



# **Solar Energy in the United States: Development, Challenges and Future Prospects**

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Abstract: The ambitious target of net-zero emission by 2050 has been aggressively driving the renewable energy sector in many countries. Leading the race of renewable energy sources is solar energy, the fastest growing energy source at present. The solar industry has witnessed more growth in the last decade than it has in the past 40 years, owing to its technological advancements, plummeting costs, and lucrative incentives. The United States is one of the largest producers of solar power in the world and has been a pioneer in solar adoption, with major projects across different technologies, mainly photovoltaic, concentrated solar power, and solar heating and cooling, but is expanding towards floating PV, solar combined with storage, and hybrid power plants. Although the United States has tremendous potential for exploiting solar resources, there is a scarcity of research that details the U.S. solar energy scenario. This paper provides a comprehensive review of solar energy in the U.S., highlighting the drivers of the solar industry in terms of technology, financial incentives, and strategies to overcome challenges. It also discusses the prospects of the future solar market based on extensive background research and the latest statistics. In addition, the paper categorizes the U.S. states into five tiers based on their solar prospects calculated using analytical hierarchy process and regression analysis. The price of solar technologies in the U.S. is also predicted up to 2031 using Wright's law, which projected a 77% reduction in the next decade.

**Keywords:** solar energy; United States; photovoltaic vs. concentrated solar power; challenges; future prospects

# 1. Introduction

The transition from fossil fuels to renewable energy (RE) has gathered significant momentum over the past decade. Due to the expanding industrialization and growing population, the global energy demand is expected to continue to increase by 50% between 2018 and 2050 [1]. This soaring demand is being matched by the increased combustion of fossil fuels, which still dominate the energy mix and come with drawbacks, such as depleting reserves, increasing prices due to carbon tax, emission of harmful by-products, such as  $CO_2$ ,  $NO_x$ ,  $SO_2$ , and mercury, and the failure to limit the global temperature rise under the 2 °C target of the Paris Agreement [2]. The decarbonization of the electricity mix, and all energy systems as a whole, necessitates shifting towards cleaner, sustainable, and renewable energy sources (RES) that are pioneering eco-friendly energy solutions. Leading the RE race is solar energy, which is the fastest growing electricity source at present [3]. In a single hour, the amount of the sun's energy that reaches the Earth exceeds the entire world's consumption in a year, making it a lucrative source of energy to tap into [4]. With



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). increasing government incentives, declining cost, and concerns for sustainable energy growth, harnessing solar power has become a widespread reality in the U.S. and is gaining popularity as a reliable and effective RES that can be a potential substitute for fossil fuels.

Among the RESs, solar energy surpassed 126 GW of installed capacity in 2020 alone, whereas the cumulative solar capacity stood at 720 GW in the same year [5]. This is a 94.3% increase from the installed global solar capacity of 41 GW only a decade earlier [3]. Despite the explosion of solar installments in recent years, solar energy still contributes a minor percentage to the global energy mix. Although solar power only accounts for 2% of the global electricity generation and 3% of the U.S. electricity mix, it should be kept in mind that it is a relatively new technology compared to hydroelectric power and wind turbines at scale, in terms of technological advancements and economic feasibility [6]. Considering the rapid development in the last decade alone, solar generation is projected to climb from 11% of the U.S. RE capacity in 2017 to almost 48% by 2050, and 45% of the total global electricity mix, making it the fastest growing source of electricity in the world [3]. The trend is already visible in Figure 1, where solar has held the record for the highest annual installments for 5 consecutive years since 2016. In addition, the gap between solar and other RE additions keeps increasing with each passing year (except wind in 2020), amplifying the relative growth rate of solar energy.



**Figure 1.** Global annual addition of RESs, indicating solar energy has the highest rising potential, topping the list of annual capacity installations for four consecutive years [5].

Many countries have joined the race towards decarbonizing their electricity mix by adopting RESs, predominantly solar. As shown in Figure 2, China leads the solar power race with 32.6% of global generation, followed by the U.S. (12.1%), Japan (10%), Germany (7.8%), and India (6.8%). In terms of solar capacity (ratio of total generation and the time of generation), the top three remain the same, except Germany overtakes India for the fourth position. A country might have more installed capacity but less solar resources that ultimately yield lower generation. Surprisingly, in terms of solar penetration (percentage of total electricity that comes from solar), none of the big solar producers actually contribute a significant amount to their total mix (<5% penetration). Countries, such as Yemen, Mauritania, Kiribati, Luxembourg, and Honduras, get over 12% to 20% of their electricity for solar energy. In 2020, China had an impressive cumulative capacity of 280 GW, while the U.S. had a total of 97.7 GW [7]. Despite the U.S. being one of the most prominent nations

in solar generation, it has not tapped into its full potential of solar, which only contributes 2.3% to its energy mix at present. The main reason behind solar power accounting for a small percentage is hydroelectric power and wind being stronger contenders in the RE market holding shares of 7.3% and 8.4% respectively in the US utility-scale electricity generation in 2020 [8]. According to the US Energy Information and Administration (EIA), the annual solar additions in the US in the year 2020 was 19.2  $GW_{DC}$ , which had surpassed the 14.2 GW addition of wind energy in a country where the wind is a dominant RES. With the unprecedented progress of solar technology, rising to be the front-runner in the global race for solar energy is certainly possible for the U.S., hindered only by extensive research and feasibility studies, pinpointing optimal locations, and the joint effort of engineers and the government.



**Figure 2.** Cumulative solar power capacity by country in 2019. The top three countries China, U.S., and Japan account for more than 50% of the total installed capacity [9].

Therefore, it is imperative to explore the current status and future prospects of solar energy in the U.S., which is the prime theme of this paper. TThis paper discusses the emergence and the evolution of solar power technologies and its integration in the energy mix in the US, focusing on historical events, policies and incentives, socioeconomic and environmental dynamics as well as prevalent technologies and applications. Furthermore, the paper presents a novel categorization of the states of the US into five tiers based on the solar prospects drawing upon relevant factors. The factors have been weighted using the analytical hierarchy process (AHP) and by combining hyperplanes from regression analysis. In addition, this paper also predicts the price of solar energy in the US for the next ten years using Wright's law. The rest of the paper is organized as shown in Figure 3.



Figure 3. Information flow of this paper.

## 2. The Emergence of Solar Energy

Harnessing solar energy has a long history that dates back more than two thousand years. The primitive applications have come a long way since then and have taken a sophisticated approach toward maximizing the harnessed energy and devising a wide variety of applications that are much more advanced than the century-old conventional applications. This section provides an overview of how solar came to being and how it gained rapid momentum since the last century.

#### 2.1. A Brief History of Solar Applications

The fundamental theory of harnessing the sun's energy dates back to as early as 7 B.C. The technology was limited to basic concepts of physics, such as concentrating the sun rays to light fires or torches and heating sunrooms. For a long time, the applications were limited to heating and concentrated solar power (CSP). Fast forward to the 1700s, the century witnessed the invention of the first solar collector, the solar dish, and the discovery of the photovoltaic (PV) effect. The 19th century gradually introduced concepts of solar engines, photo-conductivity, solar water heaters, and the first solar cell. The first half of the 20th century observed more intricate and theoretical research on solar technology, such as discovering new photosensitive or PV materials, introducing the photoelectric effect, and calculating efficiencies of materials with different band gaps. The latter half of the century started seeing gradual commercialization of solar energy. The U.S. became a pioneer of commercial solar power when the world's largest solar thermal energy (STE) facility was commissioned in California in 1986. The National Renewable Energy Laboratory (NREL), in Colorado, engineered some of the most memorable solar technologies, such as a recordbreaking 30% conversion efficiency from Gallium Indium Phosphide/Gallium Arsenide solar panels, 18.8% efficiency from thin-film solar panels, and the highest efficiency of 32.3% from PV panels combined with concentrating lenses or mirrors. The end of the century marked a global cumulative capacity reaching 1 GW for solar PV. However, it was not until the 2000s that commercialization of solar power truly started gaining momentum. From 2010 onward, the world witnessed full commercialization of solar energy, while government incentives and policies drove the solar boom in the U.S., which emerged as the second largest solar producer in the world. A compact overview of the solar evolution timeline has been illustrated in Figure 4, which highlights some of the turning points for solar energy. The figure classifies the journey of solar energy into four phases, the criterion being the type of contribution each era made—the discovery phase in the 18th and 19th centuries, the experimentation phase in the early 20th century, the developing phase in the late 20th century, and the advanced phase at the dawn of the 21st century to now.



Figure 4. Solar energy timeline classified into four phases.

#### 2.2. Literature Review

Extensive research has been carried out in the development and deployment of solar power. These studies focus on different aspects, such as technical, applicative, and comparative analysis of solar power in terms of efficiency, operating conditions, feasibility, and socio-economic reverberation. The significance of solar as an energy source which will meet the increasing energy demand and its superiority to other sources have been reviewed in several works [10]. Keeping the variable nature of RE in focus, hybrid power plants have the potential to mitigate the compromised reliability of a single intermittent source [11]. The prospects of combining the two leading RESs, wind and solar, to create a hybrid system which can act as a substitute for grid system in rural and undeveloped countries is discussed profusely in Reference [12]. A region-based assessment of the potential of solar is explored for multiple countries, such as China [13], Brazil [14], Australia [15], United Arab Emirates [16], Turkey [17], etc. Finally, a comparison of solar policies in different countries has been assessed extensively in Reference [18,19].

There have been a limited number of studies exploring prospects of solar power in the U.S. Incorporating solar energy into the generation portfolio of the U.S. and how natural capital affects the deployment of utility-scale solar plants is examined in Reference [20]. The land requirements for solar deployment in the U.S. has been assessed in Reference [21,22]. The development of shared solar initiatives in the recent history of U.S. energy policy and how it can be applied in other developed nations have been reviewed and explored in Reference [23]. Identifying key socioeconomic factors in correlation with solar deployment density and building a solar installation database for the U.S. has been analyzed in Reference [24]. Further studies are carried out on certain states, narrowing down the outlook to specific regions. For instance, California has been a leader in solar generation in the U.S. resulting in papers that explore its land sparing opportunities [25], policies and incentives [26], over-generation problems [22], and technical challenges of solar plants [27]. More state-oriented case studies have been carried out for Nevada [28], Florida [29], Arizona [30], and Georgia [31].

