Advancements in Solar Photovoltaic-Thermal (PVT) Systems: A Comprehensive Review of Solar Energy

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Abstract— An abundant and sustainable energy source that is essential for sustainable development is provided by solar energy, which is emerging as a major force in environmentally friendly technologies. Its daily abundance positions it as a compelling resource for electricity generation, with concentrated solar power and solar photo voltaic continuously evolving to meet global energy demands. Concentrated solar power (CSP) and solar photovoltaic (PV) are two different technologies that use solar energy for different purposes. They have their unique characteristics, working principles, and applications. This section gives an introduction to both technologies. This paper examines Solar PV and CSP systems, which offer two diverse approaches to tap into solar energy. Solar photovoltaics (PV) is an adaptable, scalable technology that directly transforms sunshine into power for a wide range of uses. CSP systems are a great option for large-scale, dispatchable power generation because they concentrate sunlight to create high-temperature heat for the generation of electricity. The choice between these technologies depends on factors such as the application, location, and energy requirements.

Key words: Sustainable Energy, Solar Photo Voltaic, Concentrated Solar Power (CSP)

I. INTRODUCTION

It is considered that in the previous one hundred years, mankind has been able to build new technologies that not only give an unrivalled capacity of economic development, but also equip mankind with a remarkable potential to be in harmony with the environment. Solar energy is a kind of renewable energy. It has plenty of resources, is free, doesn't need transportation, and doesn't pollute the environment. Humanity adopts a new way of life thanks to solar energy, ushering in a period of conservation of energy and a decrease in pollution. Solar thermal conversion device industry makes solar energy technology fulfill its potential in the construction area, including hot water, heating, and air conditioning.

Solar thermal conversion industry is studying solar water heating systems and building integration with the construction industry, and there have been some demonstrations. Solar air conditioning has been included in the science and technology research, and there is a large scale demonstration plant whose economy has yet to be assessed. Therefore, based on the facts previously provided, solar energy technology has many benefits, like being an abundant, clean, renewable energy source with lower prices and less maintenance and environmental friendliness. This study is important to academics, engineers, and consumers alike because it highlights the uses of solar energy to guarantee sustainable development. The aim of this study is to provide an overview of Solar Photovoltaic Technology and concentrated solar power research and development evolution by using bibliometric methods. The main goal of the post is to increase public knowledge and spread the belief that using solar energy in everyday life is the greatest option going ahead.

II. SOLAR ENERGY

Renewable energy sources play an important part in today's global energy policy. Photovoltaic and Concentrated Solar Power have recently emerged as the primary drivers of renewable energy adoption. Nonetheless, their development is hampered by a mismatch between available resources and energy demand. For the time being, there are no economically or technically viable remedies to this mismatch.

Ehsanul Kabir et.al (2018): Potential and future of solar energy. This article discusses solar energy technology pros and cons. Technical issues impacting renewable energy research are also addressed, along with favorable linkages between regulating policy frameworks and their future possibilities. For that, they propose a worldwide solar energy technology picture, including potential, capacity, prospects, restrictions, and policies. This increased their grasp of how much solar energy can fulfill future energy demand. Despite significant drawbacks, they discovered that solar energy technology is among the most promising renewable energy sources to meet the world's energy needs in the future.[1]

Suhas bannur (2018): Concentrated solar power in India: status, challenges, and outlook. In this article, several of the obstacles to concentrated solar power expansion are recognized and remedies are proposed. CSP has problems from PV competition, a lack of good direct normal irradiance data, and local manufacturing. This study examined how indigenous manufacturing and economics of scale affect capital costs and normalized cost of electricity. It found that even with indigenous manufacturing and economics of scale, the capital cost per megawatt of installed capacity is higher than central electricity regulatory commission benchmark costs. [2]

The COVID-19 epidemic reduced power sector CO2 emissions by 1% in 2019 and 7% in 2020, demonstrating a decline in coal-fired energy output as energy requirements diminish, renewables expand, and fossil fuels are replaced. By 2020,

the energy sector is expected to produce ~13 Gt CO2, contributing to ~40% of worldwide CO2 emissions. Annual electricity production recovered to pre-crisis levels in 2021, but a changing fuel mixture will raise power sector CO2 emissions until 2030 [3].

