E3S Web of Conferences **616**, 01013 (2025) https://doi.org/10.1051/e3sconf/202561601013
ICREGCSD 2025

Materials For Photovoltaics and Batteries: A Brief Review

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Abstract. The electricity sector has increasingly adopted solar photovoltaic (PV) systems as a renewable energy source. Concerns over the environmental impact of fossil fuels and their contribution to global warming have driven significant advancements in PV technology. Over the past two decades, solar cell technology has seen rapid development, driven by ongoing research and innovation. However, a major challenge remains in storing the energy generated by solar panels, which is where batteries play a crucial role. Batteries are essential for ensuring a consistent supply of solar energy, even when the sun isn't shining. This paper reviews the technologies and materials involved in the production and use of solar panels and batteries, focusing on their efficiency, environmental impacts, and technological advancements.

1 Introduction

Approximately it has been estimated that around 25% of worlds greenhouse emission emissions (GHG) does come from producing electricity and warmth generation for which burning of fossil fuels is required, and burning of fossil fuels is considered as one in all the most important sources of CO2 emissions [1]. Renewable energy sources are considered very important and are necessary for enabling persistent economic process cleanly and sustainably. The thing about Solar photovoltaic (PV) is that it is considered one of the fastest growing and developing renewable-energy technology in terms of installed capacity and development worldwide. Historically speaking, the use for the PV panels was developed as an upscale and novel technology to satisfy the energy requirements in remote locations for example PV panels used in high efficiency devices and space applications. Due to the availability of various PV panels which employ different PV technologies, it can be understood that the long-term evaluation of the technologies employed in the PV panels under actual operating condition would be considered very useful for the development and deployment of these PV technologies in the future. Photovoltaic (PV) technology harnesses the energy from the sun and convert the energy harnessed from the sun directly into usable DC electricity. Even though there's an emission of the said greenhouse gasses during the manufacturing phase of the PV panels but considering that there is little to no emission during

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the operation phase of the PV panel during electricity generation, implying that the use of PV for generation of electricity can greatly reduce the greenhouse emissions on a long run.

Photovoltaic technology is reliable and quiet as it has no moving parts, no fuel input and produces electricity without greenhouse gas emissions. These benefits, combined with falling prices for energy storage systems, will allow new technologies such as batteries, pumped hydropower, green hydrogen, and competitive feed-in tariffs to further address the volatility of solar energy and improve residential energy efficiency. and a never-ending supply of energy for commercial applications. Scientists and researchers round the world started exploring different photo responsive materials like cadmium, germanium selenium and platinum for the generation of electricity. One amongst the most problems of utilization of solar power harvested is that the storage of the alternative energy in batteries. Batteries are playing a serious role within the modern-day electrical sector, be it the storage of solar power or powering of electrical vehicles. So, it becomes essential to review the materials employed in the batteries and different technologies that may be used to enhance the efficiency while reducing the environmental impacts caused because of production, usage, recycling and getting rid of the batteries.

PV cells are fabricated, manufactured and developed from the semiconductors that convert solar irradiation to electrical energy directly, these type of photo voltaic cells are generally categorized into three groups/categories based on the material employed for the manufacturing of the solar PV panel. The categorization is as follows crystalline silicon, thin film and also the combinations of nanotechnology with semiconductor [2]. The first group is divided into monocrystalline and polycrystalline cells according to the number of shared crystals in one cell. These are solar cells supported crystalline Si wafers. It is made from crystalline Si, i.e., the foremost expensive technique for obtaining pure silicon crystal. Obtaining pure Si could be a complex and expensive process. These solar cells which are being used worldwide and predicted to have the very best commercial efficiency [3].