## 2.3. Motivation of This Work

Despite these discrete studies on certain aspects of solar energy in some particular regions, an overall case study of the U.S. is yet to be scrutinized which truly explores the prospective and feasibility of solar energy utilization. This paper aims to bridge the gap

between the disjunct studies and present a complete case study of solar energy in the U.S. Since solar energy has been accelerating in the U.S. at an unprecedented rate and is likely to dominate the energy mix very soon, a lot of new researchers are entering the field of solar energy without having a holistic idea about the field. This paper will be a rich resource of facts and figures, as well as insights, that will help further research and development of solar technologies in the U.S.

#### 3. Solar Energy Technologies

Solar energy primarily comprises of light and heat energy. Efficient conversion of energy to electricity plays a crucial role in maximizing the utility of the available solar resources. The energy can be harvested using a wide range of conversation technologies, such as solar PV, different types of CSP technologies, and SHC. Figure 5 illustrates the different names given to solar energy harvesting methods based on their applications and technology. While solar PV focuses on harnessing the light energy from the sun, CSP and SHC technologies are oriented towards capturing the heat energy from the sunlight, which comprises more than 50% of the spectrum of solar irradiation. Of the three leading technologies to harness solar energy, PV technology clearly dominates the global market in terms of the energy supplied, which can be observed from Figure 6.



Figure 5. Breakdown of different solar technologies and application sectors.



**Figure 6.** Change in global cumulative generation of the main solar technologies in a span of 3 decades. PV has witnessed the highest growth in the last decade, substantially more compared to CSP and SHC applications [32].

#### 3.1. Solar Photovoltaics

Solar PV is the most common solar electricity generation technology which employs the direct conversion of sunlight into electricity based on the photoelectric effect. There are three major types of PV solar panels-monocrystalline, polycrystalline, and thin-film PV panels. Monocrystalline Si solar panels are produced from the highest grade Si, resulting in high efficiencies of 17–22%. These are the most commonly deployed solar panels but more costly compared to polycrystalline or thin-film panels. Polycrystalline panels have slightly lower efficiencies around 15–17% and a shorter lifespan, but the manufacturing process is much faster and cheaper. Thin-film panels have special features, such as lightweight and flexibility. They are easier to produce than crystalline panels and cost much less. Traditionally, they have the lowest efficiency, but recent developments have significantly reduced the efficiency gap with crystalline solar panels. This resulted in thin-film panels becoming increasingly popular and occupying a market share of around 40% in the U.S. in 2019. These solar panels are best suited for spacious applications, such as commercial or utility-scale plants. Thin-film solar cells are upgrading continuously since higher efficiency of the panels is one of the key concerns of the current solar market. New solar cells are under development but far from mass production, such as the organic solar cell, perovskite solar cell, amorphous Si solar cell, CdTe solar cell, dye-sensitized solar cell (DSSC), and so on [33]. The evolution of the efficiency of solar panels from a mere 5% to as high as 47% is articulated in Figure 7.



**Figure 7.** Evolution of Research-Cell Efficiency from a mere 5% to as high as 47% <sup>*a*</sup> [34]. <sup>*a*</sup> This plot is courtesy of the National Renewable Energy Laboratory, Golden, CO.

PVs are widespread and versatile as they can be installed on the rooftop of residential and commercial buildings, as well as in utility-scale power plants. Rooftop PVs can operate in standalone or grid-connected mode. The standalone rooftop PVs are commonly known as solar home systems (SHS). SHS is gaining the most popularity in rural areas of lowincome countries because of their wide-scale potential within the latitudes within  $45^\circ$  from the equator [35]. In the U.S., PVs installed on rooftops are referred to as residential PVs, which can either operate off-grid/islanded or grid connected mode. On the other hand, commercial or utility solar plants require around 5–10 acres/MW (20,000–40,500 m<sup>2</sup>/MW) of land, depending on the technologies used. Among the solar technologies, PV is the most widespread and deployed in most solar farms. Many countries now possess massive PV plants, such as the 2.25  $GW_{AC}$  Bhadla Solar Park in India, which is the largest solar PV plant in the world as of 2021 [36]. The 579  $MW_{AC}$  Solar Star (U.S.) was the largest solar PV plant in the world until 2015 and is currently the largest operating solar plant in the U.S. According to the International Renewable Energy Agency's (IRENA) 2020 report, global PV capacity reached 580 GW, and the U.S. had a cumulative capacity of 97 GW. A study published by NREL claimed that PVs covering 0.6% of the U.S. land area can generate enough electricity to match the national demand [37].

## 3.2. Concentrated Solar Power

CSP or solar thermal energy (STE) plants utilize solar heat energy and yield higher efficiencies compared to PVs. CSP environs four distinct types of technologies—parabolic trough collectors (PTC), linear Fresnel reflectors (LFR), solar towers (ST), and solar dish (SD) systems. The fundamental concept of all CSP technologies are similar, but the construction and the mechanism are quite different. An overview of the different types of CSPs can be observed from Table 1. The main components of a CSP system are reflectors, a receiver, heat transfer fluid (HTF), and an adequate cooling system. Reflectors (lenses or mirrors) concentrate sunlight into a narrow beam and point it at the receiver. In most types, an HTF is heated and circulated through the receiver and used to produce steam, which is converted into mechanical energy to drive a turbine to produce electricity. In CSP plants, the thermal energy needs to be stored before converting it to electricity. This type of storage is called thermal energy storage (TES). The block diagram of a CSP plant is shown

in Figure 8. CSP projects are large-scale constructions that are most often owned and operated by electric utilities. The U.S. was once the pioneer of mega CSP plants and home to five of the most innovative plants of that time—Solana, Mojave Solar One, Genesis Solar, Ivanpah Solar Electric Generating System, and Crescent Dunes—all of which were located in Southwestern U.S. However, after PV started gaining popularity by entering the niche markets of distributed generation (DG), CSP projects were impacted negatively in the U.S., while other countries started deploying mega-scale CSP projects in recent times. CSP plants are elaborated in Section 3.5 of this paper, which attempts to shed light on the state-of-the-art CSP plants and their stance in the solar market.



Figure 8. Block diagram of a concentrating solar power plant.

Figure 9 summarizes the basic diagrams of solar PV panels, PTC, FPC, and ST with molten salt TES system.



**Figure 9.** Four prominent solar technologies at a glance—Solar PV, parabolic trough collector (PTC) as an example of the CSP technology, flat plate collector (FPC) as an example of the SHC technology, and solar tower (ST) with thermal energy storage (TES) system.

# 3.3. Solar Heating and Cooling

The SHC technologies utilize the thermal energy of the sun by absorbing it and using the heat to provide hot water, pool heating, space heating, etc., for residential, commercial, and industrial heating applications. A breakdown of residential energy usage in the U.S. shows that 45% of the primary energy is consumed for space heating, followed by 18% for heating water and 9% for space cooling [38]. Solar energy can be utilized in all three applications, a majority of which is supplied by fossil fuels at present. Adopting solar in these sectors would significantly cut down residential energy consumption and benefit both the environment and the expenditure of residents. This is especially the case in countries, such as China, Brazil, South Africa, and Turkey, where the costs are three to ten times lower than in the U.S. or in European countries [39].

Table 1. Types of CST technology.					
Type of CSP	Mechanism	Capacity Range	Working Temperature	Efficiency	Plants in the U.S.
Parabolic trough collector	Sunlight is concentrated on a receiver pipe by parabolically curved, trough-shaped reflectors. The receiver is located at the focus of the parabola. An HTF circulating through the absorber tubes absorbs heat and gets transferred to a conventional steam generator or thermal energy storage (TES) system.	Medium, or High	150–400 °F or 60–200 °C	10–16%	Solar Energy Generating System (SEGS) with 356 $MW_{AC}$ installed capacity in California. Ninety percent of the CSP plants in 2018 utilized PTC, such as the Solana (250 $MW_{AC}$ ), Genesis solar (280 $MW_{AC}$ ), etc.
Solar tower	Sun tracking mirrors or heliostats concentrate sunlight on a central receiver. The receiver in this case is mounted at the top of the tower. The HTF heats up and is used to generate steam for the conventional turbine generator.	High	300–1200 °F or 150–650 °C	10–22%	The 392 $MW_{AC}$ Ivanpah Solar Electric Generation System in California and 125 $MW_{AC}$ Crescent Dunes project in Nevada are the only two STs in the U.S.
Linear Fresnel reflector	Similar to PTC, the main difference being shallow curvature or flat mirrors instead of parabolic shape and several mirrors sharing one receiver. Stationary receiver does not require fluid coupling as PTC does, and the overall system is cheaper.	Medium	150–400 °F or 60–200 °C	8–12%	A demonstration CLFR (Compact Linear Fresnel Reflectors) plant was constructed in 2008 near Bakersfield, California, but currently is not operational.
Solar dish	A 2-axis tracking dish-shaped surface direct the sun's rays onto a receiver, which collects the heat and transfers it to an engine generator. The receiver may be a Stirling or Brayton cycle engine mounted on the receiver moving with the dish structure.	Low	300–1500 °F or 150–820 °C	16–29%	There are no utility-scale solar dish/Stirling engine projects in commercial operation in the US.

 Table 1. Types of CSP technology.

## 3.3.1. Solar Water Heating System

Solar water heating systems (SWHS) or domestic solar hot water systems (DSHWS) can be obtained by using a solar collectors or solar thermal panels that absorb solar energy and use it to heat a conductive fluid inside a tube. The HTF transfers the heat to a water tank which in return heats the water. Thermal solar panels follow a simple mechanism compared to other solar technologies and can exhibit 70% more efficiency in collecting heat from sun rays compared to PV panels [40]. The solar collectors primarily come in two variations: flat-plate collectors (FPC) and evacuated-tube collectors (ETC). FPCs are more cost-effective in warmer regions, while ETCs perform better only in colder regions [41]. However, most modern collectors are designed to be functional even during overcast days and cold climates. SWHS can provide 60 °C domestic hot water for most of the climates in the U.S. given an adequate solar collector area. FPCs were found to be more suitable for the U.S. considering lower initial cost and higher solar fraction than ETCs [42]. However, ETC systems are the most common in Asia, especially for water heating applications.

# 3.3.2. Space Heating and Cooling

The energy consumed by the heating, ventilation, and air conditioning (HVAC) system of a building constitutes more than 50% of the building's total energy consumption in the U.S., and as high as 70% in Australia [43]. Active and passive HVAC systems using solar energy and thermal storage are important applications of SHC. Solar-assisted HVAC with thermal storage can account for more than 90% of the total heating requirements, and solar cooling assist can reduce the total cooling energy requirement by 33% to 43% [44]. Many countries have already widely adopted solar-assisted HVAC systems, such as China, which accounted for about 74% of global thermal heating and cooling additions in 2019, followed by Turkey, Brazil, and the U.S. [45].

