Solar Energy Focusing on UAE China and Japan

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Abstract

The global photovoltaic (PV) market is experiencing rapid growth, driven by innovations in materials and improvements in silicon-based solar cell efficiency. This study examines the performance, durability, and scalability of new photovoltaic materials, evaluating their potential under various environmental conditions. Focusing on China, Japan, and the UAE as case studies, the research highlights the essential roles of financial investment, technological advancements, and supportive legal frameworks in promoting solar energy adoption. China and Japan are identified as industry leaders, with significant financial commitments and government-backed initiatives that have bolstered their solar sectors. Meanwhile, the UAE has shown substantial progress through financial allocation and regulatory support, positioning itself as an emerging leader in renewable energy. The literature review indicates the UAE's potential for a full transition to renewable energy sources. This study contributes to understanding the factors influencing PV cell efficiency and underscores the need for integrated financial and policy frameworks to advance solar energy worldwide.

1. Introduction

1.1. General Introduction

Several fossil fuel resources are available in the whole world that are ultimate source of energy and have become major part of the modern industrialization. For example, oil, coal and natural gas are playing their role in industrial economy for several years in terms of electric power. From cooking to industrialization and transport utilities, everything is now based on electric power for human activities. Electrical energy has become the world's most important conventional utility nowadays (Z. Zhou *et al.* 2008). With conventional energy generation accounting for over 40% of global primary energy and nearly 40% of global power output, it is now the main source of greenhouse gas emissions worldwide, especially in developing nations (Fang *et al.*, 2022; Xie and Gou, 2024). As a result, fossil fuel power plants emit huge amounts of harmful pollutants into the atmosphere, including CO_2, NO_2, and SO_2. The primary source of the rise in CO_2 emissions in emerging nations is the significant increase in the use of conventional fuels such as coal, oil, and natural gas to meet the world's rapidly rising energy demands (Madsen and Hansen, 2019). As a result, solar energy is the most effective solution to tackle energy poverty and can offer significant opportunities to reduce greenhouse gas emissions and indoor air pollution by substituting firewood for cooking and kerosene for illumination (Hayat *et al.*, 2018). It is considered as the sustainable source of energy that can incorporate into any sector for development and growth of a country if it is used according to the planning for the future concerns. It has high energy efficiency and less negative impacts in our environment. (H.K. Florig *et al.2002).*

Table 1: GHG emissions in Kg/MWh from fossil fuel-based energy sources (Turconi et al., 2013)

GHG Emissions	Natural gas	Oil	Coal
Carbon dioxide equivalent, kg/MWh	380-1000	530-900	660-1050
Sulfur oxides, kg/MWh	0.01-0.23	0.85-8	0.03-6.7
Nitrogen oxides, kg/ MWh	0.2-3.8	0.5-1.5	0.3-3.9

One of the most popular renewable energy sources, solar energy has a lot of potential to promote sustainable growth in many different fields. In principle, we have enough sunshine to fulfil the world's energy requirement (Trivedi, Meshram and Gupta, 2023). For example, the earth's surface receives enough sunlight in an hour and a half to meet the entire world's energy needs. Existing solar technologies use solar cells to convert sunlight into electrical energy, whereas concentrators turn solar radiation into heat energy. Solar cells or PV cells are made of semiconductor material. When exposed to light, semiconductors absorb the energy and transfer it to negatively charged particles within the material. This increased energy enables electrons to flow through the material as an electrical current. The efficiency of a PV cell is defined as the quantity of electrical power going out of the PV cell in relation to the energy entering in as light (Dada and Popoola, 2023). Following (Figure 1) representing the solar cell technologies.

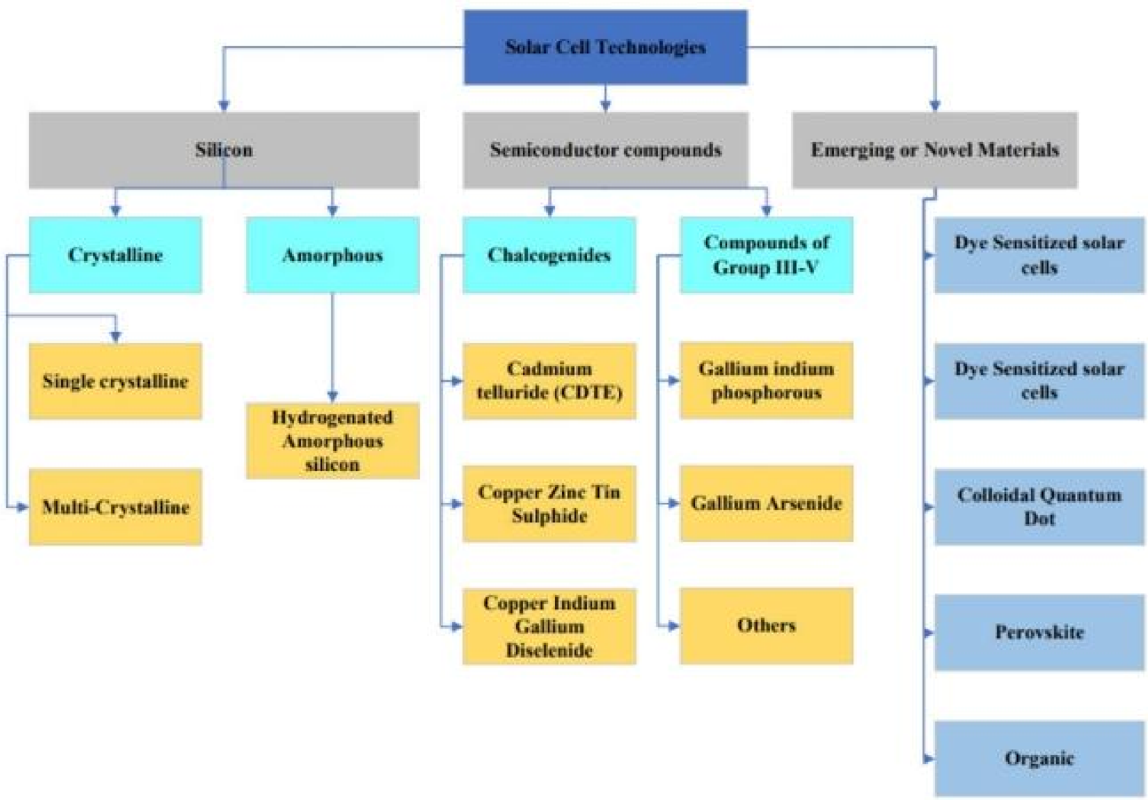

Figure 1 . Technologies of solar cells (Source: Makkiabadi et al., 2021)

The need for sustainable energy sources has increased due to the growing global energy consumption as well as the negative environmental effects of fossil fuels (H. Zhang *et al.*, 2023). Solar energy is unique among these because of its abundance and potential for broad use. It has now become a core center of focus in every part of the world in every country for its use in human technologies because it is the most safe, transparent and permanent source of energy on the planet. (Goswami *et al.*, 2004) By calculating the solar energy fallen on the total area in a country, every country can take an idea about the use of solar energy at industrial, commercial and domestic level. The development of material components, manufacturing techniques, and applications for photovoltaic (PV) and balance of system (BoS) technologies is a key area of research in the contemporary era (Lema, Fu and Rabellotti, 2020). Any region's ability to produce solar energy is influenced by a number of factors, including dust pollution, solar shadowing, temperature, and solar insolation.

Rapid advances in solar technology are improving the present designs of various solar energy conversion devices. Recent advances in photovoltaic cell technology have decreased costs and improved economics, assisting in the spread of solar energy systems throughout various nations, especially in underdeveloped nations where the cost of the photovoltaic system was previously a substantial barrier (Daniela-Abigail *et al.*, 2022). China, the United States of America, Japan, Germany, India, Italy, Australia, the United Kingdom, the Republic of Korea and Vietnam were the top 10 nations in 2019 that installed solar energy systems on various scales (Bulut and Menegaki, 2020). For example, China is consuming solar energy in a large amount with a ration of more than two third of the country area on an annual basis. China experiences solar light hours and radiations on its territory land greater than 2000 h and 5000 MJ/m^2, respectively (Luo *et al.,* 2005). Direct utilization and indirect utilization of solar energy has been applied in many sectors. The vast area of utilization occurs in buildings and industries as they contain heavy work load and machinaries. Solar water heater systems, solar heating systems in buildings, solar system in refrigeration and air conditioners have become the common and most extensive source of solar energy these years. (Tsur and Zemel, 2000; Muneer *et al*., 2006). Another example is taken under course of UAE. UAE is almost facing high solar energy because it is present in the middle east and is under the direct light of sun. It has the huge potential for photon consumption, they can increase their country's economy at higher levels by making solar equipments and further growth in power consumption via solar energy. (El Chaar, L.; Lamont, L. 2010).

Table 2: PV and CSP capacity of various countries

Country	PV capacity (MW)	CSP (MW)	References
China	392436	596	(Li et al., 2014; He and

			Kammen, 2016; Zhang et al., 2020)
India	62804	343	(Ramachandra et al., 2011; Kapoor et al., 2014)
Israel	4169	242	(Becker, 2001; Fischhendler et al., 2015)
Japan	78833	-	(Yang et al., 2001; Ohtake et al., 2013)
Kuwait	43	50	(Bou-Rabee and Sulaiman, 2015)
Mongolia	95	100	(Adiyabat et al., 2006)
Pakistan	1243	-	(Stokler ¨ et al., 2016; Tahir and Asim, 2018)
Saudi Arabia	390	50	(Zell et al., 2015; Almarshoud, 2016)
Turkey	9425	1	(Sozen ¨ and Arcaklioğlu, 2005; Sozen ¨ et al., 2005)
UAE	2940	100	(Islam et al., 2009; Gherboudj and Ghedira, 2016)
Yemen	257	-	(Khogali et al., 1983)
Egypt	1704	20	(Effat, 2013, 2016)
Morocco	318	540	(Ouammi et al., 2012; Bouhal et al., 2018; Tazi et al., 2018)
France	17410	9	(Notton et al., 2017)
Germany	66552	2	(Mainzer et al., 2014; Romero Rodríguez et al., 2017)
Italy	25077	6	(Bocca et al., 2015)
Spain	18214	2304	(Carrion ´ et al., 2008; Izquierdo et al., 2011; Yousif et al.,

			2013)

Shubbak's (2019) stated that the BoS's components are essential for attaching, physically attaching, and chemically shielding the cells into panels. They also electronically control the output levels of the cells so that they may be used, stored in batteries, or sent into the utility grid. The system also includes solar-powered portable devices for operational monitoring and testing. PV systems, whether they distributed or centralised utility-scale, are therefore made up of two different sets of components for solar cells and BoS, including electronics, energy storage, and PV panels. However, the effectiveness of energy conversion and storage remains a significant problem in the field of solar energy (Ardente, Latunussa and Blengini, 2019). To meet this challenge, photovoltaic (PV) technology research and innovation must continue in order to improve the efficiency and dependability of solar energy systems. One of the most effective approaches for producing power sustainably from renewable sources is to use PV technology. Following Figure 2 illustrates the basic schematic diagram of photovoltaic system:

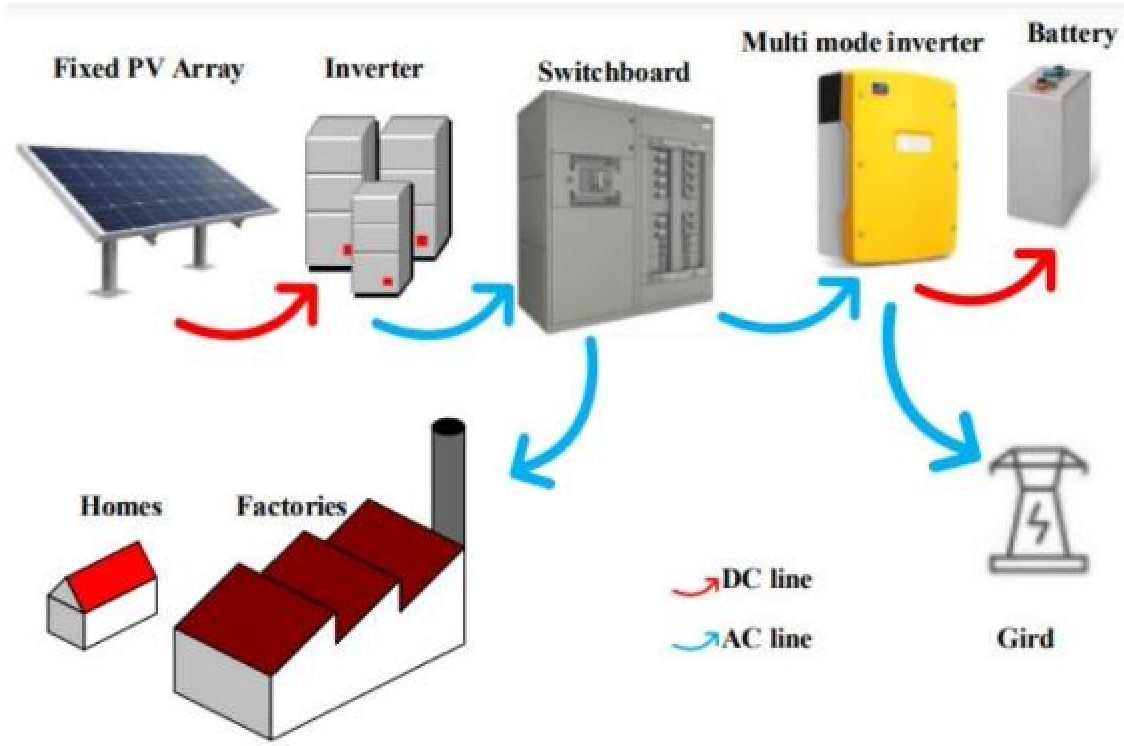

Figure 2. Schematic representation of basic PV system (Li et al., 2021)

Solar cells maximize power conversion efficiency (PCE) by using incoming photon energy to generate usable electricity. Furthermore, one expects the highest performance, a long operational lifetime, low manufacturing costs, and minimal environmental hazards from each component of a photovoltaic system. Combining photovoltaic technologies encompasses a wide range of devices, such as organic, dye-sensitized, and perovskite solar cells (Almora *et al.*, 2020). These devices are fabricated from various materials such as polymers, molecules, or colloidal precursors, in addition to many other material classes including oxides, chalcogenides, and silicides. These technologies usually relate to families of materials rather than individual absorber materials, and in some situations, other device designs are required. Every new class of materials or developing photovoltaic technology may disclose hitherto undiscovered behaviours. Research in developing photovoltaics is primarily focused on long-term performance stability, particularly for organic and hybrid materials that are prone to quicker degradation routes (Klugmann-Radziemska and Kuczyńska-Łażewska, 2020). In actuality, inline tests conducted under one solar light intensity at 65 °C for 200 hours or at 85 °C for 1000 hours, or eight days or six weeks, respectively, may already provide a satisfactory assessment of stability (Daniela-Abigail *et al.*, 2022). In particular, 200 hours may be a more appropriate time frame for the average length of university research projects, especially those using more recent and emergent PVs. The expansive development of solar energy plants, along with effective utilisation, promises to boost energy supply and reduce reliance on fossil fuels. However, solar energy's contribution to energy consumption is still at the minimal level, and it faces various economic and environmental hurdles (Solak and Irmak, 2023).

In order to produce energy, photovoltaic systems typically use semiconductor materials; silicon-based solar cells are the most widely used type like, single-crystalline (sc-Si) or multi-crystalline (mc-Si) crystalline silicon (c-Si) photovoltaic (PV) cells or modules. PV modules are essential parts that can provide electronic loads with high energy density while operating in challenging outside conditions (Feng *et al.*, 2022). These solar cell types make up more than 90% of the PV market and are the most widely used ones. PV modules need to be at least 14% efficient, cost less than 0.4 USD/Wp, and have a minimum 15-year service life. Wafer-based crystalline silicon technologies now meet the most requirements because to their high efficiency, low cost, and long service life. Because they are readily available, they are also expected to dominate the production of PV electricity in the future (Ardente, Latunussa and Blengini, 2019). While typical industrial cells are limited to 15–18%, the highest known energy conversion efficiency for research on crystalline silicon photovoltaic cells is 25%. Since it is difficult to optimise these cells, new approaches have been developed to overcome the 25% efficiency barrier. These include wafer-slicing technologies, equipment for manufacturing solar cells and modules based on ultrathin wafers, and equipment for direct slicing ultrathin (50 m) wafers with minimal kerf loss (Cheng *et al.*, 2024).

Superior polycrystalline ingot technologies that surpass the performance of monocrystalline cells, contact-forming procedures, and materials at a lower cost than burnt silver paste and screen-printing are employed (Guo, Dong and Ren, 2023). Low-concentration and high-efficiency module technologies are employed to lower the total cost of the PV system. Semiconductor devices with spectrally selective absorbers are crystalline silicon sun cells (Dada and Popoola, 2023). The absorption factor of a photovoltaic cell is the percentage of incident solar irradiance that the cell absorbs. This absorption factor is one of the main factors regulating cell temperature under operating conditions. It is possible to compute the absorption factor empirically by using transmission and reflection data (Klugmann-Radziemska and Kuczyńska-Łażewska, 2020).

Low-cost solar cells built on hybrid polymer semiconductor materials with a light-harvesting substance that catches photons with energy equal to or higher than the band gap are among the other materials now in use. In most organic semiconductors, this results in the formation of excitons, or bound electron–hole pairs, which range in size from 5 to 15 nm. These excitons dissociation to the distinct charge carriers. The photoactive material is paired with a strong acceptor of electrons with a high electron affinity to boost exciton dissociation and increase PV cell efficiency. Thin films (TF) only account for 10% of the worldwide PV market. However, academics all around the world are looking at various ways to generate power more effectively utilizing solar cells, therefore R&D for new materials is now underway (Yifeng Chen *et al.*, 2022). Solar energy has always been encouraged by almost all countries at an international level. Incentive policies should be considered now at an international level for adoption of these policies. These policies must include cost effectiveness and market level problems that can be addressed by solar companies for solar use. Including China every country supports the system of solar renewable energy with its commercial development. (Tsai and Chou, 2005; Okoro and Madueme, 2004). The utilities, application incentives, forecasts, growth and development of solar energy is passing the policy implementation at a global level. There is a prediction that total urban areas, rural lands and public and urban housing societies, industries and institutional sectors etc will be boomed by the use of solar energy in every technology in future. This will be going to use the sun energy for beneficial purposes of humankind.

1.2. Background and Rationale

The photovoltaic market has made significant progress in the last several years, especially in the creation of novel materials for solar cells (Trivedi, Meshram and Gupta, 2023). The industry-dominant traditional crystalline silicon solar cells have significantly increased in efficiency. They must investigate substitute materials and methods, though, as they are getting close to their theoretical efficiency limitations (Guo, Dong and Ren, 2023). The objective of this study is to examine new materials for photovoltaic applications, with an emphasis on how they could improve solar cell efficiency. Through the investigation of the main research topic, "How can advanced photovoltaic materials improve solar energy conversion efficiency?" This study aims to promote the creation of solar energy systems that are more sustainable and efficient.

The market for PV-based power units have grown significantly over the course of the last few years as people’s interest in green energy increased which resulted in lowering of PV costs, and improvement in efficiency of the unit (Madsen and Hansen, 2019). Large-scale power generation is now dominated by crystalline silicon (c-Si) PV cells due to their easy installation, low maintenance costs, low cost of manufacture, and mass production (Lema, Fu and Rabellotti, 2020).

Perovskite solar cells have gained popularity because of their low production costs and excellent power conversion efficiency. Perovskites have demonstrated efficiencies of more than 25% in laboratory conditions, positioning them as viable rivals for the development of next-generation solar cells. However, the scalability and temporal stability issues must be solved to permit commercialization on a vast scale. Organic photovoltaics (OPVs) have a bright future as well, which is mainly due to their lightweight design, versatility, and promise for low production costs. While acknowledging the improvements in OPV efficiency, it is necessary to highlight the need for greater study into the devices' long-term stability and practical performance (Ahmad, Khan, & Kim, 2022; Kalogirou, 2023; Rabaia et al., 2021).

By the end of 2019, the total installed power capacity with a solar PV system had reached 627 GW, able to serve around 3% of worldwide energy consumption while contributing 5% to a reduction in global electricity-related CO_2 emissions. This installed capacity can increase to 2.1 TW by the end of 2025, up from 773.2 GW in 2020 (Cheng et al., 2024; Agrawal et al., 2022). Despite the fact that solar technology is an established renewable energy source, much more study and research is still needed, especially in the areas of variables influencing photovoltaic efficiency and, therefore, environmental performance. Of these, the temperature of the PV panel is regarded as a critical aspect since it can be properly controlled to enhance the panel's usable life, performance, and environmental profile (*Renewable energy market update*, 2022). The percentage of incident solar energy that a typical PV module converts into electricity ranges from 5% to 40%. The remaining radiation is either deflected or converted into heat. The latter results in energy losses (e.g., Si-based PV modules' peak power output drops by around 0.25%–0.5% for every degree Celsius increase over 25 °C) and shortens the panel's lifespan due to thermal degradation (Feng *et al.*, 2022; Sajjad *et al.*, 2019).

In 2021 a global market share of over 95% was owned by monocrystalline and polycrystalline silicon (Si) as the most common semiconductor materials that were being used in photovoltaic cells. The source of silicon, metallurgical grade silica mining, may produce silica dust, which might cause workers to suffer from serious respiratory conditions. Consequently, an important step in the manufacturing of semiconductors is the extraction and purification of silicon. More than 90% of the polysilicon manufacturing market was controlled by the Siemens chemical vapour deposition process, which used the trichlorosilane ($SiHCl_3$) precursor. The fluidized bed reactor (FBR) method, which used the monosilane (SiH_4) precursor, followed with a 3%–5% market share. H_2 reduction and hydrochloric acid chlorination are two common Siemens processes. A large amount of hazardous pollutants, such as dust, silicon tetrachloride, volatile organic pollutants, nitric acid, hydrogen fluoride, and other byproducts, would be produced in these processes (Lema, Fu and Rabellotti, 2020).

