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Review

A review on the classifications and applications of solar photovoltaic technology

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Abstract: Our aim of this work is to present a review of solar photovoltaic (PV) systems and technologies. The principle of functioning of a PV system and its major components are first discussed. The types of PV systems are described regarding the connections and characteristics of each type. PV technology generations are demonstrated, including the types, properties, advantages and barriers of each generation. It was revealed that the first generation is the oldest among the three PV generations and the most commonly utilized due to its high efficiency in spite the high cost and complex fabrication process of silicon; the second generation is characterized by its low efficiency and cost and flexibility compared to other generations; and the third generation is not commercially proven yet in spite the fact that it has the highest efficiency and relatively low cost, its raw materials are easy to find and its fabrication process is easier than the other generations. It was shown that the target of all the conducted studies is to study the PV technology to enhance its performance and optimize the benefit from solar energy by reducing conventional energy dependence, mitigating CO_2 emissions and promote the economic performance.

Keywords: solar energy; photovoltaic; review; classifications; applications

1. Introduction

Energy is the backbone of industrial and economic developments and is considered essential not only for the comfort but also for the survival of any modern society. With soaring energy prices due to inflation and geopolitical tensions and the increasing pressure to move away from fossil fuels, recent years have witnessed a growing interest in topics related to energy generation from renewable sources, grid integration of renewables, and energy management [1–5]. Energy management is mainly concerned with system optimization [1], energy storage [2] and energy recovery [3–8]. Renewable energy is a green, clean, and sustainable source of energy that is currently supplying about 13.5% of the world energy demand [9]. Among renewables, solar energy occupies the dominant position. It has become a popular renewable source of energy due to the fact that the amount of solar energy absorbed by the earth is about 1.8 × 1011 MW, which is more than 10000 times the world energy demand [10,11].

Solar energy systems provide a wide range of applications to harvest solar energy [12–17]. Solar systems can be categorized into two major categories: The first converts solar energy into thermal energy, while the other transforms solar energy into electrical energy. Solar photovoltaic systems are an excellent choice for generating clean electrical energy without harming the environment. Photovoltaic cells are made up of semi-conductive material which absorbs spread and concentrated solar radiation to convert solar energy into direct current electricity. Recently, solar systems have shown potential in meeting growing global energy demands. In 2022, solar PV generation witnessed an exceptional increase, rising by a remarkable 270 TWh (26%) to reach about 1,300 TWh [18]. This rise outpaced wind power generation for the first time in history and was the most significant in absolute terms of all renewable energy technologies throughout the year. In 2022, the global photovoltaic industry entered the TW, and the cumulative installed capacity reached 1,185 GW [19].

We aim to present a review on solar photovoltaic technology regarding its principle of functioning, components, and type of systems and technologies.

Hence, the originality of this work resides in the following points:

(1) To describe the three generations of PV technology including the type of each one and the advantages and barriers of each type;
(2) To proffer a brief comparison between the three generations of PV technology;
(3) To discuss and summarize the latest research works on solar photovoltaic technology.

2. Photovoltaic systems

2.1. Principle of PV system

The solar cell mostly consists of three layers of semi-conductors: An upper layer of an N-type semiconductor that has excess of electrons, a semiconductor band gap, and a lower layer of a P-type semi-conductor that has an excess of positively charged holes. When a photon is absorbed, it forms in the semi-conductor electrons (e-) and holes (h+), which are responsible for generating electricity. Figure 1 is a schematic that shows the structure of a PV solar cell and the mechanism of electricity generation [20].

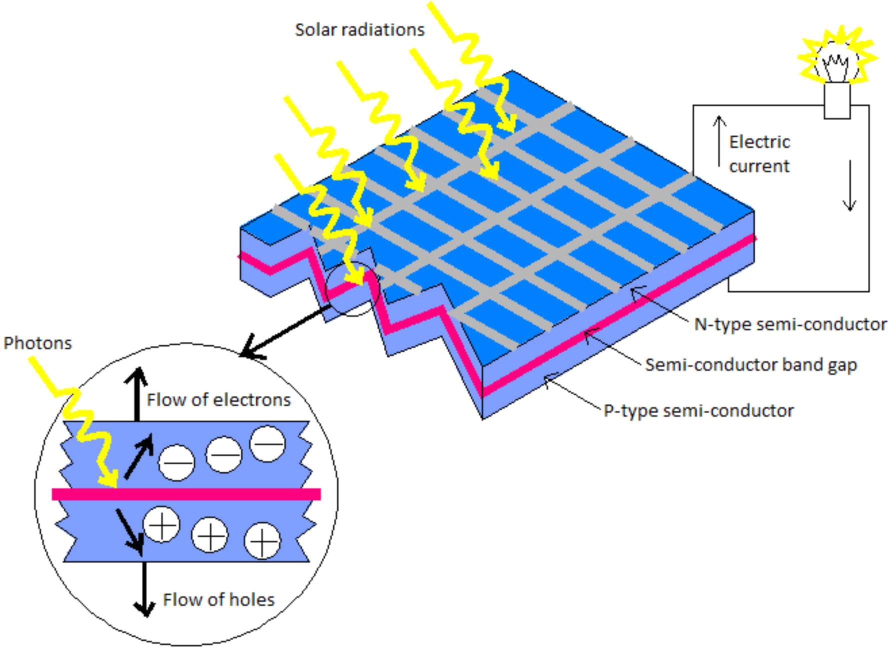


Figure 1. Solar photovoltaic cell [20].