## 3.3.3. Solar Heat for Industrial Processes

Solar thermal technologies that are used to supply heat in different industrial applications is referred to as solar heat for industrial processes (SHIP), which has shown promising growth in recent years. China and Mexico were the global leaders for SHIP addition in 2018 [39]. A record-breaking 2  $GW_{th}$  solar steam plant was announced in Oman in 2018, and construction began on the first large scale SHIP plant using the PTC technology in Brazil in 2019 [45]. Until 2013, 9  $GW_{th}$  of SHC capacity was installed in the U.S., which ranked 36th in the world in installed capacity relative to its population [46]. Each year, approximately 30,000 SHC systems are installed in the U.S., generating an estimated \$435 million in annual revenue. With nearly 72% of energy consumption in the U.S. directly attributable to heating and cooling, SHC can play a significant role in providing an environmentally sustainable and economically viable long-term solution to these primary necessities and contribute billions of dollars in annual positive economic impact.

# 3.4. Application Sectors

The application of solar technologies can be residential or small scale, commercial or medium scale, utility or large scale. Rooftop PV has a growing market in the U.S., with 3.2  $GW_{DC}$  annual addition in 2020, while commercial installments were 2.7  $GW_{DC}$ . Figures 10 and 11 present the graphical overview of annual solar additions globally and inside the U.S., respectively. It can be observed that the U.S. has more residential PV penetration than the global scenario, whereas the global market has higher commercial installments. Until recently, off-grid systems were only seen in small-scale PV, as the relatively high levelized cost of energy (LCOE) and costly storage limited large-scale deployment. Now, the cost of PV and storage have decreased enough to make PV and battery systems are often used as backup power during the blackouts that frequently occur in some countries. The off-grid electricity sector attracted a record \$512 million of investment in the corporate sector in 2018, 22% higher than the previous year. Start-



ups providing off-grid solar PV systems raised \$339 million in 2019, a 6% increase from 2017 [45].

**Figure 10.** Global installed capacity of different solar applications. The utility-scale solar applications have the largest penetration, followed by commercial and residential deployments [3].



**Figure 11.** U.S. installed capacity of different solar applications. The utility-scale solar applications have the largest penetration, followed by residential and commercial deployments [47].

Utility PV installations in the U.S. crossed 14  $GW_{DC}$  in 2020 and holds the record for being the largest sector for both cumulative capacity and annual installed capacity [47]. At present, the U.S. has more than 2500 utility-scale solar PV electricity generation facilities. Commercial solar projects mount the panels on the property of businesses, homeowners, offices which supply solar power to distributed solar projects, such as personal properties, industrial, agricultural, school, government, or nonprofit organizations. On the other hand, community solar is a project where consumers lease or purchase solar energy from an off-site array. This is a great option for people who do not own a house, who live in apartments, or houses with roof orientation that does not face the sun. In general, the customers receive credit on their electric bill for electricity generated by their share of the leased or purchased community solar system. Commercial or community solar projects are much smaller than utility scale plants, so utility operators can benefit from setting up these solar projects in areas that have less free land.

Alongside rooftop and ground-mounted PVs, a third addition in PV applications is the floating solar PV (FPV), which refers to solar panels installed on stagnant, man-made water bodies to maximize utility of resources. Aside from electricity generation, it comes with added benefits, such as addressing conflicts regarding excessive land usage for electricity in regions with limited land, lower land acquisition, and site preparation costs. At present, 60 countries are making plans to deploy FPV, and more than 35 countries have already implemented 350 operational FPV systems and occupy a cumulative global capacity of 2.6 GW until 2019. Despite the U.S. being the first country to implement a commercial FPV a decade ago, at a California winery, the FPV market is still a niche inside U.S. A study published by researchers at NREL in 2018 claimed that, if solar was installed on just a quarter of the man-made water bodies in the U.S., it would account for 10% of the country's electricity needs [48]. As of 2021, the largest FPV installation in the U.S. is the 4.78 MW Healdsburg Floating Solar Project in California. With less than 20 MW of FPV currently tapped into, the U.S. has great potential for FPV growth in the near future.

The major solar plants based in the U.S. are illustrated in Figure 12, which indicates that the Southwestern U.S. is the CSP hub of the country, but PV is the more dominant technology for utility plants in all states.



**Figure 12.** The state-wise heat map of the US showing the installed solar capacity and major solar plants classified by the type of solar technology used.

# 3.5. PV vs. CSP

The rise in the popularity of solar energy comes with intense competition between the existing solar technologies to see which prevails in terms of efficiency, cost, reliability, and ease of deployment. In the 1980s, CSP was the best bet for large-scale solar plants, as PV technologies were far more expensive. While the latter was more often used in small-scale consumer plans, the former harvested the sun's energy to produce steam and drive turbines, which was a mechanism already widely adopted by conventional coal plants. So, CSP came with less risks involved, not to mention higher economic feasibility. Between 1984 and 1990, the largest existing PV plant was the 2 MW SMUD PV solar plant, while the largest CSP plant was the 354 MW SEGS plant, which clearly shows the upper hand of CSP in the initial stages of solar [49]. Twenty-five years later, the face of solar technology has changed dramatically, with PV (97 GW) occupying 99 times more cumulative installed capacity than CSP (only 1.7 GW) in the U.S.

An interesting observation about the gradual overtake of PV in the global and the U.S. scenario can be extracted from the logarithmic view in Figures 13 and 14. Initially, both the cases were dominated by CSP, eventually falling behind PV. However, the time frame shows that the U.S. solar market was dominated by CSP for a longer time period, even when other countries started shifting to PV. PV overtaking CSP occurred around 1995 in the global scenario, while CSP was persistent over PV until late 2004 in the U.S. Moreover, while the cumulative capacity of CSP follows an upward trend on the global scale (as it normally should), the U.S. actually shows a decline in cumulative CSP capacity, indicating there were failed projects. The uprise of PV was possible due to the 70% cost reduction in PV panels and, more importantly, the penetration of PV in the DG sector, which has taken up a large share in the electricity market. This discussion will be limited to a comparative analysis of the two technologies for deployment of utility-scale projects. DG is clearly a major sector for PV which is not applicable in the case of CSP plants that are mostly large-scale, so this discussion will focus on utility-scale PV or CSP plants that can provide insight for upcoming mega solar projects.



**Figure 13.** Timeline of CSP and PV deployment in the U.S. since solar plants were first introduced. The logarithmic scale helps to better perceive how PV caught up and surpassed CSP technology in the U.S. around the early 2000s [50].



**Figure 14.** Timeline of global CSP and PV deployment. The logarithmic scale helps to better perceive the global perspective of how the PV caught up and surpassed CSP technology globally in the 1990s [51].

Table 2 presents a comparative overview of CSP and PV technologies specifically for utility-scale power plants. CSP technology is superior in terms of technical performance and efficiency, while PV technology is far more executable and economically feasible than CSP. A comparative analysis and performance assessment of PV and CSP plants was presented by Desideri and Campana, who found that CSP plants with TES exhibits higher electricity output than a PV plant of the same size. In this regard, the cost of energy is not the only factor that reflects the economic feasibility of a project [52]. For instance, the simple payback period of the best case CSP plant in Saudi Arabia was almost four times longer than a PV plant of the same size [53]. The study concluded that the CSP plant had 4.5 times higher net capital cost (NCC) compared to PV plant, while the LCOE of the PV plant is 2.73 times lower than the LCOE of a CSP plant.

Feature	PV	CSP
Storage and intermittency [54]	Directly generates electricity, which is difficult to store. Batteries are not economically feasible for large scale plants. So, PVs are mostly non-dispatchable. Intermittency is a prime drawback of PV systems.	TES is an attractive feature of CSP, making it dispatchable and increasing the penetration of CSP in the power industry by overcoming intermittency and continuity of supply at night.
Efficiency [55]	Maximum efficiency around 10–28%. The performance decreases with temperature.	The average efficiency of a Spanish CSP plant is 41%, but ST has achieved higher peak efficiencies. The efficiency of CSP increases with temperature.
Capacity factor [52]	10–35%	28–29% without TES, and 29–33% with TES.
Equipment [56]	Inverters are required to convert the DC to AC.	Inverters are not required since the output is AC.
Land efficiency [57]	2.5–5 acres/MW or 10,000-20,000 m <sup>2</sup> /MW.	5–10 acres/MW or 20,000–40,000 m <sup>2</sup> /MW.
Land geometry [57]	Easily tolerates slopes from $510^\circ$	More sensitive to slopes, requiring reasonably flat terrain less than 1.5–3 $^{\circ}$ of slope (exception: SD).
Solar irradiance [56]	Utilizes Global horizontal irradiation (GHI) and can work under diffused light. African regions, Australia, Saudi Arabia, and the Southwestern U.S. experience highest GHI.	CSP exclusively utilizes the direct normal irradiation (DNI). DNI varies from 65–85% of the overall GHI. The highest GHI is seen in Australia, Middle East, Africa, some parts of South America, and the Southwestern U.S.
LCOE [55]	In 2010, the cost of PV in the U.S. was \$0.378/kWh, which reduced to \$0.068/kWh at present. In some countries, it is as low as \$0.03/kWh.	In 2010, U.S. cost from CSP plants was \$0.12–0.18/kWh. At present, the price still remains \$0.135/kWh in the U.S., whilst it has reduced to \$0.185/kWh in the global CSP market.

# Table 2. Comparison between PV and CSP for utility-scale power plants.

Location assessment is perhaps the most important factor for CSP plants. CSP is most efficient in regions with high levels of DNI. For regions, such as Saudi Arabia, with high levels of both global horizontal irradiation (GHI) and direct normal irradiation (DNI), CSP has a large potential for mega-scale generation. In the U.S., technical potential of CSP exists predominately in the Southwest, which observes the highest DNI in the country. A study by NREL had predicted that Texas and New Mexico have the highest potential for CSP plants, although the currently existing CSP plants are located predominantly in California, Nevada, and Arizona [58,59].

The contribution of PV will be higher than CSP for a long time because of DG, decreasing cost, and available incentives for DG. The LCOE of PV is less than half the cost of CSP and is expected to remain so until 2030. After the net-metering incentives are dropped and the growth of DG slows down, CSP will play a significant role in the energy mix alongside PV. The amount of CSP in the electricity mix will increase as daytime production is saturated by PV and power systems approach full decarbonization. The results from a recent auction and power purchase agreement (PPA) programs suggest that the cost of CSP generated electricity will fall into the range of \$0.06–0.10/kWh in the next 4 years, resulting in CSP emerging as a strong competitor of PV in the solar market.