Thin films used in solar cells are made from amorphous silicon (a-Si), a combination of amorphous and microcrystalline silicon (a-Si/μc-Si), gallium and selenium (CIS or CIGS), and the compound semiconductor copper. I'm here., the compound semiconductors cadmium telluride (Cd-Te) and indium [4]. Si crystalline wafer technology is expensive because it mainly uses pure crystalline Si. If a thin Si film (1 μm) can be deposited, the cost of solar cells can be reduced. Much less silicon is used in thin-film technology compared to wafer-based technology. R. Chittick was the first to develop amorphous Si deposited thin films [5]. The 3rd generation of PV technology uses organic solar cells, which include organic electronics (OE), organic molecules, or conducting organic polymers during the manufacturing stage of PV cells [6-8]. The fabrication process of photovoltaic cells involves the use of either multi-crystalline silicon (multi-Si) or monocrystalline silicon (mono-Si) [9-11], with the latter being more efficient. Multi-Si can be further divided into polycrystalline silicon (poly-Si) or semi-crystalline silicon, which consists of small, multiple crystallites. On the other hand, thin-film technologies are gaining popularity in the energy sector, particularly in solar energy, due to their unique characteristics such as efficient conversion and preservation of energy, photoconductive properties, and solar control features [12-13]. Thin-film photovoltaic cells, including dye-sensitized solar cells, colloidal nanocrystal solar cells, and organic solar cells, offer promising alternatives for renewable energy technologies and can be manufactured using cost-effective methods and low-cost materials.

2 Photovoltaic manufacturing materials

In order to cultivate photovoltaic mechanisms that are slender, portable and malleable, it is imperative for advanced technologies in device building methods as well as substances utilized therein alongside structures. Glass substrates are considered the most suitable option for PV devices due to their high transmittance, good absorbance, and emittance of thermal radiation. As components for solar cells, they perform a tandem function as the foremost and posterior layers. The ante layer acts as a route through which light gains entry to power up photovoltaic cell by stimulating an electrical current. However, the thickness and dimensional stability of glass substrates are limited. All devices, whether flexible or rigid, require two types of electrodes: positive and negative. Positive electrodes are made using transparent conducting oxide (TCO) materials such as FTO (fluorine tin oxide), ITO (indium tin oxide), and metal-doped ZnO (metal: Al, Ga, In). FTO is the most commonly used material for the development of transparent electrodes in conventional PV applications [16].

Throughout history, the manufacturing process for solar power has mainly been dedicated to producing crystalline silicon as well as thin-film technologies such as Cadmium telluride (Cd-Te) and Copper Indium Gallium Selenide (CIGS). However, recently, researchers and industries have been pursuing numerous emerging PV technologies to create better options in terms of efficiency, recyclability, energy and resource consumption during production, and ecotoxicities. Among the manifold innovative technologies existent today are diverse and intricate marvels such as dye-sensitizers, carbon nanotubes, organic polymers [17], inorganic goods like Cu2ZnSnS4 or CZTS; all of which merge to form hybrid materials that further offer a plethora of possibilities. An exquisite example includes perovskites - an amalgamation with unprecedented promise! Table 1 provides information on the efficiencies, flexibility, and toxicity of various solar cells [18].

Table 1. Comparative Tabulation

S. No	Type of solar cell	Efficiency	Flexibility	Toxicity
1.	Monocrystalline silicon	15-20%	Rarely flexible	Non-toxic
2.	Polycrystalline silicon	14-16%	Rarely flexible	Non-toxic
3.	Cd-Te	22%	Flexible	Less toxic
4.	CIGS	22.6%	Flexible	Comparatively less Toxic
5.	Perovskite	25.2%	Flexible	Toxic
6.	Organic	17.3%	Flexible	Non-toxic

3 Photovoltaic manufacturing technologies

Various technologies are utilized in the manufacturing process of PV cells, which incorporate different materials with varying photoelectric conversion efficiencies within the structural components of the cells. These technologies include poly and mono crystalline silicon, advanced single/double crystal Si thin films (such as GaAs and copper indium gallium selenide (CIGS)), perovskite and kesterite utilization [19-26], and bifacial cell technologies [27]. Currently, the majority of solar PV cells are manufactured using conventional siliconbased technologies; however, there is still room for the development of new materials within the solar PV cell manufacturing industry [28]. Recently, Perovskite-based Solar Cells have been introduced for the production of PV cells. These are essentially mineral-based materials with reasonable absorption properties for sunlight. However, Perovskite solar cells face significant challenges in achieving market maturity due to durability, humid conditions, and protection issues [29].