Furthermore, heavy or rare metals are needed by the majority of solar cell technologies in order to increase photovoltaic conversion efficiency. The type of cell being manufactured determines how much metal is present in PV panels (Yifeng Chen *et al.*, 2022). Notably, crystalline silicon (c-Si), amorphous silicon (a-Si), and copper-indium-gallium-selenide (CIGS) PV cells have substantially lower cadmium (Cd) contents than do these other PV cells; in contrast, c-Si PV cells have comparatively high lead (Pb) contents. Even at modest levels, the extremely poisonous metals, including lead and mercury, can cause cancer. If disposed of improperly, they would pose major risks to the environment (H. Zhang *et al.*, 2023). For instance, if appropriate control measures were not used, precipitation seeping through damaged modules disposed of in an open area or landfill may pull down metals within the modules, release them into the leachate, and pollute the surrounding soil and water (Xie and Gou, 2024). In a similar vein, a variety of other dangerous substances that are employed as solvents to remove dust and grime off solar panels, such toluene and acetone, may leak into the surrounding environment (Hayat *et al.*, 2018).

Furthermore, large-scale PV power facilities may have an impact on microclimates. The photo-electricity conversion efficiency of new-generation modules is generally between 17.4% and 22.7%, with more than 77% of solar output wasted as heat. The physical shielding and absorption of solar radiation by PV panels would result in a "PV heat island effect" by cooling the ground surface of solar parks and heating the ambient air around the PV panels (Xu *et al.*, 2023). The fast paced adaptation of PV panels in urban areas may alter the present surface albedo and radiation balance in those areas, which can results in disturbance of the wind field, evaporation, and precipitation patterns of the region (Sajjad *et al.*, 2019).

Previous research frequently concentrates on increasing efficiency without offering thorough evaluations of these materials' size complexity and temporal stability

(Solak and Irmak, 2023; Ahmad, Khan and Kim, 2022). To the best of our knowledge, no study has comparatively evaluate the efficiency and viability of photovoltaic material in China, Japan, and UAE. There is a need to assess the viability of various photovoltaic materials for large-scale applications, more thorough comparison studies. The research aims to offer a comprehensive knowledge of the efficiency and scalability of modern photovoltaic technologies through the combination of laboratory experiments and field tests.

1.3. Significance of the Study

The aim of this study is to investigate innovative materials for solar systems in order to increase efficiency. Despite tremendous advancements in crystalline silicon solar cells, their efficiency is approaching the theoretical maximum of 29%. Thermalization losses, sub-band gap absorption, and non-radiative recombination all contribute to its low efficiency. The literature has extensively documented concerns regarding the stability of different photovoltaic systems and the cost-performance of building materials. Researchers are looking at other materials and techniques to overcome these limitations. Improved solar cell efficiency can reduce system costs, boosting the affordability and accessibility of renewable energy. This might help accelerate the worldwide transition to a sustainable energy future by increasing the usage of solar energy.

Photovoltaic materials are revolutionizing the durability, dependability, and efficiency of solar energy systems that include organic photovoltaics, perovskites and quantum dots. These materials offer unique advantages and challenges, such as high efficiency, stability with flexibility and low-cost production, as well as tunable absorption properties. However, their durability remains a major concern as most PV cells have a specific life span of a few years. To achieve future success, these technologies must be improved in a way that overcomes the current limitations in stability and durability. Ongoing research and development should focus to unlock the full potential of these advanced materials and contribute to the adoption of sustainable solar energy solutions on a larger scale. Another critical issue that is face by majority of the PV users is the energy conversion and storage efficiency of these cells. These issues are the main reason that makes solar energy less efficient. If these problems can be overcome there will be endless potential for the upcoming generations to utilize solar power as the sole energy source. The development of next-generation solar technologies with improved efficiency, stability, and scalability may be facilitated by the study's findings.

1.4. **Objectives**

The main objectives of this study focus on the performance, durability, and dependability of the new-generation photovoltaic materials. This study aims to

1. Evaluate the efficiency of innovative photovoltaic materials such perovskites, organic photovoltaics, and quantum dots for solar energy conversion.
2. Assess the stability and durability of these materials under different environmental situations.
3. Evaluate the scalability and lifespan performance of innovative photovoltaic materials vs. traditional silicon solar cells.
4. Identify elements that affect the efficiency and dependability of modern photovoltaic materials.

1.5. **Research Overview**

This research will comprise of six main chapters. Chapter 1 provide the brief overview of research background, rationale, and aim of this study. Chapter 2 will highlight the overview of literature on the subject under investigation. Chapter 2 will be followed by chapter three that will describe the methodology undertaken to complete this research. Chapter four will report the research results whereas chapter 5 will discuss the results in comparison to literature review. Lastly, chapter six will conclude this research.

Chapter 2: Literature Review

2.1. Global Solar Energy Context

Energy is necessary for the social and economic progress of a country and globally 80% of fossil fuels fulfill this demand. The traditional electricity generation technologies are fossil fuel-based and exert pressure on the ecosystem and environment. Moreover, these are indefensible due to the scarcity of resources in the future (Zhang et al., 2022). Coal, oil, petroleum, and natural gas are non-renewable energy sources and cause environmental effects. Among all non-renewable sources, coal contributes a major portion of electricity generation (Lyu et al., 2024). However, it is claimed that by 2035 thirty-seven percent of electricity generation from coal will be declined because of non-renewable nature. It is estimated that in developing countries mega-scale industries consume approximately 50% of total energy (Sahu, 2015). Therefore, different organizations like the World Energy Council (WEC), the International Energy Agency (IEA), the International Atomic Energy Agency (IAEA), and the US Energy Information Administration (EIA) have projected that future energy demand will increase by 40-50% and these fossil fuel-based resources will not be enough to fulfill this demand. This increasing demand of energy and depletion of fossil fuels pose a threat to our energy security.

The necessity for better and new energy sources has become challenging with increasing energy demand and maintaining sustainable energy growth. Moreover, the environmental impact of GHG has surged the demand for green, sustainable, and renewable sources for the world. Excessive emissions from industrial chimneys, transportation, and agricultural burning have resulted in climate change and increased the earth's temperature by trapping carbon dioxide (Sun et al., 2021). In this regard, different countries like Japan, South Korea, the United Kingdom, China, and European countries have committed to a goal of net zero emissions of carbon by 2050 through consenting vows against global warming (World Economic Forum, 2021). In response to the vow, many countries have started to invest in low-carbon energy technologies to replace fossil fuel-based sources. Such steps towards zero emissions are very crucial as global warming has increased to its alarming stage.

The shift towards renewable energy sources is significant for humans and planet viability. Therefore, resources like wind, geothermal, hydropower, tidal, and solar energy are suitable for energy generation globally with minimum environmental impacts. By 2050, the mission of 36.9 Gt carbon dioxide emission reduction will be possible if technologies like Solar (PV and CSP), onshore and offshore wind power, geothermal, biomass, tidal, and hydropower energy are adopted according to the perspective of (IRENA, 2021) global energy transition. Among them, solar energy is the most feasible source as abundant in nature with negligible negative effects (Gallego et al., 2019). Moreover, it has now become a hot and emerging topic of discussion among energy stakeholders and governments globally. It is considered the cleanest and cheapest energy source among all to substitute traditional energy sources for increasing the social, economic, and environmental growth of a country (Hao et al., 2022; Krishnan et al., 2023; Ndzibah et al., 2022). Solar energy is abundant and non-polluting, in contrast with finite fossil fuels such as coal and petroleum. Despite its vast potential, only a small fraction of it is used to convert it into electricity. The part of solar energy in sustainable development involves optimizing energy systems, promoting clean energy infrastructure, and reducing emissions. The share of PV solar electricity in global electricity will reach 16% by 2050 according to the international energy agency (IEA) prediction (IEA, 2010). Moreover, countries with abundant solar resources, as lying in "Sunbelt" have tremendous potential for solar energy technology. In these countries, solar energy can contribute in meeting clean energy targets through investments and support environmental protection without hindering economic development.

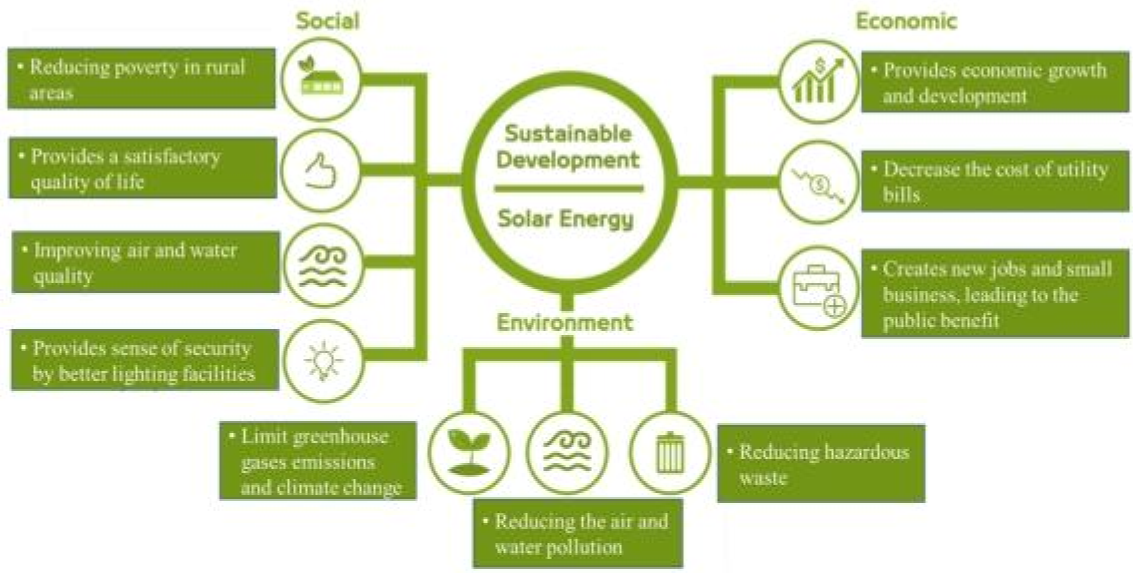

Figure 3 solar energy and three pillars of sustainable development (source: Obaideen et al., 2021)

Solar energy is the light and heat of the sun, which could be transformed into electric energy or heat using technology such as photovoltaics or solar heating systems. Photovoltaic systems use semiconducting materials to convert light into electricity. They can be made up of one or more solar modules, each with numerous solar photovoltaic cells. Photovoltaic systems generate electricity that is fully carbon neutral. They can be put on roofs or on the ground. The size of a single plant can range from small-scale residential to utility-scale power stations, making it especially appealing to tiny households.

Electricity generation from solar energy is carried out through utilizing solar irradiance. There are two technologies involved: photovoltaics and concentrating solar power (Azad and Parvin et al., 2022). The technology of photovoltaics uses the photoelectric effect to convert sunlight into electricity from chemicals like silicon acting as a semiconductor. On the other hand, concentrating solar power focuses the sunlight on the high-temperature receiver that converts the solar energy into thermal energy. These semiconductors are minerals like cadmium, indium, germanium, gallium, selenium, and tellurium but are present in low a quantity on Earth and mostly extricated as by-products of primary metals mining. These are present mainly only in China and the USA which increased their price in recent years with the advancement towards soar energy (Stratiotou Efstratiadis and Michailidis, 2022). Generally, these are categorized through their easy maintenance, predictable energy output, minimum cost, environment-friendly components, and flexible installation from small to large-scale utility (Zhang et al., 2021; Ndzibah et al., 2022). It is believed that by 2050 solar photovoltaic technology is the leading technology for decarbonizing the planet Earth and minimizing carbon emissions to as low as 10 Gt (IRENA, 2019). Many countries have made policies and regulations for fostering renewable energy resources and sustainable growth of the PV sector. This has also encouraged the solar energy-related industries in their development. Among them, 57 countries have set their goals for achieving 100% renewable energy utilization (REN21, 2018). They have introduced different steps like portfolio standards, production incentives, feed-in-tariffs, tax credits, quota requirements, pricing laws, and trading systems (Chen et al., 2020). China has introduced different policies to foster the use of renewable energy like federal investment, portfolio standards, and tax credits. Moreover, to support the development of projects based on renewable energy guarantees of federal loans have also been provided in the USA (Mehos et al., 2016). Similarly, in China, solar power research programs, operational subsidies, and investment subsidies are aimed at carrying 27.5% parts of renewable energy by 2050 through support of different programs (Mir-Artigues et al., 2019).

The largest producer of solar energy electricity in the world is China. In 2018 the electricity production was 175GW, in 2020 it reached 254 GW from solar energy. (Figure 2) shows electricity generation in 2018 in major countries of the world.

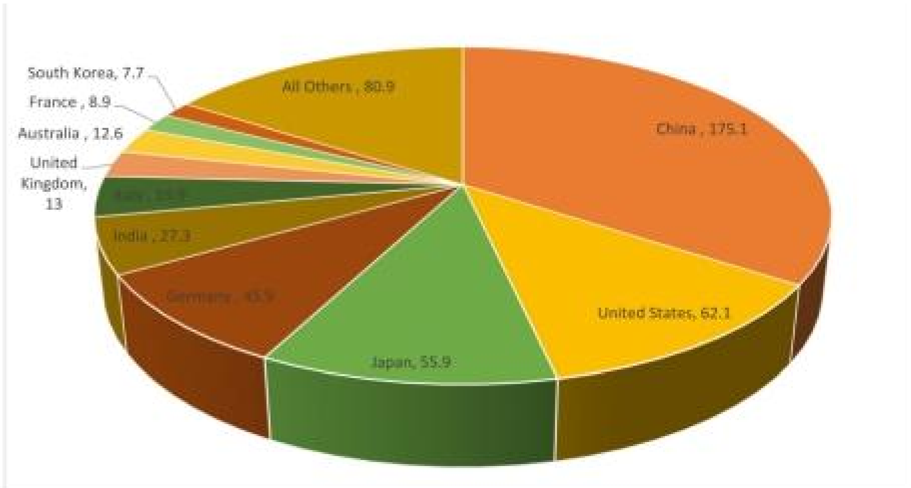

Figure 4. World electricity generation from Solar energy in 2018

According to the forecast for 2021, electricity production in China alone will reach 44 GW in 2023 (Yoo et al., 2021). Additionally, electricity production increased in Persian Gulf bordering countries in 2019 and 2020. For Example, in UAE largest world solar project was installed with 1.2GW capacity. Almost 3.2 million panels were used in this project, fulfilling the 90000 people’s energy demand and minimizing one million metric tons of carbon dioxide emissions (Zubair and Awan, 2021). Moreover, Japan and Saudi Arabia are on the path after signatory to a memorandum to develop a huge solar project that could produce 100 GW of electricity by 2030 in Saudi Arabia.

2.2. Solar energy in China

In China the sector of solar photovoltaic has expanded substantially in the previous decade. The government has made significant efforts to improve its solar capacity, which has grown from 4.2 gigawatts in 2012 to more than 390 gigawatts by 2022. In the previous year, new solar capacity additions set a record of about 85 gigawatts. China is by far the world's top solar market, accounting for the majority of total solar capacity installed and new capacity additions. China's solar capacity is expected to grow in the next years, with new installations ranging from 413 to 569 gigawatts between 2022 and 2026.

"Medium- and long-term development plan for renewable energy in China" was established in 2007 by the Chinese government which declared that by 2020 energy consumption from renewable energy resources will increase by 15%. Setting such targets is helpful in sources of renewable energy development and energy planning methods (Sahu, 2015). The major constituents of the model are (i) the implementation of the national energy target (ii) the Plotting of more effective incentives (iii) the scheme for enhancing the reliability of renewable energy (Liu et al., 2012). The RE policy of China can be categorized into three levels of policies. The policy of the first level describes the guidance and directions for renewable energy development for the advantage of the environment. The second-level policy promotes renewable energy technologies in rural areas by providing the major objectives and development. Similarly, the third-level policy provides managerial guidelines and specific incentives. Renewable energy law in China was reformed in 2009 and aided by two types of funds. The first fund is collected from all end users of electricity as an RE surcharge at a 0.8 cents per KWh rate and the second fund is rightly managed by the Ministry of Finance in China. China is located in the eastern region of Asia and solar energy flux is 3360 to 8400 MJ/m^2. On land solar radiation energy is about 1700 billion tce annually (Liu et al., 2009). China has given a major focus on provinces acquiring the major solar radiations present in the western part. However, these regions face issues like electricity distribution, grid connection, and transmission. Therefore, in this regard "New FIT Regulation" was introduced by the Chinese government. This a scheme for four regions of the country for the establishment of huge-scale ground-mounted systems. The new level of this scheme is for the minimization of current FIT of up to 25% in different regions. The level of Solar radiation is also determined by this scheme ensuring the achievement of 8% IRR in four regions.

In 2012, the charges of an average grid connection system and module decreased from RMB 10 Yuan/Wp to RMB 4.5 Yuan/Wp. The top 10 modules manufactured in China were of 16.9 GW production capacity with an annual yield of 12.18 GW production. Similarly, in 2012 China contributed 61.8% of global output by delivering

PV modules of 23 GW capacity which is a 9.5% increase from the previous year 2011. China was the foremost country in manufacturing solar cells and hold 50% of solar total installed capacity (Fang et al., 2012). China continues to grow at an unprecedented pace in solar installation capacity and reached at 28.05GW at the end of 2014. This was 30-fold increased capacity from the year 2010 which was 0.9 GW. The total electricity generation was 25TWh in 2014 and contributed about 0.45% of the country's total electricity consumption (CEC, 2015).

China is playing a huge role in PV electricity supply. According to guidelines of the 13th Five-year Plan by 2020 more than 110 million KW of solar installation was planned (National Energy Administration, 2016). It was also predicted that the global installed capacity of solar energy 40% will be shared in China by 2023 (IEA, 2018). Similarly, according to the Chinese renewable energy development report of 2018 wind and solar power were the main electricity generators among other renewable energy sources (NDRC, 2019).

In 2022 China introduced its 14th five-year plan targeting 33% of electricity generation from renewable by 2050 including 18% from solar technologies. In 2023 Solar energy continues as a larger contributor to China's clean technology economy. The recorded growth valued 1tn yuan as a new investment, services, and goods and 63% increase yearly as the value increased from 1.5tn yuan in 2022 to 2.5 tn yuan in 2023. The growth in 2023 was unprecedented in both the manufacturing and installation industries. For installation purposes, two huge initiatives introduced by the central government are a "Clean energy base and whole country distributed solar" programs. Similarly in an annual legislative meeting of 2023 spring, 15 other provinces organized solar energy development of industry in their agendas. The solar energy installation development from year 2010 to 2023 is shown below:

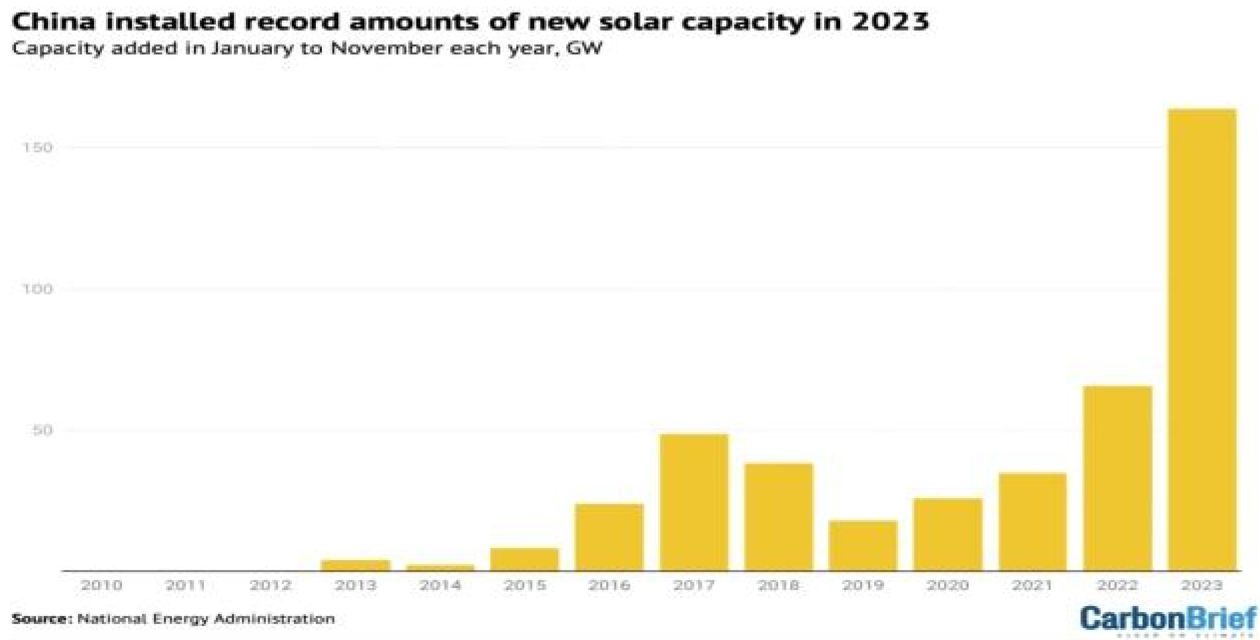

Figure 5 solar installation in China from 2010 to 2023

Similarly, the manufacturing industry recorded positive growth in 2023. In 2023 (Figure 4) China increased 300GW of cell, modules, and wafer production capacity and 340GW of polysilicon according to IEA (Yang et al., 2023). The top countries of solar energy installation have relied 60-80% on China to import solar cells. The high production in China is due to low labor costs, low overhead, and investment costs. Therefore, the cost in China is 35% less than in Europe, 10% less than in India, and 20% less than in the US (IEA, 2022). Similarly, China is leading the world in installation as well. According to the report, the installation of Solar PV increased from 72GW to 1TW in 2011 to 2022. Its part in production increased from 60 to 80% in 2021 (IRENA, 2022).