# 3.5.1. U.S. CSP Market

Figure 15 depicts that the U.S. had been the undefeated front-runner in the CSP market for two decades before global markets started catching up. As there are some failed CSP plants, lessons from those projects can provide crucial insight that should be assessed if the CSP market of U.S. is to regenerate. At present, there are less than 10 operational CSP utility plants in the U.S., out of which the 110 MW Crescent Dunes in Nevada is on the verge of shutting down due to technical failure. This \$1 billion project was one of the highest-profile solar plant failures in the country. It officially halted operation after an eight month lay-off caused by a leak in the plant's molten salt thermal storage tank, which brought down the capacity factor to only 0.3% [60]. At present, the PVs can supply electricity that costs 38% less than the \$0.135/kWh cost of Crescent Dunes. This failure, combined with the plummeting price of PV has resulted in a loss of investor confidence in CSP. However, there are a number of operational CSP plants outside the U.S., which indicates that CSP has not lost its potential as a viable market.



**Figure 15.** Cumulative installed capacity of CSP. The U.S. was the front-runner of installed CSP capacity, until Spain started deploying major CSP plants during the 2010s. Currently, Spain has the largest cumulative capacity for CSP plants, followed by the U.S. [39].

## 3.5.2. Global CSP Market

Noor Solar Tower in Morocco or the leading CSP market of Spain are successful deployments of CSP. In recent years, Morocco and China led in new additions (200 MW each), followed by South Africa and Saudi Arabia [39]. Spain had an explosion of CSP additions in the last decade, overpowering the U.S., and even most other countries combined. Spain is currently the leading CSP generator with 2.3 GW of CSP installed, but the U.S. is only 500 MW behind them, securing the second position. With the right steps, the U.S. can rise to be on top of the CSP market once again. The U.S. Department of Energy's (DOE) Solar Energy Technologies Office (SETO) is working to make CSP more affordable, with the goal of reaching \$0.05/kWh for baseload plants with at least 12 h of TES and \$0.10/kWh for plants with 6 h of energy storage. The latest research on CSP is being carried out by the researchers at DOE to usher the next generation of CSP, being referred to as the Generation 3, concentrating solar-thermal power plant. These plants will utilize falling particles to store the thermal heat absorbed by the CSP plant, which is capable of handling much higher temperatures compared to the conventional molten salt storage systems. The DOE has announced \$25 million to be awarded for building a demonstration for a Generation 3 CSP power plant and an additional \$40 million for PV and CSP R&D projects [61]. In order to make a successful and competitive market for CSP in the U.S., the pre-planning should scrutinize the technical and economic factors by addressing the following:

- Solar resource and optimal location assessment.
- Integration of thermal storage. CSP projects can achieve the lowest LCOE by including storage to improve the overall utilization of the projects.
- Performance models to accurately simulate the plant operation accounting for transient behavior of the plant, such as start-ups, shut-down, operational transitions, and intermittent clouds.
- Problems that arise from frequent fluctuation, such as thermal stress associated with temperature gradients.
- Hiring experienced engineers to assess the performance of the plant at all phases of the project.
- Plant automation with robust and sophisticated control systems.
- Creation of a strong administration and a cost-competitive market for CSP.

However, one of the biggest potential applications of thermal storage based CSP plants lie in hybridizing it with other generation plants, due to its ability to integrate TES and provide energy on demand. This is specially useful as a complementary source of the intermittent PV and wind plants, making them dispatchable and more reliable.

# 3.6. Hybrid Power Plant

One of the drawbacks of RE power plants is the intermittency that results in reduced reliability. This can be mitigated to some extent by integrating complementary sources into the same plant, resulting in a hybrid power plant (HPP) which encompasses multiple sources of energy or different technologies of the same source connected to a network at one node. These sources operate optimally under different conditions in the same location. So, sources with negative correlation can be brought together to utilize their ability to supply loads and different times. This way, a continuous supply can be obtained even from intermittent RESs. Moreover, HPPs can increase land efficiency, exhibit higher capacity values, optimize the use of the network, solve bottleneck problems, ease dispatch, and reduce the cost of infrastructure and land. The capacity value of a plant is an important factor in determining a plant's reliability in meeting demand. A matrix of the capacity value is the capacity factor (CF) defined as the ratio of how much energy (MWh) is produced by a plant to the maximum possible output (MWh) of the plant, typically calculated over an annual basis. It is measured as a percentage (%) using Equation (1).

$$CF = \frac{Annual generation (MWh)}{(365 \times 24) hrs \times name plate capacity (MW)}.$$
 (1)

Solar panels have one of the lowest CFs at 10–35% due to its variable output based on multiple factors, such as seasonality, array orientation, latitude of installation, dust accumulation, cloud formation, etc. For comparison, wind plants have CFs around 25–50%, and nuclear plants have the highest CF of over 90%, such as the Prairie Island Nuclear Generating Plan in Minnesota, which actually crossed 100% in 2019. Combining sources to achieve a baseload generation profile benefiting from each source's availability to mitigate intermittency can help to obtain higher CFs. Many combinations of sources are possible, but R&D of HPP is still very limited, and the policies regarding HPPs are still vague and have large room for improvement, especially regarding standardized grid connection requirements, point of common coupling, integration of thermal storage, and economic analysis of on-grid or off-grid HPPs. This paper attempts to discuss HPPs, with an emphasis on solar plant integration, and categorized into intra-source solar HPPs and inter-source solar HPPs.

# 3.6.1. Intra-Source CSP-PV Plant

CSP is not directly competing with PV in a growing number of projects. Since CSP produces thermal energy, it can act as a form of energy storage rather than a method of direct generation. CSPs can be used as huge batteries, storing the daytime heat in TES tanks, such as molten salt or thermal oils. The thermal energy produced during daytime is stored and subsequently converted to electricity during periods of solar unavailability. In this regard, PV and CSP become complementary sources with well-defined roles for each technology, one supplying power during the daytime (33% generation using PV) and one supplying it during the night (67% generation from CSPs, such as ST, PTC). Thus, a hybrid CSP-PV solar plant can deal with the discontinuity of solar energy. The concept of a CSP-PV HPP integrates TES to achieve a baseload generation profile, taking advantage of the low cost of PV while using the CSP with TES as a backup to the PV plant to generate a constant power output, thus converting the discontinuous solar energy into a reliable, dispatchable resource.

CSP-PV plants have been shown to be highly cost-effective for constant power output for daily time period requirements longer than 16 h [62]. A battery energy storage system (BESS) can also be integrated with the PV to further increase dispatchability [63]. Despite the separate PV and CSP plants reaching a lower LCOE than the hybrid CSP-PV, the hybrid CSP-PV plant enables 24-h electricity supply and reaches higher capacity factors than the separate plants [55]. In fact, CSP-PV hybrid plants offer a 1.7% lower LCOE compared to standalone cases [64]. A recent CSP-PV project in Dubai has set a record for the lowest LCOE among all solar projects in the world [65]. The U.S. has a 28 MW CSP-PV hybrid plant which occupies a part of the Stillwater GeoSolar Hybrid Plant in Nevada.

CSP-PV hybrid plants are growing in number globally; in fact, most utility scale CSP projects are being planned to be integrated to a PV plant to increase the capacity factor. One such intra-source HPP is the on-going 950 MW Noor Energy 1 plant in Dubai, UAE, which is the world's largest single-site CSP-PV plant. It is an ambitious \$3.9 billion project with 700 MW of CSP and 250 MW of PV power. It is equipped with 550,000 tons of molten salt TES, a record amount for any solar project, and also achieved the lowest LCOE of just \$2.4/kWh for PV plant, and \$.029/kWh in daytime, \$0.092/kWh in night time for the CSP technology, which is the lowest for any country or solar project. Dubai Electricity & Water Authority (DEWA) will take electricity from the hybrid project at \$0.073/kWh, a price that enabled CSP to become a direct competitor of the fossil fuel-based power generation market [65].

# 3.6.2. Inter-Source Solar Hybrid Plant Solar & Gas

Solar power plants can be integrated into other generating sources, such as diesel, gas, coal, or other RE-based plants. TC, LFR, and ST technologies can utilize natural gas to aid system startup and provide backup power. One of the most common solar-fossil hybrid plants is the integrated solar combined cycle (ISCC) power plant, composed of a CSP component and a natural gas-fired combined cycle (NGCC) plant, resulting in a reduction of fossil fuel usage and mitigation of solar intermittency. Martin Next Generation Solar Energy Center is the 75 MW CSP component of an ISCC plant, located in Florida,

providing STE capacity to directly substitute fossil fuel usage [66]. Its combined cycle is the 3.7 GW Martin County power plant, which is currently the U.S.'s the single largest fossil fuel power plant, as well as the first hybrid solar facility in the world to combine CSP with NGCC [66]. Alqahtani et al. (2016) carried out a techno-economic analysis of the ISCC plant which showed that the hybrid plant reduces the LCOE of solar electricity by 35–40% compared to a standalone CSP plant, and the capacity factor can reach as high as 86%.

#### Solar & Wind

Integrating two of the most promising RES, a hybrid wind-solar plant is gaining interest of researchers and engineers. Co-location configurations of hybrid wind-solar plants is typically of three types—solar and wind sharing the same substation and coupling point, PV panels integrated into or closely located to the wind turbines, and solar and wind with separate substations and separate coupling points. Besides wind and solar, an electric storage system (ESS) can also be integrated either as a supplementary component, as an independently operated component or as a partly independent component and partly supplementary component [67]. In the U.S., wind speeds are low during summertime and strong in winter. On the other hand, longest sunshine hours and GHI are observed in summer, whereas less sunlight is available in winter. With this negative correlation, a hybrid wind-solar plant might be a viable option because the peak operating periods for wind and solar power systems occur at different times of the day and year. Some of the existing wind-solar plants are Cynog Park in the UK (3.6 MW wind, 4.9 *MW*<sub>P</sub> PV), Kavithal solar-wind project in India (50 MW wind, 28.8 MW PV), Kennedy energy park in Australia (43 MW wind, 15 MW PV, 4 MWh storage capacity), etc.