A zero energy building is one that produces no carbon dioxide emissions and is intended for zero net energy emissions. Solar energy causes and devices in buildings that are used to satisfy energy demands are combined with building-integrated photovoltaic (BIPV) technology. Consequently, innovative technologies like solar cooling are included into building-integrated PVs employing thermal energy (BIPV/T) [4].

A general layout of a CSP based power plant consists of solar field, storage facility, and power block. The layout is shown in Fig.1.

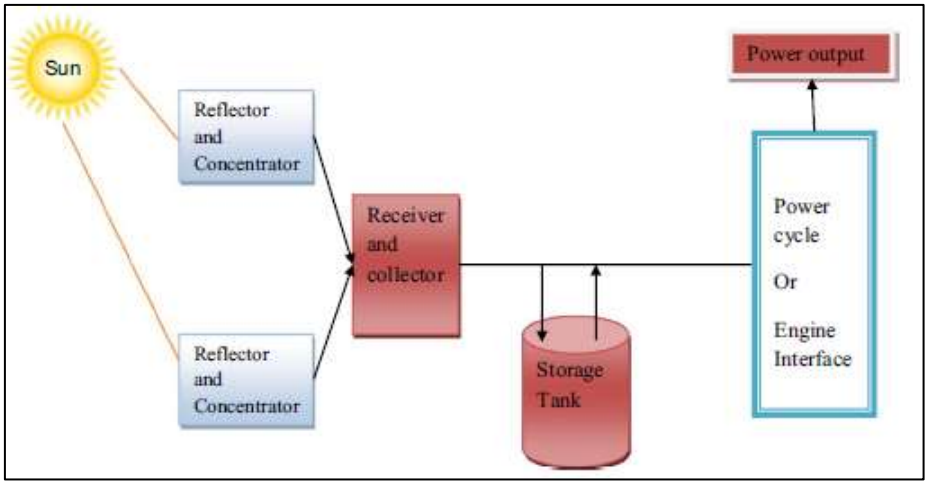

Fig. 1: CSP Technology [5]

The configuration of the solar collectors and the output of thermal energy in a CSP-based power plant are intimately correlated with the solar field. The power plant's thermal capacity is required for the solar field design. A crucial design factor for the necessary land area is the solar multiple (SM). In CSP technology, the storage based power plant should have greater values of the SM factor, which represents the aperture area multiple of the power block capacity (Fig. 2) [5].

Given its superiority over renewable energy sources in terms of affordability, accessibility, efficiency, and capability, the solar sector is unquestionably the greatest choice for meeting future energy demands. In order to address the energy problem, this article addresses the necessity of the solar industry, including its basic principles, the global energy situation, the research that has been done to improve the solar industry, its prospective uses, and the obstacles that will need to be overcome in the future [6].

III. APPLICATION OF SOLAR ENERGY

Solar energy comes directly from the Sun. Since solar energy can provide heat, electricity, and desalinate water, its usage has grown globally. The following are solar energy applications: CSP and PVs. Fig. 2 illustrates solar energy application taxonomy.

A. Application of Concentrated Solar Power Generation.

By heating fluid using sun energy, solar thermal power plants create electricity. Water absorbs this fluid's heat, becoming superheated steam. A power plant uses steam to spin turbines, which a generator converts into electricity. This method of generating is similar to fossil fuel based electricity generation, however it warms steam with sunlight instead. Sunlight is concentrated on one place by solar collectors in these systems to raise temperatures.