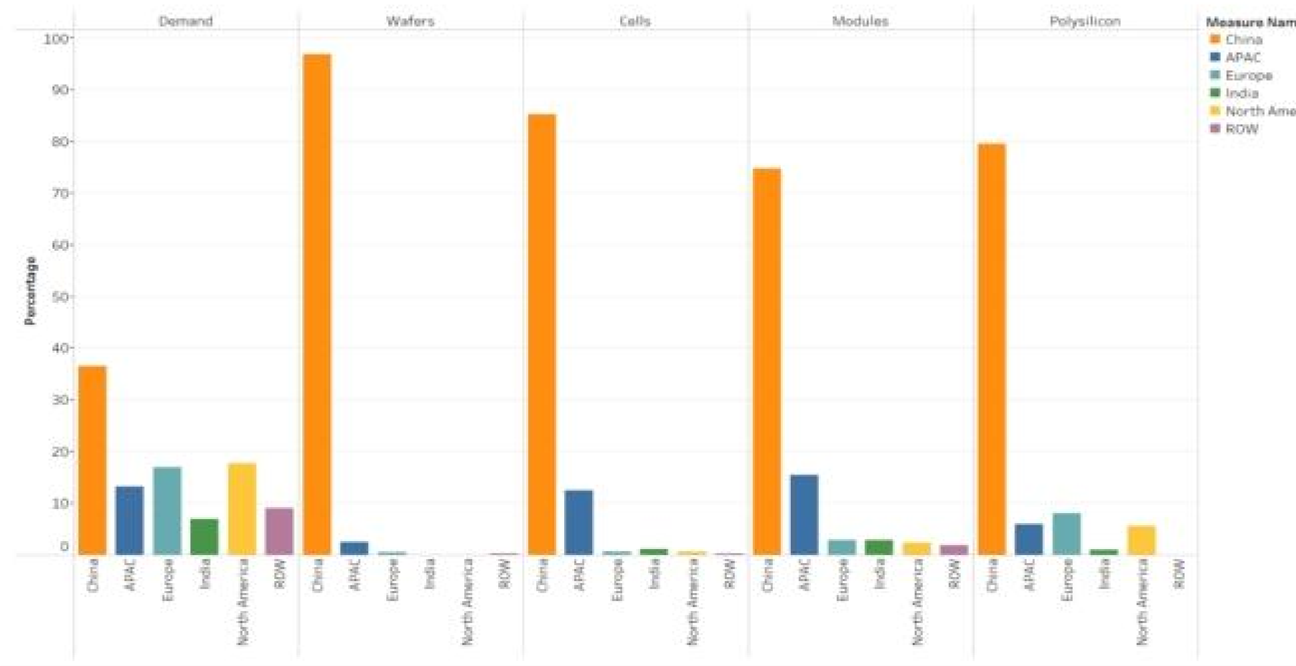

Figure 6 Major producers of cells, modules, wafers, and demand globally (source: Chadly et al., 2024)

According to the International Trade Center in 2022, China exported 4000445 tons of singular PV cells, and 42377643 tons of assembled PV cells, to approximately 200 countries globally adding a total of 46378088 tons of PV cells (International Trade Center, 2023). Overall, china has experienced remarkable growth in solar energy sector. Fueled by strategic planning, government support, and significant investments, china is emerging as dominant solar energy player over the past few decades. Chinese government's support to such initiatives through tax incentives, subsidies, and favorable policies proved to be remarkable steps in country's move to become global leader in solar energy. Due to its vast domestic market and exponential export potential, china's solar industry get benefits to produce large quantity of solar panels at reduced price. This industry in china has not only focused on domestic consumption but also on significant export industry.

2.3. Solar energy in Japan

Japan is the world's fourth greatest energy consumer, despite its population of 120 million, which accounts for only 2.1% of the global population. Oil and coal are the most widely used energy sources in Japan, accounting for more than 60% of total energy consumption. Japan has limited resources, thus around 80% of its oil is imported from OPEC, particularly the United Arab Emirates, Saudi Arabia, Kuwait, and Iran. The majority of coal originates from Australia and the United States.

Energy policies have played a major part in the development of renewable energy resources in recent decades (Wen et al., 2021). Solar PV has greater potential to reduce emissions and fulfill energy demands increasing day by day among all resources (Sen and Ganguly, 2017). However, high cost of solar energy is the main hindrance to installation. The Japanese government has tried to execute subsidies and incentives for promoting solar energy since the 1900s (Ito, 2015). In Japan, the Ministry of Economy, Trade and Industry is responsible for promoting the development of renewable energy. A national subsidy program was introduced in 1994 for residents that give 50% subsidy on the cost of PV system installment (Ito, 2015). This policy played an important role in the quick growth of photovoltaics in Japan in the 1990s. Two years before the completion of the subsidy program in 2003 Japanese government introduced another energy policy named as renewable portfolio standard to continue PV development. This new policy mandated the electricity suppliers to produce a specific amount of electricity from renewable energy. However, on account of the closing of other subsidies, there seems of less interest in renewable energy development (Chowdhury et al., 2014). Therefore, the policy failed and reduced solar energy development.

The government of Japan again launched the excess-produced electricity purchased system for solar energy in 2009. This policy was not as fruitful as expected by the government and only targeted the residential installed PV systems. Therefore, the Japanese government again introduced a subsidy program to grow again. Moreover, in 2010 only 0.3% of the solar energy contributed in electricity generation despite many efforts (Japan For Sustainability (JFS), 2010). According to Japan's Strategic Energy Plan 2010, nuclear energy will become a major source of electricity supply by more than 53% by 2030 (World Nuclear Association, 2020). the major turning point for renewable energy development in Japan was the Fukushima nuclear accident in 2011 and the Great East Japan earthquake. Therefore, the Japanese government decided to evolve a reliable, alternative to nuclear energy and a stable energy supply for the future (Morita, 2012). An act was passed in 2012 by electricity companies for special measures for renewable energy as a fixed-price purchase system afterward referred as FIT. This policy aimed to more investment in renewable technologies by producers with long-time contracts and a fixed price of purchase (Couture et a., 2010). This new FIT act has majorly contributed to solar energy development. It aimed to achieve 20-35% of electricity supply from solar energy by 2030. It offers two solar energy methods with varying time duration and fixed prices (Muhammad-Sukki et al., 2014). It provides huge benefits for investors and attracts large capital to the PV market. Japan was the world's 2nd largest solar market by the end of 2017 (Yamada and Ikki, 2017). Many implementation problems led to criticism despite of successful promotion of solar PV with the FIT Act. Therefore, the major amendment was introduced in 2016 revised FIT Act was implemented in 2017. The part of PV public energy demand increased up to 7.4% in 2019. Japan is ranked as a leader in PV energy development and fourth on installation rank in the world (ISEP, 2020).

Japan has also emerged as a kingpin in solar energy innovation. There are a lot of companies like Panasonic and Mitsubishi that are working towards better solar technologies. Although Japan is contributing massively in the production of solar panels it lags in solar electricity production with a major contribution to the national grid from nuclear energy. The country is exploring many new solar technologies, such as floating solar panels, to further expand its solar capacity.

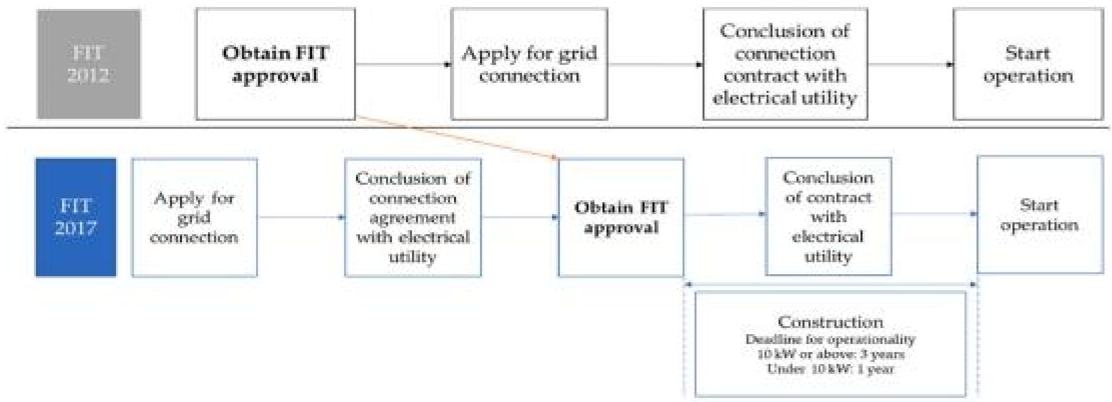

Figure 7 process of approval of FIT (Wen et al.,2021)

2.4. Solar energy in UAE

UAE is known as the initializing country in the Middle East shifting towards renewable energy sources from conventional sources. However, it is known as a top natural gas and oil producer country. However, due to their negative environmental effects UAE announced to shift towards clean energy sources and minimizing carbon emissions (Salim and Alsyouf, 2020). In addition, the geographical location showed huge potential for solar energy to produce electricity as the country receives huge levels of solar irradiance annually. In UAE the average global horizontal irradiation is 227 Wh/m^2 yearly (Abuzaid et al., 2022).

Even when UAE was a non-annex country in the United Nations Framework Convention on climate change it has introduced many green power plants in the last decade. That includes Masdar City in 2006, Sheikh Zayed Solar Park in 2013, and Shames Solar Power Plant in 2013 on purpose to reduce fossil fuel dependence for electricity accounts for about 90%. UAE has integrated its energy strategy to achieve 24% of electricity generation from clean sources including 5% from solar energy (Reiche, 2010; Sustainable Environment and Infrastructure, 2015). Despite solar energy being abundant in the UAE, power generation is still limited by seasonal variations and disturbances in the working of solar energy systems. In reality, solar irradiance is related to the insolation parameter which depends on the season, weather conditions (water vapors, wind, dust, rain, and clouds), time of day, and topography (Gherboudj and Ghedira, 2010). Several experimental studies show that the working efficiency of solar systems decreases with an increase in air temperature. A study conducted in Saudi Arabia confirmed that the efficiency of PV modules decreased by 11% with a temperature increase from 38C to 48C (Adinoyi and Said, 2013). It is also studied that the influence of humidity on PV efficiency is greater than air temperature. A study conducted in Qatar showed that relative humidity impact is 50% greater than air temperature (Touati et al., 2013).

The solar market in the United Arab Emirates has been estimated to grow at a 15% annual growth rate from 2020 to 2025 (Enerdata, 2020; Government of UAE, 2020). Moreover, UAE has announced the "Energy Strategy 2050" in 2017. It explained that the UAE plans to raise the clean energy percentage by up to 50% in the energy mix of the country constituting 6% nuclear and 44% renewable energy by 2050 (Al Naqbi et al., 2019). Government policies also urge to expand the solar market to meet clean energy demand and minimize dependence on fossil fuels and carbon footprint. The decline in the price of solar panels attracts people to use solar panels at home. International organizations are supporting the solar sector and renewable energy innovations are becoming profitable than non-renewable sources. With time electricity demand in the UAE increased by about 310% in the past twenty years. Therefore, high authorities are focusing on adopting renewable technologies. There was observed huge jump in 2019 and 2020 (Figure 6) in the installation of 2.5GW capacity solar systems. Both the utility and non-utility projects were included in this total capacity, 125MW PV were installed in industrial buildings, residential and commercial areas, and leftover were installed in utility scales mostly in Dubai and Abu Dhabi (MESIA, 2020).

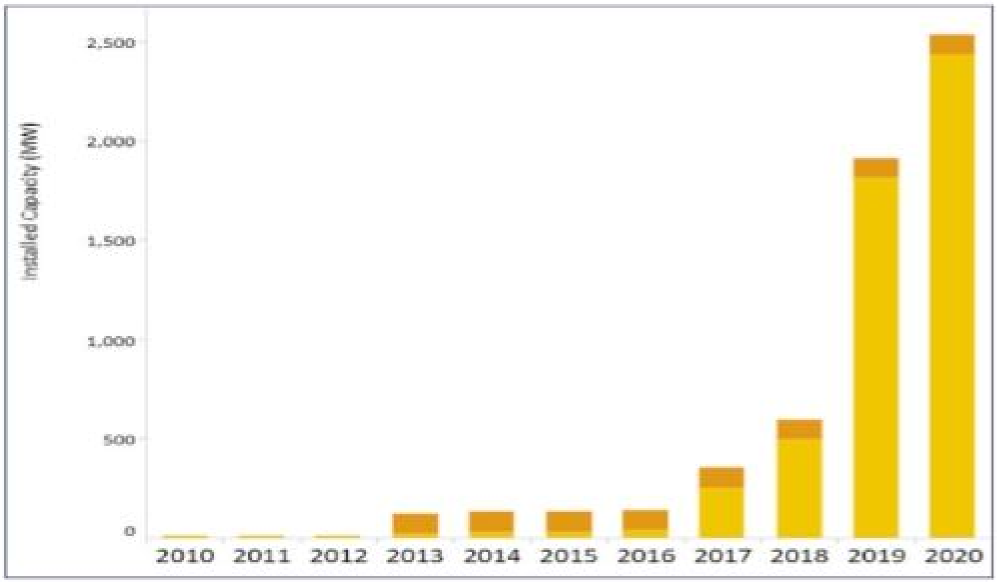

Figure 8 Solar energy installation capacity of UAE 2010 -2020 (source: IRENA, 2021)

In addition, the UAE decided on a well-structured energy plan to generate 15% of electricity in Dubai from renewable sources till 2030 to reduce carbon dioxide emissions by up to 70% by 2050 and focus on increasing the usage of solar energy as much as possible (WWF, 2018). In 2009 the government of UAE aimed to generate 27% of electricity from renewable sources by 2021 while introducing its first renewable energy policy (Malik et al., 2019). To achieve this goal a quota mechanism was set in Abu Dhabi for 10 MW solar plant installations in Masdar city. However, some companies face challenges like taxation but the UAE remains obligated to its renewable energy policy. UAE made climate change its top priority by signing the Paris Agreement in 2016 and committing to introducing renewable energy sources into the energy mix of the country. In this regard, the Ministry of Climate Change and Environment was established (IRENA, 2020).

The roadmap for sustainability up to 2050 national climate change plan was established in 2017. Dubai and Abu Dhabi for addressing climate change issues have implemented net metering policies and resulted in becoming top sustainable cities. To meet increasing electricity demand, UAE is pursuing renewable development to achieve sustainable development in the long run. The initiative of Dubai Shams net metering in 2014 allows customers to produce and submit back excess energy to the grid. The legislation and guidelines for the connection of solar to the grid and the installation of bidirectional meters were operated by the Dubai Electricity and Water Authority during the initiative. The excess energy will be automatically transferred to next month's bill and no payment of extra energy. Under this net metering mechanism, 900 MW of solar PV rooftop projects were installed until 2021 (Alsalman et al., 2023).

The Gulf Corporation Council of Oman, Saudi Arabia, United Arab Emirates, Kuwait, Bahrain, and Qatar have increased their energy utilization in the last decades. The headquarters of IRENA moved to Abu Dhabi in 2015. In 2019 one huge single-site solar project was installed having a 1.17GW capacity. UAE can be dependent more on PV solar energy with technological advancements and low cost to meet future electricity demand without using fossil fuels (Elrahmani et al., 2021; Pagliaro, 2019).

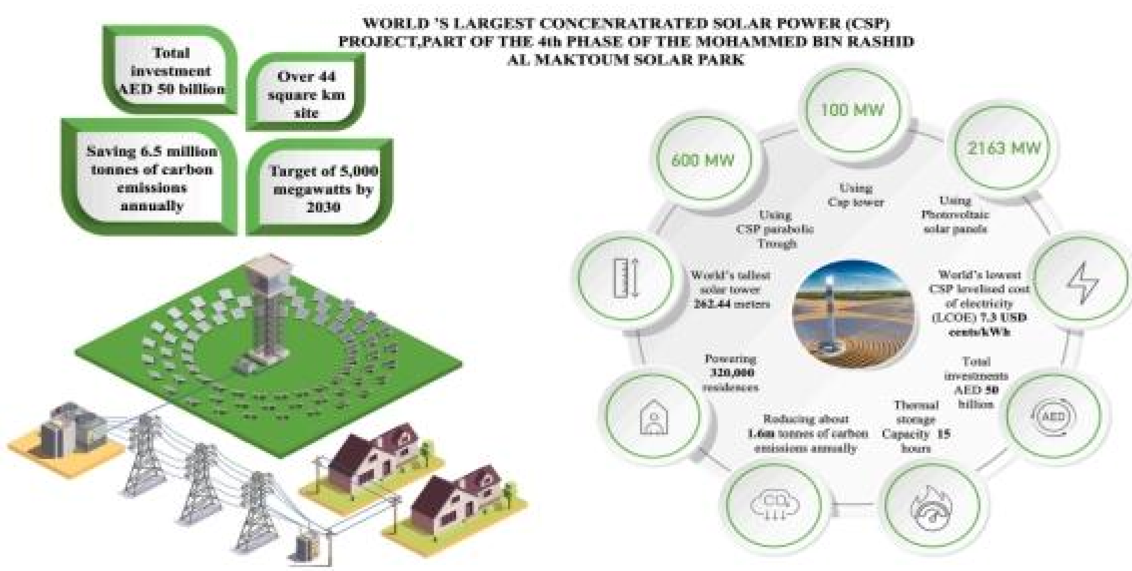

Figure 9 summary of MBR solar project (Source: Obaideen et al., 2021)

With these aims, UAE in Seih Al Dahal (Dubai) launched the Mohammad bin Rashid Al Maktoum Solar Park (Figure 7). It covers over a 44-kilometer square area as the world's largest solar plant. For 250 MW solar, the balanced cost of electricity for PV is $ 2.4 cent/KWh and 47.3 cents/KWh for a 700 MW concentrating solar power plant (Azouzoute et al., 2020). This project will help in achieving "sustainable development goals in UAE, the policy of renewable sources in UAE, and UAE energy strategy 2050". This project comprises different phases as the first phase operated with 13MW of PV solar panels since 2013. The second phase was operational with a 200 MW capacity in 2017. The third phase develops for 800 MW capacity. This is the first project in the history of the Middle East and North Africa to use single-axis solar tracking. Moreover, robots are used for cleaning purposes to increase panel efficiency. Similarly, the fourth phase was funded for building 950MW capacity which is the largest investment in global history with combined technologies of PV and CSP power. The fifth phase is again 900 MW capacity and based on PV technology. It will support DEWA in achieving Dubai's clean energy strategy by 2050 (Obaideen et al., 2021). Moreover, MBR Solar Park is targeted to power 320000 residencies and minimize approximately 1.6 MT of carbon emissions on an annual basis (Figure 8).

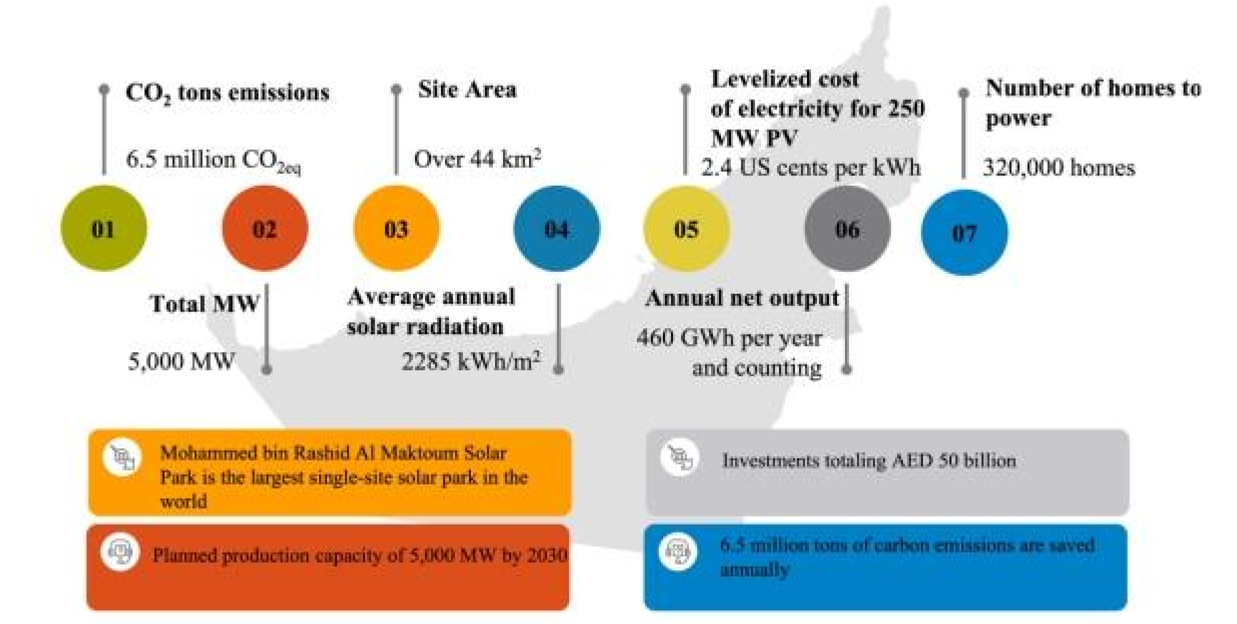

Figure 10 Contribution of MBR Solar project in the sustainable development of UAE (Source: Obaideen et al., 2021).

UAE is among the leading countries in the world for deploying solar systems. With installed photovoltaic solar systems at large scale, it has become third biggest market for solar energy in the world. This rapid growth has been driven by government support, policies and large scale solar panel deployment. Due to its geographical location, UAE has a huge potential in solar energy production. Solar energy will help the UAE a lot in reducing its carbon emissions and meeting its sustainability goals. UAE's strategic focus on solar energy, supported by government policies and large-scale investments, has positioned the country as a dominant player in the solar energy market. Upcoming projects such as Noor Energy 1 and Abu Dhabi PV3 will help the country a lot in achieving its ambitious plans.

2.5. Socio-Environmental impacts of Solar Energy

Using renewable energy can have a variety of societal benefits, like poverty eradication, mitigation of climate change, and improved health by lowering pollution caused by petrol emissions. Furthermore, renewable energy can promote gender equality by minimizing the negative health effects on women's health in South Africa and many poor nations caused by the widespread use of firewood for energy purposes. Meanwhile, investing in renewable energy projects can assist in alleviating poverty by creating work opportunities in rural communities. China, Brazil, and India, the three largest developed nations, aggressively pushed renewable energy investments, which increased gradually from $94.8 million to $197.5 million between 2016 and 2017. It provides jobs in different sectors like logistics, manufacturing, engineering, and installation. Solar energy provides employment in the USA with about 43% in the electrical sector in comparison to 22% from non-renewable sources. According to estimation solar power will offer job opportunities for about 4.18 million in 2050 (Ram et al., 2020).