#### Solar & Hydropower

Hydropower also holds a large share in the RE market. However, with limited water resources, one way to increase the maximum capacity for hydropower is by integrating it with other sources. Most often, it is challenging to interconnect sources on land and water, which is why hybridization of hydroplants is less common. Solar is an exception in this regard, as ongoing research is trying to incorporate PV with hydroplants to create optimal scheduling when each source can contribute to the output power [68]. On the other hand, a special type of hydro-FPV plant has shown potential to increase a country's FPV capacity dramatically, as well as be smarter use of water resources, since both of the individual systems reside in water bodies. The sources can be coupled at a common substation which enables operations to be co-optimized and dispatched in concert. Lee et al. [69] explored the technical potential of hydro-FPV power plants and the role it can play in creating cleaner sources of energy. The authors claimed that global potential of 400–1000 GW for standalone FPV rises significantly to 4400–5700 GW when FPV is paired with hydropower. Co-located hydro-FPV plants come with benefits, such as increased efficiency of PV panels due to the temperature regulation by water, less evaporation, reduced algae growth, mitigation of shading effects, and lower capital cost. It can also provide storage integration by using FPV's excess solar generation to pump water into an upper reservoir to be conserved during peak production hours, and later be used for hydro production. With the growing interest of FPV systems, this can be a good area for future work.

## Solar and Hydrogen

For off-grid solar power systems, oversized batteries and solar generators are required to supply seamless electricity when the solar insolation delivers a very small amount of energy. Along with bulky size, batteries also come with disadvantages, such as selfdischarging upon long-term usage and low energy density. Many systems avoid oversizing by adding diesel generators that supply load during critical periods. Adding a proton exchange membrane fuel cell (FC) can be a possible substitute to diesel generators [70]. Hydrogen possesses advantages, such as technological advancement in its production and conversion technologies, high efficiency, and minimal environmental effect [71]. When the hydrogen is produced from RESs, such as solar, it is referred to as green hydrogen. Different methods of hydrogen production using solar energy has been discussed extensively in Reference [72]. A solar-hydrogen system is described as a potential energy storage medium to offset the intermittency of solar energy. Many successful implementations of solar-hydrogen systems have been discussed in Reference [71]. Current challenges with hydrogen technologies include high cost, underdeveloped infrastructure, existing mass hydrogen production from coal and natural gas at a cheaper cost than RESs, and undefined regulatory policies. With technological advances and economies of scale, the cost of making hydrogen with solar PV electricity can become competitive with hydrogen made with natural gas [73]. This scenario makes clean hydrogen from solar PV cost-competitive with hydrogen from natural gas, even without carbon capture, usage, and sequestration (CCUS).

#### HPP in the U.S.

There are two prominent HPPs in the U.S., one being the previously mentioned 75 MW Martin next generation solar energy center in Florida. The second one is the Stillwater GeoSolar Hybrid Plant in Nevada, which is a triple HPP that combines 61 MW solar energy with a geothermal power plant. Covering 240 acres (0.97 km<sup>2</sup>), the plant uses polycrystalline PV panels that have a capacity of 26 MW. An additional 2  $MW_e$  using CSP PTCs adds 17  $MW_{th}$  of thermal energy aiding 2 MW of boost in power generation to the geothermal power plant.

The future energy mix will not be dominated by a single RES; rather, all standalone and hybrid sources will be working together to supply the demand. The key concern should be allocating resources in such a way that they complement each other to maximize the CF of a plant. A conceptual timeline for the daily deployment of power is presented in Figure 16, where the timeline is broken down into 24 h. The 2020 scenario shows that majority of the loads are still supplied by fossil fuels, with a slight peak during 8 am to 5 pm when PV generation is abundant. In the short term (2030) and long term (2050) scenario, fossil fuel based generation gradually decreases, mostly being used as a complementary source rather than the baseload supplier in the last scenario. An important factor is the gradual deployment of CSP, which will play a significant role to compensate for the unavailable hours of PV generation. In order to ensure the harmonious operation of all the sources, it is crucial to carry out research in location assessment, timeline optimization, resource allocation, and grid integration of all the sources.



**Figure 16.** Conceptual daily electricity mix for short term (2030) and long term (2050) supply. Rather than a single dominant generator, all sources will work in harmony to maximize efficiency and mitigate intermittency.

#### 4. Development, Milestones and Current Scenario of the U.S. Solar Industry

The U.S. has a diverse electricity mix that encompasses fossil fuels, nuclear energy, and RESs, which can be observed from Figure 17. It is apparent that the energy mix is still largely dominated by fossil fuels, with RESs only accounting for 11% of the total energy mix. Biomass (wood, biofuels, biomass wastes), wind, and hydropower make up most of the RES, but, considering the delayed boom in solar deployment, projections show that solar will account for 48% of RE generation in 2050 compared to the present 9% [74]. These sources have changed gradually over the past two decades and are continuing to change at a fast pace. Between 2008 and 2018, almost 90% of the increase in the U.S. renewable electricity sector came from solar and wind generation [75]. Solar energy, in particular, has

shown huge potential to emerge as a scalable and sustainable RES in the U.S. At present, the U.S. is the second largest producer of solar power in the world with 108.7  $GW_{dc}$  (2021) installed capacity. Since 2008, the production of solar power capacity has grown from just 0.34 to 62.4  $GW_{DC}$ , showing a 75-fold increase in less than a decade [76].



**Figure 17.** The U.S. energy mix is dominated by fossil fuels as of 2019, with renewable energy sources comprising a mere 11%. Solar energy has still a long way to go to emerge as a trusted energy source [77].

The 2010s was a golden decade for solar energy in the US. Over the last decade, the solar industry grew from a niche to a dominant source of energy, hitting numerous milestones along the way. In May 2016, the US hit a landmark of 1 million solar installations. It took 40 years since the deployment of solar to get to 1 million solar installations around the country, but in less than 3 years, it reached the milestone of 2 million installations in 2019, and 3 million in 2021 [78]. In 2010, only 4% of new electric capacity additions was solar. That had changed drastically by 2016, when nearly 40% of all new capacity installed was solar. The Catalina Solar Project (2012) was the first standalone US solar plant to surpass 100 MW of electricity generating capacity, paving way for the solar boom in California. 2016 marked the highest installment of solar capacity, with an annual record of 15.1 GW. Perhaps the most significant reason behind solar development and commercialization in the 2010s is the rapid fall in the cost of PV. The US solar industry grew 43% over 2019 and added a record 19.2  $GW_{DC}$  of capacity in 2020 alone. The 43% new additions set a new record to solar's largest-ever share in new energy installments which resulted in solar energy ranking first among all electricity generating technologies for the second year in a row [59]. 2021 continues to make record additions with over 10.7  $GW_{DC}$  installed in the first half of 2021, and is expected to continue breaking records for the next three years until the investment tax credit (ITC) fully phases down.

Recently the U.S. ranked as the most attractive RE market in the world. Renewable Energy Country Attractiveness Index (RECAI) lists the top 40 countries based on their investments in developing and adopting RESs, a list where China has occupied the first position since 2016. However, the U.S. triumphed over China for the first time in 2020, being recognized as the best country with RES imperativeness, policy stability, quality project delivery, capital availability, artificial motivators, such as RES incentives, and a diversity of natural resources [79]. Much of this success is a result of the numerous federal/state incentives and government investments, coupled with other factors that are driving the RE

market of the U.S. to reach the ambitious goal of 100% RE in the power sector by 2035 and net-zero emission economy by 2050, announced by the government in 2021.

# 4.1. State-Level Solar Adoption

As of June 2021, the total installed solar capacity in the U.S. is 102.8  $GW_{DC}$ . According to the annual reports of EIA, Solar Energy Industries Association (SEIA), and Woodie Mackenzie, the list of states excelling in the solar market is summarized in the following points:

- The states with the highest installed solar capacity in 2021 are California (31,872.79 MW), Texas (9311.01 MW), and North Carolina (7132.32 MW).
- Based on the percentage of electricity coming from solar, the leading states are California (22.69%), Massachusetts (18.4%), and Hawaii (15.83%). Massachusetts and Hawaii rank 8th and 16th, respectively, in terms of states with the installed capacity. It is clearly observed that the size of the state along with other factors play a big role in the amount of solar energy it is able to accommodate. So, there are states that might not have the highest generation capacity but generate enough to make a significant impact on their in-state energy mix. Nevada, Vermont, Utah, North Carolina, Arizona, New Jersey, New Mexico, and Rhode Island all have solar penetrations > 10%. On the contrary, Texas and Florida, being the two states with the highest solar additions 2020, only have solar penetrations of 1.97% and 3.03%, respectively.
- In terms of annual PV addition in the year 2020, the top states are California with 3904 *MW<sub>DC</sub>* annual addition, Texas with 3425 *MW<sub>DC</sub>*, and Florida with 2822 *MW<sub>DC</sub>* [59].
- As of 2020, the states with the most small-scale PV capacity are California with 10.6 GW, New Jersey with 1.9 GW, and Massachusetts with 1.8 GW installed small-scale PV. New Jersey, New York, and Massachusetts are among the leading states for small-scale solar capacity, despite having less favorable solar resources than western states.
- Nevada is the only state to accommodate all large-scale technologies, including PV, PTC, ST, and CSP-PV HPP. After the halt of Crescent Dunes, California is the only state to accommodate an operational ST plant.

This study aims to provide a complete state-wise overview of the current situation of solar energy. Table 3 summarizes the key indicators of a state's stance on the solar market (installed capacity, number of solar plants, state penetration of solar), the future targets (renewable portfolio standards (RPS)/goals, solar or DG provision in RPS), and the incentives each state is deploying to reach the target. It also gives an idea of a state's relative stance compared to the other states. All the data has been collected from credible sources and latest available data up to June 2021 [80]. Following the table, the paper moves to address some of the significant states that has made an impressionable impact on the solar market.