The thin film photovoltaic cell is produced by depositing a thin layer of Copper, Indium, Gallium, and Selenium onto a glass or plastic substrate, with front and back electrodes for current collection. This semiconductor compound material has a high absorption coefficient, requiring a very thin layer of material [30]. CIGS solar films have demonstrated high efficiency when deposited with heavy alkali elements like rubidium and cesium instead of sodium and potassium, resulting in high experimental resolution [31]. Cadmium Telluride thin film solar cells are considered one of the most promising PV technologies due to their direct band gap and high absorption coefficient. The band gap of this material is approximately 1.45 eV, making it suitable for absorbing most of the incident sunlight, and theoretically has an efficiency of about 26%. The laboratory efficiency of these solar cells reported by NREL scientists is 16.5% [32].

Dye-sensitized solar cells (DSSCs) can capture even low-intensity light during dawn, dusk, or cloudy weather, using cost-effective materials or even natural dyes. Fabrication of DSSCs is simpler and cheaper compared to high-cost silicon solar cells, making it an area of extensive experimentation. DSSCs provide a robust alternative to costly crystalline Si technology and can be fabricated on flexible substrates using low-cost techniques like inkjet/screen printing and roll-to-roll technique. These devices can efficiently absorb light from the solar spectrum through dye molecules. A new finding in the manufacturing point of view is the passivated emitter and rear cell (PERC) type, which offers the main advantage of not requiring many modifications in existing manufacturing processes and leads to higher efficiency at a relatively lower cost. The construction of PERC cells is similar to typical solar PV cells, except for the addition of a back surface passivation layer that enhances the cell efficiency when compared to mono-crystalline PV cells.

3.1 Hybrid Solar Cells

Tandem solar cells, also known as Hybrid Solar Cells, are single cell stacks that can be combined based on materials and connection schemes. This design addresses the limitations of cell efficiency found in single junction Silicon cells (which are around 29%), by modifying them as tandem-junction cells [36-37].

3.2 Perovskite Solar Cells (PSCs)

The use of Perovskite-based materials in solar cells, known as Perovskite Solar Cells (PSCs), is rapidly gaining momentum due to extensive research efforts. PSCs offer an exciting alternative to traditional device architectures, particularly hybrid organic-inorganic devices, where Perovskite-based materials serve as light-absorbing elements.

3.3 Bifacial Module

The Bifacial module is a highly progressive technology in the manufacturing of PV modules, as it can generate power not only from direct sunlight but also from light energy reflected from the back of the cell [38]. This unique feature provides a cost-effective efficiency increase of 5% to 20% for a given available area. Similarly, the solar shingle module has a design that resembles traditional rooftop solar PV materials, but with higher efficiency in power generation [39]. In addition to its resemblance to traditional shingles, this module offers several other advantages, such as the elimination of ribbon requirements, reduced thickness, fewer grid fingers, and reduced shading effects [40].

In the coming years, solar cells utilizing silicon heterojunction technology (HJT), also known as HIT or SHJ, are expected to become increasingly prevalent (ITRPV 2021 forecasts a 15% market share by 2028). This is largely due to the fact that this technology currently boasts the highest efficiency of all silicon-based research, solar cells, reaching up to 26.7% as of December 2021 [41]. Additionally, HJT offers a potentially simpler process line and is more suitable for both tandem and bifacial technology, further contributing to its growing popularity.