In terms of installed base, the United Arab Emirates Solar Energy Market is predicted to develop from 7.90 gigawatt in 2024 to 36.06 gigawatt by 2029, at a CAGR of 35.48% during the forecast period (2024-2029). Over the medium term, factors such as encouraging government policies and pressure to meet electricity demand with renewable energy to reduce reliance on fossil fuels and carbon footprints will contribute significantly to market growth.
On the other hand, the increasing use of alternative clean energy sources is likely to limit market growth. Nonetheless, with the implementation of the innovative UAE Energy Strategy 2050, the country is on track to grow its clean energy contribution to 44% by 2050 through investments in nuclear and solar energy. As a result, the United Arab Emirates solar energy market is likely to benefit from several new prospects in the future.

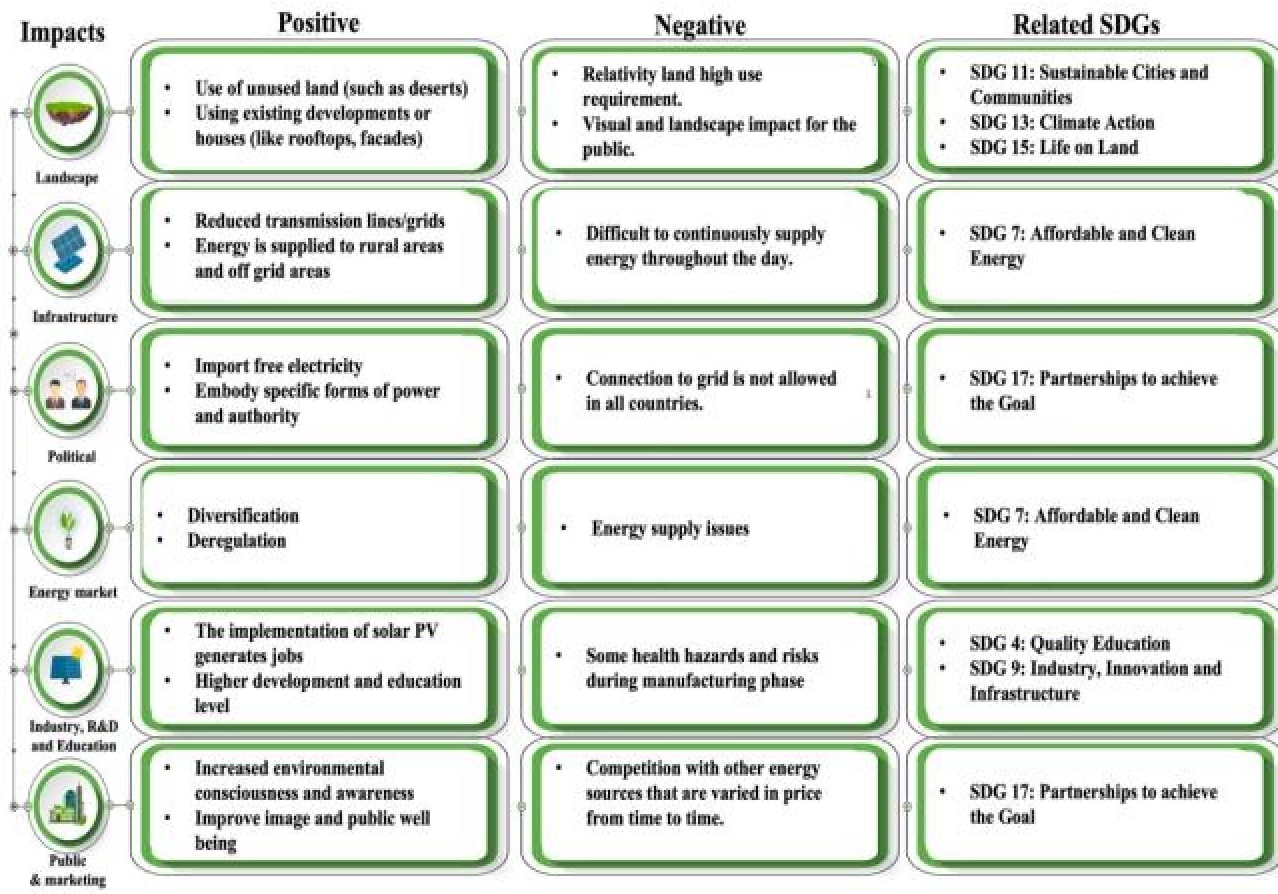

Figure 11 Economic and social effects of Solar photovoltaics and their relation with SDGs (Source: Obaideen et al., 2021).

Solar energy significantly reduces carbon emissions by providing an alternative to fossil fuels. The environmental inspection revealed that the greenhouse gas emissions are 90.1% lower than the diesel system (Malik et al. 2021b). The technological and economic feasibility results showed that the biomass/photovoltaic/battery storage hybrid renewable energy system is the most economically practical system for meeting power needs, with a levelized cost of \$0.1498/kWh (Ji et al. 2022).

It helps mitigate climate change and protect the environment from harmful greenhouse emissions. In addition, solar systems require minimum land compared to other sources. They can be stalled on rooftop or barren land, minimizing environmental impacts and preserving land resources. Solar energy does not contribute to any form of pollution unlike fossil fuel based energy production, leading to cleaner air, water, land and environment. This leads to ecosystem restoration as solar energy has potential to restore environmental aesthetics by reducing habitat destruction and promoting biodiversity, and contributing to sustainable development and environmental conservation. Also, solar energy helps to cope up with the problem of finite resources as solar energy is infinite.

Solar energy has a range of social impacts as well such as job opportunities, lower energy costs and energy independence. Solar energy gives high return on investment which is an important social and economic impact. Solar power reduces the energy dependence over other resources, price fluctuations, and allows a country to meet their energy needs domestically. Unlike coal and petroleum which are mostly imported and have huge impacts on electricity price, solar energy provides more reliable and cost-effective power source. In turn, it benefits developing and under developed countries for economic development and coping up with price problem. Solar energy creates a large number of jobs thus contributing to economic prosperity. It creates jobs across various sectors including manufacturing. installation, engineering, sales, and logistics, impacting both urban and rural communities. It also contributes to regional development by providing electricity to the areas with no access to electricity enhancing the human welfare and living standards.

Researchers from academia and industry have shown a great deal of interest in perovskite solar cells (PVSCs) due to their recent rapid efficiency growth—from 3.8% to 22.1%. Nonetheless, there are still a lot of obstacles in the way of PVSC development. It is crucial to develop stable, high-efficiency devices in addition to environmentally friendly perovskites, but there are still difficult problems in PVSC research. We concentrated on the most recent developments in related fields in this review paper. After introducing the methods for producing high-efficiency PVSCs, the topics of instability and lead-free perovskite were covered. Lastly, a brief summary of the conclusions and future directions for PVSC advancement in the direction of reliable and efficient solar-to-electricity technologies has been given.

Perovskite solar cells (PSCs) have recently shown a notable and rapid development. In just roughly ten years, the emerging PCSs' efficiency has increased from 3.8% to 25.5%. Perovskites' distinct structural characteristics, high absorption coefficient, adjustable band gap, long electron-hole diffusion length, and elevated charge carrier mobility are responsible for the remarkable improvement in PSC performance. Effective PSC devices are typically created in a lab setting with a very tiny surface area (approximately 0.1 cm2) and in an inert atmosphere. However, large-scale PSC development in an ambient environment is required for practical applications.

The design of ambient-environment processable PSCs has received a great deal of attention lately, with special focus on how moisture and oxygen affect the stability and effectiveness of these materials. We first clarify the primary crystal and electronic characteristics of PSCs in this review. The recent developments in ambient-environment processed PSCs are then the main topic of discussion, and the effects of oxygen and moisture on the growth, morphology, and stability of perovskite crystals are covered in detail. A thorough discussion of the various methods that could be used to regulate the production of effective and stable perovskite solar cells has taken place. The approaches that can be used to develop PSCs on a large scale and in controlled or uncontrolled lab environments have been reviewed and compiled (Oing Peng 2021)

The solar atlas' results for PV electricity output and solar irradiation indicate that solar power has a lot of potential across the Pakistan. 4.1 kWh/kWp on average per day can be obtained with an installed capacity of 1 KWp. Additionally, Pakistan's solar energy potential is estimated to be around 2900 GW, and if it is used effectively, it can reduce the need for fossil fuel imports, which will boost the nation's economy. It is anticipated that current research will assist countries in developing and effectively utilizing solar power in their own nations. We have already surpassed the stage at which a trio of solar cells were developed, and the next generation of solar cells are hybrid perovskite solar cells (PSCs) based on metal halides. PSCs, a relatively new class of photovoltaic devices, have brought about a significant shift in the field of photovoltaic research. They have demonstrated remarkable stability and efficiency gains, making them an extremely effective technology. Preventing the material from deteriorating in damp environments and overheating are the main issues with it. In addition, lead (Pb) toxicity is the second matter of concern, as it may pose a hindrance to large-scale production because of environmental concerns. As a result, a great deal of work has gone into developing substitute halide perovskites with superior optoelectronics applications that are entirely inorganic and comprise inexpensive, less hazardous elements. All-inorganic lead-free perovskites employ eco-friendly materials in an effort to mitigate these issues.

Moreover, a wide range of inorganic materials have the ability to form perovskite structures, offering material flexibility for particular uses. The literature on Pb-free perovskite materials is thoroughly reviewed in this review paper, which also covers issues related to environmental stability, morphologies, and design techniques. First, the elements of Tin (Sn) and Pb are compared, and some Pb is substituted with Sn. It is highlighted that this element can be substituted with Germanium (Ge), transition metals, and elements from other columns of the periodic table. The research offered a critical evaluation of the issues at hand and possible future paths for this quickly advancing field as we wrap up our investigation. (kumar et al., 2023)

We offer a critical evaluation of the issues at hand and possible future paths for this quickly advancing field as we wrap up our investigation. A tribute to human ingenuity and the unwavering search for sustainable energy solutions is the development of photovoltaic (PV) cell technology. PV cells have evolved through time thanks to ground-breaking developments in materials science and manufacturing techniques, from the earliest days of solar energy research to the most complex systems of today. Crystalline silicon was a key component of solar cell development in its early stages and has remained so because of its durability and proven efficiency. The industry has made substantial progress as the efficiency has increased from 15% to 28% from 1950s to date. And one of the primary reasons is the improvement in material used.

In July 2022, researchers at the École polytechnique fédérale de Lausanne (EPFL) and the Swiss Center for Electronics and Microtechnology (CSEM) broke the previous record for solar power generation when they produced a 1 cm2 tandem perovskite-silicon solar cell with a power conversion efficiency of over 30%. The US National Renewable Energy Laboratory (NREL) validated the breakthrough. Following the breakthrough in the Lausanne lab, researchers worldwide have focused their efforts on breaking through the 30% barrier. "Overcoming this threshold provides confidence that high-performance, low-cost PVs can be brought to the market," state Stefaan De Wolf and Erkan Aydin (2023). Experts estimate that perovskite-silicon tandems could achieve efficiencies of roughly 45%. The optimal perovskite band gap, or the wavelength that can be consumed in relation to the wavelength that the solar cell can effectively utilize, is limited by the thickness of the perovskite material and parasitic energy absorption. This results in power loss rather than the planned direct conversion of solar energy to electricity. On July 7, 2023, two different international research teams reported using different strategies to create perovskite-on-silicon tandem solar cells with power conversion efficiencies higher than 30%. Chin and a team of scientists used a technique to halt energy losses, which allowed them to break through the barrier. In the interim, Mariotti and colleagues have been investigating methods to improve the stability and efficiency of the tandem cell.

Tandem solar cells are expected to reduce the levelized cost of electricity (a metric used to compare the cost of producing electricity over the lifetime of the solar cell when compared to other methods of generation), and researchers are now well on their way to realizing their potential. Ignacio Mártil, an electronics professor at the Complutense University of Madrid, states that photovoltaic energy "is the fastest growing renewable source of all the power generation technologies." Given this, the current discussion about clean energy and climate change can benefit greatly from the introduction of the perovskite-on-silicon tandem solar cell.

Apart from being the most commonly utilized semiconductor in solar cell manufacturing, silicon is the second most abundant element in the universe, right after oxygen. Silicon solar cells may be built on amorphous or crystallized silicon. Crystallized material is the most preferred and commonly used form because it has the highest power conversion efficiency (PCE). However, the material must be extremely pure and devoid of structural flaws in order for it to function effectively, which drives up the cost of production. For silicon, the maximum efficiency has typically been in the range of 29%. Compared to crystalline silicon, perovskite absorbs light far more efficiently. It can also be "tuned" to use portions of the solar spectrum that silicon photovoltaics is generally unable to access.

Perovskite has a far higher defect tolerance and can work effectively in the presence of impurities and imperfections. As a result, this amazing substance has caught the interest of scientists everywhere and shows promise as an affordable method of producing electricity in the future. This is in contrast to silicon photovoltaics, which are relatively expensive to produce because they are fabricated at high temperatures and under vacuum. In contrast, perovskites are easier and more flexible to produce. The key word here is flexibility as well because, in contrast to rigid silicon cells, which take up a lot of space when combined, perovskites are printable and can even be rolled up (think solar panelled rooftops).

Because silicon is well-known and reliable, it continues to dominate the solar energy market; perovskites by themselves have not yet been able to match the performance standards set by silicon. For perovskites to work better while maintaining stability, they must be incredibly thin, which presents a challenge for a material that is sensitive to changes in humidity and temperature. The fact that perovskites produce hazardous lead during processing is another disadvantage. Thus, scientists worldwide have been "chasing new, more stable perovskite materials" and experimenting with various approaches to optimize perovskites and their architecture in order to produce solar energy.

2.6. Solar Energy Investment Trends

Investing in solar energy has been a priority for China, Japan, and the United Arab Emirates. These countries have implemented policies and incentives to attract investment in solar energy technology and infrastructure. China, as the world's largest emitter of greenhouse gases, has made significant strides in expanding its solar energy capacity. Through the implementation of various policies and incentives, China has attracted a significant amount of investment in solar energy. Japan, on the other hand, has a strong commitment to renewable energy and has implemented policies that support the development of solar energy projects. These policies have resulted in a significant increase in solar energy investment in Japan. The United Arab Emirates is also making significant investments in solar energy, driven by its commitment to diversify its energy mix and reduce dependence on fossil fuels. Through policies such as feed-in tariffs, renewable energy targets, and tax incentives, the United Arab Emirates has successfully attracted investments in solar energy projects. China, Japan, and the United Arab Emirates are leading in solar energy utilization due to their commitment to renewable energy, effective policies, and significant investments. "Investing in solar energy has become a priority for China, Japan, and the United Arab Emirates (Yu et al., 2016). These countries have implemented various policies and incentives to promote the development and deployment of solar energy systems. The Chinese government has implemented a series of subsidy policies to boost the renewable energy industry, including direct and indirect funding allocation, tax incentives, and price control. Japan has also implemented policies to support the development of solar energy projects, which has resulted in a significant increase in investment in the sector. The United Arab Emirates, driven by its commitment to diversify its energy mix and reduce dependence on fossil fuels, has implemented policies such as feed-in tariffs, renewable energy targets, and tax incentives to attract investments in solar energy. These efforts have made the three countries leaders in solar energy utilization, with significant investments and a commitment to renewable energy.

China, Japan, and the United Arab Emirates are leading in solar energy utilization due to their commitment to renewable energy, effective policies, and significant investments. These countries recognize the importance of transitioning to cleaner and more sustainable energy sources, and they have taken proactive measures to promote the development and deployment of solar energy systems. Their policies include subsidies, tax incentives, and feed-in tariffs, which have incentivized investment in solar energy projects. Additionally, these countries have set renewable energy targets and implemented measures to reduce dependence on fossil fuels. As a result of these efforts, China, Japan, and the United Arab Emirates have become global leaders in solar energy utilization. China, Japan, and the United Arab Emirates have actively pursued the development of solar energy as a means to transition to cleaner and more sustainable energy sources. Through the implementation of effective policies and significant investments, these countries have become leaders in solar energy utilization. These countries have recognized the potential of solar energy to address their energy needs, reduce greenhouse gas emissions, and enhance energy security.

China, Japan, and the United Arab Emirates have all recognized the potential of solar energy as a sustainable and clean source of power. They have implemented various policies to promote the development and utilization of solar energy, such as subsidies, tax incentives, and feed-in tariffs. These policies have attracted significant investments in solar energy projects and have made these three countries leaders in solar energy utilization. China, Japan, and the United Arab Emirates have all recognized the potential of solar energy as a sustainable and clean source of power. Their commitment to renewable energy and effective policies have enabled them to attract investments, set renewable energy targets, and provide tax incentives to accelerate the transition to solar energy. China, Japan, and the United Arab Emirates have made significant progress in solar energy utilization due to their commitment to renewable energy development and effective policy implementation.

2.7. Challenges and Opportunities for Solar Energy

The adoption and implementation of solar energy policies in China, Japan, and the United Arab Emirates have undoubtedly contributed to the growth of solar installations in these countries. However, there are also challenges that need to be addressed. These challenges include issues such as grid integration, high initial investment costs, and the need for storage solutions to address intermittent generation. Despite these challenges, the opportunities for solar energy in China, Japan, and the United Arab Emirates are immense. These countries have abundant solar resources and high energy demand, making solar energy an attractive option for meeting their electricity needs. Additionally, the decreasing costs of solar technology and the advancements in energy storage systems have further enhanced the attractiveness of solar energy in these countries (Devabhaktuni et al., 2013). Overall, the effective policies and initiatives implemented in China, Japan, and the United Arab Emirates have made these countries leaders in solar energy deployment (Yu et al., 2016). The high solar energy potential, government support, and favorable policies have positioned China, Japan, and the United Arab Emirates as global leaders in solar energy deployment and have paved the way for a sustainable and renewable energy future (Devabhaktuni et al., 2013).

The effective solar energy policies and initiatives in China, Japan, and the United Arab Emirates have accelerated the growth of solar installations in these countries (Yu et al., 2016). China, Japan, and the United Arab Emirates have made significant progress in harnessing solar energy through their effective policies and initiatives. These countries have implemented subsidies, tax incentives, price control measures, and demand assurance mechanisms to promote the adoption of solar energy. These policies have incentivized investment in solar installations and encouraged the development of a robust solar industry. As a result, these countries have seen a significant increase in the deployment of solar energy systems and have become leaders in solar energy utilization. The successful implementation of solar energy policies in China, Japan, and the United Arab Emirates has led to a significant increase in solar installations, making these countries global leaders in solar energy deployment. China, Japan, and the United Arab Emirates have recognized the potential of solar energy in addressing their energy needs and mitigating climate change. The governments of China, Japan, and the United Arab Emirates have implemented effective policies to promote solar energy deployment. These policies have not only attracted investments in solar installations but have also created a favorable environment for the emergence of a domestic solar energy industry.China, Japan, and the United Arab Emirates have implemented effective policies to promote the development and deployment of solar energy systems. These policies include subsidies, tax incentives, price control measures, and demand assurance mechanisms. China, Japan, and the United Arab Emirates have emerged as global leaders in solar energy deployment due to their high solar energy potential, government support, and favorable policies.

Global Innovations and Challenges in Solar Energy: Insights from China, Japan, and the UAE

The UAE boasts one of the highest solar exposure rates globally. It makes UAE an ideal location for projects like solar energy. The government has taken significant initiatives to enhance the usage of renewable energy, particularly solar power. This expenditure is mainly through projects like the Masdar Initiative. The Masdar Initiative program emphasizes concentrated solar power (CSP) plants and has set ambitious targets, including achieving 7% of its energy from renewable by 2020 (Mezher et al., 2011). A study by Ramachandran et al., (2022) highlight the rapid evolution of photovoltaic (PV) technology. It specifically addresses the UAE's increasing energy demands while reducing reliance on fossil fuels. There are still underlying challenges in integrating solar energy systems into the existing infrastructure (Alahdal et al., 2022).

China has emerged as a leader in the global economy for the development of solar energy. China has implemented renewable energy electrification goals, mainly focusing on poverty alleviation in rural regions since 2014, (Filkin, 2023). Due to large-scale manufacturing capabilities, China have enabled the production of affordable solar panels.These solar panels made the technology accessible domestically. This program have transformed it into one of the largest solar energy producer. This program is highly affective due to substantial investments in solar farms and rooftop installations. According to the study of Yamada et al., (2015) Feed-in Tariff (FiT) project played a significant role in accelerating solar installations in this country. This program encouraging commercial participation. As the UAE emphasizes massive solar farms and technical CSP plants, China leads in rural solar electrification, and Japan focuses on innovative programs such as floating solar farms. The UAE's high solar exposure positions it as a leader in the Middle East, while China's vast investments and policies ensure global dominance.

Japan, though constrained by land and resources, excels in technological innovation and strategic deployment. In the research by Li et al., (2020), the deployment pattern of solar energy are shifted from from stationary to distributed systems. It driven by subsidy structures and policy differences. This change emphasize the critical need for cohesive national policies to streamline solar energy integration.

Xu et al. (2013) provide a comprehensive review regarding China's solar power sector.It had been facilitated by financial incentives and regulatory frameworks. However, this large-scale solar capacity integration poses significant grid management challenges. These challenges includes intermittent supply and mismatch geographic distribution. According to research of Sullivan et al., (2014), there is a need for advanced capacity-expansion models .It is necessary to accommodate the validity of solar energy. These models must account for operational properties. These characteristics includes value of solar energy and the need for ancillary services to maintain its stability.

Institutional and policy frameworks play a crucial role in shaping China's solar energy trajectory. Shen et al., (2018) analyze the political economy of China's renewable energy expansion. They found a notable difference between state-led models and the influence of present institutional structures. The evolution of this new policy paradigm highlighted a critical shift in the policy of China's renewable energy resources. According to research of Wang et al. (2021), policy fragmentation, market uncertainties are the key obstacles in the expansion of solar energy. It was found that standardizing subsidy mechanisms and promoting R&D investments is crucial in advancing solar technologies.

Iizuka (2015) examines the diverse pathways of low-carbon development in China. Solar PV diffusion was used in that study. It was found that the complexities of fulfilling national strategies with local implementation realities, particularly in a rapidly developing economy. In response to the 2011 Fukushima nuclear disaster, solar energy policies of Japan emerged robustly. It played a pivotal role in accelerating solar energy adoption. This made Japan one of the world's largest solar markets at the time (Wen et al., 2020). The progress of the sector obscured due to high costs of solar installations, land constraints, and integration issues. These change in policies causes self-consumption and promoting energy storage systems. According to Iizuka, (2015), these policy changes creates a more sustainable and decentralized approach to solar energy. These technological innovation provides leadership role in renewable energy technologies (Li et al., 2022).