Rank	State	Installed Capacity (MW)	No. of Solar Plants	Solar Penetration (%)	RPS and Goals	RPS with Solar or DG Provisions	Total RE Incen- tives/ Policies
1	California	31,872.79	1,255,360	22.69	44% by 2024; 52% by 2027; 60% by 2030, 100% clean energy by 2045.	N/A	146
2	Texas	9311.01	104,855	1.97	10 GW by 2025 (goal; achieved)	N/A	112
3	North Carolina	7132.32	20,822	7.68	12.5% by 2021 (IOUs)	0.2% solar electricity by 2018	65
4	Florida	7073.98	80,997	3.03	N/A	N/A	71
5	Arizona	5247.7	176,544	7.39	15% by 2025.	4.5% DG by 2025	55
6	Nevada	3903.82	64,206	14.72	50% by 2030; non-binding 100% carbon-free by 2050.	1.5% solar electricity by 2025 2.4 for PV (M)	28
7	New Jersey	3653.07	133,849	6.23	50% by 2030	4.1% solar electricity by 2028	46
8	Massachusetts	3262.74	111,810	18.4	35% by 2030 and an additional 1% each year after	N/A	71
9	Georgia	3068.97	2589	3.43	N/A	N/A	33
10	New York	2840.34	141,106	2.46	70% RE by 2030; 100% zero-emissions electricity requirement by 2040	0.58% customer—sited by 2015	95
11	Virginia	2546.39	16,043	1.64	100% RE by 2045 for Phase II utilities and 2050 for Phase I utilities	N/A	39
12	Utah	2336.20	47,248	8	20% by 2025	2.4x multiplier for Solar Electric	27
13	South Carolina	1891.44	22816	2.1	2% by 2021	0.25% DG by 2021	40
14	Colorado	1755.94	77,721	3.96	10% or 20% for municipalities and electric cooperatives depending on size; 100% clean energy by 2050 for utilities	3.0% DG by 2020, 1.5x multiplier to electric co-ops for energy generated by community solar gardens 1.5% CST by 2020	95
15	Minnesota	1601.61	8243	3.32	26.5% by 2025 (IOUs), 25% by 2025 (other utilities).	1.5% solar electricity by 2020, 0.15% PV DG by 2020	134
16	Hawaii	1426.94	91,633	15.83	30% by 2020; 40% by 2030; 70% by 2040; 100% by 2045.	N/A	28
17	Maryland	1342.44	73,241	4.23	50% in 2030.	2.5% solar electricity by 2020	69
18	New Mexico	1210.94	28,469	5.87	40% by 2025; 80% RE by 2040; 100% electricity supplied by zero-carbon resources by 2045	4% solar electricity by 2020 0.6% DG by 2020	39

Table 3. State-wise overview of installed solar capacity, goals, and incentives.

Rank	State	Installed Capacity (MW)	No. of Solar Plants	Solar Penetration (%)	RPS and Goals	RPS with Solar or DG Provisions	Total RE Incen- tives/ Policies
19	Oregon	1122.62	23,164	2.03	25% by 2025 (utilities with $\geq$ 3% of the state's load); 50% by 2040 (utilities with $\geq$ 3% of the state's load); 10% by 2025 (utilities with 1.5–3% of the state's load); 5% by 2025 (utilities with <1.5% of the state's load)	20 MW PV by 2025. 2x multiplier for solar PV between 500 kW and 5 MW installed within Oregon prior to 2016	100
20	Indiana	939.10	4268	0.65	10% by 2025.	N/A	56
21	Connecticut	908.48	51,990	2.22	44% by 2030	N/A	48
22	Pennsylvania	786.74	33,889	0.31	18% by 2020–21	0.5% PV by 2021	52
23	Illinois	617.83	24,442	0.29	25% by 2025–26.	1.5% PV by 2026, 0.25% DG by 2026	64
24	Idaho	577.82	8092	3.34	N/A	N/A	30
25	Ohio	527.09	7703	0.35	8.5% by 2026.	0.5% solar electricity by 2027	41
26	Michigan	520.92	11,052	0.3	15% by 2021 (standard), 35% by 2025 (goal, including energy efficiency and demand reduction)	3.2 x multiplier for solar electricity	46
27	Wisconsin	450.21	7679	0.36	10% by 2015	N/A	50
28	Iowa	423.71	6293	0.38	105 MW generating capacity for IOUs	N/A	47
29	Rhode Island	412	7692	5.86	14.5% by 2019, with increases of 1.5% each year until 38.5% by 2035	N/A	28
30	Arkansas	386.08	2579	0.68	N/A	N/A	26
31	Vermont	381.74	8971	14.03	55% by 2017; 75% by 2032.	1% DG by 2017 + 3/5ths of 1%/year until 10% by 2032	40
32	Tennessee	356.16	2609	0.55	N/A	N/A	15
33	Mississippi	316.53	850	0.68	N/A	N/A	18
34	Missouri	302.98	12,083	0.61	15% by 2021 (IOUs)	0.3% solar electricity by 2021	60
35	Alabama	283.13	157	0.38	N/A	N/A	17
36	Washington	258.24	23,788	0.27	100% GHG neutral by 2030; 100% RE or zero-emitting by 2045.	2 MW with 2x multiplier for DG.	80

Table 3. Cont.

# Table 3. Cont.

Rank	State	Installed Capacity (MW)	No. of Solar Plants	Solar Penetration (%)	RPS and Goals	RPS with Solar or DG Provisions	Total RE Incen- tives/ Policies
37	Maine	245.77	2884	1.14	80% by 2030, statewide target of 100% RE by 2050.	N/A	21
38	Louisiana	190.51	21,147	0.31	N/A	N/A	20
39	Delaware	154.37	7327	3.48	28% by 2030 and 40% by 2035. The changes retained the state's previous target for 2025 of 25%	3.5% PV by 2026 3.0 for PV (M)	25
41	New Hampshire	140.46	9622	0.88	25.2% by 2025	0.3% solar electric until 2014	39
40	Wyoming	139.76	2617	0.43	N/A	N/A	20
42	Montana	118.35	2026	0.27	15% by 2015	N/A	27
43	Kansas	84.85	1104	0.19	15% by 2015–19; 20% by 2020	N/A	12
44	Oklahoma	79.84	2689	0.11	15% by 2015	N/A	29
45	Nebraska	63.27	1317	0.22	N/A	N/A	17
46	Kentucky	61.21	2594	0.15	N/A	N/A	37
47	Alaska	12.67	1415	0.11	N/A	N/A	15
48	West Virginia	12.53	410	0.03	10% from 2015–19, 15% from 2020–24, 25% by 2025	N/A	10
49	South Dakota	1.89	41	0.02	10% by 2015	N/A	17
50	North Dakota	1.15	23	0	10% by 2015	N/A	14

# 4.1.1. California

The RE hub of the U.S. and an exemplary state for utilizing RESs, California's solar production exceeds every state by a large margin and accounted for 33% of U.S. annual solar generation in 2020. It has the highest cumulative solar capacity, with three times more installed capacity than its immediate competitor Texas, while having the highest utility-scale solar installed in the country, standing at 16 GW [47]. California recently reached the remarkable milestone of 95% RE in their electricity mix in April 2021. Figure 18 shows that the supply from RESs drastically rises during sunlit hours, indicating the significant contribution of solar in the RE mix. The out-of-state import curve actually dips to negative territory during peak hours because California produces so much solar power that the surplus amount can be exported to other states [81]. In fact, most of the mega solar projects in the U.S. are located and planned in California.



**Figure 18.** California's daily power consumption curve shows sharp increase for RES during sunlit hours, indicating solar energy playing a significant role in the energy mix [81].

# 4.1.2. Texas

Texas is the second largest producer of solar in the U.S. With more than 9 GW of solar installed, it is underwhelming considering the rich solar resources that Texas possesses. With only 1.97% of solar penetration in the state electricity mix, Texas has major potential for growth in the upcoming years. It has already surpassed California in terms of new solar additions in 2021, with 1525  $MW_{DC}$  installed in the first quarter alone (3 times higher than that of California). According to the EIA and SEIA, Texas ranks as the state with the highest solar growth projection in the next 5 years. A report by EIA stated that one-third of the U.S. solar utility planned to come online in the next 2 years will be in Texas, with 10 GW solar addition by the end of 2022.

# 4.1.3. Washington, DC

Washington, DC is the capital city of the U.S. and is listed separately from the 50 states. Although Washington, DC ranks 44th with cumulative installed capacity of 107.7 MW (2020), it has the highest penetration of solar in the entire country. With an impressive 40.46% of the state's electricity coming from solar, it is twice more than the highest penetrated state, California with 22.69%. D.C. set a goal to reach 100% renewable electricity mix by 2032, with 5% coming from solar. D.C. occupies the highest number of government buildings in the U.S. taking into account both federal and municipal government build-

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ings, and every government building in D.C. is powered by RESs [82]. The achievements and efforts for going clean led to Washington, DC receiving the title of a Leadership in Energy and Environmental Design (LEED) Platinum city, the first city in the world to reach this milestone.

# 4.1.4. Other States

Rhode Island ranked 27th in the country for cumulative capacity and 29th for installed solar capacity in 2020, which is impressive as it is much smaller than the 21 states it triumphed over. New Jersey, Massachusetts, Hawaii, and Vermont have impressive solar penetration despite their lower installed capacity. On the contrary, New Mexico, Utah, Arizona, Oregon, and Colorado have comparatively low solar penetration (less than 10%), despite their rich solar resources. Florida made major solar additions and placed 3rd in 2020, as well as has the largest growth projections after Texas and California in the next 5 years [80]. Minnesota has the largest community solar garden, followed by Massachusetts, New York, and Colorado.

# 5. State Categorization Based on Solar Prospects

This section presents a novel contribution to analyze the prospects of solar energy in the U.S. by 2031 based on relevant factors. In the subsection that follows, the considered factors are elaborated in addition to their correlation to the solar growth projections. Then, the methodology of work has been narrated briefly, followed by the discussion of the findings of the simulation.

# 5.1. Considered Factors and Their Correlation

A total of five types of factors have been considered for the simulation, that are grouped as market, economic, solar resource, social, and technical factors. Each of these factors are described in Table 4. The set of weights assigned for the rooftop PV systems and the utility scale PV systems are different.

