Research Article

STEM Education in Solar Cells: An Overview

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Abstract.
The remarkable developments in photovoltaic (P.V.) technology over the past five years require a new assessment of its performance and potential for future advancement. Photovoltaic (P.V.) technology development, divided into four, should begin to be studied and implemented in schools through STEM education. Solar cells or photovoltaic (P.V.) offer an important and timely field for STEM education exploration due to their potential to generate broad social, environmental, and health benefits by mitigating climate change, pollution, water scarcity, and more. This article reviews many of the basics of solar cells, such as the working principle of solar cells, solar cell materials, the state of the art of solar cells, and applications of solar cells in everyday life. Furthermore, this article presents the application of solar cells in STEM education. The application of solar cells in STEM education will be discussed regarding the interdisciplinarity of STEM subjects in the context of solar cells. In addition, this paper also explores the hands-on activities done on the topic of solar cells and the challenges and prospects of STEM education in solar sell for future learning.

Keywords: STEM education, solar cells, efficiency, materials science

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1. INTRODUCTION

Students' interest in science and mathematics is decreasing every day worldwide [1–3]. This trend is very concerning, especially considering the high demand for professionals in science and technical fields today [4, 5]. The U.S. Department of Economic Administration and Trade Statistics, a government agency that tracks job growth figures, notes that science and math jobs are growing more rapidly from 2019 to 2029 than non-science jobs. Employment in science and math is expected to grow 8% percent by 2029, compared to 3.7% for all occupations[6]. However, a study by the Organisation for Economic Co-operation and Development's (OECD's) Programme for International Student Assessment (PISA) found that 15-year-old students in math and science in Indonesia scored lower than the OECD average in reading, math, and science. About 40% of students in Indonesia achieved Level 2 or higher in science (OECD average: 78%), ranking Indonesia 72 out of 78 countries [7]. To overcome this, increasing scientific literacy is critical so that students recognize phenomena in everyday life and participate in solving societal problems, which can later increase students' interest in science [8–10].

The quality of science teaching and instruction is a crucial factor influencing students' interest in science [11, 12]. Research has shown that more than traditional approaches are needed to increase interest in science education that includes only field-specific information in science lessons. [14]. As a result, students' interest in math and science gradually decreases [13]. Therefore, science teaching requires innovative approaches to motivate and interest students. In the 1990s, the National Science Foundation (N.S.F.) adopted an innovative approach integrating various disciplines, namely SMET - Science, Mathematics, Engineering, and Technology. In the 2000s, this approach became known as STEM (Science, Technology, Engineering, and Mathematics). In this approach, the subjects are not taught separately but integrate practical learning content from an engineering perspective [14]. In recent years, STEM education has increased student interest in science and math disciplines in curricula prepared by many leading world countries such as the United States, Australia, and the United Kingdom [15].

STEM education is an integrated approach to teaching science, technology, engineering, and math through inquiry-based learning [16–18]. STEM education is an interdisciplinary approach in which academic concepts are integrated based on real-life contexts by applying science, technology, engineering, and math [14, 19–21]. STEM education can focus on integrating the understanding of science, technology, engineering, and mathematics to improve students' academic level [22] and the economic well-being of society [23]. STEM education aims to make students individuals who can solve real-world problems, look at issues from an interdisciplinary perspective, understand the nature of technology, think systematically, ask questions, have high self-confidence, and are open to communication and creativity [24–26].

STEM activities can be applied in many fields of study, one of which is the field of renewable energy sources. Using renewable energy topics increases students' awareness of environmental issues and global warming [27, 28]. Then the introduction of learning with the subject of renewable energy is used to introduce alternative energy to reduce people's dependence on fossil fuels and carbon emissions in the atmosphere [29]. Solar power is one of the most potential forms of alternative energy to be developed in Indonesia. Indonesia is located on the equator and gets sunlight from morning to evening with an average solar radiation intensity of 4.8 kWh/m^2 daily. Solar power has been utilized as one of the most promising energy sources in the 21^{st} century because it is clean, renewable, and highly intense in Indonesia [30].

Solar cells offer an important and timely field for STEM education exploration [31] because they can generate broad social, environmental, and health benefits by mitigating climate change, pollution, water scarcity, and more [32]. From a STEM learning perspective, solar cells are an interdisciplinary field that requires the intersection of knowledge across all STEM disciplines to advance solar technologies and integrate them with existing new energy systems [33–35]. Therefore, STEM teachers should be provided with learning opportunities to build on their existing knowledge base and promote their understanding of solar cell projects in a learning environment, and prepare the next generation of scientists and engineers to progress in advancing renewable energy innovations [36, 37].

The integration of solar cell-based STEM lessons offers a transformative educational experience for students by encouraging a deeper understanding of solar cells and renewable energy, empowers future generations to address global challenges, and contributes to developing a sustainable and environmentally friendly future. Based on this, this research aims to systematically review several publications related to STEM-solar cells, which can be considered later in future studies.

2. RESULTS AND DISCUSSIONS

The results and discussion of this article focus on the content of Solar Cells Overview, the integration of science, technology, engineering, and mathematics on the working principles of solar cells. Then the discussion of this article also presented the importance of STEM Education in solar cells, Hands-On activity STEM education in solar cells, and prospects of solar cells research. The discussion will be written following the order of the research questions presented below.