According to the research of Alsalman et al., (2023), policies such as renewable energy targets and competitive solar auctions have further contributed in the development of solar technologies. The UAE's leadership in the region is backed by its higher rates in solar insolation and its goal to achieve 50% clean energy by 2050. Nevertheless, in the research of Ramachandran et al., (2022), it was found that obstacles such as financial viability, and the need for technological advancements persist. Across these countries, the policies regarding the solar energy are evolving to address specific challenges. It also aimed for long-term sustainability. China's scale, Japan's innovation, and the UAE's strategic investments exemplify diverse pathways toward a low-carbon future.

The research of Yu et al., (2016) showed that the basic feature China's strategy has been the implementation of both supply-push and demand-pull policies. This strategy significantly reduced solar panel costs and creating a dominant global manufacturing sector. Wen et al., (2020) showed that tax incentives, and the establishment of feed-in tariffs increase the domestic solar installations and technological advancement. They work to reduce dependency on fossil fuels and increasing the share of renewable resources. In contrary, the solar energy policies made by Japan emphasize the integration of both market-driven solutions and strong government support. Wen et al., (2020) research found that Japan's Feed-in-Tariff (FiT) program is considered as a most successful policy tools in order to promote solar energy adoption. The producers of FiT incentive solar power drives rapid growth in both solar installations and technological advancements. However, the Japanese government has also faced challenges, regarding the scale of solar installations and grid capacity (Yu et al., 2016). These obstacles include market oversupply. Japan still remains one of the leading countries in the successful adoption of solar energy. Their goal is to integrate solar into its energy mix as part of its broader efforts to decarbonize the economy.

The UAE faces a unique challenges in its transition to renewable energy. The UAE government has taken strategic steps to develop a solar energy sector. It is amplified by the creation of the Mohammed bin Rashid Al Maktoum Solar Park.It is considered as one of the largest solar installations in the world (Obaideen et al., 2021). According to the research of Nayfeh et al., (2023), key policies in the UAE attracted both domestic and international stakeholders. Challenges still exists in all three countries, particularly related to the integration of solar energy into existing power grids. In China, the aggressive expansion of solar panel production has led to global market oversupply. It creates trade tensions, particularly with Europe (Yu et al., 2016). Japan's solar market has also experienced fluctuations due to oversupply. It leads to policy adjustments to ensure long-term market stability (Wen et al., 2020). In the UAE, while solar potential is high, the country's dependence on oil has decreased the route of transition to renewable energy. It requires continued innovation and investment in the emerging field of research and development (Alahdal et al., 2022).

The country's large-scale solar photovoltaic (PV) projects have benefited from substantial government subsidies, tax incentives, and long-term development plans. It aimed at reduce dependence on fossil fuels and lowering carbon emissions (Xu et al., 2013). China's market-driven approach has resulted in its dominance in solar panel manufacturing. This aaproach leads to global oversupply and trade disputes, particularly with Europe (Yu et al., 2016). The massive scale of China's solar energy installations has made it a global leader.

Japan, on the other hand, accelerated its efforts to adopt renewable energy. It includes solar power, as part of its energy transition strategy (Kaewkhunok, 2019). The Japanese government introduced feed-in tariffs (FIT) in 2012 to incentivize solar power investments. It leads to the increase in the deployment of PV systems. The focus on technological improvements has led to advances in solar panel efficiency and integration with other energy systems. These energy systems includes storage technologies and electric vehicles (Wen et al., 2020). Despite these efforts, Japan's energy transition has been challenged by its limited land area But it complicates the transition to a renewable-based energy system (Zhang et al., 2020).

In the UAE, solar energy development symbolize the country's strategy to diversify its energy mix. It on the other hand reduces reliance on oil and gas. With one of the highest levels of solar irradiance in the world, the UAE has significant potential for solar energy utilization. The government has introduced several ambitious initiatives to promote renewable energy. These initiatives including the Mohammed bin Rashid Al Maktoum Solar Park. It aimed to generate up to 5,000 MW of solar power by 2030 (Obaideen et al., 2021).

The UAE has also prioritized research and development (R&D) to improve solar technologies. It is best match to combat harsh desert climate, where dust and high temperatures can reduce solar panel efficiency (Nayfeh et al., 2023). Additionally, the UAE has made significant strides in integrating solar power into its national grid. It is also essential for ensuring a stable energy supply as solar energy penetration increases (Salim et al., 2020). Despite these advancements, challenges remain, particularly in scaling up renewable energy to meet growing domestic demand and aligning the interests of key stakeholders in the energy sector (Salimi et al., 2022).

Overall, while China, Japan, and the UAE are all committed to expanding solar energy, their strategies reflect distinct national contexts. China's focus on large-scale production and market expansion contrasts with Japan's emphasis on technological innovation and integration. The UAE, with its unique solar resources, is pursuing a hybrid approach that combines large-scale infrastructure projects with targeted R&D efforts. Each country's experience offers valuable lessons for other nations seeking to transition to renewable energy.

China's industry of solar water heater has grown from massive innovation in the spread of solar technologies. This industry has relying more on individual consumer demand a compare to government support. These interchanging dynamics within solar industry of China highlight the importance of innovative strategies for different solar technologies (Urban et al., 2018). There is significant increase in technological advancements due to these policy mechanisms and industrial strategies made by Japan (Yu et al., 2016).

In the UAE, the government has displayed high transitioning from an oil-dependent economy to renewable energy, particularly solar power. The Mohammed bin Rashid Al Maktoum Solar Park stands as a testament to these efforts.It contributed to multiple Sustainable Development Goals.It mitigated millions of tons of CO_2 emissions and promoting sustainable energy use (Obaideen et al., 2021). However challenges still persist in the UAE's substantial solar exposure.It is particularly due to high initial capital costs for solar installations and a lack of public awareness about solar energy benefits (Salimi et al., 2022).

The use of GIS-based multi-criteria decision-making techniques in UAE benefited to identify suitable locations for concentrated solar power (CSP) projects.. It expanded the development of solar infrastructure. Advancements in computational modeling have proposed solutions to improve PV panel efficiency in the UAE's desert climate. These technological innovations are still limited to theoretical and experimental models, necessitating real-world validation (Hughes et al., 2011). UAE had been working on projects like solar car parking systems and solar-powered metro. These projects demonstrate the UAE's efforts to integrate renewable energy into urban infrastructure. According to the research of Philip et al., (2022) tracking PV panels outperformed fixed panels in power generation and economic feasibility. It highlights the importance of technological optimization in maximizing solar energy utilization (Philip et al., 2022).The UAE still faces specific climatic challenges which significantly impact the performance of solar panel. A study on optimal solar panel orientation in Abu Dhabi found that south-facing panels at a 25-30 degree angle yielded the highest power output. However, long-term effects of heat and soiling remain inadequately understood. It highlights the need for research into materials and maintenance solutions to mitigate these issues (Nayfeh et al., 2023). China's decentralized approach as compare to the UAE's centralized governmental initiative for renewable energy provides state-level policies and private-sector initiatives, . These wide range of strategies underscores the significance of context-specific solutions in driving solar innovation and adoption (Adewumi et al., 2024).

2.8. The Future of Renewable Energy in Asia and the Middle East

Focus on Solar China, Japan, and the United Arab Emirates have demonstrated strong commitment to renewable energy development, particularly in the area of solar energy. These countries have set ambitious targets for increasing the share of renewable energy in their energy mix.
China, Japan, and the United Arab Emirates have recognized the potential of solar energy as a clean and sustainable source of power. They have implemented various policies and initiatives to promote the development and deployment of solar energy systems. These policies have incentivized investment in solar installations and encouraged the development of a robust solar industry. China, Japan, and the United Arab Emirates have made significant progress in harnessing solar energy and have become global leaders in solar energy deployment. China, Japan, and the United Arab Emirates have taken significant steps to become leaders in solar energy utilization. China, Japan, and the

United Arab Emirates have implemented various policies and initiatives to promote the development and deployment of solar energy systems (Devabhaktuni et al., 2013). These policies have included subsidies, tax incentives, price control measures, and demand assurance mechanisms (Yu et al., 2016).The governments of China, Japan, and the United Arab Emirates have shown a strong commitment to promoting solar energy as a key solution to mitigate climate change and transition to a cleaner and more sustainable energy future. China, Japan, and the United Arab Emirates have implemented a range of effective policies and incentives to promote the development and deployment of solar energy systems. These include subsidies, tax incentives, price control measures, and demand assurance mechanisms. China, Japan, and the United Arab Emirates have recognized that the development and deployment of solar energy is crucial for their energy transition and for mitigating climate change. China, Japan, and the United Arab Emirates have implemented effective policies and incentives to become leaders in solar energy utilization. China, Japan, and the United Arab Emirates have shown remarkable progress in the utilization of solar energy, thanks to their strong commitment and effective policies.

China, Japan, and the United Arab Emirates have set ambitious targets for increasing the share of renewable energy in their energy mix, with a specific focus on expanding their solar energy capacity. China, Japan, and the United Arab Emirates have emerged as leaders in the utilization of solar energy due to their strong commitment to renewable energy and effective policies (Devabhaktuni et al., 2013). China, Japan, and the United Arab Emirates have emerged as global leaders in the utilization of solar energy due to their strong commitment to renewable energy, effective policies, and significant investments in solar energy infrastructure (Yu et al., 2016). China, Japan, and the United Arab Emirates have emerged as global leaders in the utilization of solar energy due to their strong commitment to renewable energy, effective policies, and significant investments in solar energy infrastructure. China, Japan, and the United Arab Emirates have emerged as global leaders in the utilization of solar energy due to their strong commitment to renewable energy, effective policies, and significant investments in

solar energy infrastructure.
China, Japan, and the United Arab Emirates have emerged as global leaders in the utilization of solar energy due to their strong commitment to renewable energy, effective policies, and significant investments in solar energy infrastructure. These countries have implemented a range of policies to promote the development and deployment of solar energy systems. China, Japan, and the United Arab Emirates have implemented various policies and incentives to promote the development and deployment of solar energy systems. China, Japan, and the United Arab Emirates have made significant progress in the development and deployment of solar energy through the implementation of effective policies and incentives (Devabhaktuni et al., 2013).

Chapter 3: Methodology

The current study aims to compare the solar energy efficiency in UAE, China, and Japan. Moreover, it explores the innovative and advanced photovoltaic materials for increasing solar energy production efficiency. Although huge advancements have been made in crystalline silicon solar cells, theoretically their efficiency is still 29%. Researchers are looking for other materials which can increase the efficiency and reduce the system cost. This will help to accelerate the worldwide transition to a sustainable energy future by increasing the usage of solar energy. Energy is a vital necessity for survival and development nowadays. Existing energy sources are fossil fuel-based based that are posing negative impacts on human and environmental health. Moreover, they are non-renewable, finite, and supposed to be depleted soon (Lyu et al., 2024). Therefore, shifting towards renewable sources is the best choice and solar energy is a viable option among all of them for electricity generation (Krishnan et al., 2023; Ndzibah et al., 2022). The present study aimed to compare the solar energy efficiency in UAE, Japan, and China which are the main leaders in solar energy production in the world. The solar energy efficiency is enhanced by using advanced photovoltaic materials. Solar energy will be helpful in the global energy transition by moving towards renewable sources and mitigating climate change as these countries are signatories to international commitments for reducing carbon emissions (Zubair and Awan, 2021). This study will help in comparing three countries in terms of advanced solar development and photovoltaic materials. It also provides economic diversification as the UAE is among the top investors nowadays in MBR solar projects in Dubai (Obaideen et al., 2021). Moreover, it will provide influence in global renewable energy trends as these countries are top investors and are developed nations.

A mixed methodological approach is considered suitable for the present study. Both qualitative and quantitative data were used for comparing the solar energy efficiency of three countries and advanced PV materials. Philosophies like positivism, interpretivism, and pragmatism are considered suitable for getting deep knowledge to address research aims. Similarly, the research strategy is comparative to compare the solar energy efficiency of the three mentioned countries and secondary data was extracted after a deep literature review from different research engines. The relevant data was used for further data analysis. Qualitative data was analyzed using thematic analysis and quantitative data was analyzed by using statistical analysis.

3.1. Research Philosophy

A research philosophy is a notion about any phenomenon in which data is collected, evaluated, and used. Research philosophy is a combination of terms ontology and epistemology that substantiate the choices of methodology in research. Ontology refers to the nature of reality while epistemology refers to the nature of knowledge (Saunders et al., 2023). It comprehends the basic principles that impact the way research is conducted, including the nature of knowledge and reality, and methods adopted to procure knowledge. These philosophies impact the various parameters like the choice of the researcher while designing the research, adopting methods, and finally the interpretation of data (Creswell et al., 2018). Apprehending and understanding any research philosophy is necessary because it offers assistance in clarifying the research approach, explaining methodological choices, and aligning with the huge scientific paradigms. There are several types of research philosophies and each of them has applications for how to design a research question, data collection, analysis, and interpretation. Investigators select that philosophy focuses on their goals, the type of phenomenon studied, and their views about existence and knowledge (Kaltenbrunner& Mathew, 2021). Here are some major philosophies discussed.

Positivism: This philosophy focuses on the view that the object is reality-based and can be described, observed, measured, and quantified. It is independent of human perception and comprises of use of quantitative, surveys, and statistical methods to conclude. In this philosophical method, information is collected through scientific methods like from empirical pieces of evidence and sensory experiences, and seemed as if the information is gathered by observations and experimentations that make it more reliable (Lincoln and Guba, 2018).

Interpretivism: This is based on subjective reality and suggests that it is man-made by their experiences and social context. Information is gathered by the interpretations given by individuals after their experience. Researchers adopt qualitative methods like interviews to comprehend the interpretations of participants experienced in their real lives. In this way, they can gain deep meanings and insights from participants (Fletcher, 2017).

Critical Realism: This philosophy describes that although reality is objective understanding is affected by historical, cultural, and social context. This philosophy is based on pointing out the mechanisms and structures involved that are fostering the observations. It shows that while reality is external and true only it is inappropriately apprehending. Researchers used both qualitative and quantitative approaches to get detailed insight and know the involved structures in observations.

Pragmatism: This philosophy comprises of practical implications of research and the conclusion of the research result. It is flexible in epistemology and ontology. These are more focused on the appropriate approach to tackle particular research questions rather than the philosophical debate of knowledge and reality. It implies that practical implications should be focused while evaluating theories and their application in the real world. Both qualitative and quantitative methods are used to get deep insight into problem-solving (Morgan, 2014).

Constructivism: This philosophy is based on information gathered through human interactions and experiences. Investigators mostly use qualitative approaches to understand how the groups and individuals create interactions including interviews and narrative analysis. Knowledge is complied by collaborative and interpretative methods of individuals and groups. It is subjective and dependent on social aspects. Each research philosophy provides a unique perspective on how to approach research, build a hypothesis, collect data, and interpret it (Aghaei, 2022).

The present study aimed to compare the development of solar energy in developed countries like UAE, China, and Japan and to explore the advanced photovoltaic cell materials to improve the efficiency of solar energy systems. This study focuses on the understanding of technological advancements, socio-economic and environmental conditions, and regional energy policy of these countries. The selection of research philosophy is difficult as it affects the whole journey from research design to result interpretation. Therefore, a mixed philosophical approach was adopted to address the multi-disciplinary aspects like technical and applied nature. It includes positivism, pragmatism, and interpretivism.

Positivism approach is suitable for evaluating the performance and technical efficiency of advanced photovoltaic materials as this philosophy is objective-centered and can be quantified. Experimental research and quantitative evaluation were adopted and measured and empirical evidenced data was collected on PV materials. In this way, quantitative data was collected on the efficiency and solar energy production of three countries. It comprises efficiency measurement under controlled conditions of different photovoltaic materials and statistical data collection on the energy output of solar cells in Japan, China, and UAE (Chadly et al., 2024; Jia and Lin, 2021; Wen et al., 2021). Interpretivism approach is suitable for comprehending the cultural attitudes, socio-economic aspects, and energy policies that are affecting the adaptation and implementation of solar energy in each country as this philosophical method is subjective and made of social and cultural collaborations. Information is collected by understanding the intentions and exposition of individuals. It helped to investigate the political, social, and economic factors influencing the development of solar energy in the UAE, China, and Japan. It involved qualitative methods like case studies, industry expert talks, interviews, and analyses of policy. It gave insights into regional differences, challenges, and opportunities for strategies of solar energy and the effect of policy and cultural aspects on the adoption of advanced solar cells in three countries UAE, Japan, and China

(Yang et al., 2023). Pragmatism approach centered on practical applications by valuing both qualitative and quantitative methods that help seek real-world problems. It combines both positivism and interpretivism to provide detailed information on the implementation of advanced PV materials to enhance solar energy conversion. It comprises pilot projects, feasibility experimentation, studies, and field testing. Implementation of advanced PV pilot projects in UAE, China, and Japan to explore the working efficiency and economic viability in real-life conditions (Yoo et al., 2021; Obaideen et al., 2021).

3.2. Research Strategy

Research strategy describes the basic directions of research. "*It is defined as how you answer your research questions and implementation of methodology".* It is an important element of methodology and consists of a research process carried out (Gravetter et al., 2017). It guides the data collection, quantification, and evaluation and describes the techniques and methods used for addressing the research question (Adam, 2023). The selection of an appropriate research strategy is dependent on research objectives, questions, availability of time and resources, the basis of philosophy, and most importantly available information. The primary goal is to select a method available that addresses the set goals appropriately. The researcher should identify the availability and kind of details required to address the research goals. Selecting the right strategy beautifies and provides a good angle to the study. It is also helpful in choosing the right methodology, for the collection and evaluation of available data to address research goals. Therefore, it is very important to select a well-suited strategy for to research goal to make the study results valid and reliable (Falzon, 2016).

To select a research strategy two most common qualitative and quantitative strategies are available. There are strategies available to be applied in research work like exploratory, fundamental, descriptive, analytical, applied, critical, predictive, and interpretive. A descriptive strategy is helpful to describe particular conditions. It focuses on and comprehends the behavior of individuals or groups of people (Yin, 2018). It provides the best observation of things without destroying their subjective integrity.

Observations and information were gathered in a natural and unchanged environment. Variables are not controlled by the investigator only describe what is happening and its effects. Analytical research strategy is based on available information and facts. It is suitable to describe complicated problems, by using available information of the study. It applied to causes and effect relations. Critical research strategy involves the critical analysis and the researcher analyzes the false perceptions made by the society.

The quantitative research strategy is most commonly used in the scientific community and based on numeric data collection and statistical analysis. It is used to analyze the causes and effects relationship by the social and natural science disciplines (Field, 2018). Experimentations, surveys, interviews, questionnaires, and observational studies are the common examples (Babbie, 2020). Interpretive strategy is based on a sense-making process and focuses on experiences by humans. Similarly, exploratory strategy is the exploration of new ideas and products so that market opportunities and strategies can be unveiled (Easton, 2010). Predictive strategy concludes based on probabilities as the name expressed. This strategy is best suitable for estimating the possible output and is mostly adoptable by business companies and organizations for forecast purposes. Narrative strategy refers to the exposition and interpretation of experiences by society.

The present study employs the comparative strategy for in-depth evaluation of solar energy efficiency in UAE, Japan, and China. This strategy is best suited for the present study as it provides a detailed exploration of the unique performance of each country and is helpful in comparative analysis. It mainly emphasize on policy-making of each country in the implementation of solar technologies and efficiency output. This solar energy efficiency helps to reduce carbon emissions and mitigate climate change to fulfill environmental commitments. China, Japan, and UAE are the main leaders in solar energy development and implementation in different approaches. China is the main contributor to large-scale projects and government incentives for solar energy. Japan is focusing on efficient land use and technological advancements for solar energy. Similarly, the UAE primarily focused on producing solar energy in desert areas that are supported by sustainable investments and planning like the MBR project in Dubai. This strategy allowed us to evaluate and compare social, economic, environmental, and policy-making aspects of UAE, Japan, and China on solar energy efficiency.

3.3. Research Design

A combination of three approaches interpretivism, positivism, and pragmatism will strengthen both qualitative and quantitative data. It makes sure the holistic approach for comprehending the practical, social, and technical prospects of enhancing the conversion of solar energy in Japan, China, and the UAE. It ensured that the present research will provide practical implications of PV along with their efficiency evaluation by rigorous testing. (Abuzaid et al., 2022; Alsalman et al., 2023). Therefore, evaluating technological development will be helpful for further technological innovations. In terms of environmental aspects, it will help these countries to meet their environmental targets as they have international commitments. By incorporating these philosophical aspects, the present study aims to provide scientific knowledge and real-life solutions to increase solar energy usage in China, UAE, and Japan (Chadly et al., 2024).

The quantitative data collection for the efficiency of solar energy production and photovoltaic materials includes the measured data collected through proper methodology for their further evaluation. It also involves the stability and price of PV materials. The qualitative data collection is accomplished through a collection of interpretations by stakeholders, industry experts, and policymakers to know the cultural behaviors, regional energy policies, and social, environmental, and economic factors affecting solar energy adoption in China, UAE, and Japan. These approaches will be helpful in understanding and illuminating the barriers so that implementation can be facilitated (Pourasl et al., 2023).

3.4. Data Collection

Primarily the secondary data was collected for the comparison of solar energy efficiency in UAE, Japan, and China and the utilization of advanced PV materials. It is the most important part of any research as it impacts the results and conclusion. In the present study, secondary data was collected after in depth literature review from different research engines, and important and relevant information was extracted. A variety of sources were used like academic journals, databases like Web of Science and Scopus, government publications, and expert industry reports. The data collection consists of technical reports and case studies on installed solar projects in UAE, China, and Japan. The data used for the evaluation of system efficiency were energy output, conversion efficiency, and system capacity. Similarly, documents on government incentives, regulations, and policies making for solar energy and their implementation in three countries were also collected. Through this method, comprehensive data was collected for further data analysis.