Demand/sq.mile

Area

Goal	Dimensions	Sub-Criteria
	Net metering	An electric billing system allowing consumers to earn credits for the energy they feed into the grid.
Market	Current utility rate	The present rate of electricity offered by the grid operators defines whether consumers would be interested to absorb energy from the grid or generate electricity from their own solar units.
	Regional competition	Negative; some states are developing other RESs, such as wind, biomass, and even nuclear energy rather than solar energy.
	Statewide policy and incentive	States, such as California, have set exemplary statewide policies and offered numerous incentives to boost the adoption of RESs.
Economic	Property cost	<i>Negative factor;</i> almost 5–10 acres (20,000–40,500) of land is required to generate each MW of solar power at the utility scale. For this reason, property cost plays a defining role in deploying solar power plants.
	Current growth rate	If the economic growth is rising for any state, then it is a positive aspect for the development of solar technologies, as it requires a relatively high initial investment.
	Global horizontal irradiance	The more the irradiance in a certain state, the more is the solar prospect.
Resource	Sunlight hours	The longer the sunlit duration, the better it is in terms of solar prospect.
	Highest temperature order	Solar technologies can provide their maximum output up to a certain threshold of solar insolation.
	Population	A higher population translates to a higher demand for electric power and, hence, a greater necessity to build solar projects to meet the additional power demand using clean electricity.
Social	Available workforce	The solar industry lays down the opportunity for employment for many people. If more people are unemployed in a certain state, more people are available to work in the solar sites. Therefore, available workforce is a positive factor for boosting the solar prospect of a certain state.
	Per capita income	The GDP is a direct indicator of the economic development of a state, and so, a higher GDP implies more prospect for the growth of the solar technology.
	Land constraints	<i>Negative;</i> solar installations require a significant amount of land space. Therefore, if more land area is free to be given up for solar installations, then the solar prospects substantially increase.
	Grid proximity	Grid proximity defines how close the grid infrastructure lies from a state and is directly involved with the grid infrastructure density. The denser the grid infrastructure is, the easier it is to inject solar power into the grid and make the necessary amendments to do so.
Technical	Weather constraints	<i>Negative factor;</i> the rainfall, disasters, dew point, sky cover, and relative humidity of each state define its solar energy potential. While it is true that the temperature, wind flow, availability of water, etc., do play a role in the efficiency of a PV system, but this study has been focused towards the socio-economic and resource potential, rather than the optimization of efficiency. As a whole, the aforesaid weather constraints are a negative factor for the flourishing of solar energy.
	Number of solar installations	If a state already has sufficient number of solar installations, then the people in the state are aware of the technology and would be more willing to invest in more such plants.

cannot fulfill the demand in a cost-effective approach.

The power density of the state is an important factor because a greater demand for power necessitates the usage of solar energy when other energy generation sources

Since solar energy requires a significant amount of land space, more availability of usable area translates to better prospects for harvesting solar energy.

# Table 4. Considered factors according to the five classes.

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# 5.2. *Methodology*

MATLAB and Simulink have been employed to model a system with each of the factors bearing a suitable weight, and the model has been run for the data of each state. Any other method, such as neural networks, may be used to obtain similar results; however, Simulink has been preferred in this case due to its versatility and ease of changing parameters. The model is simulated with the weighted hyperplanes for each state, which gives an output indicating the prospect of solar growth in that particular state. An important point to note is that the size of the state obviously accounts for what the maximum capacity of that state is. The larger the state, the more solar installations it is capable of accommodating. So, the study aims to project the relative growth prospects of a state, not the actual solar additions; however, the additions it will make relative to the state's present stance on solar energy.

Figure 19 illustrates a concise overview of the eight steps followed in the entire process. A two-level approach has been adopted to achieve the goal: a local level and a global level. In the figure, the blue-colored steps denote the local level, and orange color denotes the global level.



**Figure 19.** Methodology of work. After categorizing the factors, weights are assigned to each of them based on their positive or negative correlation with the growth of solar. Next, the hyperplanes are mapped, and, finally, the solar prospect of each state is calculated. Thus, the states are categorized into five tiers.

#### 5.2.1. Local Level

As described previously, all the considered factors have been classified into five groups. Each group contains multiple factors, each of which are assigned a specific weight based on its correlation to the solar prospect. This is how the local level hyperplanes were calculated for each group. Analytical hierarchy process (AHP) multi-criteria decision-making was employed to rank the states based on these factors. The assigned weight of the individual factors was acting as a slope for the each factor. From the regression analysis, each factor was mapped in a hyperplane. As the criteria input for AHP, each factor was projected up to the year 2031.

#### 5.2.2. Global Level

From the individual hyperplane of the factors (i.e., the local level), a combined hyperplane was calculated for each of the five category of factors. In this hyperplane, the weight of each category was again calculated using AHP. From the global hyperplane, the solar prospect was calculated as a probability. Based on the probability, the 50 states were grouped into 5 tiers, with ten states in each category. According to the categorization, Tier 1 has the least solar prospect, and Tier 5 has the maximum solar prospect.

#### 5.2.3. Analytical Hierarchy Process

The AHP is among the most prominent multi-criteria approaches and is frequently used. In this methodology, rating alternatives and aggregating procedures are merged to discover the most appropriate alternatives. The method is used to classify several alternatives or to choose the best alternatives in a group of options. The rating is based on an overarching objective, which is divided by a series of criteria. The use of the approach consists of determining the weight of importance to be linked with the criteria for determining the overall objective. The criteria are compared in pairs. Two criteria,  $C_j$  and  $C_k$ , should be considered. Regarding the relative relevance of  $C_j$  over  $C_k$  in the objective, the stakeholder is requested to offer a comparison judgment on the pair. The comparison assessment is captured in a semantic scale and is transformed to the number integer value  $a_{jk}$  (as important/moderately more important/very important, etc.).  $a_{kj} = 1/a_{jk}$  is defined as the relative significance of  $C_k$  over  $C_j$ . A comparison matrix A is then built with  $a_{jk}$  in pairs for all j and k. Take note of  $a_{jj} = 1$ . The weights of criteria were commonly agreed upon by determining the major vector w of Matrix A, as given by Equation (2).

$$A_w = \lambda_{max} w. \tag{2}$$

If the vector w is standardized, the criterion's priority vector about the objective;  $\lambda_{max}$  is the greatest individual value of matrix A, and the associated eigen vector w only contains positive entries. The technique also includes predefined processes to assess the coherence of stakeholders' opinions. The weights of the alternatives are calculated following each criterion using comparable processes. The weighted summation then calculates the total weights of various solutions.

## 5.2.4. Hyperplanes from Regression Analysis

The linear regression data model is that some hyperplanes are limited to the data points. This is also seen as treating one of the coordinates as 'dependent' and the others as 'independent'; the dependent coordinate is then linear to the independent. The data can be selected on a line according to a specific probability distribution. A known pattern of independent coordinates can be established (for example, they are selected on the grid), in which the dependent coordinates are measured for each location. The dependent and independent variable does not matter much for the probability distribution models. However, this decision can change if the independent coordinates are not allocated, or the sound model just adds noise to the dependent coordinates are independent. To find out the hyperplanes for each factor, at first, the present status of that factor is evaluated. After normalization, the prospect factor was assigned to each factor, which acts as the slope of the hyperplane. Combining these two variables, each factor's hyperplane is evaluated in terms of Equation (3).

$$=mx+c, (3)$$

where m = future prospect of factor x, and c = present status.

Y

## 5.3. Insights from the Map

The finding of the simulation has been visualized in Figure 20. The deeper the color, the higher is the solar prospect of a certain state, as can be understood from the legend in the map. The five tiers are enumerated from 1 through 5, with Tier 1 states having the least prospect (64.24–67.75%), and Tier 5 states having the highest prospect (74.92–95.86%). It can be observed from the map that the states situated within the sun belt of the U.S. have a higher solar prospect, particularly in the southwestern part, which enjoys the highest GHI and DNI. It can be noted that Arkansas, Tennessee, and Georgia are relatively weaker in terms of solar prospect, despite being in the sun belt owing to the lack of solar incentives in these states due to the presence of nuclear power plants. Again, Missouri, Illinois, Indiana,

and Ohio have a good prospect among the states in the midwest due to the higher number of incentives and a high grid infrastructure density. Besides, the east and west coast of the U.S. are more focused on RESs for their energy demands, implying that the solar prospects in the states in these areas are higher. It is also noteworthy that the solar prospect is not necessarily dependent on the area and temperature of a state. For instance, Rhode Island is a very small state, yet it is a Tier 5 state. Alaska, on the other hand, is a very cold state in terms of its annual average temperatures, yet it is a Tier 3 state due to the large number of government policies and incentives. A key realization is that there is no factor that single-handedly contributes to the growth of solar in a particular region. There are regions that might not have the best solar resources but are expected to thrive due to employing impressive supporting incentives. On the contrary, there are regions that have quality solar resources, but slow progress has been estimated due to a lack of supporting factors.



Figure 20. Categorization of the U.S. states into five tiers based on solar prospects.

#### 6. Solar Price Prediction in the U.S. Using Wright's Law

In order to determine the price in 2031, Wright's Law, or the "learning curve", was used. In most technologies, Wright's law asserts that each doubling of the cumulative production scale will lead to a stable percentage drop in technological costs. This is done via education, a blend of the invention that enhances the technology and innovation itself, which minimizes the amount of work, time, energy, and raw materials required to create the technology. The cost of solar modules is widely known to apply. For every doubling of cumulative production, the price of solar modules per watt of power falls by around 25%.

Wright's Law operates exponentially on learning-by-doing. Each doubling of cumulative output leads to a shift in cost percentage. That indicates that reducing cost percentage through learning requires the industry to scale twice as much as the previous time. Generally speaking, if a numerical event is exponential, it appears on a log scale as a straight line. It is an uphill straight line when it shows exponential growth, or a downhill line if it shows an exponential drop in some metrics (such as cost). The historical data reveals that the price of solar power from utilities decreases by 30–40% every time the cumulative solar deployment is doubled. Considering 30% learning rate because of the saturation probability of solar technology in near future, the following Gaussian bell curve equation has been derived for price prediction of solar in LCOE (Equation (4)). To find out the optimistic and pessimistic case, the learning rate was varied across the years. For an optimistic case, a 35% learning rate, and, for a pessimistic case, a 25% learning rate, has been considered.

$$y = ae^{-\frac{(x-b)^2}{2c^2}},$$
 (4)

where *a* = 638,927,900,000, *b* = 1635.67, and *c* = 56.07587.

The predicted price of solar energy in the U.S. over the next ten years are plotted in a graph in Figure 21. The prices are estimated based on the cumulative installed capacity in MWh. The curve demonstrates an exponentially declining trend, inferring that the price of solar technologies is expected to reduce substantially from \$45/MWh in 2019 to only about \$10.5/MWh in 2031—almost a 77% reduction in price within a 12-year span.



Figure 21. The predicted price points of solar energy in the U.S. up to 2031.

# 7. Growth Factors: Reasons Behind the Growing Popularity of Solar in the U.S.

An evident reason behind solar gaining ground worldwide is its characteristics that make it an ideal source for generating long-term sustainable energy while mitigating climatic adversities. However, solar resources alone are not enough to drive deployment and adoption. There are numerous policies and calculated risks that instigated the adoption of solar energy in the U.S. The combined effort of the brightest researchers, pro-solar governments, and aggressive investors is what drove the U.S. to excel in solar installations faster than most countries in the world. Federal, state, and local policies implemented to incentivize RE have played a crucial role in the mass uptake of RESs. Remunerations, tax or bill credits and energy policies give investors and homeowners a motive to shift from their conventional energy source to cleaner sources of energy. These policies can be under federal jurisdiction or state jurisdiction, both of which act in favor of increasing solar generation and stimulate rapid succession of clean energy. These lead to further drivers of solar, such as PV, as a distributed energy source, plummeting costs, and storage systems being integrated into solar technologies.