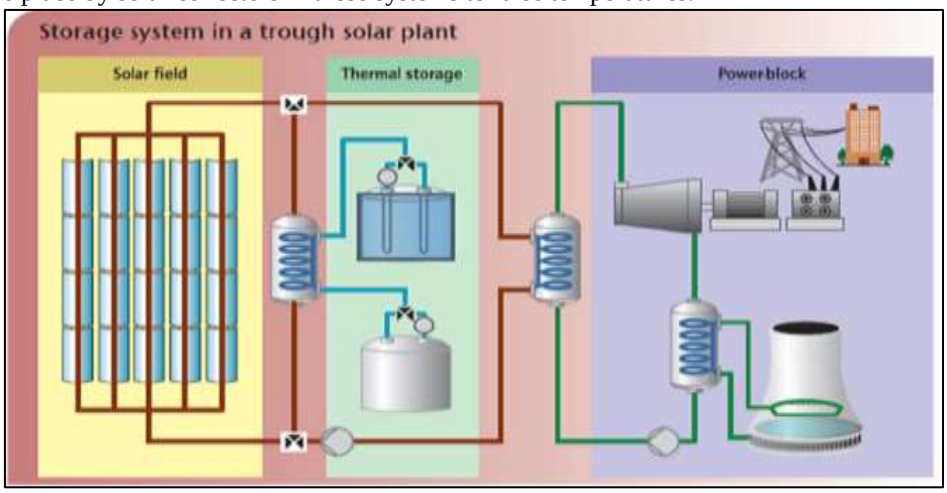

Fig. 2: CSP with Thermal Energy storage [2]

The use of concentrated solar energy in further distinct applications.

Concentrated solar power generates heat, electricity, and other power from the sun. Although CSP is most commonly associated with the production of electricity, it has a wide range of other uses as well, each suited to a particular set of circumstances and demands. Some applications for concentrated solar power:

1) Electricity Generation: The production of electricity is the most typical use for CSP. In a CSP system, high-temperature steam is produced by heating a transfer fluid through the use of mirrors or lenses to focus sunlight onto a receiver. This steam powers a generator connected turbine, which generates energy. Power tower, dish/engine, or parabolic trough systems are the three types of CSP facilities.
2) Desalination: By heating saltwater to produce steam and then condensing the steam into clean water, CSP may be utilized in desalination procedures to convert saltwater into fresh water. This is especially useful in dry areas where freshwater is scarce.
3) Process Heat: High-temperature heat is frequently needed for industrial operations, such as those in the chemical, cement, or metallurgical sectors. This heat may be produced by CSP systems, which lessens the need for fossil fuels and lowers greenhouse gas emissions.
4) Solar Cooking: CSP may be utilized for solar cooking in areas with lots of sunlight and limited availability to conventional cooking fuels. In place of wood or other fossil fuels, solar cookers use concentrated sunshine to heat meals in an environmentally friendly and sustainable manner.

These varied applications highlight concentrated solar power's adaptability, making it a promising and sustainable option for a wide range of energy needs across many sectors and countries. Because of its potential to offer clean, dependable power and heat, it is an important participant in the transition to more sustainable energy sources.

Low temperature heat processes (below 150°C)	Medium temperature heat processes (150-400°C)	High temperature heat processes(above 400°C)
food and beverages	Cement and Lime Production	Solar Thermal Energy
Paper Industry	Heat Treatment and Metallurgy	Glass Manufacturing
Textile Printing and Dyeing	District Heating	Plastics Industry
Pharmaceuticals Industry	Chemicals	Foundry Operations
Plastics Industry	Waste-to-Energy Plants	Refractories Manufacturing
Chemicals Industry	Metallurgy	Steel and Metal Production

Table 1: Industrial Applications for Process Heat Low and Medium and High Temperature [7]

B. Implementations of Solar Power

Solar energy is the heat and radiation released by the sun. Figure 1 shows that solar thermal energy, solar architecture, solar heating, molten salt power plants, and artificial photosynthesis need continually changing technologies. Abundant solar energy is appealing. Ocean, clouds, and land absorb 31% of solar light.

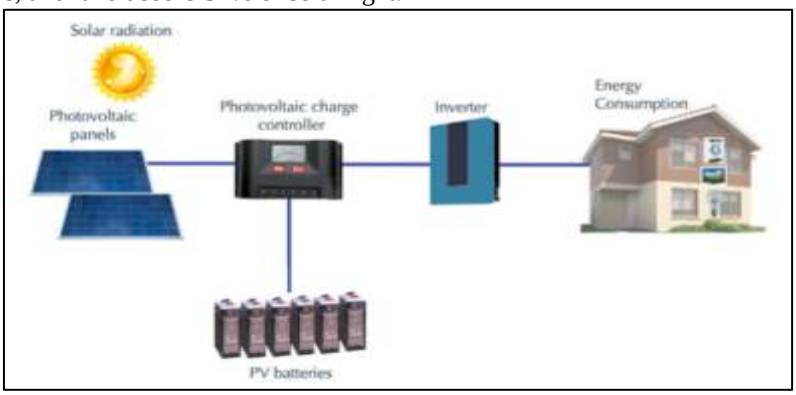

Fig. 3: Solar PV cell technology [8]

It is used for electricity, evaporation, water heating, building heating and cooling, food processing, water pumping, and more.