2.1. Solar Cells Overview

Solar energy is one of the most essential alternative energies in the world to reduce the consumption of fossil-based fuels. According to the BP Statistical Review of World Energy, the potential of fossil energy derived from petroleum is about 57×10^{21} J, with a consumption rate of 0.18 ZJ per year [38]. Consequently, without considering the energy consumption growth rate, it can be estimated that the product will be exhausted in 316 years. On the other hand, the Sun transfers an average of about 5.6×10^{24} J of energy to Earth every year. The potential of solar energy is equivalent to 10,000 times the current solar energy consumption. The technology that converts solar energy into electricity is called photovoltaic (P.V.) modules [39].

Solar cells, or photovoltaic (P.V.) cells, are devices designed to convert sunlight directly into electricity through the photovoltaic effect. This process involves the creation of voltage or electric current in a material when exposed to light [40–42]. Solar cells are made of semiconducting materials, most commonly silicon. In simpler terms, no light absorption happens when the energy of incoming light is below the band gap (also known as the absorption edge) of the semiconductor material used in solar cells. This aspect influences the photocurrent and, consequently, the electrical power that the devices can generate. Additionally, fundamental physics principles and the materials' characteristics determine voltage, another crucial factor in power generation [43].

Photovoltaic (P.V.) cells are structured into a 'p-n' junction. The 'p' layer contains positive charges, and the 'n' layer has negative charges. When sunlight hits the cell, it knocks electrons loose from the atoms, and these electrons can be captured as electric current [40]. In this structural arrangement, when a photon of sufficient energy strikes the p-type and n-type junction, an electron is ejected by gaining energy from the striking photon and moves from one layer to another. This creates electrons and holes in the process, generating electric power [44].

The efficiency of a solar cell is the ratio of the electrical energy produced to the intensity of light that hits it. In 2021 solar cell efficiency ranged from 15-22% for commercial panels. Solar cells are used in various applications, from small devices to larger installations for homes, businesses, and power plants. They provide a renewable and environmentally friendly energy source with minimal emissions compared to fossil fuels. The cost-effectiveness of manufacturing photovoltaic cells and their efficiency depend on the material from which they are made. Much research has been done to find the most efficient and cost-effective materials for building photovoltaic cells. Specifications for ideal materials for P.V. solar cells include The cells are expected to have a band gap between 1.1 and 1.7 eV; Must have a direct ribbon structure; Must be easily accessible and non-toxic; and Must have high photovoltaic conversion efficiency [45].

2.2. Materials of Solar Cells

The phenomenon known as the photovoltaic (P.V.) effect was first identified by Alexandre-Edmond Becquerel in 1839. This discovery was further expanded in 1946 when Russel Ohl created the first modern silicon-based solar cell [46]. The early iterations of these photovoltaic solar cells were composed of thin slices of silicon that could convert sunlight into electricity. Modern photovoltaic technology functions are applied based on creating electron holes within each cell. These cells consist of two distinct layers, or p-type and n-type materials, of a semiconducting substance. This energy prompts the electrons to move from one layer to another, generating an electron and a hole in the process. This mechanism is responsible for producing electrical power. Various materials are employed in the construction of photovoltaic solar cells, including different forms of silicon (single crystal, multi-crystalline, and amorphous silicon), cadmium-telluride, copper-indium-gallium-selenide, and copper-indium-gallium- sulfide [47, 48].

Some materials are classified as thin films, such as inorganic layers, organic dyes, and organic polymers deposited on supporting substrates [47]. Some of the most fundamental P.V. materials and their related issues are listed below.

2.3. Silicon-based solar cells

Over 95% of all solar cells produced worldwide are composed of Si. The si-based cell has been improved remarkably; their current efficiency record is 25%, about 8% less than the theoretical limit [49]. Table 1 lists the data on different types of Si solar cells.

Table 1: Different types of Si solar cells.

Type	**Advantages**	**Disadvantages**	**Limitations**
Single crystal Si	The abundant supply of raw materials, reasonably high efficiency, low ecological impact, high stability, highly reliable outdoor Application.	Complicated manufacturing method and high cost	Indirect band gap type with lower absorption coefficient
Polycrystalline Si	Cheap	Low conversion efficiency	Grain boundaries and increased concentration of in-grain defects
Amorphous Si	High light absorption can be deposited on different cheap substrates, with a low cost of materials and manufacturing.	Low cell energy conversion efficiency, outdoor reliability issues	Staebler-Wronski effect (S.W.E.), the boundary structure between amorphous and crystalline Si
Crystalline thin film Si	It can be deposited on cheap substrates with low total material costs.	Low absorbance	
a-Si/c-Si heterostructures	High-efficiency potential, excellent surface passivation, low processing temperature (below 2000 C), reduced energy return time		

2.4. GaAs

The crystal structure of GaAs as a semiconductor compound is similar to that of Si. However, Si crystals require a thickness of 100 μm or more to absorb sunlight, while GaAs with an almost ideal band gap of 1.43 eV must only be a few micrometers thick. GaAs shows higher efficiency with an energy conversion efficiency of 25-30% than crystalline Si. Because it is highly resistant to heat and radiation damage, GaAs is often used for concentrator systems and aerospace applications. The high cost of single-crystal GaAs substrates is a significant issue in developing GaAs cells for terrestrial use. Two approaches for cost reduction include the fabrication of GaAs cells on low-cost substrates such as Si or germanium (Ge) and the growth of GaAs cells on removable GaAs substrates. These removable GaAs substrates can be reused to produce other cells and even create GaAs thin films similar to CIGS and CdTe thin films [47].

