also pointed to the possibility of converting radiation into light, which, in turn, activates PV panels. Prelas was one of the first researchers to propose the Radioisotope Energy Conversion System (RECS) concept and its various variants [150]. The process efficiency potential was estimated to be at a 10%, nuclear power to electricity conversion. The systems had different executive arrangements, but the idea of converting ionizing radiation energy into electricity remained constant. A more detailed analysis
of the research data presented in the article [151] prompted the authors to be a bit more skeptical of the application. They stated:

The supply of radioisotopes is a significant issue for commercialization of nuclear batteries. Even though this paper does not advocate the use of rules of thumb, a simple rule of thumb is useful for gaining perspective on the commercial potential of nuclear batteries when considering the supply of radioisotopes: 1 Ci of activity translates to about 1 mW of power output for a very optimistic 10% efficient nuclear battery. So, considering the world supply of one of the most abundant isotopes released in fission, Sr-90 (estimated at $1.09 \times 10^9$ Ci), the potential power production is only 1.09 MW. Given that a desirable sized unit would be 100 W, approximately 10,000 units could be constructed based on the world supply of Sr-90. Other sources of isotopes would not even fare that well.

A research team led by Guo [131] proposed the concept of a multi-level radioisotope battery based on a $\gamma$ Co-60 source and a LYSO scintillator, converting radiation into photons of light, which, in the radio-voltaic (RV)/radio-photovoltaic (RPV) effect, gave electric voltage, demonstrating the possibility of combining two energy conversion mechanisms in order to achieve an efficient use of radiation energy. A kind of structural optimization idea for an efficient multi-level isotope battery has been proposed. This radioisotope battery has enormous output potential, providing a stable and independent power supply for miniature electronic modules. The results of the studies presented with MCNP5 showed that the RPV effect produced more electricity than the RV effect, but the contribution of each electric potential to the battery was significant. The best results were obtained for the dose rates of 0.103 kGy/h and 0.68 kGy/h.

Liakos [152] examined the possibility of generating electricity with the ionizing radiation emitted from the Co-60 source via a scintillator of NaI (Tl). A new theoretical model of gamma radiation photovoltaic cells is presented with the calculation of efficiency (PCE), open circuit voltage ($V_{oc}$) and maximum output power ($P_{max}$). The model contains a scintillator placed (positioned) between the high-energy nuclear isomer and the semiconductor materials of the photovoltaic cell. High-energy $\gamma$ photons, $E_{\gamma 1} = 1.333$ MeV and $E_{\gamma 2} = 1.173$ MeV, originated from Ni-60$^{m}$ nuclear isomers formed during Co-60 decay.

According to the model shown in Figure 18, the scintillator converts $\gamma$ photons into many low-energy light photons. The latter photons illuminate the semiconductor materials of a photovoltaic cell. Such devices can have an improved PCE and $V_{oc}$ and a much longer service life than that of the track-229 m1/m2. Results are reported for scintillator devices with different $\lambda_{max}$ emission maximum wavelengths and yields. One mole of Cobalt-60, in combination with a high yield and short $\lambda_{max}$ scintillator, can produce $V_{oc} \sim 10$ V and $P_{max}$ several hundred W/m$^2$ to several times the AM0 power at approximately 70%. They are significant, indicating that these gamma ray photovoltaic cells can make a significant contribution to generating electricity. Calculations are also made using the Hafnium-178 two isomers ($E_{r} = 2.4$ MeV, $T_{1/2} = 31$ years).

An interesting concept of a nuclear battery was presented by Russo [130]. He made a comparison of two nuclear battery systems: betavoltaic and beta-photovoltaic. He showed (Figure 19) that junctions are the volume and depth of the collection region. It should also be emphasized that the inclusion technique (3D) of radioisotope incorporation was used to increase the efficiency of luminescence (scintillation).

The volumetric configuration showed that a larger amount of radioisotopes can be loaded into the phosphor volume than those loaded in the separated one, as a separate element. Then, 100% of the source’s nuclear energy is used. Using the volumetric configuration, the $\beta$ source may be surrounded by a nuclear and optical converter, phosphor and PV cell, respectively. This technology allows for the power limit of a nuclear battery to be increased from microwatt to milliwatts per 1000 cm$^3$. 