Mundo-Hernández et al. [21] presented an overview of energy policies and the potential of solar photovoltaic energy in Germany, the world leader in producing photovoltaic technology, and Mexico, which has great potential of solar photovoltaics. The authors also reviewed the characteristics, advantages, and disadvantages of photovoltaic technology. Lin et al. [22] performed a study to provide policy makers with evaluation agents to simulate concrete scenarios and optimal conditions that serve in progressing solar energy as an applicable renewable energy source in Taiwan. In [23], Paiano simulated the exponential growth in the installed photovoltaic system to evaluate the prospective waste emerging in Italy from utilizing end-of-life phases of these renewable energy systems in the coming years and their recycling or/and elimination. Moreover, Khan and Pervaiz presented a technological review on solar photovoltaic in Pakistan [24]. The optimum components and appropriate technology for producing energy in remote places within the country were identified

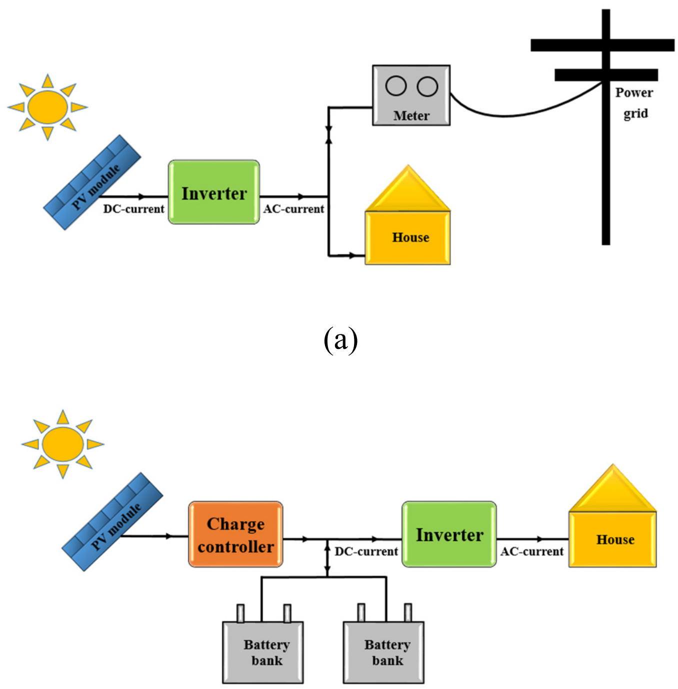
2.2. Components of PV systems

Photovoltaic systems consist mostly of three parts: PV module, power electronics and balance of system (BOS). The PV module is made up of solar cells, formed from semiconductor materials, and role is to convert light into electricity by collecting photons from sun light. When these photons hit the surface of the semiconductor materials they produce pairs of electrons and holes that diffuse in electric field, generating direct current (DC). When solar modules are connected together in series they form strings. Strings of modules are connected in parallel to form an array. Power electronics is important in PV installation, since the solar cell produces DC and all electrical applications found at home need alternating current (AC). Power electronics are mainly DC/AC inverters or regulators for the voltage. This is due to several factors such as meteorological and economic factors, in addition to the intrinsic parameters of the inverter. The remaining components to produce a complete PV system is called the “BOS”. It includes wiring, switches, a mounting system, a battery bank and battery charger and other installation components.

Khatib et al. [25] presented a review including the present research on size optimization of PV systems and the size optimization techniques for the inverter in the photovoltaic systems. The authors concluded from the review that the optimization of PV system is significantly affected by the meteorological variables such as solar irradiance, ambient temperature and wind speed. In [26], Makki et al. presented a comprehensive review of different design and operating parameters that affect the cooling capacity of photovoltaic systems and hence their performance. Another review was done in [27] by Jordehi of the existent research works on photovoltaic cell parameter evaluation problems in addition to some recommendations for future works.

2.3. Photovoltaic systems

Photovoltaic systems have two major types: Grid-connected and off-grid PV systems. Figure 2 presents schematics for grid-connected and off-grid PV systems [28]. A grid-connected system is a system that is connected to the local electricity network. This system is characterized by a bidirectional energy flow; electricity flows from the grid when the PV panels are not producing sufficient energy, and electricity is supplied to the grid when the panels are producing excess energy. Wong et al. [29] presented a review to study the voltage issues of grid-connected photovoltaic systems in Malaysia, where a 7.2 kW grid connected PV system had been installed.



(a)

(b)

Figure 2. (a) Grid connected solar PV system; (b) Off-grid solar PV system [28].

An off-grid PV system or a stand-alone system refers to a system that is not connected to the local electricity network. Such a system is mainly composed of a number of photovoltaic panels that are connected to form a single array that supplies the desired output power, a charge controller, an inverter, and batteries. A charge controller is also known as a charge regulator. It is connected between the solar panel and the batteries and regulates the output from the solar array to prevent the overcharging or over discharging of the batteries. The inverter is utilized to transform the direct current (DC) from the solar array and batteries into an alternating current (AC) to power the AC main appliances. Furthermore, such systems need a backup battery to overcome the insufficient power production by the solar panels due to low irradiation or at night.

2.4. Photovoltaic technologies

In this work, PV technologies are classified according to their generation. Figure 3 illustrates the types of each generation of PV technology.