2.5. CdTe

CdTe, as a polycrystalline semiconductor, has a high light absorption rate, which is only about 1μm thick and can absorb 90% of the solar spectrum. Another advantage is its relatively easy and cheap manufacturing process. However, its conversion efficiency is low, similar to a-Si. Some of the dominant issues of CdTe solar cell development include the difficulty of doping p-type CdTe, difficulty in obtaining low-resistance contacts against p-type CdTe, recombination losses associated with the junction interface [50], and precautions related to cadmium toxicity that must be considered during the manufacturing process. A significant issue in developing CdTe for P.V. applications is the understood instability of cell and module performance [51].

2.6. Copper indium diselenide (C.I.S.) and related compounds

Copper indium gallium selenide (CIGS) solar cells, often called C.I.S. solar cells, are a type of thin-film solar cell gaining increasing interest due to their potential for high efficiency and low manufacturing costs. The active layer of a CIGS cell is composed of the compound copper indium gallium selenide, which has an optimal band gap for absorbing sunlight and converting it into electrical energy[44]. This layer is thin, generally only a few micrometers thick, which makes the manufacturing process potentially less expensive than that for crystalline silicon solar cells, which require thicker, high-purity silicon layers. CIGS cells can achieve higher efficiencies than other thin-film technologies, such as cadmium telluride (CdTe) or amorphous silicon (a-Si), with laboratory efficiencies reaching over 20% [52].

2.7. Perovskite Solar Cells

Perovskite solar cells have emerged as a promising new class of solar cells due to their high power conversion efficiency and relatively low production cost. The term "perovskite" in these solar cells refers to a unique crystal structure first discovered in a mineral called perovskite. The specific perovskite material used in these solar cells is typically a hybrid organic-inorganic lead or tin halide-based material with the formula ABX_3[53]. Perovskite solar cells have attracted significant attention due to their excellent light absorption properties, high charge-carrier mobilities, and long diffusion lengths. As a result, they have the potential for increased efficiency in converting sunlight into electricity. Laboratory tests have already demonstrated efficiencies exceeding 25%, rivaling traditional silicon-based solar cells [54]. Another advantage of perovskite solar cells is that they can be produced using relatively simple and low-cost methods, such as solution processing. This condition allows for the production of lightweight, flexible solar cells on a large scale.

2.8. Organic Photovoltaic Cells (OPVs)

Organic photovoltaic cells (OPVs) are a type of solar cell that utilize organic materials, typically carbon-based polymers or molecules, to absorb light and convert it into electricity. They represent an exciting area in the field of solar energy due to their potential for low-cost production, flexibility, and ability to be incorporated into various applications [34]. The primary active layer in an OPV is a blend of a donor material and an acceptor material, creating a type of charge separation when excited by light. This charge separation allows for the flow of electrical current. The choice of organic materials, which can include polymers or small molecules, is critical in determining the performance of the OPV [55].

2.9. The Mechanism of Solar Cells

A solar cell is an essential solar energy generation system unit in which sunlight is immediately converted into electrical energy. The n-type refers to the negatively charged electrons contributed by the donor impurity atoms, and the p-type refers to the positively charged holes created by the acceptor impurity atoms, referring to Figure 1 of the P.V. structure [57].

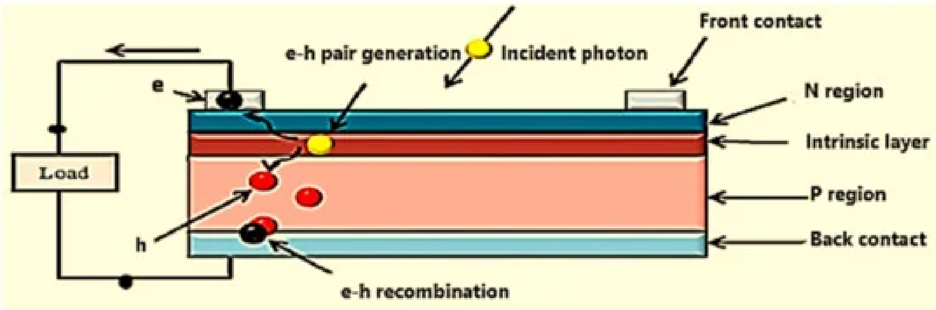

Figure 1: A p-n junction P.V. cell.

The working principle of solar cells is based on the photovoltaic effect. The P.V. effect can be divided into three critical procedures [57, 58].

1. Absorption of photons in electronic semiconductor p-n junctions to generate charge carriers (electron-hole pairs). Absorption of a photon with energy ($E = h\upsilon$) higher than the gap energy 'Eg' of the doped semiconductor material means its power is used to excite an electron from the valence band 'Eυ' to the conduction band 'Ec', leaving a vacancy (hole) at the netting level. The excess photon energy ($h\upsilon - h\upsilon_0$) gives additional kinetic energy to the electron or hole. '$h\upsilon_0$' is the semiconductor's minimum energy or work function required to produce an electron-hole pair. The work function here represents the energy gap. The excess energy is dissipated as heat in the semiconductor.

2. The consequent separation of charge carriers that light produces. In an external solar circuit, holes can flow away from the junction through the p-region, and electrons can flow across the n-region and pass through the circuit before rejoining the holes.

3. Finally, the separated electrons can drive the electrical circuit. Once the electrons pass through the circuit, they recombine with the holes.

The n-type must be designed to be thinner than the p-type. Thus, electrons can pass through the circuit quickly and generate current before recombining with holes. In addition, an anti-reflective coating is applied to the n-layer to reduce surface reflections and increase light transmission to the semiconductor material.