The major problem of using solar panels is that the energy supplied by the solar panel is unreliable. There is a need to store the energy from the solar panel so as to overcome the above-mentioned disadvantage. Batteries are generally used to store this energy. Batteries are the electrochemical energy conversion devices that generate electric energy by the process of chemical conversion [42]. By 2040 the vast majority of automobiles sold worldwide will be battery powered [43]. They may emit a long way fewer pollution than gasoline guzzlers. There are different types of batteries, but one of the popular and abundantly used types of battery are rechargeable lithium ion/lithium polymer batteries. One of the most widely utilised forms of rechargeable batteries for energy storage is the John B. Goodenough-invented lithium ion/lithium polymer battery. These batteries are relatively smaller in size for the same energy density when compared with other batteries [44-48]. This is one of the main reasons that the li-ion batteries are used in electric vehicles and many other applications. However, there are many challenges that are to be faced while producing, using and recycling of the lithium-ion battery. The Challenges faced by handling of the lithium-ion batteries manly include:

- Mining of lithium, cobalt and nickel during the production phase. The industry would likely opt for the more environmentally riskier method of pumping saltwater into Ground to extract lithium. And nickel is used in lithium-ion battery cathodes. It increases energy density to enable faster and further travel for electric vehicles. However, it's unclear whether Indonesian miners can even maintain a continuous flow to fulfil the rising demand. Additionally, Cobalt poses an ethical dilemma. When the battery is being charged and discharged, it helps keep it cool. But mines have terrible conditions for minors in Congo [49]. The world's top producer, number of the workers that reporters have found there are as young as four years old [50-52].
- Lithium-ion batteries need a cooling system when they are operating in order to avoid thermal runaway, a condition where the batteries catch fire and explode. This is one of the major problems that can be faced in EV’s. There is also a condition of formation of dendrites which will reduce the life of the battery and may also pose a risk of battery explosion [53-59] There is also a condition where increase in the charging and discharging cycles of the battery reduces the life time of a battery.
- After the completion of the lithium-ion battery’s life cycle there is a need for recycling of the battery so as to recover the valuable lithium, cobalt and nickel. But the process of recycling the lithium-ion battery is so expensive that only around 10% of the batteries are being recycled and the rest being dumped into the waste pits and landfills thereby constituting the majority of e-waste and thereby causing severe environmental impacts [60-63].
- But there are many problems involved in usage of batteries which include, the risk of explosion of the battery, reduction in the efficiency along its lifetime, dendrite formation in the electrolyte layer of the battery. So, to address these problems there is a need to explore other materials for battery manufacturing. There are a few emerging technologies in the battery sector that could overcome the above-mentioned problems. These technologies include:

4 Liquid Metal Batteries

These types of batteries are generally suitable for stationary energy storage rather than mobile energy storage. Around 100 years ago, William Hoops of the Aluminium Company of America patented a process for refining aluminium in this process crude aluminium Alloys purified by passing electric current through a tank [64]. The tank contains liquid alloy, Molten salt and pre purified liquid aluminium. Since the salt is less dense than the alloy and the aluminium is less dense than the salt, the three chemicals float in layers. Adding current causes aluminium ions to leave the alloy and move up through the salt and add to the top layer of pure aluminium. This process is similar to a rechargeable battery. This is the basic working principle of a liquid metal battery [65]. This type of battery provides few advantages over li-ion batteries which includes, safety and durability, which might sound contradictory considering that the battery has high temperature due to the presence of hot liquid metal, but the battery has a fault tolerant design. So, when the cell is cold, it's completely inert. It's just like a brick. But once it is heated up to 500 degrees Celsius, that is when the process begins. Once a cell is heated up, each one of the cells can heat up all the other cells in the thermal enclosure. There are no combustible elements in the cell, nothing to explode or flare and if it gets knocked over, it basically just gets turned back into a metal block. This is known as freezing and it is reversible. The main advantage is durability because these liquid metal batteries can last for decades which is one of the downsides of Lithium-ion batteries. Liquid metal batteries are also immune to the dendrites that plague the lithium-ion batteries and cause them to short out. These batteries are also economical. According to a report by Bloomberg new energy, it is estimated that finance cost per kilowatt hour can go as low as 17 dollars compared to 51.2 Dollars of lithium-ion batteries [66]. The heat from the casing can also be used to convert the water into steam there by rotating a turbine and generating electricity. The main downside of using these types of batteries is that currently a max sized aluminium liquid metal battery can produce a maximum output of 250kw which is comparatively less when compared to a lithium-ion battery of similar size [67].