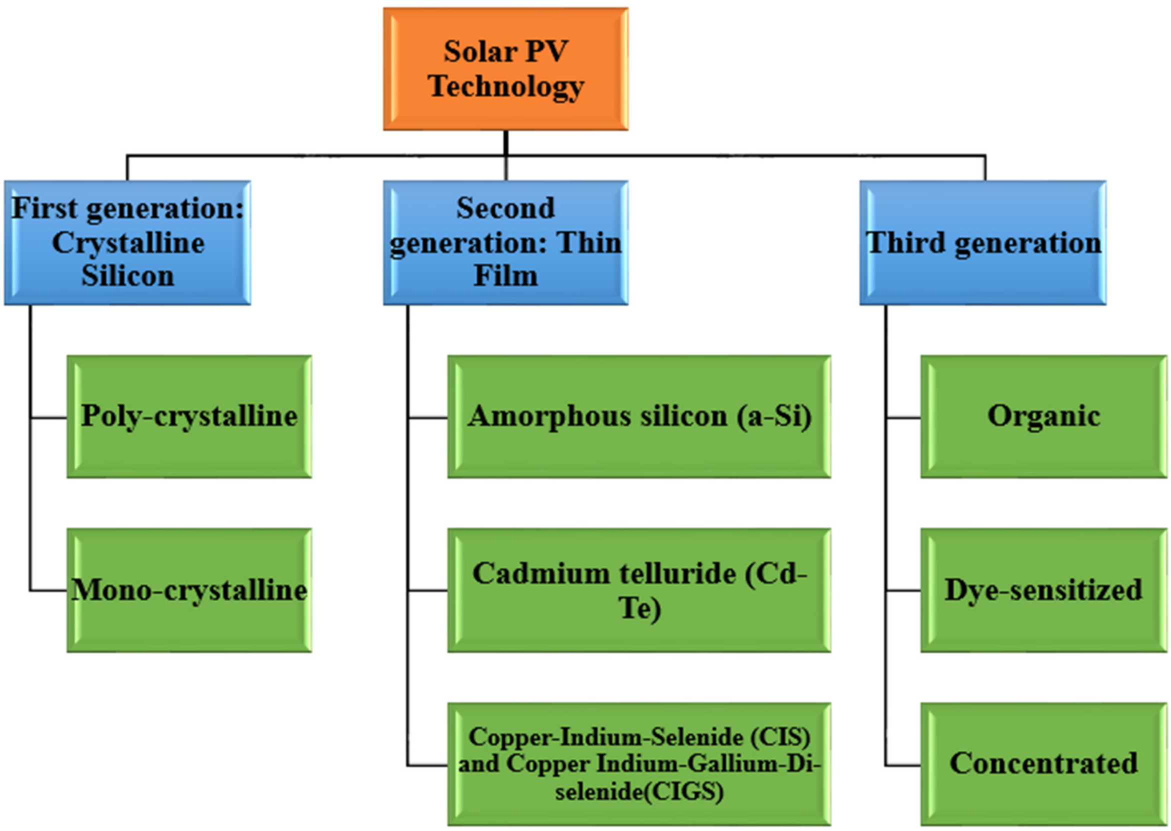


Figure 3. Solar photovoltaic technologies.

The performance and overall efficiency vary greatly from one generation to another due to the difference in the type of semi-conductive materials utilized in each one. Contrary to the third generation, the first and the second generations are commercially mature. Table 1 illustrates the commercial and maximum PV module efficiency for each type of the three technologies [30,31].

Table 1. Commercial and maximum PV module efficiency of photovoltaic technologies [30,31].

Technology		Commercial PV module efficiency (%)	Maximum PV module efficiency (%)	Average cost for solar panel for 2023 ($/watt)
First generation: Crystalline silicon	Mono-crystalline	15–19	25	1–1.5
	Poly-crystalline	13–15	20.4	0.9–1
Second generation: Thin film	a-Si	5–8	12.2	0.7–1
	CdTe	8–11	19.6	
	CIS/CIGS	7–11	19.8	
Third generation	Concentrated	25–30	40	2–4
	Dye-sensitized	1–5	12	0.5–2
	Organic	1	11	1–4

2.4.1. First generation PV technology: Crystalline silicon cells

In the world market, the most manufactured type of the photovoltaic solar cell is the crystalline silicon. It occupies about 90% of the market, one third is monocrystalline silicon and two thirds are polycrystalline silicon. The power output of monocrystalline and polycrystalline modules of the same area is similar. Both are efficient, very durable and have stable power output over time. Monocrystalline has commercial module efficiency (15–19%) greater than that of the polycrystalline (13–15%). This difference is related to the grains found in the polycrystalline, which are not found in monocrystalline. However, monocrystalline is more expensive than polycrystalline due to hard formation of single crystal. Such generation is stable, simple and environmentally friendly. However, it requires thick absorber area in order to achieve high efficiency. Also, the cell is made up of silicon of high purity which is expensive, thus crystalline silicon cell requires high cost. Figure 4 presents monocrystalline and polycrystalline PV modules. Solar panels made on crystalline silicon are extremely recyclable. In order to recycle a panel, the semiconductor material (silicon wafers) must be removed from it while the glass, aluminum, and other components are separated. The creation of new panels can then employ these materials again. Generally, Monocrystalline and polycrystalline crystalline silicon photovoltaic panels are mostly utilized for domestic applications on farms. However, based on the size and energy demand of the industrial processes on the farm, such technology can be used for moderate industrial applications such as water pumping or small-scale machinery operation.

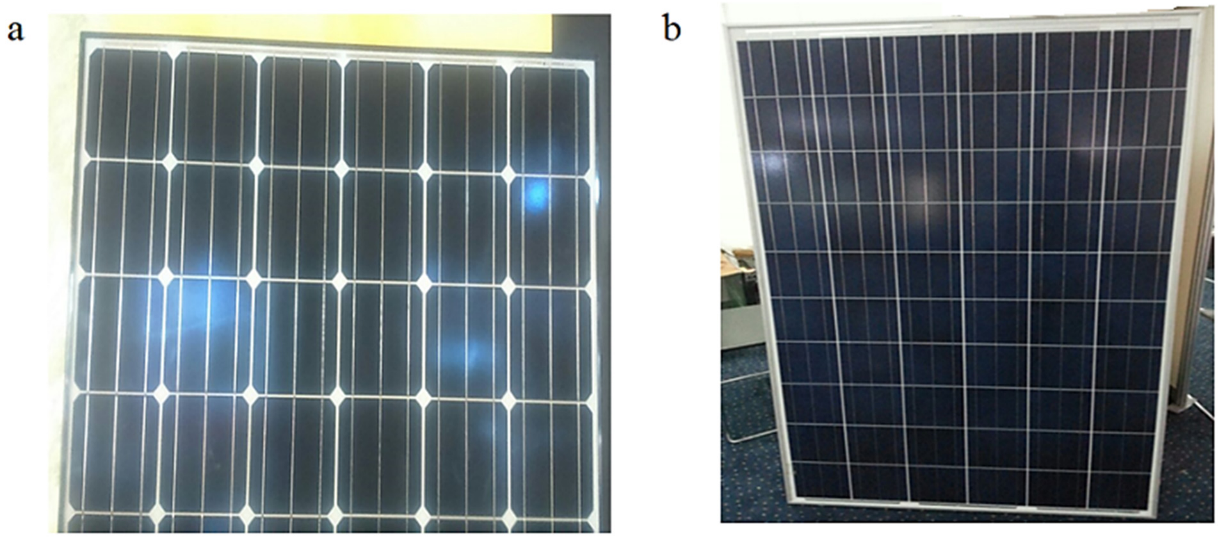


Figure 4. (a) Monocrystalline; (b) polycrystalline PV modules.