2.10. State of The Art in Solar Cells System

A photovoltaic cell (P.V.C.) is a device that converts solar radiation into electrical energy through the photovoltaic effect. P.V.s present an architecture based on the union of two semiconductor regions with different electron concentrations. These materials can be either N-type (semiconductors with an excess of electrons) or P-type (semiconductors with many positive charges, called holes), although the materials are electronically neutral in both cases. The different P.V.s that have been developed can be classified into four main categories called generations [59], which can be seen in Figure 2 :

1. First generation (1GEN): It is based on crystalline silicon technology, both monocrystalline and polycrystalline, and gallium arsenide (GaAs);
2. Second generation (2GEN): This includes amorphous silicon (a-Si) and microcrystalline silicon (μc- Si) thin-film solar cells, cadmium telluride/cadmium sulfide (CdTe/CdS), and copper indium gallium selenide (CIGS) solar cells;
3. Third generation (3GEN): This involves technologies based on newer compounds, including nanocrystalline films, active quantum dots, tandem or inorganic multilayer stacks based on III-V materials, such as GaAs/GaInP, organic (polymer) based solar cells, color-sensitized solar cells;
4. Fourth generation (4GEN): Also known as "inorganic-in-organic", combines the low cost/flexibility of polymer thin films with the stability of new inorganic nanostructures such as metal nanoparticles and metal oxides or organic-based nanomaterials such as carbon nanotubes, graphene, and their derivatives.

Meanwhile, Figure 3 shows the best research efficiencies achieved for different types of solar cells. The goal of each generation is to reduce the cost and simultaneously increase efficiency compared to the previous generation. In this regard, calculations and economic and funding feasibility features must be performed before designing a P.V. system [60]. On the other hand, there needs to be more agreement in the literature regarding the classification of P.V.C.s, and some authors sort them into different generations, as is the case for GaAs and polycrystalline silicon [8] or silicon nanotubes [61].]. In addition, there is controversy regarding the existence of 4GENs, as some authors include them in the 3GEN frontier [62], while others believe that it is different [61].

Based on the analysis of Luceño-s & Mar (2019) [66], most 1GEN (m-Si, p-Si, and GaAs) and 2GEN (a-Si, μc-Si, CdTe/CdS, and CIGS) technologies are highly standardized and have undergone little change in recent years; they exhibit high efficiencies (20-25%) and are usually expensive, although there has been a reduction in the cost of

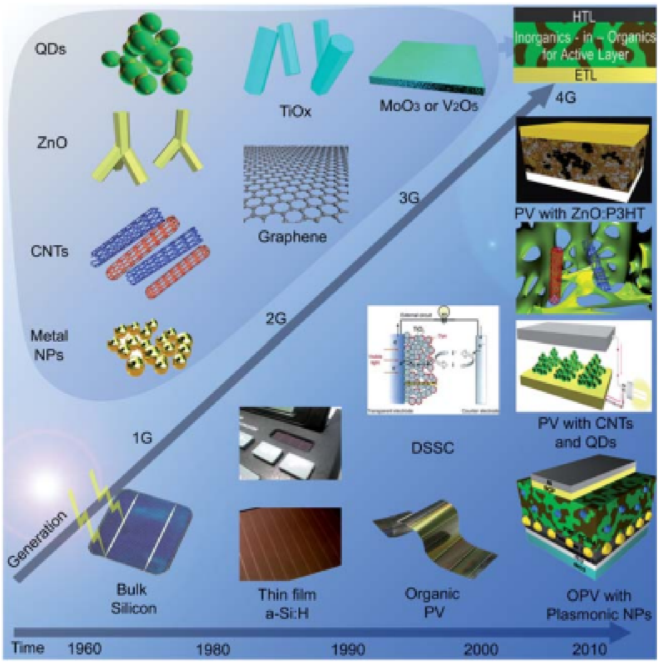

Figure 2: Timeline of four generation photovoltaics cells [59].

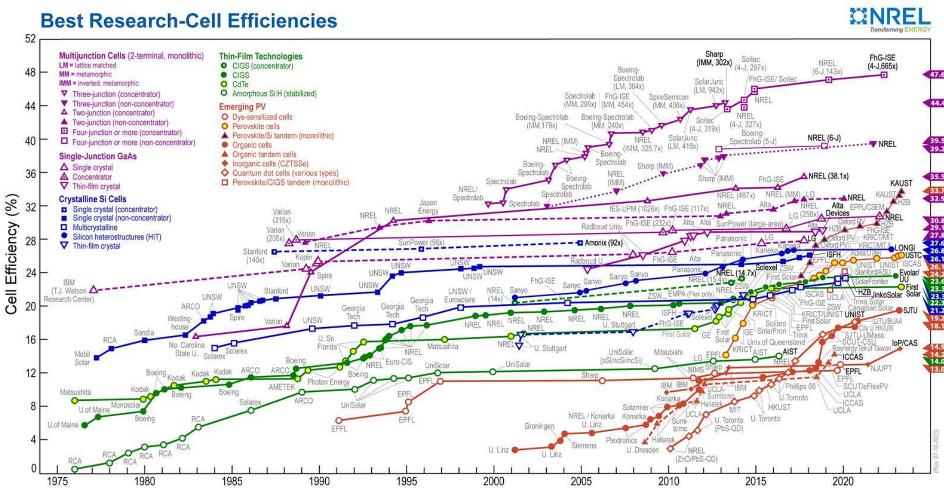

Figure 3: Best research-cell efficiencies [63].