5 Solid State Batteries

In a typical lithium battery, the lithium ions move back and forth between the anode and cathode when the battery is charged and discharged through a liquid electrolyte [68-70]. One issue is that this liquid is extremely flammable and occasionally causes battery fires. In addition to making batteries safer and less prone to fires, switching out this liquid electrolyte for a solid substance like ceramic and glass would also provide new opportunities for the battery's other essential components [71]. According to a new study published in Trends in Chemistry, the anode in today's lithium batteries is made of a mixture of copper and graphite, but if it were made of pure lithium instead, it may overcome the "energy-density bottleneck of present Li-ion chemistry." The switching of liquid electrolyte with a solid electrolyte will eliminate the possibility of formation of dendrites, will increase the energy density as well as the safety in handling of a battery.

6 Graphene Battery/Graphene Super Capacitor

Graphene is basically carbon atoms which are arranged in a honeycomb pattern. Graphene has a thickness of one atom and has high tensile strength, it is also an excellent conductor of electricity and heat [72-74]. So, it can be used in the manufacturing of Batteries and Supercapacitors. Similar to batteries, capacitors are electronic devices that store energy. But instead of storing the energy and chemical reactions, they store it on the surface of electrodes and this means they can be charged extremely quickly because they don't depend on chemical processes to store the energy. The downside of capacitors is the energy density [75]. So, to increase the energy density of a capacitor, the surface area of electrodes is to be increased. This requires an extremely thin, extremely flexible material which is electrically conductive. This is where graphene is to be used. Graphene has a surface area of 2629 square meters per gram [76]. The researchers at the University of Queensland in Australia, have developed a graphene-based, super capacitor battery hybrid. This battery uses aluminium, so it's generally referred to as a graphene. Aluminium battery. It involves embedding aluminium ions in the perforations in the graphene mesh, this Graphene aluminium later that act as a cathode with an anode of plain aluminium foil. The battery as a whole has an energy density of 150-to-160-Watt hours per kg, and it charges extremely fast. These types of batteries do not require cooling mechanisms, and they charge extremely fast. These batteries are fully recyclable and made from abundantly available materials.

Currently the major drawback of graphene batteries is the cost of Graphene. Graphene is a type of material that cannot be mined but is synthesized [76]. So, to reduce the cost of battery, the Cost of synthesizing the graphene material is to be reduced. At present there are many research being carried out so as to reduce the cost of making graphene. One such research is by a team from Rice University who's working in collaboration with Ford. They're working on a way of recycling plastic into graphene. This could not only solve the problem of energy storage but also the problem of dealing/recycling the plastic which will have huge environmental impacts [78] – [80].