2.4.2. Second generation PV technology: Thin film solar cells

The first type of thin film solar cell is perfectly suitable for curves and flat surfaces as industrial roofs and its commercial module efficiency is 5–8%. Micro-crystalline silicon (μc-Si) can be added to a-Si cell in which it becomes thicker and more stable and increases its module efficiency to 9.5%. CdTe is the most economical and currently available thin film technology due to its manufacturing low cost and solar cell efficiency up to 11%. The CdTe-based PV panel does not have any hazardous effect on human health. Despite the fact that such generation contains cadmium, which is a potentially hazardous heavy metal, it is considered safe for human health and the environment due to the low cadmium content. Also, CdTe solar cells are typically encapsulated within a protective glass or other materials, which prevents direct human exposure to the cadmium telluride. Besides, CdTe solar panels are recyclable, where recycling processes recover valuable materials. The CIGS and CIS manufacturing process is expensive due to its complexity. It has module efficiency of 7–11%. Thin film solar cell requires low raw material. It has good performance at high ambient temperature and low sensitivity against overheating. On the other hand, it has a low efficiency and needs large area to attain high power, which increases its cost. Thin-film PV panels can be recycled, but the procedure is more difficult because different thin-film technologies use a range of different materials. For instance, CdTe panels can be recycled by isolating the semiconductor material from the rest of the panel. Thin film technology is suitable for large-scale industrial applications on farms.

2.4.3. Third generation PV technology

Concentrated PV technology (CPV) requires lenses that must be constantly oriented towards the sun to concentrate the sunlight to the solar cell and generate electricity. Thus, it needs less semi-conductive materials to absorb solar radiation. It has the highest commercial module efficiency (25–30%). It requires sun tracking systems, which increase its capital cost. Recycling can be more difficult by the frequent use of specialized optics and materials in CPV systems. Dedicated recycling infrastructure may not be as established as it could be because CPV technology is less widespread than other PV varieties. CPV are suitable for farms with high-power industrial needs, such as manufacturing or large-scale processing. Dye sensitized solar cells utilize photo-electrochemical solar cells of semiconductor structures formed between photosensitized anodes and electrolytes. It has 1–5% commercial module efficiency. Dye sensitized solar cells have high efficiency, are simple in fabrication and cheaper than other photovoltaic appliances; however, they have limited lifetime and stability since the dye degrades when exposed to ultraviolet rays. An organic photovoltaic solar cell is composed of organic or polymer P-N junction, mostly perlyene and phthalocyanine. Its commercial module efficiency is 1%. Recycling dye-sensitized PV cells presents unique challenges and opportunities due to its distinctive materials and design. Organic photovoltaic materials are inexpensive, abundant and nontoxic, but it is not stable and has low efficiency. Organic PV panels are lightweight and flexible, making them challenging to recycle. Additionally, the organic materials used may degrade over time, reducing recycling potential. Dye sensitized and organic solar cells can be used to provide electricity for domestic uses on farms, such as lighting, portable device charging, and powering home appliances.

Table 2 presents a brief comparison between the three generations of PV cells.

Table 2. Brief comparison between the three generations of PV cells.

First generation PV technology: Crystalline silicon cells	Second generation PV technology: Thin film solar cells	Third generation PV technology
• Oldest and established technology • Most commonly used due to its high efficiency • The availability of Silicon is intricate because of its high cost • Requires thick absorber area • Fabrication process of the silicon based solar cell is complex • Longevity and proven performance • Relatively low degradation over time	• Lowest Efficiency • Lowest cost per watt peak price • Lower manufacturing costs due to less material usage • Better performance in low-light conditions • More applicable on windows, cars, building integrations etc. • Can be grown on flexible substrates • It has high absorption coefficient	• Novel technologies which are promising but not commercially proven yet • Highest efficiency • Lower Manufacturing Costs • Lower cost per watt peak price than first generation • Raw materials are easy to find • Easier fabrication process rather than other two technology • Faces competition in terms of market adoption and acceptance
• Suitable for various applications, such as residential and commercial installations • Highly recyclable • Commonly used for domestic applications • Can be used for moderate industrial applications	• Environment contamination starts from fabrication process. • Materials are hard to find • Faster degradation over time • Limited market share due to competition with crystalline silicon • Recyclable but the process is complex • Suitable for large-scale industrial applications	• Limited recycling potential • CPV is suitable for industrial applications • Dye sensitized and organic PV are used for domestic applications

3. Recent research on solar photovoltaics

Many researchers spent many years in studying solar photovoltaic to enhance its performance and achieve the optimum system. Figure 5 shows the number of studies conducted from 2015 to 2023. It is clear that the number of studies is increasing over the years, which reflects the importance of solar PV and the aim to enhance and optimize this technology.