silicon-based cells. On the other hand, most 3GEN technologies (Q.D., perovskite, P.S.C., DSSC), as well as 4GEN (polymers combined with metal nanoparticles, CNTs, G, or their derivatives), are in a state very close to the so-called “basic research”; laboratory prototypes giving good results have been developed although they have not yet been implemented on an industrial scale (10-15% efficiency). However, 3GEN multi-junction cells are already commercial and have achieved high energy conversion rates (>40%), making them the best alternative if efficiency is sought. 4GEN cells based on CNTs, G, or their derivatives are in early research, hence a promising field to investigate. The versatile nature of such carbon nanostructures makes it possible to incorporate them throughout the P.S.C. architecture, including the transport layer, active layer, and electrodes, with inexpensive, stable devices with improved performance. G and CNTs have proven to be effective, processable solutions and replacements for traditional transport layers such as PEDOT: P.S.S. Moreover, CNT doping effectively tunes charge transport within the active layer. In addition, there is also promise in the creation of hybrid architectures involving metal oxide/carbon nanostructures as transport layers in DSSCs. A summary of the technologies, production methods, characteristics, and efficiencies achieved by P.V. cells can be seen in Table 2 [64].

Table 2: P.V. technologies.

GEN	Technology	Production Method	Characteristics	Efficiency (%)
1GEN	m-Si	Czochralski	Expensive, stable	24.4
1GEN	p-Si	Siemens	Low cost, high defect content	19.9
1GEN	GaAs	Epitaxial growth	Expensive, reasonable design control	18.4-28.8
2GEN	a-Si	Large-area deposition	Non-toxic, short life cycle	10.2-12.7
2GEN	$\mu c-Si$	Roll-to-roll	Low defect content. Good degradability	11.9-14.0
2GEN	CIGS	Deposition, co-evaporation	Tuneable band gap	22.3
2GEN	CdTe	Deposition	High-temperature tolerance, low fooling	21
3GEN	DSSC	Roll-to-roll	Work in low light conditions, robustness	5.0-20.0
3GEN	Q.D.s	Solution casting	Efficient conductivity	11..0-17.0
3GEN	OPSCs	Solution casting	The high work function, thermally stable	9.7-11.2
3GEN	P.V.S.C. ($CH_3NH_3PBI_3$)	Sputtering/printing	Cheap, simple	21.1-21.6
3GEN	MJ[1]	Stacking	Wide range of design, challenging manufacture	35.8
3GEN	IMM[2]	Monolithic growth	Cheap, high band gap	40.0-44.4
4GEN	BHJ[3]PSC[4] with GO/PEDOT: P.S.S.	Solution casting	Reproducible and stable	4.28
4GEN	PSC with G/PEDOT:PSS	Solution casting	Good functionality	2.82-11,8
4GEN	PVSC[5] with Li-GO	Monolithic growth	Stabe, long lifetime	1.07-11.14
4GEN	P.V.S.C. with rGO/PEDOT: P.S.S.	Solution casting	Long lifetime, reduced elec-hole recombination	5.7-11.95
4GEN	P.S.C.s with B-doped C.N.T.s	Solution casting	Improved electron transport	4.1-8.6

[1] M.J.: multi-junction; [2]I.M.M.: inverted metamorphic multijunction; [3]B.H.J.: Bulk heterojunction; [4]P.S.C.: polymer solar cell; [5] P.V.S.C.: perovskite

2.11. The Application of Solar Cells

Solar energy, a combination of light and heat, is produced by the Sun. This energy travels from the Sun and reaches the Earth, where humans collect it through solar collectors and convert it into the desired form of energy. According to assumptions, this renewable energy source is powerful enough to replace the electricity from 650 barrels of oil annually [65]. The applications of solar cells in everyday life are as follows:

1. In conventional power plants, non-renewable energy sources boil water and form a flow so that the turbine can spin and the water generates electricity. But with solar energy, the Sun's heat can boil the water to produce steam and rotate the turbine. Photoelectric and thermoelectric technology converts sunlight into electricity solar panels [66].

2. Home, residential appliances can easily use electricity generated through solar power. Additionally, this solar energy runs solar heaters to supply hot water in homes. Through photovoltaic cells installed on the roof of the house, energy is captured and stored on batteries to be used throughout the day at home for various purposes. In this way, energy expenditure is reduced by home users [67]

3. Ventilation system, solar energy is used for ventilation purposes in many places. It helps run bath, floor, and ceiling fans in buildings. Fans work almost all the time in buildings to control humidity and odors and in homes to remove heat from the kitchen. This can add a significant amount to the electricity bill; to reduce this bill, solar energy is used for ventilation [68].

4. Water pumping, utilizing solar energy for water pumping, is one of the most straightforward and fitting applications of photovoltaic technology. It serves various water-related needs, from irrigating crops to supplying water for livestock and domestic usage. The beauty of most of these systems lies in their ability to store water for use during non-sunny periods, thereby eliminating the need for batteries, simplifying the design, and reducing overall costs. Many folks are deterred by the initial cost of installing a solar water pumping system. However, if one were to consider this expense spread over a decade, it would provide a more accurate picture of the actual cost. When you factor in installation expenses (labor included), fuel costs, and maintenance over ten years, you might discover that going solar is economical [69].

5. Solar Lighting, also known as natural lighting, works with the help of solar power. It stores the Sun's natural energy during the day and then converts it into electricity to light up at night. This system reduces the load from the local power plant [70].

6. Solar Cars are electric vehicles recharged from solar energy or sunlight. The solar panels in these cars absorb light and convert it into electrical energy. This electrical energy is stored in the battery used with the car, so at night, we can also drive these vehicles[71].