The comprehensive literature review resulted from in depth search of academic reports, articles, review papers, conference papers, short communications, and pertinent publications. ResearchGate and Google Scholar were the primary research engines to collect secondary data. Data was searched with primary keywords like “Comparision of Solar energy efficiency in UAE, Japan and China”, “socio-economic benefits of solar energy”, “environmental aspects”, “policymaking in UAE, China, and Japan on solar energy”, “use of advanced and efficient photovoltaics materials in UAE, China, and Japan” etc. to focus and filter most relevant data different operators were utilized like AND, NOT, and OR for a thorough understanding of the conceptual and theoretical base of the subject under study. Furthermore, it helped out in finding the research gap and establishing research questions. Other than ResearchGate and Google Scholar other sources are also used like Science Direct, Springer, institutional repositories, and JSTOR. As a result, more in-depth research and data collection ensures the understanding of complicated factors of the study comparison of solar energy efficiency in UAE, Japan, and China. Involving diversity of viewpoints, empirical results, and different approaches resulted in a comprehensive vision of the study. Hence adopting sophisticated searching, and the use of keywords the literature provides a huge perspective and useful implications for the study. The strong foundation for the goal of the study established by thorough analysis and knowledgeable data is ensured through a comprehensive literature evaluation approach.

3.5. Data Analysis

In the present study to address the research questions the comparison approach was adopted to perform data analysis. This was made between UAE, China, and Japan regarding solar energy efficiency, policy and regulation making and their implementation trend in these countries. Both the qualitative and quantitative analyses were performed. Qualitative data was evaluated by using thematic valuation to point out key themes, opinions, patterns, and insights on solar energy-adopting practices and technologies. Which are impacting the efficacy of solar energy in UAE, China, and Japan. "*Thematic analysis refers to identifying, evaluating and reporting of themes in data"*. It facilitates the flexible approach to examining the qualitative material for brief and holistic understanding. It helps to identify the expert viewpoints and experiences that result in quantitative outcomes. This procedure uncovers the lifetime experience and interpretations of industry experts on advanced PV materials.

Quantitative data analysis was performed using different statistical techniques. It includes correlation analysis, descriptive statistics, and regression analysis to compare the efficiency improvement and implementation of solar energy in three countries and the use of advanced PV materials in UAE, China, and Japan. Correlation helped to evaluate the relationship among different parameters like studying the relation between efficiency enhancement and investment in solar technology. Similarly, regression analysis described the effect of different parameters on the efficiency of solar energy. In our case, the multiple regression model is best suited to study the effect of environmental conditions, technological innovations, economic factors, and governmental incentives and policies impacting the efficiency of solar systems in UAE, China, and Japan. These statistical methods for comparison are employed to know the similarities and differences in pointing significant parameters influencing the solar energy performance and system efficiency in three countries.

3.6. Research Validity and Ethics

The credibility of the study is dependent on the validity of the research findings. Both internal and external validity is crucial. Internal validity describes the accuracy of results within the study context. Rigorous data collection and analysis methods helped to achieve internal validity. Triangulation will be utilized by adopting multiple data methods like qualitative and quantitative analysis and data sources like academic and educational journals, platforms, interviews, and industry reports to cross-check the results and conclusion. External validity describes the result's generalizability outside the context of the study. Choosing the UAE, Japan, and China to represent the diverse economy, geography, and policy-making increases the external validity. Through a selection of various cases, the present study succeeds in drawing diverse conclusions on the efficiency of solar energy and could be implacable in different contexts.

Research ethics are vital to maintaining transparency, integrity, and respect for any research. Secondary data was utilized in the present study therefore it is necessary to carefully consider the ethical principles. Ethical aspects are vital for carrying out credible, valid, and responsible research. The present study adheres to ethical guidelines by following informed consent, avoiding conflict of interest, confidentiality, anonymity, and ethical approval. Proper acknowledgment and citations are provided where secondary data was used. There are some figures adopted from research papers therefore proper citation was added in their caption to maintain the integrity of the source and avoid plagiarism. Misuse and misinterpretation have been avoided while collecting and using secondary data. The present study complied with legal guidelines for using secondary data.

Chapter 4: Results

This chapter presents the results of data for different variables in three countries: China, Japan, and the UAE. The data regarding finance, the legal systems of these three countries, technological innovations, environment and sustainability, and R&D were compared and presented in the tables below. The findings could help devise a strategy for effective solar power implementation in the United Arab Emirates.

4.1. Finance Allocated

The qualitative and quantitative analysis of data available on different websites on the internet has shown that the factor of allocation of finance has a huge impact on the extent of solar development in a business. More capitalization implies that major projects are developed, the economy grows, new workplaces are provided, and the goal of making the world use more clean energy is achieved.

Finance Allocation	**Investment Overview**	**Key Projects**	**Government Initiatives**	**Annual Investment**
	China remains the largest investor and the country with the largest installed solar power capacity globally. The government has supported the solar	• **Datong Solar Power Top Runner Base** Mainly focus on the construction of energy-saving and low-carbon projects	• Five-Year Plans • Subsidies and Incentives	Annual expenditure on solar energy is at over $25 billion in China signifying the country's supremacy in solar energy market (Mihajlovna, 2023).

China	industry in many ways; therefore, the solar industry is flourishing and has positioned itself as a global leader in the production and use of solar panels (Li & Umair, 2023).	as a part of the country's top runner program with an investment of ten billion dollars (Autry & Navarro, 2024). • **A Project on Solar Power Plant in Qinghai** A large scale solar project put into the grid (Lv & Tang, 2024).		
Japan	The increased capacity addition post Fukushima Daiichi nuclear disaster that happened in 2011, indicate that Japan is interested on increased generation of solar energy as a way of diversifying sources of energy in	• **Solar Frontier Kunitomi Plant** An efficient solar panel manufacturing company (Parrish, 2023). • **Kyocera Kagoshima**	• Feed-in Tariff (FiT) Scheme • Renewable Energy Strategy (Zhang	Japan has been a major investor in solar power annually. Its investment has been in the range of $5 billion to $10 billion in recent past (Barry 2024).

	a way that improves energy security (Taghizadeh*et al.,*2023).	**Nanatsujima Mega Solar Power Plant** An exceptionally large solar power plant in Japan.	*et al.,*2023)	
United Arab Emirates	The UAE in particular has grown rapidly in solar energy generation mostly due to its efforts and goals for green energy and carbon footprint (Alsalman *et al.,*2023).	• **Mohammed bin Rashid Al Maktoum Solar Park** It is one of the largest single site solar parks in the world and the capital investment estimated to be about $ 13.6 Billion (Alzaabi, 2024). • **Shams 1** A $600 million CSP or concentrated solar power project are introduced.	• Dubai Clean Energy Strategy 2050 • Masdar Initiative of Abu Dhabi	Annual spends on solar energy are estimated to be between $1 billion to $2 billion in USA which is a part of UAE (Quamar *et al.,*2023)

Japan's contribution toward solar energy is $5-$10 billion per year, highlighting its commitment to diversifying energy sources, particularly in the wake of the Fukushima disaster. The country's sophisticated Feed-in Tariff (FiT) scheme effectively incentivizes solar energy adoption by guaranteeing fixed payments to energy producers, thereby encouraging investment. Other improvements could also be made in line with the Japanese policy model on various energy sources and financial assistance. Thus, integrating the UAE's economic plans with the elaborated models will help the country enhance solar energy development and achieve sustainability objectives. In addition, Japan, coupled with a financial support program for SMEs, focused on the diversity of energy portfolios and provided a framework that the UAE adopts. The diversity of the energy portfolio not only enhances the power security but also enhances the fluctuations in the market. Thus, the UAE could stimulate urban innovation and contribute broadly to the renewable energy sector that follows the financial support mechanisms in Japan.

Thus, the UAE stands to gain significantly by adopting financial strategies identified in China and Japan to enhance its solar energy development. China's annual investment of over $25 billion, coupled with favorable government policies, has propelled its solar industry forward. These policies, including generous subsidies, tax incentives, and dedicated funding for research and development, could create a more robust environment for expanding the UAE's solar energy infrastructure. By implementing similar large-scale investments and supportive frameworks, the UAE could see a substantial improvement in its solar energy sector, potentially transforming its energy landscape. The UAE could apply similar mega investments and stimuli seen in China in its Five-Year Plans, paving the way for a brighter, more sustainable future.

Table 1: Description of solar energy projects in UAE, China and Japan

Private Sector Investments	**Cost Breakdown**	**ROI and Projections**	**Comparison to Other Renewable Sources**
Growing private sector investment from companies like **LONGi** and **JA Solar**, focusing on innovation in solar panels (Wideanbach, 2021).	**Research & Development**: 30%, **Installation:** 40%, Scaling: 20%, **Maintenance:** 10% (Statista, 2023).	China projects 30% annual solar growth, ROI at 12-15% (Peter & Petri, 2023) .	Solar: 68%, Wind: 22%, Hydro: 10% (Hilton, 2024).
Companies like **Sharp Solar** and **Panasonic** are leading with significant investments in solar PV (Bischoff *et al.,* 2024).	**Research & Development**: 25%, **Installation:** 45%, **Maintenance:** 15%, **Scaling:** 15% (WeXpats, 2023).	ROI projection of 8-10% due to technological advances in solar efficiency (CBRE, 2023).	Solar: 50%, Wind: 30%, Nuclear: 20%. (Institute for Sustainable Energy Policies, 2024)

Masdar and **ACWA Power** have expanded investment in utility-scale solar projects (Haque, 2024).	**Research & Developmen**t: 20%, **Installation:** 50%, Scaling: 20%, **Maintenance:** 10% (Pierce, 2024).	Expected ROI of 10% annually, driven by demand for renewables (Best Property, 2024).	Solar: 80%, Wind: 10%, Hydro: 10% (U.S Department of Energy, 2023).

The UAE has the potential to significantly enhance its solar energy development by revising its financial support strategies, drawing inspiration from China's substantial investments and Japan's effective policy measures. By following in the footsteps of these countries, the UAE cannot only improve its energy production from solar sources but also contribute to the sustainability of the environment. This shift could lead to a reduction in carbon emissions, the burning of fossil fuels, and the carbon ratio in the surroundings. Ultimately, the UAE could achieve success in solar energy, marking a significant step towards both economic and environmental sustainability.

4.2. Technological Innovations

Growing global demand for clean energy has underlined the development of new technologies in the solar industry. This paper will compare the developmental sectors of solar energy in UAE, China, and Japan to see how far they have advanced and what strategies they have adopted.

Table 2: Description of technological innovations in solar energy projects in UAE, China and Japan

Country	**Technological advancement**		
China	Advanced Manufacturing Techniques China has been seen to have mastered the high-efficiency solar panel manufacture, it is currently the largest producer of solar panels in the world	Government Incentives Policy drivers like subsidies have helped boost the solar projects' technological development spur (Wu *et al.,*2023).	Solar Farm Larger solar farms like the Datong Solar Power Top Runner Base are evidence of China's ability to incorporate new ideas into large scale projects (Ye *et al.,*2023).

	(You *et al.,*2024).	Subsidies boosting technology.	Datong Solar Power Top Runner Base integrating new technology
Japan	Bifacial Solar Panels Current development has also seen the use of bifacial panels whereby the panels can capture light from both tops and bottoms boosting efficiency (Vimala*et al.,*2023). Bifacial Solar Panels capturing light from both sides	Interconnection with Smart Grids The smart grid concept practiced in Japan as a form of enhancing the grid system to control the distribution of solar energy efficiently (You *et al.,*2024). Smart Grid Interconnection, enhancing energy distribution.	Residential Solar Systems Most of the sales are inclined towards residential solar products due to government policies that have enforced the use of solar energy by residents (Ahmad *et al.,*2023). Residential Solar Systems is driven by government policies
UAE	Concentrated solar power or CSP Due to CSP technology, the UAE will be able to generate electricity	Low Cost Solar Panels One area of focus has been in efficient photovoltaic panels which has seen	

	during the time of the day that is cloudy, and therefore not sunny (Das *et al.,*2024). **CSP** is a Stable energy generation during cloudy periods	enhanced energy generation and value for money (Alsalman *et al.,*2023). **Low-Cost Solar Panels** focusing on efficiency and cost-effectiveness	

Concentrated Solar Power (CSP) technology has positioned the UAE as a global leader. This innovative technology allows the production of solar energy even when sunlight is not properly produced, such as on cloudy and rainy days. To use the sunlight in a proper manner through the use of reflection mirrors to generate solar energy is challenging for the UAE's pioneering spirit. The time when PV system not works properly the practice of utilization of reflection mirrors provide reliable power for UAE enabling them extraordinary in solar infrastructure landscape. The UAE's commitment towards solar energy renewable sector is further highlighted by the construction of the Mohammed Bin Rashid Al Maktoum solar park like mega projects.

Furthermore, the UAE'S ambition for renewable energy like solar energy is inspiring. They are focusing for concentrated solar panels strategies to help the solar panels to work efficiently at less cost, possible them as affordable and easy to use along with working for changes in conventional photolytic technology. Moreover, it is further proved by the investment in solar energy through government initiatives and Masdar that UAE is committed to become powerhouse of renewable energy. It could be concluded that the UAE's efforts for solar energy production on large scale and focus on CPE strategies and conventional photolytic technology systems is appreciable contributing towards a sustainable environment.

The world's largest installer and producer of solar energy panels and technology is China. They provide energy through the manufacturing of advanced technology at an affordable price. The price of solar panels drops significantly making it more accessible at low price in different countries globally. The example of central role of China in solar energy is project of Datong Solar Power as top runner base meeting the country's energy demands. Moreover, the other important role is played by government incentives for the growth of solar energy in China. Various policies like tax incentives, solar energy project related subsidies and carbon emission reduction commitments by government all have surges the advancement in solar technology in China. The solar industry and development of renewable energy is more strengthen through the prioritizing of China's five-year plan. It is aim of China to lead the world in advancement of solar sector and contribution in mitigation of environmental pollution and climate change. In addition, the solar sector of China emphasizes the experimentation and enhanced technological advancement thus benefiting the own country and other nations globally.

In present time of discoveries and innovations, China is at top in regional solar energy ideas and introduction of new techniques for storage of energy at large scale. China is working heavily on solar energy tracking system in order to capture maximum solar energy and increasing the technological efficiency of panels, by offering them to absorb more energy and formation of large amount of solar power. Furthermore, China is tactically working to produce a strong position in world solar energy market through fostering leadership and technological advancement. The innovation introduced by Japan in solar panel infrastructure is not only advanced but also greatly adopted by different countries. The new introduced infrastructure is known as bifacial solar panels are designed to produce solar energy from both side of panel by capturing sunlight. Such panels are more efficient is regions with dense urban environments, high pollution level and heavy cover of clouds where sunlight cannot reach easily. They are also space efficient and possessing huge capability to store energy. Japan has also developed a grid system alongside the bifacial solar panels. This grid uses advanced communication technology to monitor and control the flow of electricity, distributing solar energy efficiently. It ensures the system can handle surplus energy production, stabilizing the energy across the grid during peak generation. Apart from solar energy, Japan also uses other energy sources in its infrastructure like wind and hydropower.

Furthermore, Japan is focusing on the technological innovation development in household solar system, aiming to made the government policies and incentives more affordable and user friendly for residentials. Primary goals is to easy the installation process so that can be easily installed on rooftop as solar panels, that will also encourage others to adopt solar energy system in residential areas. The country's Feed-in Tariff (FiT) scheme, which guarantees fixed payments to solar energy producers, has further encouraged investment in solar energy at both the residential and commercial levels.

Thus, the UAE has concentrated on big solar plants and CSP technology, while China has opted for a massive production capacity and numerous massive solar plantations. Japan, on the other hand, implements new technologies to adapt existing infrastructure and focuses on solutions for homes. Each country leads in different areas: the UAE in CSP, China in manufacturing and utility-scale deployment, and Japan in panel innovation and integration to smart goods (Vimala*et al.,*2023; Ahmad *et al.,*2023; Wu *et al.,*2023). While providing giant and prompt government impetus, China is strategic and large-scale, while Japan concentrates on high-tech residence. The technological advancement of the three selected countries in the solar developmental sectors aligns with their intended national strategies. The UAE teaching the world lessons in solar energy, China's manufacturing and scale in solar energy, and Japan's integration of technology in the field of solar energy offer critical lessons in the advancement of solar energy technologies (You *et al.,*2024; Alsalman *et al.,*2023).

This cross-structural comparison also compares the different approaches of each country in promoting the development of solar technology, thus indicating that national objectives and resources have much influence on the solar energy prospects in the relevant countries. The **UAE's** focus on large-scale projects, **China's** manufacturing prowess, and **Japan's** technological innovations all offer valuable lessons for other nations looking to expand their renewable energy capabilities. By understanding and adapting the best practices of these countries, other nations can accelerate their transition to a sustainable energy future.

4.3. Legal System

Solar energy is well determined by the legal environment within the sector. This paper considers and compares the legislation affecting the solar business in the UAE, China, and Japan. This study employs secondary research analysis and includes qualitative and quantitative data that describe the nature of the legal environment to explain how the legal systems affect solar industries in such countries.

Table 3: Comparison of Legal framework of renewable energy in UAE, China and Japan

Country	Legal System	Regulations and Incentives	Regulatory Bodies	Incentives
China	China has a socialist legal system, all the laws and regulations in current China are top-down governing laws and policies. The solar energy industry is controlled by the National Energy Administration (NEA) and other related departments (Ali *et al.,*2023).	The NEA is pivotal in both policymaking and implementation, focusing on fostering the growth of renewable energy (Hu, 2023). Policies include **feed-in tariffs** that guarantee a fixed price for solar energy producers, **subsidies** for solar projects, and significant	The NEA is involved in policy making and more so implementation of the same (Hu, 2023).	Some of the Chinese solar energy policies include feed-in tariffs as well as subsidies. The country is also acclaimed for its appropriate support to research and development associated to solar energy technology (Huang *et al.,*2023).

		support for research and development in solar technology (Huang et al., 2023). The government also promotes large-scale solar farm projects through financial incentives and favorable policies to encourage investment in renewable technologies.		
Japan	In Japan, feed-in tariffs and different sorts of subsidies help to make the use of solar power. The country's legal system also has strong legislative measures towards the protection of the environment to	The Japanese legal framework includes comprehensive environmental regulations that promote energy sustainability. The **Feed-in Tariff system** ensures that solar energy producers receive	METI is responsible for the administrative functions of solar energy policies (Kohyama & Kohsaka, 2024).	In Japan, feed-in tariffs and different sorts of subsidies help to make the use of solar power. The country's legal system also has strong legislative measures towards the protection of the environment to

	enhance energy sustainability (Kohsaka & Kohyama, 2023).	guaranteed payments, fostering a conducive environment for renewable energy investments. Additional regulatory measures require energy companies to integrate renewable sources into their energy mix, reinforcing sustainability commitments (Kohyama et al., 2024).		enhance energy sustainability (Kohsaka *et al.,*2024).
UAE	The UAE has a federal system of laws with mundane legislation differing from one Emirate to another but must conform to the Federal laws.	FEWA and DEWA supervise policies and regulations related to solar energy, ensuring compliance with both federal and emirate-specific	Policies and regulations related to solar energy are supervised by FEWA and DEWA (Daniel*et al.,*2024).	Various incentives are granted by the UAE like the Mohammed bin Rashid Al Maktoum Solar Park which is one of the projects to

	The renewable energy is mainly being regulated by the Federal Electricity and Water Authority (FEWA) and the Dubai Electricity and Water Authority (DEWA) (Sajwani *et al.,*2023).	laws. They play crucial roles in the implementation of national renewable energy strategies, including the **UAE Energy Strategy 2050**, which aims to increase the contribution of clean energy to the country's energy mix (Daniel et al., 2024).		expand capacity of solar energy in the country. There are also material incentives such as grants and tax credit (Sunilkumar *et al.,*2023).

The above data illustrates that the UAE should borrow some financial planning models from China or Japan to improve its solar energy sector. Thus, NEA's dominant and coordinated governance model has efficiently created comfortable conditions for solar development with high feed-in tariffs and significant R&D support. The Ministry of Economy owns feed-in tariffs combined with environmental legislation to safeguard the nation's environment and resources.

Japan is offering a distinct approach through its Ministry of Economic, Trade, and Industry, playing a vital role in shaping policies that can be integrated into robust environmental legislation. This design not only encourages the use of renewable energy but also ensures that natural resources are utilized sustainably. Resultantly the environmental protection is also prioritized along with the economic incentives. Japan explain it as a good, modern and holistic way to promote solar energy while balancing the environmental conservation and economic growth.

According to stated scenario it is clear that there is urgent need for UAE to adopt a comprehensive legal method that will environmentally friendly besides financially sustainable. The establishment od roadmap by government of China and legislation bodies of Japan provides a valuable strategy for UAE to be adopted that will increases the efficiency of energy policies of UAE. These strategies are about to meet the objectives of nation for use of natural renewable energy resources along with advancement in solar technology. Thus, UAE can improve its position in renewable sector and support sustainability efforts globally by aligning the stated approaches. It is not only important but also urgent for UAE to incorporate such incentives and legal frameworks in solar energy policies. These measures are necessary to ensure a sustainable and prosperous future for the country.

4.4. Environmental Perspective

As, solar energy is directly related to environment, so, it is crucial to investigate the environmental aspects related to photovoltaic cells. This section will compare the developmental sectors of the solar energy in China, Japan and UAE.