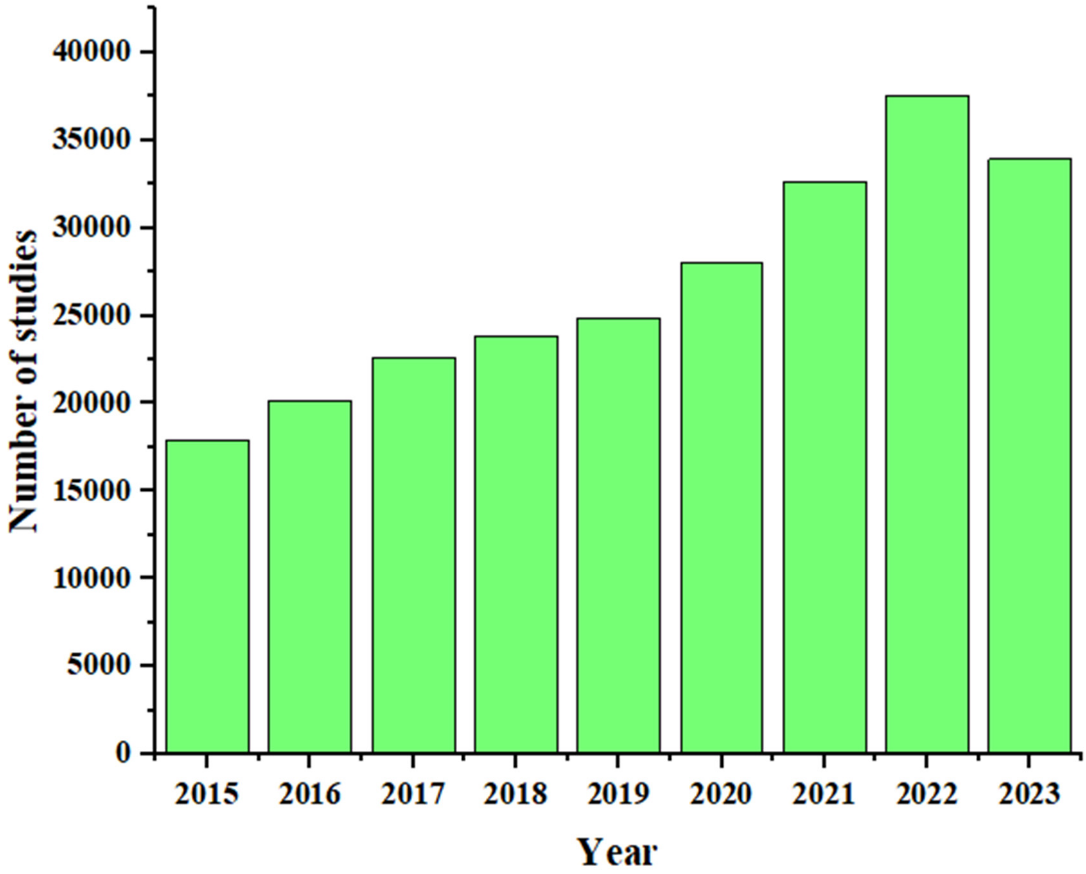


Figure 5. Number of studies conducted on PV technology from 2015 to 2023.

Table 3 summarizes several recent works that have been conducted on solar photovoltaic technology.

Table 3. Recent performed studies on solar photovoltaic systems.

Author's	Type of study	Types of PV cell	Topic(s)
Zarmai et al. [32] (2015)	Review	Crystalline silicon	➢ Present a review on contacts and interconnection technologies utilized to assemble and progress crystalline silicon solar cells.
Sugathan et al. [33] (2015)	Review	Dye sensitized	➢ Summarize all works and researches performed to enhance the performance of dye sensitized solar cells.
El-Khozondar et al. [34] (2015)	Numerical and parametric study	-	➢ Conduct a parametric study using Matlab simulation to investigate the characteristics of a PV array under different conditions.
Ramli et al. [35] (2015)	Numerical	-	➢ Analyze the optimal photovoltaic array and inverter sizes for a grid-connected PV system.
Hernández-Moro and Martínez-Duart [36] (2015)	Analytical	Crystalline silicon	➢ Implement an analytical method to estimate the future (2013–2050) mitigation of CO_2 emissions when deploying solar photovoltaic systems according to three scenarios from IEA. ➢ Estimate the financial extra-cost endured in the installation of photovoltaic systems which could be used instead of traditional power production systems.
Dean [37] (2015)	Review	-	➢ Review of the studies and improvements performed on PV technology in general and its status in India in particular.
Sahoo [9] (2016)	Review	-	➢ Discuss the development of current solar photovoltaic energy in India. ➢ Expose the renewable energy trend in India with analysis of solar parks and industrial applications. ➢ Discuss the government policies in India to support solar energy.
Guerrero-Lemus et al. [38] (2016)	Review	Crystalline silicon	➢ Describe the state-of-art in bifacial PV technology and specify areas where future study may promote introduction of PV technology to the market.
Kow et al. [39] (2016)	Review	-	➢ Study the negative influence of photovoltaic grid-tied system on the power networks. ➢ Investigate the performance of artificial intelligence and traditional methods in reducing power quality event.
Sengupta et al. [40] (2016)	Review	Dye sensitized	➢ Discuss the impact of affecting parameters on the photovoltaic characteristics of photo anode for dye sensitized solar cell application.

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Author's	Type of study	Types of PV cell	Topic(s)
Humada et al. [11] (2016)	Case study	Monocrystalline CIS	Analyze and compare the performance of two major technologies of PV modules: Monocrystalline silicon (c-Si) and copper–indium–diselenide (CIS).
Forcan et al. [41] (2016)	Numerical	-	Investigate a new theoretical approach named "theory of reference PV string" to analyze the influence of partial shading of a PV string system.
Jordehi [27] (2016)	Review	Poly-crystalline Mono-crystalline Thin film	Review of the present research works on PV model parameter estimation problems.
Teffah and Zhang [42] (2017)	Modeling, experimental and numerical	Silicon	Suggest a model which gathers in a roof multi-junction solar cell (MJSC) with TEG-TEG module. Investigate the behavior of the MJSC under distinct high sun concentration factor. Demonstrate the ability of using the whole hybrid system to attain a high efficiency. Conduct experiments to illustrate the cooling and the electric contribution of the TEC-TEG to the system overall efficiency.
Singh and Banerjee [43] (2017)	Numerical	Polycrystalline Monocrystalline	Discuss a suggested Hydrothermal-Solar scheduling (HTSS) algorithm to combine solar photovoltaic generation with an available hydrothermal system at grid level.
Qureshi et al. [44] (2017)	Review and modeling	Polycrystalline Monocrystalline	Demonstrate the issue of diffusion of solar PV at household level by using Rogers' Theory of Innovation Diffusion - a more systematic analytical framework.
Jayaraman et al. [45] (2017)	Review	Silicon	Discuss the parameters that affect utilization of the natural solar energy resources through the installation of PV panel system. Evaluate the role of customer acceptance and efforts to demonstrate its effects on photovoltaic panel usage.
Vasel and Iakovidis [46] (2017)	Analytical and case study	-	Analyze the field data from a solar farm to study the influence of wind direction on the overall performance of a utility-scale PV plant. Determine the best orientation of the area of solar PV plants.