2.12. Solar Cell in Education: STEM Education

STEM (Science, Technology, Engineering, and Mathematics) education is vital in solar cell research. This field relies heavily on a deep understanding of complex scientific concepts, technological innovation, and the application of engineering solutions [29, 30, 72–74]. Solar cell technology is driven by the principles of physics and chemistry, requiring robust knowledge that STEM education provides [40, 75, 76]. Progress in solar cell efficiency, cost-effectiveness, and scalability are all underpinned by STEM principles, especially regarding technology [50]. The interdisciplinary nature of solar cell research demands a versatile STEM skill set, and cultivating these skills in the next generation of innovators ensures continued advancements in renewable energy solutions [36]. In addressing pressing global issues like climate change, STEM education is irreplaceable in fostering the necessary skills to tackle such challenges [77].

STEM education can ignite curiosity and interest in renewable energy, creating a pipeline of talented individuals eager to contribute to advancing solar cell technology [31, 72]. STEM education equips individuals with the knowledge, skills, and interdisciplinary mindset necessary to drive innovation and advancements in renewable energy [73, 78]. Solar cell research involves complex scientific principles, materials science, engineering, and technological development [76, 79, 80]. STEM education fosters a culture of critical thinking, problem-solving, and experimentation, encouraging researchers to push the boundaries of solar cell technology [81]. As the world faces pressing energy and environmental challenges, investing in STEM education for solar cell research is critical to developing sustainable and clean energy solutions that can positively impact society and the planet. By nurturing a new generation of STEM professionals, we can create a sustainable future powered by renewable energy sources like solar cells [82].

2.13. The Interdisciplinary Nature of Solar Cell Research

Solar cell research is inherently interdisciplinary, requiring expertise from various STEM fields. This section explores science, engineering, and technology convergence in solar cells. Solar cell research is inherently interdisciplinary, drawing on different scientific, engineering, and technological disciplines [30]. The interdisciplinary nature of this research field is crucial as it allows researchers to approach the complex challenges of solar cell technology from multiple angles, fostering a comprehensive and holistic understanding of the subject [81]. Solar cell research involves physics, materials science, and chemistry to comprehend light, semiconductors, and electron-hole interaction behavior. Understanding the properties of different materials and their response to light is essential for developing efficient solar cells [79, 83, 84].

The first STEM subject is science. Science in STEM involves applying scientific understanding by students to identify problems and understand natural events or generate new insights through investigative processes. Solar cells, also known as photovoltaic (P.V.) cells, convert sunlight directly into electricity by harnessing the power of the photovoltaic effect [76, 79, 80, 85–87]. The fundamental science behind the operation of a solar cell involves physics and materials science concepts, primarily in semiconductors and quantum mechanics [88, 89]. The photovoltaic effect is the basic principle that allows solar cells to convert light (photons) into electricity (voltage). When light shines on certain materials, it can cause them to absorb photons and release electrons, generating an electric current [75, 76, 79, 83, 86, 90]. The working principle of natural dye-based solar cells is similar to natural photosynthesis in plants. In the first layer, DSSC is dye as a photosensitizer, which absorbs light. This is similar to the function of chlorophyll in plants. In dye, there are positive and negative carriers in the cell. The dyestuff molecule will absorb photon-shaped light with a wavelength corresponding to the energy difference between HOMO and LUMO in the dye [76, 79, 80]. In the process of making, DSSC can use natural ingredients such as banana peel, lemon peel [76], black sticky rice[80], singonium leaves [79], and *Andrea cordifolia* [87]. In natural materials, there are color pigments that can be used as sensitizers in making DSSC layers, such as anthocyanins [75, 84, 85], carotenoids [76], and dan beta-carotene [79]. Natural pigments bound to photovoltaic surfaces are used for dye molecules and color substitutes that can later be bound by TiO_2 [76].

In addition, solar cells typically use semiconducting materials, most commonly silicon. Semiconductors have properties between those of conductors (which conduct electricity) and insulators (which don't conduct electricity) [88, 91]. Their conductivity can be influenced by the introduction of energy, such as light, which is why they're used in solar cells [92]. Then in semiconductors, the band gap or energy gap is the energy difference between the valence band (where electrons are usually present) and the conduction band (where electrons can move freely to conduct electricity). When sunlight strikes the solar cell, the energy of the photons can be absorbed by the electrons. If the photon energy exceeds the band gap, electrons are excited to the conduction band and can move freely, contributing to the electric current [86, 91].

A solar cell is usually made from two layers of semiconductor material. One layer is "doped" to create an excess of negative charge (n-type), and the other layer creates a lot of positive charge (p-type). Where these layers meet is called the pn junction [40]. At the junction, an electric field is established that drives the flow of electrons from the n-type to the p-type layer once they have absorbed enough energy from the sunlight. The next concept is about electrical circuits. When the cell absorbs light, the electric field pushes the excited electrons at the p-n junction, causing them to move through the external circuit, creating an electric current. The direction of the electric field ensures that the electrons move in a specific direction, creating a directional (or "D.C.") current. Electrons from the ground state will be transferred to the excited state. These excited electrons will enter the TiO_2 conduction band layer. Then the electrons will join the current collector through the semiconductor by diffusion. Electrons can flow to the cathode through an external circuit where it can generate electrical power. Then the electrolyte solution will undergo an oxidation-reduction process [80, 83–85]. Important parameters that can be used to see the performance of natural dye-based solar cells are fill factor (F.F.) and energy conversion efficiency (η). Short circuit current density (J_{sc}) and open circuit voltage (V_{oc}) are affected by electrolytes. The electrolyte is required to contain redox ions that function as mediators between TiO_2 and counter electrodes. I_3^- acts as a positive charge carrier towards the counter electrode, while I^- will move in the opposite direction [75, 79, 85].