A spherical gamma ray photovoltaic cell (GRPVC) of radius $r$ utilizes high-energy-photons that produce a large number of low-energy photons (LEPs) in the scintillator. The LEPs illuminate the PV cell of the device. Copyright permission from [152].

A slightly different approach to the topic of nuclear batteries was presented by Lee at al. [122]. In the article, he presented the problems of generating electricity from spent nuclear fuel. The work was theoretical and the process of converting gamma ray energy into electricity using scintillators and photovoltaic cells was investigated using various mathematical models. The OrigenArp code was used for the gamma radiation environment analysis and the MCNPX 2.7.0 code was used for analyzing the scintillation process. The team developed a new simulation model for scintillation photon analysis and photovoltaic cell analysis, which was used for a comparison with experimental data. Based on using 14 energy conversion system units in a spent fuel storage pool in a PWR, with CdWO$_4$ as the scintillator and SiO$_2$ as the photovoltaic cell, the generation of electric energy was estimated to range between a few hundred watts and a few watts depending on the cooling
time. According to theoretical considerations, the expected amount of electricity from the spent nuclear fuel energy conversion was not sufficient for large-scale applications.

Hong and the team [153] investigated the radioluminescent capabilities of a nuclear battery. The $\beta$ radioactive isotope Pm-147 was used as a source. Two types of scintillators were used: ZnS:Cu and Y$_2$O$_2$:Eu. A diagram of the battery is shown in Figure 20.

![Schematic of a radioluminescent nuclear battery. Copyright permission from [153].](image)

**Figure 20.** Schematic of a radioluminescent nuclear battery. Copyright permission from [153].

The correlation between the type of phosphor layer on the battery performance was investigated. A higher energy conversion efficiency was obtained in the ZnS:Cu cell than in the Y$_2$O$_2$: Eu cell. According to the authors, the energy conversion efficiency of the cell is very low mainly due to the following factors:

- Too low activity and contamination of the Pm-147 radioisotope;
- Self-absorption of photons in the phosphor layer.
- Using the Monte Carlo method, the authors also described the mechanism of selecting scintillation layer parameters that should improve the battery output parameters.

**9. Concluding Remarks**

In this review, it was shown to the best of our knowledge that the development of various type of solar cells at the current time includes not only the architecture of solar cells, new materials, techniques, etc., but also the kind of irradiation to make photovoltaics independent from the intensity of the Sun during various seasons in the year. Instead of a final conclusion, we propose five postulates:

**Postulate 1:**

The structure of the scintillation layer should contain inclusions in the form of microcapsules of the radioactive substance. This will increase the spherical luminescence efficiency and improve the light photon transmission coefficient to the PV surface. The outer scintillation layer should be surrounded by a mirror material reflecting light towards the PV array.

**Postulate 2:**

Possibilities of both the modulation of scintillation colors and observations with the naked eye are possible due to doping with various elements. Preliminary observations of an increased scintillation intensity and color during exposure to X-rays give inclusions in the organic structure of UO$_2$-uranil. The first scientific reports showing an increase in luminescence in the X-ray beam ($E > 20$ keV) have already appeared. An increased radiation resistance and reduced hygroscopicity were also observed compared to commercially available CsI: Tl or NaI: Tl scintillators [154].

**Postulate 3:**

The efficiency of a nuclear battery depends largely on the matching of the emitter ($\alpha$, $\beta$ or $\gamma$ source) with the scintillation material in the process of converting radiation energy into photons of light. Nuclear batteries that use a single flat (layered) arrangement of components will generally have a low energy conversion efficiency. Spatial layouts give much better results.
Postulate 4: According to Dujardin [15] the content in the scintillation material K, Rb and Lu as a dopant, due to the high natural radioactivity, is highly desirable for radiation conversion applications.

Postulate 5: A perovskite single crystal may be a key scintillation material in photovoltaic technology applications. They have a very high photoluminescence quantum efficiency and light efficiency conversion over a wide temperature range. According to literature reports, the luminous efficiency is $1.5 \div 3 \times 10^5$ photons/MeV and may be proportional to the energy gap of these materials, which is estimated to be below 2 eV. The use of the latest technology using quantum dots and nanocrystals can also improve light conversion in perovskite scintillators.

We hope that this review will be useful for scientists by providing new concepts for new practical applications of photovoltaics and scintillators in different aspects of our lives in the future.

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