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Author`s	Type of study	Types of PV cell	Topic(s)
Quansah et al. [47] (2017)	Analytical	Polycrystalline Monocrystalline CIS a-Si	Analyze the outdoor performance of five solar photovoltaic (PV) systems with five different solar cell technologies: polycrystalline (pc-Si) and monocrystalline (mc-Si), Copper Indium disulfide (CIS) thin-film, Amorphous Silicon (a-Si), and Heterojunction Incorporating thin (HIT) film.
Prasanth Ram and Rajasekar [48] (2017)	Modeling, numerical and experimental	-	Suggest a new flower pollination algorithm for solar PV maximum power point tracking.
Rezaee Jordehi [49] (2018)	Modeling, numerical and case study	Monocrystalline	Estimate the PV cells and modules parameter by utilizing an improved PSO variant, named as enhanced leader PSO (ELPSO).
Dhanalakshmi and Rajasekar [50] (2018)	Modeling and numerical	-	Suggest a new mathematical methodology following dominant square puzzle procedure with inherent ability to perform row and column wise shade dispersion. Validate the suggested approach by analyzing a shade dispersion on a 5×5 PV array for different shade conditions.
Palm et al. [51] (2018)	Analytical	-	Analyze the electricity consumption and energy-saving behaviors of households that own photovoltaic (PV) systems in Sweden.
Honrubia-Escribano et al. [52] (2018)	Analytical and modeling	Monocrystalline	Analyze the impact of solar technology on the economic performance of distinct topologies of PV power plants. Suggest an economic model to determine the most convenient type of installation for a wide range of input parameters.
Andenæs et al. [53] (2018)	Review	-	Present a review to study the effect of snow and ice coverage on the energy generation from photovoltaic solar cells.
Moslehi et al. [54] (2018)	Modeling	-	Assess the distinct inverse models for estimating the power output of solar photovoltaic systems under different practical scenarios.
Dehghani et al. [55] (2018)	Modeling and case study	Polycrystalline Monocrystalline	Implement a two-phase approach according to data envelopment analysis and robust optimization models to design and plan a solar photovoltaic supply chain in an uncertain environment.
Xu et al. [56] (2018)	Analytical	Polycrystalline Monocrystalline	Analyze the environmental costs and benefits of China's solar PV industry for the period of 2011–2016.

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Author's	Type of study	Types of PV cell	Topic(s)
Saxena et al. [57] (2018)	Experimental and analytical	-	Conduct a laboratory scale experimental study for continuous and interrupted water cooling, which is tested for distinct flow rates. Perform mathematical analysis of temperature over PV panel with and without water cooling system.
Hoffmann et al. [58] (2018)	Analytical	Polycrystalline	Develop a two-axis solar tracker and assess the performances of a solar panel in comparison with a fixed system.
Jakica [59] (2018)	Review	Silicon	Overview of almost 200 solar design tools, analyze their numerous features regarding accuracy, complexity, scale, computation speed, representation as well as build design process integration in about 50 2D/3D, CAD/CAM and BIM software environments.
Ram et al. [60] (2018)	Review	Polycrystalline Monocrystalline Thin film	Review on different PV emulator topologies. Present a detailed analysis of each technique emphasizing on its realization cost, accuracy and level of complexity, sensitiveness to varying environmental conditions, hardware implementation and efficiency.
Belarbi et al. [61] (2018)	Modeling and numerical	-	Suggest a new Maximum Power Point Tracking (MPPT) architecture that enables significant improvement of the system output.
Hyder et al. [62] (2018)	Review	-	Review the components of the solar tree and its design. Discuss the various commercial designs along with applications of the solar tree. Present the limitations involved with this technology.
Shayestegan et al. [63] (2018)	Review	-	Discuss the main challenges in transformer-less topologies. Present a review on new single-phase grid-connected PV systems, which are classified into six groups based on the number of switches required in the system.
Novaes Pires Leite et al. [64] (2019)	Modeling and analytical	Silicon	Present an economic analysis taking into consideration technical sides concerning the integrated utilization of solar PV as a complement energy source and air conditioning systems connected to the utility grid. Implement a mathematical model to assess the economic avail of the integrated use of PV systems.
Rahnama et al. [65] (2019)	Analytical	Polycrystalline	Suggest and implement the approach of solar exergo-economic and exergo-environmental maps for PV systems. Carry out a detailed case study to investigate how the suggested concept can be practically applied to enhance PV systems.

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Author's	Type of study	Types of PV cell	Topic(s)
Zhao et al. [66] (2019)	Analytical	-	Propose an adaptive PID control method to enhance the performance of power tracking of solar PV air conditioners.
Fernández et al. [67] (2019)	Analytical	-	Suggest a new concept to integrate thermochemical energy storage in PV plants. Analyze the sustainability of the calcium Looping process as thermochemical energy storage system in solar PV plants. Develop an economic analysis to compare the suggested system with batteries.
Rosas-Flores et al. [68] (2019)	Review and analytical	Polycrystalline Monocrystalline	Verify the state-of-the-art implementation of an interconnected PV system network. Review the current legislation for PV energy in Mexico. Conduct an energy savings analysis for solar PV technology execution on a large scale in rural and urban residences in Mexico.
Rajvikram and Sivasankar [69] (2019)	Experimental	Polycrystalline	Suggest a method to enhance the efficiency of solar PV panel by controlling the temperature and utilizing phase change material which is integrated to external finned sink to enhance its thermal conductivity. Investigate the concept by experimental setup under direct sun rays for four different cases in the environmental conditions.
Troncoso et al. [70] (2019)	Numerical	-	Develop an economic decision-making tool for the case of Chile which calculates the number of solar PV panels and batteries that optimize the economic return. Conduct a personal computer implementation and numerical example.
Trindade and Cordeiro [71] (2019)	Numerical	-	Suggest an algorithm which conducts the automated verification method to formally check the sizing and operation of a certain stand-alone PV system. Assess the verification method by comparing three states of the art model checkers in five real case studies.
Liu et al. [72] (2019)	Review	-	Present the recent progress in hybrid PV electrical energy storage systems for buildings regarding the whole installation status and research development on the system optimization and performance analysis.