Furthermore, Engineering subject pertains to students utilizing engineering principles and design processes to address complex challenges, fostering their curiosity and enthusiasm for the subject [72, 81, 93]. Electrical engineering is pivotal in designing and optimizing solar cell devices, ensuring they can efficiently convert sunlight into electrical energy and integrate into larger energy systems [93]. In recent years, nanotechnology has also emerged as a vital component of solar cell research. Nanomaterials and nanoscale structures offer unique properties that can enhance light absorption and electron transport within solar cells [80, 94]. Then, technology literacy involves students employing skills in handling, understanding, and assessing various technologies to create inventive solutions.

Additionally, they should be proficient in analyzing new technologies and their environmental impact. On the other hand, mathematics literacy pertains to students' capacity to analyze and interpret mathematical concepts, facts, and tools in diverse contexts, enabling them to comprehend and explain natural phenomena. The interdisciplinary approach fosters collaborations between experts from various fields, encouraging the exchange of ideas and perspectives. By integrating knowledge from different disciplines, students can push the boundaries of solar cells, thus paving the way for a more sustainable and renewable energy future. The more specific content of solar cell subject integration for all students can be seen in Table 3 [72]. Figure 4 also shows the scope of scientific knowledge learned through dye-sensitized solar cells (DSSCs).

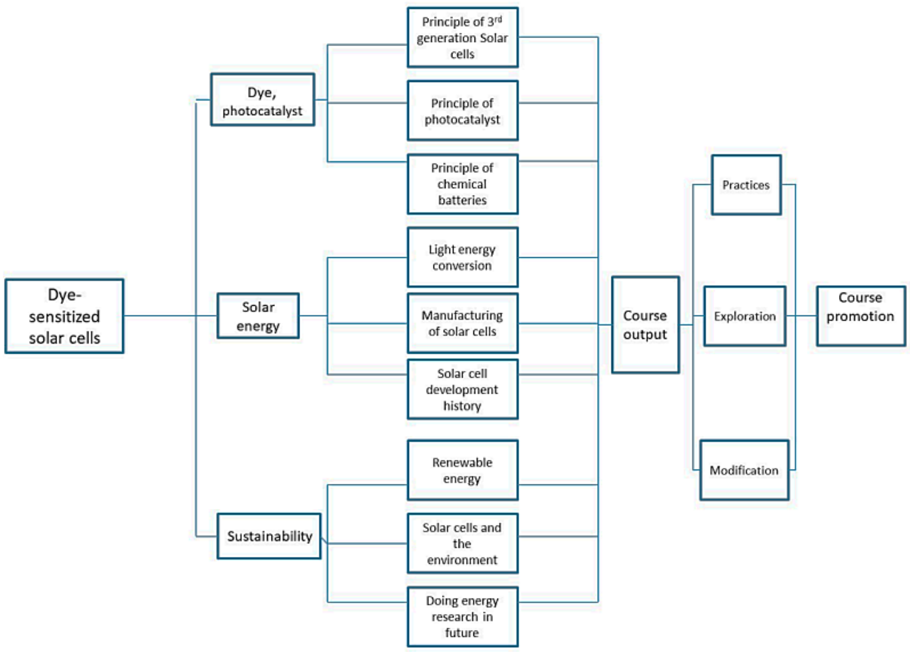

Figure 4: Scope of scientific knowledge learned through dye-sensitized solar cells (DSSCs) [72].

2.14. Fostering Hands-On Learning with Solar Cell Projects

DSSC is a third-generation solar technology with a lower production cost threshold than previous-generation silicon-based solar technologies. Hands-on learning with DSSC is a fantastic way to engage students in renewable energy education while promoting critical thinking, problem-solving, and practical skills. DSSCs can be adapted for various age groups and educational levels, from elementary school to college. By incorporating

Table 3: Interdisciplinary approach dimensions in the hands-on DSSC course.

Content			Science Club Students	Energy Technology students	Junior high school science students
Science	1	Redox reactions	✓	✓	O
	2	Renewable resources	✓	✓	O
	3	Solar Energy	✓	✓	✓
	4	Photosynthesis	✓	X	O
	5	History of solar cell	✓	✓	✓
	6	Energy conversion and conservation	✓	✓	✓
	7	Principle of chemical batteries	✓	✓	O
	8	Electron energy levels and transitions	✓	O	X
Technology	1	Conductive glass	✓	X	X
	2	Polymer film	✓	O	X
	3	Nano photocatalyst	✓	O	X
	4	Current-voltage detector	✓	X	X
	5	Illuminometer (detecting luminance)	✓	X	X
	6	Multimeters (detecting voltage and currents)	✓	✓	✓
	7	Fan and motor (observing the cell powering the motor)	✓	✓	✓
	8	Taking photos and videos with a camera (capturing the experimental and activity processes)	✓	X	X
	9	Mobile phones (recording the activity with mobile devices)	✓	X	X
Engineering	1	Assembling energy panels	✓	✓	✓
	2	Pressing energy panels with a hot press	✓	✓	✓
	3	Circuitry assembly	✓	✓	O
	4	Maximizing energy output	✓	X	X
	5	The angle of light source illumination	✓	O	X
	6	Distance of light source illumination	✓	O	X
	7	Discussing how different light sources, illumination distances, and illumination angles affect cell efficiency	✓	X	X
	8	Discussing the effects of modules with connecting and parallel designs on teaching	✓	X	X
Mathematics	1	Long performance tests	✓	X	X
	2	Minimum driving voltage (statistics)	✓	X	O
	3	Maximum driving voltage (statistics)	✓	O	O
	4	Designing mathematical charts (student-driven success rates)	✓	X	✓
	5	Mathematical processing	✓	X	X
	6	Voltage and current differences in panel designs	✓	X	X