Cooking food

Water pumping

Heating water

PV cell technology, which transforms solar energy into electricity, is widely used worldwide. Additionally, there are hybrid, inorganic, and organic solar PV systems accessible today. Silicon solar PV devices have led the solar market, although they are expensive, time-consuming, and have other downsides. Solar energy fails at night, in overcast weather, and in sandstorms. PV battery storage is commonly utilized to improve reliability. Thus, alternative materials have been sought to overcome these limits. Current dominance is threatened by new solar PV systems using perovskite, organic, and organic/inorganic hybrid materials.

IV. MERITS OF SOLAR ENERGY

Solar energy offers several advantages that make it a compelling choice for clean and sustainable power generation:

1) Renewable and Abundant: The sun, an almost limitless and reliable source of energy, is the source of solar energy. Solar energy is a fully renewable resource since we can depend on it as long as the sun shines.
2) Environmentally Friendly: The production of solar power is a green and clean energy source. It helps to slow down climate change and enhance air quality because it doesn't emit any dangerous substances or add to air pollution.
3) Reduced Energy Bills: By installing solar panels on their homes or businesses, consumers may significantly reduce their power costs. An important long term cost savings is offered by the choice to either store excess energy or sell it back to the grid.
4) Energy Independence: Solar energy minimizes our reliance on imported fossil fuels, boosting energy security and lowering our sensitivity to variations in energy prices. This independence improves a country's energy resiliency.
5) Low Operating Costs: Solar panels require little upkeep. Routine cleaning and inspections are usually all that is required. Solar systems, once installed, can function efficiently for 25 years or more, resulting in long-term cost benefits.

Solar energy has many benefits, but it also has drawbacks including weather-related power outages and the necessity for energy storage. However, solar energy's many benefits make it a popular clean and sustainable energy source.

V. LIMITATION OF SOLAR ENERGY

Solar energy has various drawbacks:

1) Intermittent Energy Source: Solar energy requires sunshine, which is unavailable at night and changes with weather. Intermittency can cause energy output swings and require energy storage technologies like batteries to maintain power supply.
2) Energy Storage Challenges: Solar electricity is intermittent, hence energy storage is needed. Large scale energy storage is expensive, and efficient and cost-effective solutions are continuously improving.
3) High Initial Costs: Solar panels have become cheaper, but buying and installing them can be expensive. The initial expenditure may take years to pay off through energy savings.
4) Environmental Impact: There may be environmental effects from the manufacture and disposal of solar panels, especially if specific materials and chemicals are used. Nonetheless, compared to fossil fuels, solar panels often have a far smaller environmental impact.
5) Energy Conversion Efficiency: Despite advancements in solar technology, the majority of solar panels only convert energy at a rate of 15% to 20%. This indicates that not all of the solar radiation is turned into electrical energy.

Recent research and technology advances are addressing many of these restrictions. Solar energy is a promising and ecologically friendly renewable energy source that might help reduce fossil fuel use and fight climate change.

VI. CONCLUSIONS

Sustainable energy development is stressed in this study. Solar energy would stabilize energy costs and provide social, environmental, and economical benefits. Solar energy supplies electricity, creates jobs, and protects the environment, promoting sustainable development. A key feature of long term sustainability must be examined. Given the depletion of fossil fuels, inventive clean energy technology implementation is expected and essential. However, solar energy, especially CSP technology, is still developing. PV technology applications are in high demand worldwide as PV systems improve. More work is needed to sustainably produce energy and consider sustainable energy sources. It is dependable and can meet rising electrical demand. CSP technology and solar energy research globally have promise.

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