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Author's	Type of study	Types of PV cell	Topic(s)
Kiyaninia et al. [73] (2019)	Modeling and experimental	-	Perform experimental investigation on direct evaporative air-cooling base solar PV system with different thicknesses of cellulose and straw pads. Conduct a mathematical model and exergo-economic analysis for the system.
Sow et al. [74] (2019)	Analytical	Polycrystalline	Present an economical comparative analysis of solar PV systems for the provinces and territories of Canada for 2013 and 2016.
Zafrilla et al. [75] (2019)	Analytical	-	Present a comprehensive sustainability assessment of the solar PV sector.
Zieba Falama et al. [76] (2019)	Modeling	Thin film silicon	Demonstrate carriers' multiplication in PV cell and its implication to enhance the efficiency of solar cell.
Sadanand and Dwivedi [77] (2020)	Numerical	-	Study the influence of photoactive layer thickness on the photocurrent of $Cu_2ZnSnS_4Se_4$ based PV cell. Implement simulation study to study several parameters of device layout MoS2/CZTSSe/ZnS/ITO to optimize the solar devices.
Ren et al. [78] (2020)	Analytical	-	Demonstrate the contribution of solar PV industry to reduce CO_2 emissions based on the relationship between efficiency of installed capacity and efficiency of CO_2 emission mitigation.
Qi et al. [79] (2020)	Analytical	Monocrystalline	Suggest a new PV utilization in which PV cells are installed on the cooling towers of a thermal power plant. Compare and study four configurations of PV in three power plants to assess the technical and economic performances of the suggested design.
Jan et al. [80] (2020)	Analytical	-	Determine the parameters that have a vital role in the social acceptability of solar PV system and proffer reasonable impacts of solar energy policy in Pakistan.
Janardhan et al. [81] (2020)	Modeling and numerical	Monocrystalline	Model and simulate solar PV system with micro multilevel inverter. Investigate the effect of solar PV input parameters (solar irradiance and panel temperature) on the output parameters (DC voltage and current).
Kumar et al. [82] (2020)	Analytical	Polycrystalline Monocrystalline a-Si	Proffer the solar PV performance analysis, resource assessment and normalized performance indices evaluation for 10 kWp solar PV array taken at climatic conditions of five islands of Andaman and Nicobar.

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Author's	Type of study	Types of PV cell	Topic(s)
Ali et al. [83] (2020)	Experimental	Polycrystalline	Suggest and investigate a new system design for PV/solar pond. Implement experimental evaluation study of the thermal performance of mini PV/solar pond.
Yang et al. [84] (2020)	Analytical	Monocrystalline	Present a Geographical Information System (GIS)-based comprehensive methodology with energy system modeling techniques to integrate the potential geographical assessment, technical assessment, and subsidy feasibility analysis for solar PV systems.
Anand et al. [85] (2021)	Review	Polycrystalline Monocrystalline a-Si	Present a review on photovoltaic thermal (PVT) collector combined with desalination technologies such as humidification dehumidification, solar still, reverse osmosis, multiple effect distillation, multiple stage flash and membrane distillation.
Syahputra and Soesanti [86] (2021)	Analytical	Polycrystalline	Carry out the renewable energy systems planning based on micro hydro and solar photovoltaic for rural areas. Implement a case study in the Yogyakarta area, Indonesia.
Alipour et al. [87] (2021)	Analytical	Polycrystalline Monocrystalline a-Si	Present a critical analysis of studies on the utilization of solar PV, solar home systems, and solar PV combined with battery energy storage system.
Kazemian et al. [88] (2021)	Modeling and numerical	Monocrystalline	Propose a new compound system which compromises a solar collector combined in series with PVT module. Develop a transient 3-D model to numerically compare the performance of four systems to assess the feasibility of the suggested novel system. Perform parametric analysis to study the effect of distinct operating conditions on the output power of the compound system module.
Bhavsar and Pitchumani [89] (2021)	Modeling	-	Proffer a new data driven modeling methodology that prunes a wide range of consumer profile features utilizing a machine learning framework to drill a model for expecting possibility of solar exploitation.
De and Ganguly [90] (2021)	Modeling	-	Propose a solar hydrogen hybrid power system to drive a remotely existing cold storage facility for progressing countries on the sustainable basis. Develop a mathematical model on the proposed system. Analyze the suggested system from energy, economic and environmental point of view.
Wang et al. [91] (2021)	Analytical	-	Determine the feasibility and availability of implementing distributed solar PV system in China`s cities.

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Author’s	Type of study	Types of PV cell	Topic(s)
Rodziewicz et al. [92] (2021)	Analytical	a-Si CIS	Study the effect of changes in the distribution of the solar radiation spectrum on the characteristics of several PV modules. Compare the relative efficiency of PV modules with different semiconductor absorbers during bright and sunny, and cloudy summer days. Investigate the influence of module tilt angle on the magnitude of surface incident scattered component and module efficiency.
Li et al. [93] (2022)	Analytical	-	Illustrate that the output of PV generation exhibits complementary coupling characteristics. Investigate how these complementary coupling characteristics can affect the load-following capability of a power system.
Yang and Wang [94] (2022)	Modeling and numerical	-	Construct a geometric model of the distribution form of the 3 × 3 solar photovoltaic panel array. Use shear stress transport turbulence model to estimate the flow field changes around solar photovoltaic (PV). Analyze the impact of different wind speeds, particle sizes, and wind angles on particle deposition.
Liu et al. [95] (2022)	Numerical	Organic	Construct a value chain integrating photovoltaic power generation and energy storage within a blockchain environment. Analyze the strategies of key players using a three-party evolutionary game model and evaluates the impact of various factors on the equilibrium outcomes within the value chain. Provide insights into the dynamics of renewable energy utilization and storage in blockchain-enabled systems.
Yuan et al. [96] (2022)	Analytical and case study	-	Optimize the configuration of photovoltaic and energy storage systems for rural microgrids by considering a range of factors, including load characteristics, local environment, and economic benefits, and applies the model to a real-world case in Guangdong province, China.
Garlet et al. [97] (2022)	Analytical	Silicon	Assess the competitiveness of Brazil's PV distributed generation value chain. Identify challenges faced by the industry and conduct interviews with professionals across the value chain. Develop strategies to address these challenges and strengthen the PV market in the country.

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Author's	Type of study	Types of PV cell	Topic(s)
Peters et al. [98] (2022)	Modeling	Organic	Evaluate the impact of innovation on the greenhouse gas displacement potential of photovoltaic modules, especially in replacement scenarios.
Micheli et al. [99] (2022)	Analytical	Polycrystalline	Evaluate the energy yield potential and cost-effectiveness of floating photovoltaic systems across various European water bodies in comparison to land-based PV systems with optimal tilt angles. Provide a comprehensive analysis of the feasibility and economic viability of floating PV installations in Europe.
Kijo-Kleczkowska et al. [100] (2022)	Case study	Polycrystalline Monocrystalline a-Si	Focus on the economic analysis of a photovoltaic installation combined with a heat pump in a single-family house in Poland. Assess the payback time and profitability of this integrated system. Highlight the economic advantages and sustainability of using clean energy sources for both electricity generation and thermal comfort in residential buildings.
Majewskiand Dias [101] (2023)	Analytical	Monocrystalline	Explore the design of end-of-life legislation for both new and existing solar panels. Address legislations for creating a second-hand market for solar panels. Consider options for levies to support a growing recycling industry for solar panels.
Sun et al. [102] (2023)	Experimental	-	Utilize a national inventory dataset of large-scale solar photovoltaic installations to investigate the spatial location choices of solar power plants. Consider 21 geospatial conditioning factors related to solar energy development. Model the location choices of solar photovoltaic installations using machine learning techniques, specifically multi-layer perceptron, random forest, and extreme gradient boosting models. Determine the performance of the machine learning models, with a focus on the random forest model. Assess the relative importance of conditioning factors, highlighting the significance of factors like the vegetation index and distance to the power grid.