Table 4: Comparison of Environmental perspective of solar energy in UAE, China and Japan

Aspect	China	Japan	UAE
Carbon Emissions	China, the largest producer of PV cells, faces significant emissions during manufacturing. However, the country is proactively seeking the zero	Japan is inclined toward cleaner production and manufacturing. Therefore, the carbon footprint	The UAE is heavily focused on solar energy, but its PV manufacturing is still

	emissions standards by opting green technology. Research by An shows that carbon footprint of PV production in China has decreased by 50% between 2011 and 2020 (An et al., 2024)	from PV production in Japan is comparatively less. Moreover, the country has Green policies to promote green energy. According to World Economic Forum, Japan aims to reduce CO2 emissions from the PV industry by 46% by 2030 compared to 2013 levels.	associated with higher emissions due to less stringent regulations compared to China and Japan. However, the country aims to reduce carbon emissions from the energy sector by 70% by 2050 (Naqbi et al., 2019).
Recycling and Waste Management	China manage the PV waste by accelerating the development of recycling technologies. China is expected to generate 214.68 GW–579.76 GW of PV waste by 2050 (Shao, 2023). The country aims to achieve a 90% recycling rate for PV modules by 2025.	Japan has an established recycling framework for PV cells, focusing on circular economy practices. The country implemented a mandatory PV recycling system	The waste management of photovoltaic cells in UAE is very limited. There are couple of factors like lack of infrastructure to handle end-of-

		in 2022, aiming to recycle 80% of decommissioned PV modules by 2035. However, progress is slower compared to China.	life PV cells. However, the country is putting effort to develop technology for recycling. Efforts to develop recycling technologies are still emerging.
Land Use Impact	China has utilized a large area of land for solar farms, making the ecological environment at risk. However, the government is taking actions to utilize rooftop solar to mitigate these concerns. By 2020, China had installed over 100 GW of rooftop solar capacity [8].	Japan, with limited land, promotes rooftop solar installations and floating PV farms to reduce the environmental impact of land use. As of 2022, Japan had over 78 MW of floating solar capacity (Hunag et al., 2024).	The UAE, with abundant desert land, favors large solar farms, such as the Mohammed bin Rashid Al Maktoum Solar Park, which requires vast amounts of space but has minimal impact on fertile land. This solar park will cover 214 square

			kilometers upon completion.
Technological Advancements	China is advancing rapidly in PV cell efficiency and reducing the environmental impact of production. The country has achieved a record 26.81% efficiency for silicon heterojunction solar cells in 2023(Lin et al., 2023). China is also leading in the development of perovskite solar cells, which promise higher efficiency and lower production costs.	Japan focuses on improving PV cell efficiency and has a strong research emphasis on reducing environmental harm through innovation. Japanese researchers have developed ultra-thin solar cells with 29.1% efficiency in 2022. Japan is also pioneering in the field of transparent solar cells for building-integrated PV.	The UAE is integrating the latest solar technologies but remains more reliant on foreign technology compared to China and Japan. However, the country is investing heavily in R&D, with the Masdar Institute developing new PV technologies suited for desert conditions, including dust-resistant and high-

			temperature tolerant solar cells.

Based on prior research and field data, Wang assessed the environmental advantages and energy application possibilities of PV-PAPs in seven Chinese provinces (Wang et al., 2020). The conclusions are as follows:

1. China's PV-PAPs offer strong economic, environmental, and energy efficiency. The discoveries of this research specify that the EPBT ranges for 23 plants are 0.79 to 1.94 years, the EROIPE-eq ranges from 15.48 to 38.15, the GHGe-R ranges from 43.34 to 106.78 g/kWh, and the CPBT ranges from 1.88 to 5.11 years. The average annual (per capita) carbon productions can be lowered by 0.82 tons throughout the entire study region. It is evident that PV-PAPs' EPBT and CPBT are shorter than their life cycle. Benefits from reduced emissions and net energy use are realized after payback period. Over 93% of the NTG in the life cycle is found in the normal economic outlay payback period of 9.72 years.
2. The solar radiation circumstances, as well as the level of operation and maintenance management, have an impact on PVPAPs' energy and environmental profits. The average environmental and energy advantages of the 7 provinces are recorded as of high to low: Shanxi, Inner Mongolia, Gansu, Ningxia, Anhui, Hubei, and Henan. The findings demonstrate that PV-PAPs still have virtuous potential for emissions reduction and energy return even in the type-3 supply area, which has comparatively the lowest solar radiation in China: the EPBT ranges from 1.17 to 1.94, the EROIPE-eq ranges from 15.48 to 25.57, and the GHGe-R ranges from 64.66 to 106.78 g/kWh. The greatest variation in GHGe-R between PV-PAPs in the same county is 51.44 g/kWh, or 0.95 times, indicating the need of proper maintenance and operation for the long-term viability of power plant

operations. It can even offset the drawback of low resource endowment quality, demonstrating positive environmental effects.

3. PV inhabits a favorable position as compared with other types of electricity generation technology. The application of PV has strong attractiveness and can decrease carbon emissions by 87.35%–94.9% as compared with outdated coalfired EG. Solar radiation resources of China are widely dispersed and have a improved application range and probable than the wind energy (which is equally vigorously promoted). Therefore, PV-PA projects can not only expand energy equality in poor areas, but also be used to participate low-carbon energy technology to settle China's grid structure, ensure upcoming sustainable energy supply, and realize the evolution from fossil energy system to low-carbon energy system.

From 1986 to 1990, the New Energy and Development Organization (NEDO) conducted a four-year demonstration project that gave the nation's PV manufacturers access to a specialized market. As a result of their continuing implementation of the program, Sharp, Sanyo, and Kyocera rose to prominence in Japan's solar PV manufacturing industry. These businesses founded the Japan Photovoltaic Energy Association (JPEA) in 1987 with goal of fostering the use of solar PV skill. Kimura (2006) described JPEA as a coalition group for the PV sector. The "Net-Metering (Billing) Program" was the first demand-pull policy for the growth of the PV sector, and it was established in 1992. Ten domestic electricity companies started this program (Suwa and Jupesta, 2012). The government introduced the "Monitoring Program for Residential PV Systems" the next year as a particular regulation pertaining to grid construction for solar PV (Kaizuka, 2012). After the "Sunshine Program" and the "Moonlight Program" combined in 1993, the "R&D Project on Environmental Technology" now known as the "New Sunshine Project" was put into action with the goal of advancing extensive and sustained research and development for photovoltaic technology (Tatsuta, 1996).

The majority of PV R&D, including basic research, was carried out by PV producers (IEA, 2017). Initiated in 2001, "the new 5-year plan for PV power generation technology R&D" is the new research and growth initiative in Japan. This program concentrated on four areas: cutting-edge next-generation PV power technologies, complete introduction of common core PV technologies, advanced solar cell technologies, and advanced PV system manufacturing technologies. Following the completion of the current five-year plan in 2006, a four-year proposal based on the "PV Roadmap toward 2030 (PV2030)" plan was introduced (Kosuke, 2007). 2009 saw the start of the "R&D for high performance PV generation system for the future" and "R&D on innovative solar cells" projects, which sought to advance next-generation solar cell technology. The projects were overseen by the Culture, Sports, Science, Ministry of Education, and Technology (MEXT) and supported by the Japan Science and Technology Agency (JST). The goal of a new set of guidelines for technology expansion based on the "NEDO PV Challenges," which were developed in 2014, is to achieve electricity generating costs of 7 JPY/kWh by 2030 and 14 JPY/kWh by 2020 (Hahn, 2014). NEDO changed its focus from "strategies to promote dissemination of PV power generation" to "strategies to support the society after penetration of PV power" under the novel context of technological research (IEA, 2014a). Instantaneous to a new monitoring database for home PV structures, the government implemented another renewable energy guideline known as the “Renewable Portfolio Standard (RPS)” in 2003 on the demand-pull policy side (Ito, 2015).

United Arab Emirates (UAE) is defined by satisfactory geographical characteristics and constitutes a most important oil producing nation. The United Arab Emirates has experienced an unparalleled economic and social metamorphosis in the last several decades. Revenue from oil has been utilized to upgrade social indicators, create jobs, and modernize infrastructure. The UAE is now one of the biggest emitters of CO_2 as a result of these expenses (Ministry of Energy, 2006). Primary energy grew by about 60% in ten years (1997–2006), with a 15.3% growth in 2007–2008 (BP. 2008). Simultaneously, the rise in CO_2 emissions resulting from energy use was observed to be between 33% and 35%. One of the greatest promising, dependable, and ecologically friendly renewable energy bases available today is the utilization of solar technology, which has the potential to make a major contribution to the UAE region's energy and environmental systems.

In UAE, numerous initiatives that prioritize the technical and financial aspects have focused on large-scale PV applications. PV technology's worth must be assessed in the context of other factors, such as social and environmental considerations. This study looked at the environmental, economic, and technical factors affecting PV use in United Arab Emirates. It evaluated the trade-off between the financial costs and environmental advantages of applying solar power to residential buildings in United Arab Emirates. A cost-study suggests that, with the exception of a few UAE emirates, there is not any need for the government or customers to use PV systems to generate electricity (Radhi, 2012). It was observed that in the majority of grid-connected applications, the cost of BiPV technology is advanced than that of traditional technology. Nonetheless, the UAE's PV market is expanding rapidly. PV technology is thought to be feasible in that it has the potential to outperform traditional power plants in terms of environmental advantages. The quantity of CO_2 emissions from typical dominant power plants is greatly reduced by each single watt produced or conserved by PV expertise. Reducing the quantity of electricity produced by these power plants will cut CO_2 releases and lessen the impact of global warming on the UAE and other countries. The UAE policy's support for photovoltaic technology is justified by the trade-off among economic costs and ecological advantages, as adoption of this technology is expected to yield social benefits that outweigh its costs. By raising awareness of the need to use less electricity and acting as a source of education, the fixing of BiPV systems can lesser overall electricity usage.

4.5. Elements affecting the efficiency and dependability of modern photovoltaic materials

The electrical power system can benefit from renewable energy sources (RESs) in a number of ways, including reduced power losses, stable voltage profiles, and more affordable electricity rates (Bayod- Rújula, 2009). However, there are obstacles and difficulties that fall into two groups: non-technical and technical. Non-technical difficulties include of capital expenditures, financial concerns, market concerns, public knowledge, stakeholders, and rules, and guidelines. The optimization methods need significant inputs. like:

Weather data: In demand to achieve a anticipated optimization, precise data regarding the primary solar system parameters-namely, dust, ambient temperature, wind speed, humidity, and sunlight are essential. Even with estimate approaches like Artificial Neural Network (ANN), one of the key obstacles in optimization is receiving such data on an hourly or daily base.

Load forecasting: To get the perfect photovoltaic (PV) device size, the outline of a full load demand throughout a year essentially be available.

Model's accuracy: For optimization, having a precise model is critical. Every significant parameter that influences the system's effectiveness needs to be included in the model.

The variety of specification: It is difficult to have comparable PV models in relations of conversion efficacy. Abundant PV brands are obtainable on the market, and recent progressions in the manufacturing procedure increase the alteration efficiency of alike models.

Simplicity and applicability of proposed methods: Simple and precise results are the aim of optimization. AI technologies and analytical approaches are two methods that can be combined to achieve this.

PV based hybrid system optimization challenges:

The main drawback of using renewable energy bases is that they are unpredictable and inefficient because of their irregular and frequently changing character, which typically results in oversizing and higher capital expenses. In order to address these issues, the hybrid method's structures have lately gained a strong reputation (Hannan et al., 2020b). According to Sinha and Chandel (2014), the goals of hybrid renewable energy system (HRES) are to lower system costs, improve efficiency, increase system reliability, and decrease energy storage capacity. Frequent research focuses widely on the application of current heuristic methods and traditional optimization practices to address problems relating to the development and process of HRES (Sinha and Chandel, 2015).

Most optimization strategies are developed using the biological or physical intelligence machinery or animal colonial behaviors as its foundation (Hannan et al., 2018b). Even yet data-driven optimization methods have extensive training times and intricate computations, these problems have been resolute by recent developments in large storage capacities, computer power, and incredibly fast processing speeds (Sulaiman et al., 2018; Lipu et al., 2020b). One hybrid structure optimization approach, for example, determines the ideal HRES configuration by combining various combinations of the separate producing systems (Othman and Musirin, 2010). Additionally, the authors inspected scale optimization and recommended that off-grid hybrid systems (such as photovoltaic and biomass systems) would suggest the maximum practical answers.

An outline for supporting corresponding calculations between small hydropower stations (SHPS) and solar systems was presented by Khatib et al. (2013). The methodology was created by combining hydrological and solar radiation data with an optimization algorithm, which suggested potential system design modifications that could improve their proficiency. According to Eren et al. (2017), a multi-objective inherited algorithm was used to enhance the hybrid system through the use of the PV-wind hybrid system's optimal design. Many techniques, including the stochastic method, the intuitive process, the deterministic procedure, and the numerical method, were employed in the optimization approaches. 38 research papers were revised for this paper; of those, about 26% employed a stochastic approach, and the remaining 74% employed a deterministic one.

The hourly solar energy series was one of the solar energy uncertainties that was addressed by the stochastic approach. With the suggested analysis, a dependable energy supply might be obtained for the least amount of money. The goal of the concept was to identify the best way to improve or raise the implemented renewable system's efficiency. Optimizing the system's influential parameters could lead to these outcomes. However, there were also difficulties and impediments that fell into dual groups: non-technical and technical.

The output power formed by the PV power structure is influenced by various external factors, including dust, humidity, temperature, and irradiance. Time and relevance are two variables that affect each of these characteristics. Although there is no direct control over these external conditions, there are ways to lessen their consequences. So, it is vital to evaluate the result of the external environment on efficiency and recommend relevant methods to optimize structure efficiency. The two main factors are the short circuit current and open-circuit voltage that express how the output power of a PV cell varies. The open circuit voltage has been lowered by an increase in the surrounding temperature and slightly raises the short circuit current, which consequences in a fall in effectiveness.

Using MATLAB the efficiency of solar cells was studied with the impact of the temperature (Nair et al., 2016). The simulation's findings proved that rising temperatures triggered the reverse saturation current to rise and V_{oc} to fall, hence causing the fill factor to drop and the solar cell's output to decrease. Simultaneously, the cell's efficiency could be enhanced by a decrease in bandgap led to a rise in J_{sc}. Therefore, as a result of the variation in V_{oc} and J_{sc}, the solar system's efficiency decreased. The study conducted by Chander et al. (2015) shown that well photovoltaic cells function depends on temperature which had a significant impact. The maximum generated power reduced by around 0.47% for every degree Celsius increase, after the surface temperature rose above 25 C (Majid et al., 2014).

Consequently, an effective way to boost its performance is lowering the external operating temperature of a PV module. By cooling the component and dropping the amount of heat that the PV cells hold, this can be achieved, while, the device is operating. Another important constituent that might reduce the PV system's efficiency by hindering some of the sunlight is dust (Furkan and Mehmet Emin, 2010). For PV system documentation, upkeep, and cleaning, the authors shaped a timetable with the goal of manipulating PV system concert.

4.6. Challenges and Expanding Solar Energy Capacity

Table 5: Challenges faced in expanding solar energy capacity

Aspect	China	Japan	UAE
Installation and Growth Capacity of Solar Energy	China is a global solar energy producer and has installed an overall capacity projected to reach 400GW by 2024. This keeps the country ahead of its target yearly by adding approximately 120GW in its renewable generation capacity. The Chinese government wants 1 200 GW in installed solar photovoltaic capacity by 2030 as part of the country's plans to generate 33% of its renewable energy. This expansion shows the nation's determination to prioritise world energy issues, focusing on infrastructure	Japan will be among the top three countries with the world's largest installed solar power capacity, with 74.5 GW. However, as most focus is on established utilities using feed-in-tariff policies for power purchase, the growth rate is at 4 to 5GW per annum, supported by policy changes and technology deployment. With the target of 100 GW by 2025, the Japanese government and companies need to define what share of this would come from renewable energy sources and how the maturing expansion of this sector will relate to the further shaping of the carbon	The UAE reached 2.2GW of solar capacity by 2023, and this is an amazing development in renewable energy. Among them is the Mohammed bin Rashid Al Maktoum Solar Park, a mega-plan with a goal of 5 GW by 2030. This massive drive contributes more to the UAE's efforts to ratify the Net Zero 2050 Strategy than promoting the use of clean energy in extreme desert climate conditions.

	development, subsidies, and technology to ensure that solar power is at the centre of the country's energy transition plan.	neutrality agenda. This progression shows a step-by-step approach to incorporating solar energy within the power grid to meet the sustainability hurdles.	
Major Challenges	China needs help integrating its rapid solar capacity growth into the national grid. The imbalance between solar energy production hubs (central regions) and demand centres (coastal cities) creates inefficiencies. Moreover, the supply chain impacts the availability of essential solar components like photovoltaic panels and batteries. Energy curtailment becomes a concern as solar output often exceeds grid capacity during peak production. This shows a need for advanced grid infrastructure and better regional energy	Japan's solar expansion is constrained by limited land availability, making it challenging to establish large-scale solar farms. High population density and mountainous terrain further reduce suitable areas for installations. Additionally, Japan heavily relied on feed-in-tariff (FIT) policies, which, while initially successful, delayed the transition to more competitive auction-based systems. Public opposition to large-scale solar farms due to aesthetic and environmental concerns also	The harsh desert environment in the UAE poses significant challenges to solar efficiency. Dust storms frequently reduce panel performance, requiring advanced cleaning systems to maintain optimal output. The high cost of utility-scale energy storage systems for a stable power supply adds to the difficulty. Despite these challenges, the UAE invests in innovative solutions to address these environmental hurdles.

	distribution.	hampers progress.	

China, Japan, and the UAE have issues concerning increasing the share of solar power. In the global market, China has the highest projected installed capacity of renewables for 2024 at an estimated 400 GW while aspiring for 1200 GW by 2030, with a 33% contribution to the global installed renewables. Governments, infrastructure, and growing technologies foster this rapid expansion. Nonetheless, integration challenges appear in such forms as an asymmetry between the manufacturing and consuming regions, supply chain constraints, and electrical grids' ability to accommodate renewable energy generation rates.

Japan has 74.5 GW and targets 100 GW by 2025, with an annual installation of 4–5 GW. Skills and talents are limited, and extensive land and other natural resources are scarce. However, the intended efforts of policy reforms and establishing the pathway for achieving carbon neutrality guarantee the progressive incorporation of solar energy in Japan.

With 2.2 GW achieved by 2023, the UAE presents a unique model of large-scale solar development, exemplified by the Mohammed bin Rashid Al Maktoum Solar Park (target: 5 GW by 2030). This corresponds to the company's Net Zero 2050 Strategy; issues such as challenging desert climate, dust storms, and high development costs of energy storage systems present the firm with operational hurdles. However, a recognised list of challenges slows down the UAE's attempts to flow to the renewable energy sector, including such environmental barriers as innovative investments support the UAE’s renewable energy plans.

4.7. Solar Energy Policies in China, Japan, and UAE

Table 6: Solar energy policies in UAE, China and Japan

Aspect	**China**	**Japan**	**UAE**
Future Investments	China's solar energy is mentioned in extensive government policies, which include low-interest loans, tax exemptions and stiff government subsidies on solar projects. The country’s exporting solar technology has become the world's largest exporter of photovoltaic panels, controlling 80% of the market share. Future investment will shift to increasing renewable energy generation and cutting out coal to have one-twelfth of 1200GW of solar technology by 2030. This aligns with China‘s commitment to adding 33 per cent	Japan has gradually moved from the predominant feed-in tariff (FIT) scheme into more competitive auction mechanisms to attract private capital and decrease expenses. The government focuses on research and innovation, such as using less-occupied areas for renewable energy sources. This was to support the country’s broader goal of achieving net-zero emissions by 2050, Japan’s policy aims for 108GW of solar power in the country by 2030. Smart investments are aimed at intelligent solutions in operating the land and the grids.	The UAE’s Energy Strategy 2050 targets 50% of the total power generation. This involves concerns about public-private partnerships to facilitate the financing of big projects, such as the Mohammed bin Rashid Al Maktoum Solar Park. The UAE aims for 5.6 GW by 2030 to meet increasing power demands through foreign investments, enhanced storage, and efficient technology. They are part of the broader drive of the UAE’s Net Zero 2050 Strategy.

	of electricity from renewable energy and carbon neutrality by 2060.		
Innovations in Technology for Solar Energy Sector	China is using the most advance application of technology within the solar energy sector, specifically the photovoltaic (PV) system. It is high in demand for solar panel manufacturing because it produces 80% of the total solar panels sold across the globe. It also targets high-efficiency PV cells like heterojunction, and bifacial, maximizing energy generation with their arrays. Furthermore, China has paid special attention to storage as a feasible solution to the problems of grid integration, such as large scale batteries and smart grids. They facilitate China to sustain her dominance in both local market and the global solar	Japan shows more research and development approach that addresses limited land availability by aiming at both floating solar farms and building-integrated photovoltaics (BIPV). The country has put into practice of solar-sharing and simultaneously the land is used for agriculture as well as for solar power. In addition, Japan also put resources in advanced inverters and energy management systems to enhance its renewable power. Such innovations are necessary to solve the problem of a lack of land and establish a stable progress towards the carbon neutrality of land. Using this method Japan emphasizes	The UAE uses modern technology to counteract its dry climate conditions that prevail in the desert. It uses dust-resistant panels and developed automatic cleansing systems for increasing the efficiency of the panel. The nation is also moving slowly towards the developed of Concentrated Solar Power (CSP) as seen in the Noor Energy 1 where CSP is combined with the PV to provide both storage and more output. The UAE is keen on AI and Smart monitoring of large scale EPS and the DPIA re- emphasizes the commitment of UAE on innovation in renewable energy.

	technology sales.	sustainability by increasing resources at the disposal.	

Solar energy has made collaboration in the Chinese governmental structures with substantial subsidies, tax credits, and, low-interest loans to boost the industry. The country takes advantage of the world's largest producer of photovoltaic (PV) panels controlling approximately 80% global market share. High-efficiency technologies including heterojunction and bifacial cells are currently under developing of China to achieve the 1,200 GW solar capacity and 33% electricity from renewable resources by 2030 and get carbon neutrality by 2060.

Instead, Japan follows a research-oriented approach shifting from feed-in-tariff (FIT) based policies to competitive bidding for cutting costs and mobilizing private capital. Its has 74.5 GW solar capacity it employs the limited land well through float solar power plant and Integrated Solar Architecture (ISA). Solar-sharing developments, which include the flexible use of agricultural and solar power facilities in the same area, embody Japan's resource efficiency. Such emphasis on sophisticated inverters and energy storage systems is compatible with the country's 2030 goal of attaining 108GW of solar and its net-zero carbon emissions target for 2050.

The UAE, adopts a different strategy of attaining 5.6GWs by 2030 through big ticket projects for instance the Mohammed bin Rashid Al Maktoum Solar Park. Specific to desert climates, the UAE has 'desert glass', panels, what it calls 'Dust Bot' cleaners, and CSP, intrinsic to the Noor Energy 1 project. Through connecting CSP with PV systems and the use of AI smart monitoring technologies, the UAE improve its RE framework according to the Net Zero 2050 Strategy.

Chapter 5: Discussion

This chapter discusses the findings of this research to explore the areas that need further improvement.