DSSC into the curriculum, educators can make learning about renewable energy fun, engaging, and relevant while empowering the next generation to be environmentally conscious and innovative problem solvers. Shaner et al. [95] found that integrating hands-on experiments on the catalytic efficiency of solar energy conversion into high school or university courses can increase learning efficacy and student interest in learning chemistry. Enciso et al. [93] used open-source microcontrollers and DSSCs to help students learn the basic principles of practical applications. Santiago-Aviles and Light [96] integrate concepts of fundamental physics, biology, electronics, and systems engineering for the benefit of engineering students by engaging students in the design and implementation of an indoor cultivation system using photovoltaic technology to energize Light Emitting Diodes that mimic the solar radiation needed for plant growth, a liquid nutrient distribution system, sensors/actuators capable of selecting harvestable crops and tracking overall system parameters.

Nicolaidis et al. [97] developed an organic solar cell fabrication kit for demonstration in undergraduate teaching classes and high school laboratories to promote the growing renewable energy field and facilitate empirical understanding of solar technology. The laboratory focuses on organic photovoltaic (solar cell) fabrication and power generation efficiency testing. Chemical hazards are minimized by limiting substances to non-toxic coating inks and Pb-free alloys on the cathode. Students learn about photoanode conductive glass, titanium dioxide nanoparticles, parallel design, coloring, and thermoplastics through hands-on processes. Students also get to practice the DSSC fabrication process, including coating stainless steel with platinum, injecting electrolytes, and sealing the cell with hot glue. The photo-to-current conversion efficiency can be measured under a light source [98]. The hands-on DSSC teaching module allows for the integration of interdisciplinary and hands-on learning, which increases students' learning motivation found that integrating hands-on experiments regarding the catalytic efficiency of solar energy conversion into high school or university courses can increase students' efficacy and interest in learning chemistry. Students can also practice the DSSC fabrication process, including coating stainless steel with platinum, injecting electrolytes, and sealing the cell with hot glue.

2.15. Challenges and Future Prospects STEM Education in Solar Cell

STEM education in solar cell technology faces various challenges and holds promising prospects. One of the significant challenges lies in providing equitable access to resources and teacher training, especially in underprivileged communities. Integrating complex solar cell concepts into the curriculum while managing time constraints and standardized testing pressures also poses difficulties. Moreover, the rapid evolution of solar technology demands up-to-date educational materials and qualified educators. Students' perception of STEM subjects as challenging or intimidating can hinder their interest and engagement. There are increasing demands for future citizens to be literate in STEM subjects and knowledgeable about socio-scientific-technical linkages and their application in addressing real-world problems. Modern citizens must be able to use the science and technology knowledge they learn in school to deal with development challenges, including environmental pollution, unpredictable climate phenomena, depletion of natural resources such as water and energy, and social and political conflicts. In addition to preparing students with STEM competencies, it enhances students' ability to innovate and responsibly shape the future. With these soft skills, modern citizens can follow a sustainable lifestyle; promote human rights, gender equality, and a culture of peace and non-violence; appreciate cultural diversity; and trigger cultural contributions to sustainable development.

Despite these challenges, the prospects for STEM education in solar cell technology are encouraging. As the world emphasizes renewable energy, there will be an increased demand for professionals skilled in solar technology, fostering career opportunities. These socio-economic challenges include poverty, youth unemployment, and gender equality. Even so, more research has investigated the potential use of renewable energy in addressing science, technology, engineering, and mathematics (STEM) education challenges. These challenges are described not only in developing countries but also in developed countries. Therefore, the current research attempts to contribute to this gap [31]. Solar cell projects can inspire environmentally conscious citizens by raising sustainability awareness. Technological advancements can be integrated into the curriculum, keeping students at the forefront of solar research. Collaborations between educational institutions, governments, and industry players can lead to better resources and funding. Hands-on solar cell projects can significantly enhance students' understanding and passion for STEM, preparing them to tackle real-world challenges and contribute to a sustainable future.

3. CONCLUSION

Solar cells, or photovoltaic (P.V.) cells, are devices designed to convert sunlight directly into electricity through the photovoltaic effect. This process involves the creation of voltage or electric current in a material when exposed to light. Solar cells have reached four generations based on efficiency levels in their development. Due to these advancements, solar cells have become a more realistic option for various applications, including electricity production, water pumping, and space exploration. These advancements make solar cells a more attractive alternative for multiple applications. Due to the low cost of solar cells, they are anticipated to be a significant form of renewable energy.

On the other hand, STEM education plays a crucial role in advancing solar cell technology. By fostering an understanding of scientific principles, engineering concepts, and mathematical analysis, STEM education equips students with the necessary skills to innovate and contribute to developing more efficient and cost-effective solar cell technologies. Then, integrating solar cell topics into STEM curricula can enhance student interest in renewable energy and sustainability. By engaging students in hands-on projects and experiments related to solar cells, educators can instill a sense of environmental responsibility and inspire the next generation of researchers and engineers.

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