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Author`s	Type of study	Types of PV cell	Topic(s)
Yu et al. [103] (2023)	Review	Silicon	Offer a comprehensive overview of techniques and applications of four kinds of photovoltaic secondary silicon-containing resource including metallurgical-grade silicon refined slag, silicon fume, silicon cutting waste and end-of-life silicon solar cell from discharged modules. Highlight challenges and opportunities for further research and development in this field.
Lv et al. [104] (2023)	Numerical and experimental	CIGS CdTe a-Si	Integrate three different types of photovoltaic cells into PV-TE (Photovoltaic-Thermoelectric) systems. Use simulation and experimental methods to assess the impact of these photovoltaic cell types on the performance of PV-TE systems. Compare the back temperatures of PV-TE systems with those of standard PV systems.
Liao et al. [105] (2023)	Experimental	Polycrystalline	Propose and develop silicon-carbon composite anode materials by using recovered silicon cells from end-of-life PV modules using subsequent impurity leaching removal and graphite integration.
Gao et al. [106] (2023)	Review	-	Provide a comprehensive overview of PCM's role in photovoltaic thermal management, highlights recent advancements, and sets the stage for future research in this evolving field. Offer insights and methods for the advancement of PV thermal management technology based on PCM.
Gao et al. [107] (2023)	Review	-	Provide a comprehensive overview of PCM's role in photovoltaic thermal management, highlights recent advancements, and sets the stage for future research in this evolving field. Offer insights and methods for the advancement of PV thermal management technology based on PCM.
Al Miaari and Ali [108] (2023)	Experimental	Monocrystalline	Reassess the effectiveness of passive cooling methods for photovoltaic panels, specifically by utilizing phase change material (PCM). Investigate how containers filled with phase change material, both with appropriate and inappropriate properties, impact the temperature and performance of photovoltaic modules.

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Author’s	Type of study	Types of PV cell	Topic(s)
Yao et al. [109] (2023)	Analytical	Polycrystalline Monocrystalline	Introduce an analytical approach for simulating photovoltaic array performance that doesn't rely on historical data. Employ an electrical model that includes a parameter extraction method and an iterative algorithm to quickly determine the I-V (current-voltage) characteristics of the photovoltaic module. This enables efficient analysis of electrical performance. Investigate various environmental factors such as irradiation, temperature, humidity, wind speed, and wind direction.
Wang et al. [110] (2023)	Analytical	Polycrystalline	Conduct an initial site-level assessment of the Photovoltaic Poverty Alleviation (PVPA) program in China for evaluating the program's implementation and impact at specific sites or locations.

Based on Table 3, it is obvious that numerous are the studies that are conducted on solar PV technology. Some researches presented review, others conducted modeling on PV system, analytical studies, parametric studies, case studies, feasibility studies, etc. All these researchers aim to investigate solar PV technology to optimize its performance and shed light on its effect on economic and environmental issues. This was mostly achieved by:

- Studying the characteristics of PV technology;
- Estimating CO_2 reduction when depending on PV systems;
- Computing the energy saved when using PV systems;
- Analyzing and comparing the performance of the types of PV cells;
- Demonstrating the effect of utilizing PV systems on the economic performance;
- Reducing the cost of PV systems.

Investigating the effect of several parameters on the performance of PV system to optimize it. The parameters include the input temperature, solar irradiance, cooling PV cells, using tracking systems or phase change materials, etc.

4. Conclusions

Solar energy is a green, sustainable, and ubiquitous renewable source of energy. It has a great influence on reducing or even eliminating utilization of fossil fuel in the future and at low cost. Solar photovoltaic system is an elegant application of solar energy. It generates electricity directly from the sun, thus it minimizes consumption of fossil fuels and emissions of greenhouse gases. In this work, a short review on solar photovoltaic was presented. Principles of solar photovoltaic, components, and types of solar photovoltaic systems are covered. In addition, classification of photovoltaic technologies is carried out with a detailed description of each type. Besides, the latest research works conducted on solar PV technology are illustrated**.**

It can be concluded from the work:

- Monocrystalline silicon solar cell has a commercial efficiency range between 15 and 19% with an average cost of 1–1.5 $/watt and polycrystalline silicon cell has a commercial efficiency that varies between 13 and 15$ with an average cost of 0.9–1 $/watt. Both types are commonly exploited for domestic applications on farms but they can be used for moderate industrial applications.

- Second generation thin film PV cells have a commercial efficiency range between 5 and 11% with an average cost of 0.7–1 $/watt. Such generation is utilized for large-scale industrial applications on farms.
- The CPV cell has a commercial efficiency that varies between 25 and 30% with an average cost of 2–4 $/watt. Such types are used for industrial applications of high power requirements.
- Dye sensitized solar cell has a commercial efficiency range between 1 and 5% with an average cost of 0.5–2 $/watt and the organic solar cell has a commercial efficiency of approximately 1% and an average cost of 1–4 $/watt. Both solar cells can be exploited for domestic uses on farms.

Use of AI tools declaration

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Amal Herez: Data curation; Formal analysis; Investigation; Methodology; Validation; Writing—original draft; **Hassan Jaber:** Formal analysis; Investigation; Writing—review & editing; **Hicham El Hage:** Formal analysis; Investigation; Writing—review & editing; **Thierry Lemenand:** Formal analysis; Investigation; Writing—review & editing; **Mohamad Ramadan:** Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Supervision; Writing—review & editing; **Mahmoud Khaled:** Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Supervision; Writing—review & editing.

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