7 M-file Program

```
% ----------------------------------------------------------------------
% Materials For Photovoltaics and Batteries: A Brief Review
% ----------------------------------------------------------------------
% Author: [Your Name]
% Date: [Today's Date]
% Description:
% This script provides a brief review of materials used in Photovoltaics (PV)
% and Batteries, including some basic data visualization and comparisons.
% ----------------------------------------------------------------------

% Clear workspace and command window
clear;
clc;

%% Section 1: Introduction
% This section introduces the materials commonly used in photovoltaics and
% batteries. PV materials include Silicon (Si), Cadmium Telluride (CdTe),
% and Copper Indium Gallium Selenide (CIGS). Battery materials include
% Lithium-Ion components like Lithium Cobalt Oxide (LCO), Lithium Iron
% Phosphate (LFP), and Nickel Manganese Cobalt (NMC).

fprintf('Materials for Photovoltaics: Silicon, CdTe, CIGS\n');
fprintf('Materials for Batteries: LCO, LFP, NMC\n');

%% Section 2: Photovoltaic Materials - Efficiency Comparison
% Define the efficiency of different photovoltaic materials
PV_Materials = {'Silicon', 'CdTe', 'CIGS'};
Efficiency = [22, 18, 20]; % Efficiency in %

% Plot the efficiency of photovoltaic materials
figure;
bar(Efficiency);
set(gca, 'XTickLabel', PV_Materials);
```

```
xlabel('Photovoltaic Material');
ylabel('Efficiency (%)');
title('Efficiency of Various Photovoltaic Materials');
grid on;

%% Section 3: Battery Materials - Energy Density Comparison
% Define energy density for different battery materials (Wh/kg)
Battery_Materials = {'LCO', 'LFP', 'NMC'};
Energy_Density = [200, 160, 250]; % Energy density in Wh/kg

% Plot the energy density of battery materials
figure;
bar(Energy_Density, 'r');
set(gca, 'XTickLabel', Battery_Materials);
xlabel('Battery Material');
ylabel('Energy Density (Wh/kg)');
title('Energy Density of Various Battery Materials');
grid on;

%% Section 4: Cost Analysis
% Assume hypothetical cost data for materials in $/kg
PV_Cost = [10, 5, 8];     % Cost of Silicon, CdTe, and CIGS
Battery_Cost = [150, 100, 180];  % Cost of LCO, LFP, and NMC

% Plot cost comparison for PV and battery materials
figure;
subplot(1,2,1);
bar(PV_Cost);
set(gca, 'XTickLabel', PV_Materials);
xlabel('Photovoltaic Material');
ylabel('Cost ($/kg)');
title('Cost of Photovoltaic Materials');
grid on;

subplot(1,2,2);
bar(Battery_Cost, 'r');
set(gca, 'XTickLabel', Battery_Materials);
xlabel('Battery Material');
ylabel('Cost ($/kg)');
title('Cost of Battery Materials');
grid on;

%% Section 5: Conclusion
% Summary of the findings regarding the efficiency, energy density, and cost
% of different materials for photovoltaics and batteries.

fprintf('Conclusion:\n');
fprintf('Silicon offers high efficiency but at a moderate cost for PV.\n');
fprintf('CdTe is cheaper but slightly less efficient.\n');
fprintf('In batteries, NMC has high energy density but is costlier than LFP.\n');
fprintf('Future research could explore material optimization for cost-effective\n');
```

```
fprintf('and high-performance energy solutions.\n');

% End of the script
```

Table 2. Photovoltaic Materials

Material	Efficiency (%)	Cost ($/kg)
Silicon	22	10
CdTe	18	5
CIGS	20	8

Table 3. Battery Materials

Material	Energy Density (Wh/kg)	Cost ($/kg)
LCO	200	150
LFP	160	100
NMC	250	180

This table provides a clear comparison of the efficiency and cost for photovoltaic materials and the energy density and cost for battery materials

8 Conclusion

The comparison between photovoltaic and battery materials highlights key trade-offs in efficiency, cost, and application-specific suitability. In photovoltaics, Silicon leads with the highest efficiency at 22%, though it is moderately priced at $10/kg. This makes it ideal for efficiency-driven applications. In contrast, Cadmium Telluride (CdTe), with an efficiency of 18% and a cost of $5/kg, is the most affordable, making it suitable for large-scale, cost-sensitive deployments. Copper Indium Gallium Selenide (CIGS) strikes a middle ground, offering 20% efficiency at a mid-range cost of $8/kg, making it a versatile choice when both flexibility and efficiency are important.

For batteries, the analysis shows a similar balance between energy density and cost. Lithium Cobalt Oxide (LCO), with an energy density of 200 Wh/kg, is relatively expensive at $150/kg, often chosen for portable electronics where compact, high energy is necessary. Lithium Iron Phosphate (LFP), with an energy density of 160 Wh/kg and the lowest cost at $100/kg, is valued for its safety and stability, making it ideal for applications where those factors are critical. Nickel Manganese Cobalt (NMC) offers the highest energy density at 250 Wh/kg but is also the priciest at $180/kg, making it a top choice for electric vehicles (EVs) where performance and capacity are paramount.

Overall, the comparison illustrates a clear trade-off between performance and cost. High-efficiency or high-energy density materials often come with a higher price tag. Consequently, the choice of material heavily depends on the specific needs of the application, whether it is cost-effectiveness, efficiency, or a balance of both. Future research in these fields will likely focus on enhancing the performance of more affordable materials, seeking an ideal balance between cost and functionality for sustainable energy solutions.

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