5.1. Finance Allocation

China's solar power industry is perhaps one of the best examples to demonstrate how the financial is highly allocated, with visions being well implemented through an interplay of the government and the private sector to make the country adopt the world's solar power sector. China is now the largest investor and has the largest installed photovoltaic power system capacity in the whole world. Governmental activities have been a major part in this achievement with increased funding along with aggressive and effective policy bolstering through programs like the Datong Solar Power Top Runner Base, one of the projects under the 'Top Runner Program' sponsored by China for efficiency solar panel production. This program coupled with large-scale solar power plant like the Qinghai large-scale solar power plant indicates China's seriousness in the development of energy saving and low carbon technologies. With estimated cost at $10 billion, these projects clearly show how much China is willing to spend on renewable energy assets (Autry & Navarro, 2024).

China's Five-year Plans also reflect the government's Party's long-term vision regarding renewable energy particularly solar energy sources. Some of these plans involve offering of rebates and grants in a bid to encourage investors in the solar sector. The annual investment, exceeding $25 billion, is illustrative of both the resource base of China and its unique role in the global solar system (Mihajlovna, 2023). Furthermore, evolutionary advancements to the technology point towards solar investments by private business organizations such as LONGi and JA Solar. This cooperation between the public and private partners has been positive in development of technology, improving capacity and also market related factors.

China’s solar power investment has also put more of its weight behind infrastructure investment with installation taking 40% of the investment, R&D taking 30% investment and scaling taking another 20% while only 10% goes to maintenance (Statista, 2023). This allocation strategy shows that China has its broad approach of developing new technologies at the same time, expanding the solar capacity, and ensuring high efficiency. The ROI in China’s solar sector is estimated to be between 12-15% they are expected to grow at an annual rate of approximately 30% to meet their target for renewable energy (Peter & Petri, 2023). Solar energy accounts for 68% of the total proportion of renewable energy sources, with wind coming in second at 22% and hydro at 10% (Hilton, 2024). This dominance shows that solar energy is a key component of China's energy mix rather than merely an additional energy source. China's strategy serves as an example for other countries looking to grow their renewable energy industries and demonstrates how a nation may lead in renewable energy through strategic investment, government support, and private sector cooperation.

The energy financing in Japan, especially after the Fukushima disaster, can be suggestive of a shift in its priorities towards the use of renewable energy especially from solar power to improve energy security supplementing environmental conservation. This transition is not a surprise because the usage of nuclear energy is gradually decreasing across the globe, and this is a way by which Japan can ensure it manages on risks related to nuclear energy. The disaster of March 2011 gave Japan the impetus to seek to reduce the share of nuclear energy as much as possible. Thanks to this investment, solar power has become one of the most significant segments of this change The Solar Frontier Kunitomi Plant and Kyocera Kagoshima Nanatsujima Mega Solar Power Plant are the evidence of Japan’s reliance on renewable sources of power. These investments have greatly increased the solar capacity and placed Japan amongst the most solar power producer countries.

There is evidence that Feed-in Tariff (FiT), an innovative stimulating policy deployed by governments, positively affected this change, as barriers constructed during previous years towards economical feasibility of solar projects were demolished. The

Japan's Renewable Energy Strategy also contributes to this emphasis by seeking to build for the long-term system for socioeconomic solar energy utilization (Zhang et al., 2023). These efforts show that the government has been spending between $5bn and $10bn yearly to invest in the solar energy production.. Moreover, emerging private firms such as Sharp Solar and Panasonic are now heavily investing in the development of solar photovoltaic (PV) technologies that increase efficiency and the efficiency of solar power generation (Bischoff et al., 2024).

The financial allocation within these projects indicates a comprehensive approach: They invest 25% of their effort on research and development as a way of encouraging innovation, with installation being the most resource demanding being 45%, followed by scaling at 15%, and maintenance at 15% (WeXpats, 2023). This proportional distribution improves functionality, is effective in combating high expenses and even the lengthens the life cycle of the infrastructure. The ROI projections for these solar ventures are estimated to be in the range of 8-10% The projections are more or less set to be based on technology enhancements that enhance performances of solar panels (CBRE, 2023). Regarding ratio of investment of renewable energy, about 50% is invested on solar energy, while 30% and 20% invested on wind and nuclear energy respectively (Institute for Sustainable Energy Policies, 2024). This investment prioritization is in accord with the Japan's long-term effort to establish a reliable energy system that the country never encountered with nuclear energy. At the same time, it is seen that this change in energy security also fortifies the Japanese position in the global RE map.

Currently, the UAE has become one of the pioneers of solar energy due to the set central objectives for the development of green energy and sustainable goals. In this regard, the Mohammed bin Rashid Al Maktoum Solar Park is one of the main large-scale projects in the UAE. Dubai has this major facility as a single-site solar power station with capital costs that are estimated to be at $13.6bn, illustrating the UAE's plans with a view of the long-term on RE (Alzaabi, 2024). Likewise, the UAE have been active; it has created programs like Shams 1, which is a $600 million concentrated solar power (CSP) system emphasizing on the early adoption of the UAE in the innovative generation technologies.

These initiatives are under the emirate's strategic framework, the Dubai Clean Energy Strategy 2050. A key development strategy for the region seeks to dramatically increase its renewable energy production capacity with the intent to develop Dubai into a global power within clean energy generation having 75% of power generation capacity from renewable resources by 2050. In Abu Dhabi specific, the Masdar Initiative cements the UAE's appetite for renewables even further. Currently, Masdar and its partner ACWA Power considerably ramp up large-scale solar investments; annual spending is expected at $1-2 billion on solar energy only (Quamar et al., 2023; Haque, 2024). The financial commitment is also very high and focuses on all stages of the renewable lifecycle where improvements are needed: R&D 20%, installation 50%, scaling 20%, maintenance 10% (Pierce, 2024).

The UAE investments guarantee 10% ROI annually because demand for renewable energy solutions is rapidly rising (Best Property 2024). Among the renewable energy sources, solar generated 80% of the UAE's electricity, followed by 10% from both wind and hydroelectric power (U.S. Department of Energy, 2023).

5.2. Technological Innovations

China has a powerful position in the industry of renewable energy as the technology of solar energy products and large-scale production developed in the country. The country has gained a lot in superior technologies including the fabrication, of high efficient solar panels. This progress has placed China in the capacity of the largest solar panels-maker globally (You et al., 2024). In this sense, through maintaining constant updating of its' production line China has been in a position to develop efficient solar panels that can be produced cheaply hence eliminating the problem of high costs of production that hitherto had posed a major hindrance to widespread adoption of the solar technology. There is evidence to substantiate the proposition that government incentives have turned out to be the key driver for the development of China's solar technology. Policies like subsidies have made the solar energy projects more financially attractive —a factor that has fueled innovation in the sector in China (Wu et al., 2023). Not only these subsidies help with the development of new technologies but it also helps firms create better and more effective solar products. It has made China today the world's leading country in the development of renewable energy technologies.

Other large-scale solar farms in China also prove its ability to integrate new technology into big projects. One such case in point is the Datong Solar Power Top Runner Base that demonstrates effective use of smart solar energy technology system built in a large complex. For example, this facility illustrates that China wants to phase out traditional energy sources on large scale as it seeks to reduce its emissions. With incorporation of these advancement into these big projects, China is playing a major role in shifting the world to sustainable energy. China's technique of strong manufacturing, government incentives, and implementation of big solar power projects can act as a model for other countries aiming to increase renewable energy and have scale. All these factors concurring show that China has been in the frontline in the promotion of solar engineering and global environmental protection.

The renewable energy sector in Japan has evolved a great deal with a willing adoption of bifacial solar panels, smart connections to the grid and tremendous focus on rooftop systems. Concept of bifacial solar panels is that it can be exposed to sunlight on top and bottom, getting more energy by light reflected on the ground. This makes the approach very efficient, suitable to use in commercial as well as residential building projects. Literature proves that bifacial panels are capable of surpassing the efficiency of regular PV panels, particularly those operating in reflective conditions, and play a crucial role in Japan's efforts to increase its solar reactivation (Vimala et al., 2023). Accompanying this technology, Japan is planning its smart grid plan to improve the distribution and consumption of solar power. A smart grid entails a digital electricity system that optimizes the use of electricity distribution for an integration of solar energy to the national grid. The effective technological tools of a smart grid are sensors that enhance communication technology; this means that energy supply can be adjusted in real-time to match demand and limit losses. This interconnectivity is entirely in line with Japan's push towards a more sustainable, resilient electricity system (You et al., 2024).

Moreover, consumers in Japan have increasingly been installing residential solar systems owing to a growth in government policies on use of solar panels. These policies form part of Japan's obligations for the reduction of carbon emission and promotion of energy self-sufficiency. The subsidies and incentives mean that more residents make arrangements for installing solar panels in their homes, which has boosted the residential popularity of solar energy (Ahmad et al., 2023). This integrated approach referencing deployment of new generation solar systems, optimized grid structure, and accommodating legislation shows that Japan has reached high levels of renewable energy utilization and serves as a good example of what other nations could do to replicate the Japanese success with positive and tangible effects on the environment and the national economy.

5.3. Legal System

This analysis gives an understanding of China's legal structure on solar energy. It supports the fact that the Chinese government has a hierarchical and collectivist socialist legal structure, and the industry players such as the National Energy Administration (NEA) dominate the systems. This supports our assumption that aggregated network based regulator model can have a big impact on RE uptake especially within the framework of existing government policies and reforms. The result we have obtained is in the same vein reminding the hypothesis put forward by Ali et al. (2023) wherein it is stated that hierarchical or socialist structures of the country can be more successful in large scale renewable energy plans. This is evident with feed-in tariffs coupled with subsidies with massive support for Research and Development in solar energy technology that helps to boost the feasibility of projects in solar energy. The conclusions pointed out from such findings suggest that not only are Peoples Republic of Chinese government motivated financial pillars aimed at encouraging investment in solar energy but also enhanced its determination in ratcheting down carbon emission and sustainable energy. The essence of the NEA's focus on implementation speaks volumes about the country's commitment to renewable energy objectives and places it on the map of global solar innovation.

For the same case, a weakness of this study is that it examines national policies within china without considering regional differences in implementation of policies. This may in one way, slightly reduce the external validity of the results to local settings in the country. Implication of these research points toward actions that such countries that wish to advance the use of renewable energy should consider emulating China such as a centralized regulatory system and financially motivated policy design. More papers could be devoted to investigation of how similar tactics could be used in other countries with different legal environment and economic development to analyze possibility of their application in various contexts of governance.

The studies show that Japanese legal landscape is highly conducive to energy sustainability through well-developed environmental legislation and promotion tools. For instance, the Feed-in Tariff (FIT) system enable payment for those producing solar energy hence encouraging investment in renewable energy sources. In line with the argument of Kohsaka and Kohyama (2023) who for instance stress that Japan's subsidies and feed-in tariffs have a potential to spur better usage of solar power, this analysis ascertains the fact that these legal incentives are fit for purpose. These results strengthen the theory introduced by Kohyama et al. (2024) stipulating that substantial regulatory support in addition to financial incentives is crucial for the diffusion of REsolutions. This study shows that legislative support and financial incentives are key factors in supporting Japan's sustainability targets. Japan's regulatory measures are a full-scale support for green energy emphasizing the reduction of environmental effects, energy diversification, and development of a strong renewable energy market. Nevertheless, these studies are confined to the parameters of solar energy regulations and incentives only. Thus, the Japan's feed in tariff and subsidy system offers great encouragement to the usage of renewable energy in the country; however, this research does not look into other forms of renewable such as wind or hydro electric power; which may have skewed the entire view of Japan's energy sustainability.

When looked at practically, it may be instructive for other nations wanting to improve the proportion of renewable energy generation within their electricity generation mix to look at Japan's model based on incentives. Such industry regulators as the METI may seek to fine-tune the model to fit other types of renewable energy forms. More researches are required to examine the impacts for economic and environmental consequences of Japan FIT system in the long term and to assess the benefits of this approach for the international use. This paper describes the UAE's approach to renewable energy regulation for solar power with an emphasis on the part that federal and emirate-level entities have played in the promotion of clean energy. The results show that although every Emirate has some legislative power, renewable energy activities are a federal priority targeting the overarching goals; FEWA and DEWA supervise these activities. It promotes the coordination of federal and emirate goals for the country's larger objectives, for instance the UAE Energy Strategy 2050 underlines the need to increase the contribution of fresh renewable sources of power in the energy supply mix (Daniel et al., 2024). Hence, it is definitively clear that the UAE renewable energy policy is properly governed and exercised by FEWA and DEWA alongside national and emirate legislation. This alignment further compliments the UAE's earmarked progression towards renewable energy and necessary progression to achieve global commitments to sustainable development. We concur with Sajwani et al. (2023) , who note that FEWA and DEWA play a key role in compliance for the solar energy programmes.With regard to these outcomes, it is possible to note that the organic law of the UAE, in which the country has a federal system combined with the emirate one, provides for the possibility of using the legislative initiatives of the country's regions that meet the objectives of satisfying regional energy needs and national orientation. Such a framework can act as a reference point for other federal countries that hope for the work of local and national energy strategies.

Yet these findings cannot be generalized across the context of the solar energy sector in other countries that operate under different regulatory environment or possess different priority in the development of the renewables. This information also implies the use of the UAE's case while developing policies for the promotion of renewable energy systems on national and regional levels. Subsequent research could investigate more such modelling explorations in other federal countries to evaluate transferability of this model.

5.4. Environmental Perspective

The analysis provides several key conclusions about China's photovoltaic (PV) industry, its emissions in production and sustainability. The significant decreases in the carbon footprint of PV production from 2011 to 2020 by 50% shows the energetic performance in reducing pollution, thus supporting the hypothesis about the appropriateness of Chinese active measures in decreasing manufacturing emissions. The answer about the thesis question regarding the management of PV waste is grounded in the setting of aims to recycle 90% of modules by 2025, in response to the expected generation of 214.68 GW – 579.76 GW of waste PV by 2050 (Shao, 2023). It is crucial to emphasize the concept of recycling technologies in the context of the analyzed PV sector as the global trend related to preventing waste.

However, considerable concern should be paid to the impact of wide uses of land for construction of solar farms. The shift towards the rooftop installation system with more than 100GW of capacity set up till 2020 is a new approach to manage the impacts arising from mass solar plants. This initiative not only saves land but also, in the same degree, increases the availability of energy in population-dense regions. The breakthroughs in cleanness have been greatly improved across all the types of PV cells, notably the record 26.81% efficiency for silicon hetero-junction solar cells in 2023 (Lin et al., 2023); this reflects technological advancement in the country. Advancements in the perovskite light-absorbing solar cells are an indication that the future of attaining sustainable energy is bright. However, there are some shortcomings to these findings. The current analysis does not include the future viability of such practices or the social ramifications of utility scale PV deployment. A more detailed research into these programs' characteristics is highly encouraged, it may include their socio-economic outcomes and the environmental responsibility of production processes. More specifically, filling in these gaps will contribute to developing a better understanding of the chronology of change in the PV industry in China.

This analysis underscores Japan's promise for cleaner production and manufacturing in the photovoltaic (PV) industry. The study reveals that Japan's Carbon Legacy to PV is moderate thus supported with Japan's progressive environmental policies for green electricity. More concretely, Japan plans to decrease CO2 emissions from the PV sector by 46 % by 2030, as it is mentioned by the World Economic Forum; this fact overturns the assumption that severe environmental regulation alters the volume of greenhouse gas emissions significantly. In addition, recycling frame work for PV cells forms a basis for circular economy initiatives within Japan's economies. The obligation of PV recycling in 2022, with a goal of reaching 80% recycling rate of end-of-life modules by 2035, is one outstanding element of sustainability in Japan. However, comparatively with China, it has set comparatively slower targets of recycling that is why the problems which Japan can face are presented in the table above indicating that Japan should improve more and invest in recycling technologies.

Due to the scarce availability of land in this country, there is a need to think out of the box as far as the impact of solar plants is concerned and this includes among others are Rooftop solar panels as well as floating PV farms. These initiatives indicate efficient working applications of Japan's sustainable development goals through installing over 78 MW of floating solar by 2022. This data provides new evidence of how countries can creatively adapt renewable energy solutions, despite the geographical conditions that they face. However, one cannot exclude that there is a difference in data quality between sources which can limit the generalization of presented results for other regions. Next stage research should involve comparisons with countries such as China in order to determine the best practice regarding the recycling of PV. In sum, Japanese activities in clean production, recycling and the efficiency enhancement in the land use for PV show its strong proactive in sustainable development.

With reference, this analysis presents an intricate perspective of solar energy in the UAE. Although, the given country is investing greatly in solar energy, our research shows that PV related emitting processes are considerably high. This is because replied compared to the leaders in the industry like China and Japan have fewer standards. Nevertheless, the UAE has quite specific objectives that presuppose the energy sector's carbon emissions cut of 70% by 2050 (Naqbi et al., 2019), so, thus, evolving the hypothesis that governmental activities are crucial for the ongoing energy transformation towards sustainability. Furthermore, the study confirms high difficulties in disposing of the end-of-life PV cells in the UAE. A major drawback is the absence of structures and mechanisms to address these cells appropriately. Our results support the view that proper waste management is essential for sustainable energy management. Nonetheless, the search for technologies to recycle electronics is on, although there are still studies in their early stages. This new focus on recycling technologies offers fresh proof of the UAE's ability to improving its circular economy. However, one of the strengths is geographical that offers the country ample of desert land to host big solar plants as the Mohammed bin Rashid Al Maktoum Solar Park that will expand to 214 square kilometers in the future. To uphold this strategic choice, there is likely to be less interference with the areas of high fertility concerning land while at the same maintaining the optimum capacities in energy production.

The data suggests that the constant growth of regulatory requirements and the expansion of infrastructure necessary for the sustainable development of the UAE are still needed. The technology needs at the recycling centres and the improvements in the waste management system ought to be developed further. Further research is required in order to evaluate those programs and determine whether the above mentioned goals have been achieved and if those programs can significantly influence the total level of emissions in UAE's energy sector.

5.5. Challenges and Expansion of Solar Energy Capacity

In China subsidies for the installation of solar systems, provision of cheap credit, and tax exemptions have been the main incentives that have fostered development of the home solar market. In the future, innovative products including heterojunctions and bifacial cells will continue to increase in China. Moreover battery scale and smart grid systems will also be given priority to ensure China has 1,200 GW of solar power by 2030. Hence UAE could follow this model and also offer them financial incentives to back its renewable energy targets.

Japan shows that scientific analysis could be used to make improvements to achieve higher efficiency in the limited area having regard to the limitations of its land size. Japan currently utilises 74.5 GW solar energy and has set a goal to achieve 108 GW by 2030. Therefore, the country has integrated platforms such as floating solar farms and solar-sharing models in order to completely utilise every available space and improve productivity. The transition from feed in tariffs to competitive auction has extended the optimisation of private investments and costs reduction that accelerate the country's net zero emission plan of 2050. In the case of the UAE, the utilisation of a similar approach could help refine its capacity to make progress on the problem of land deficiency and to encourage private sector involvement in the field of renewable energy.

However for UAE the focus of its green energy plan is still dominated by solar energy with flagship projects in building up the Mohammed Bin Rashid Al Maktoum Solar Park at 5.6 GW by the year 2030. In order to overcome such regional problems as dusting the UAE has used dust protective panel, superior cleaning technology and diversification of CSP plant combined with photovoltaic systems as employed in Noor Energy 1. AI-driven monitoring is a powerful demonstration of how the UAE may become the global pioneer in renewable energy solutions. Therefore for the UAE to build on its position on new renewable energy and realize its Net Zero 2050 Strategy, there is a dire need to continue with the expansion of such measures alongside global cooperation.

5.6. Solar Energy Policies In China, Japan and UAE

The increase in Chinese solar power capacity signifies that there is a need for firm government backing such as subsidies and physical investment in renewable power bases such as solar bases. They proclaim the target of reaching 1200 GW of renewable power generation capacity by 2030 and occupying 33% of total power generation capacity from renewable sources. Moreover China has shown the possibility of how ambitious policies can lead to massive scale of the renewable energy market development despite supply chain disruptions and integration of renewable power into the grid. In doing so, the UAE can also follow this approach and direct its efforts on funding solar infrastructure and solving issues that in future enhance the growth of large scale solar energy.

In the case of Japan, floating solar farms and solar-sharing helps prove that land limitations and population density can be handled to work on the 100 GW goal by 2025 in Japan. So, UAE can also benefit by extending its use of land through utilising technology in the development of land resources while ensuring that Emirati policies are updated to progress in order to meet the growing energy requirements in a more effective way.

The UAE also made a lot of progress, especially in projects such as the Mohammed bin Rashid Al Maktoum Solar Park in Dubai, aiming for 5 GW of capacity in 2030. Some of the major drawbacks like dust, which affects drilling or high cost of storage are still issues but the dust resistant panels and AI for self monitoring of the equipment show that such issues can be solved. Global Relations demand the establishment of international cooperation and investment in innovative technologies to ensure the UAE that it must work on securing its renewable energy sector for the achievement of the Net Zero 2050 Strategy.

Chapter 6: Conclusion

Photovoltaic global market is growing rapidly with the development of innovative material and improved efficiency of silicon-based solar cells. And with this improvement, solar energy has become an integral part of global energy mix. China and Japan are leading the industry with advance technology. Another emerging leader in photovoltaic market is UAE because the country has allocated finance and developed legal frameworks to support renewable energy technology. This research aims to evaluate the efficiency of photovoltaic material to assess the stability and durability in different environmental conditions. The study identified the factors that influence the efficiency of photovoltaic cells. The literature review showed that UAE has a potential to shift entirely on renewable energy. The development of solar energy in China, Japan, and the UAE demonstrates the critical role of financial allocation, technological innovation, and supportive legal frameworks in driving national solar initiatives. China’s substantial annual investment of over $25 billion, coupled with government-backed projects and incentives, has established the country as a global leader in solar power. Japan, spurred by its Renewable Energy Strategy and Feed-in Tariff (FiT) scheme, invests $5–$10 billion annually and has made strides in integrating advanced technologies like bifacial panels and smart grids. The UAE, meanwhile, focuses on concentrated solar power (CSP) projects, exemplified by the Mohammed bin Rashid Al Maktoum Solar Park, and aims to boost solar deployment with policies and incentives through authorities like DEWA and FEWA. Each country’s approach aligns with its unique energy goals: China excels in large-scale deployment, Japan prioritizes technology integration and residential solar, and the UAE focuses on CSP and efficient photovoltaic solutions. By adopting elements of China and Japan's strategic financial models, the UAE could further accelerate its solar ambitions, complementing its legal initiatives for a sustainable energy future.

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