#### 7.1. Solar Resources

Solar resources are a prerequisite to any country hoping to make significant additions of solar in their energy mix. Although it was previously mentioned that the amount of energy reaching the Earth from the sun is far greater than what it consumes, the reason it has not been adopted by every country is because of the non-uniform distribution of solar resources. A recent report by the World bank ranked countries by their theoretical potential of PV generation based on possession of solar resources [83].

There are two main components of solar irradiance, GHI and DNI. CSP makes use of DNI, while PV requires GHI. Diffuse irradiation and global tilted irradiation are also taken into account for PV and flat-plate collectors. The Middle East, Northern and Southern Africa, Australia, Southwest Latin America, Mexico, and parts of the U.S. experience excellent GHI. On the other hand, countries witnessing high DNI are Mexico, Southwest Latin America, Southern Africa, and Australia. Surprisingly, the Middle East, Saudi Arabia, and Morocco have implemented impressive CSP projects, despite having low DNI. The U.S., in particular, is blessed with adequate DNI and GHI. The levels highly fluctuate during different times of the year. On average, the Southwest U.S. observe the highest level of GHI and DNI. However, from May to August, almost all states observe high GHI. Similarly, the GHI levels drop across all the states from November to February. The seasonality of solar resources are discussed in Sengupta et al. [84].

# 7.2. Federal Policies, Incentives and Rebates

The solar Investment Tax Credit (ITC) is one of the most important federal incentives promoting the expansion of solar energy in the U.S. It is one of the main drivers of rooftop solar and has coincided with 60% annual growth in solar adoption [85]. The ITC was originally introduced by the Energy Policy Act of 2005, which created the principal 30% tax credit for the cost of solar installations on residential (under IRS Section 25D—also known as Residential Renewable Energy Tax Credit) and commercial (under IRS section 48—also known as Business Energy Investment Tax Credit) properties. The ITC was initially set to expire in 2006, but, after several renewals, the latest ITC rate is 26% as of 2020. Eligible costs on which ITC can be claimed include labor on site, assembling, and installing the system, the cost of piping and wiring, etc. The Solar ITC can be filed once for the tax year in which the system is installed. Residential solar power systems cost an average of \$20,000 in 2020. A solar tax credit of 26% off the purchase price of a solar system would give a \$5200 credit. The credit received is then calculated dollar-by-dollar as a reduction of the owner's federal tax liability, so, if \$6000 is owed in federal taxes, a tax credit of \$5200 causes the net liability to drop to \$800 [86].

Since the ITC was approved in 2006, the U.S. solar market has grown by more than 10,000%, creating thousands of jobs and bringing billions of dollars in the U.S. economy through solar investments. As a result, Congress has extended the expiration date multiple times to continue supporting that growth. The ITC was set to drop rates several times, but the 30% rate remained the same from 2006 through 2019. The correlation of ITC with the solar market growth can be clearly observed from Figure 22, which depicts the direct impact of ITC extension on mass solar additions in 2016, which broke the records of all previous years and held that record for several more. In order to push the installations further, the latest extension of ITC was announced in December 2020, that sets the expiration date to the end of 2023 [87]. Under the current law, the ITC for most non-solar technologies will expire at the end of 2021 [85].

The timeline of upcoming ITC rates is as follows (if there are no further extensions):

- 2006–2019: Residential and commercial projects installed before 31 December 2019 received 30% federal tax credit.
- 2020–2022: Residential and commercial projects installed before 31 December 2022 will receive 26% federal tax credit.
- 2023–2024: Residential and commercial projects installed before 31 December 2023 will receive 22% federal tax credit.
- 2024 onward: Residential credit drops to zero, commercial projects continue to receive a permanent 10% federal tax credit.





**Figure 22.** Impact of ITC on the growth of the solar industry in the United States. Significant impact observed in 2016, when the ITC extension of 2015 resulted in the highest recorded solar additions and held the record for several years to come [9].

The Emergency Economic Stabilization Act of 2008 provided a 10% credit for combined heat and power (CHP) property through 2016. In 2015, the Consolidated Appropriations Act further extended the credit. The 30% credit rate for solar heating or solar electric property was extended through 2019. In the 2018 Legislation, the Bipartisan Budget Act extended the ITC again for five years for CHP [88]. Starting in 2008, the Joint Committee on Taxation (JCT) provided energy credit tax expenditure (ECTE) on different qualifying technologies. ECTE has witnessed an increase recently, and the majority of the increase is going towards solar credits. In 2018, the estimated ECTE was around \$2.8 billion, with \$2.5 billion attributed to solar, representing 90% of the recent costs. This gives a glimpse of how fast solar is growing in comparison to other RESs. Between 2018 and 2022, the JCT has estimated ECTE to be around \$13.5 billion, with \$12.5 billion to the solar industry alone.

The Modified Accelerated Cost Recovery System (MACRS) is a depreciation system in the U.S. which enables businesses to gradually recover the capitalized cost of tangible assets over a specified life through annual deductions. The MACRS has proven to be a significant driver of private investment [89]. Over the 5-year depreciation period, a business can recoup 10–25% of the solar power system's capital cost, depending on the tax rate of the business. MACRS can be claimed alongside ITC, i.e., if a project deducts 26% through ITC, and receives a MARCS credit on its tax liability, the project owner can deduct a massive 87% (100% – (26% × 0.5)) of the total system cost. The 5-year MACRS schedule allows for larger deductions in the early years, gradually slowing down with the lifetime. The Tax Cuts and Jobs Act of 2017 recently announced a bonus depreciation up to 100% for qualified assets deployed in service after 2017 and before 2023 [90].

The SunShot initiative was a collaborative national effort launched by the DOE in 2011 which aggressively drove the cost reduction of solar energy to become cost-competitive with traditional energy sources. The target was to minimize solar power cost to \$1/W or \$0.06/kWh for central station systems and \$1.5/W for residential systems by the year 2020 [91] and to reduce carbon emission to 20% of 1990 level by 2050 [92]. In 2017, the DOE announced that the target of \$1/W was achieved three years before the targeted year. There was also a decline on the residential and commercial solar system costs, which went down to \$0.16/kWh and \$0.11/kWh, respectively [93].

Federal policies aimed at promoting the adoption of RES and DG ultimately play a major role in the expansion of the solar market. As of 2020, there are 16 financial incentives and 3 regulatory policies. PPAs are also an attractive incentive for utilities to have a guaranteed market after opting for solar plants. PPAs are contracts made between generators and investors or the government which obligate them to purchase the produced energy at a fixed price for a fixed time period. In 2006, investors offered a free solar panel installation by making customers sign a 25-year contract to purchase electricity from them at a fixed price. By 2009, over 90% of commercial PV installed in the U.S. was installed through a PPA. The ongoing federal incentives for solar and relevant technologies have been presented in Table 5 [85]. Note that not all the policies are exclusive to solar, and some of the policies cover other RESs, as well.

Policy Type	Policy Name	Starting Year	Last Update
Regulatory	Green Power Purchasing Goal for Federal Government	2004	2018
	Energy Goals and Standards for Federal Government	2006	2018
	Interconnection Standards for Small Generators	2007	2016
Loan	Energy-Efficient Mortgage	2002	2020
	Fannie Mae Green Financing	2015	2020
	Qualified Energy Conservation Bonds (QECBs)	2008	2018
	USDA—Rural Energy for America Program (REAP) Loan Guarantees	2003	2018
	Clean Renewable Energy Bonds (CREBs)	2008	2018
	U.S. Department of Energy—Loan Guarantee Program	2008	2016
	FHA PowerSaver Loan Program	2014	2016
Grant	USDA—High Energy Cost Grant Program	2010	2016
	USDA—Rural Energy for America Program (REAP) Grants	2003	2018
	Office of Indian Energy Policy and Programs—Funding Opportunities	2003	2020
Corporate tax credit	Business Energy Investment Tax Credit (ITC)	2002	2021
-	Renewable Electricity Production Tax Credit (PTC)	2002	2021
	Residential Energy Conservation Subsidy Exclusion (Corporate)	2002	2018
Personal tax exemption	Residential Energy Conservation Subsidy Exclusion (Personal)	2002	2018
	Residential Renewable Energy Tax Credit	2005	2021

# **Table 5.** Current Federal Incentives in the U.S.

The U.S. is leading the way of ambitious decarbonization goals by being one of the highest investors in clean energy sources [79]. So far, the DOE has spent around \$2.3 billion on R&D to accelerate the innovation of PV technology, with net economic benefits totaling more than \$15 billion. In 2021, the DOE has announced \$128 million in solar incentives, with funding available for PV and CSP R&D projects, demonstration for a Gen 3 CSP power plant, advancing perovskite PV device, manufacturing, and validation projects, a new consortium to develop CdTe thin-film solar cell technologies, and entrepreneurs looking to launch new businesses to accelerate commercialization of perovskite solar technologies.

# 7.3. State Policies, Incentives and Rebates

#### 7.3.1. Renewable Portfolio Standards and Goals

A Renewable Portfolio Standard (RPS) is a regulation that requires the electric utilities and other retail electric providers within a given jurisdiction to generate a portion of their electrical power from a RES, especially solar DG. Although the RPS is a federal regulation, there is currently no RPS program in place at the National level, while the state-based RPS policies vary widely from one state to another [94]. State RPS policies vary based on several elements, including RPS targets, compliance mechanisms, qualifying resources, cost, and generation caps. Currently, 30 states and Washington, DC have RPS, while 8 states have set RE goals [95]. If an RPS policy has a solar-specific carve-out, the compliance mechanism is referred to as Solar Renewable Energy Certificates (SREC). In SREC state markets, SRECs allows homeowners to sell certificates for solar energy to their utility. Utilities are obliged by law to claim a specific number of SRECs. There are 6 states that currently have an SREC program—Delaware, Illinois, New Jersey, Massachusetts, Maryland, Ohio, and Washington, DC have the highest rates of \$435 and Pennsylvania having the lowest rate of only \$20 [96]. Twenty-two states and Washington, DC have an RPS with solar or DG provisions as of 2017. There are 12 states that have plans to get 100% of their electricity from RES in the future, namely Wisconsin, Washington, Virginia, Rhode Island, New York, New Jersey, New Mexico, Nevada, Maine, Connecticut, Colorado, California, and Washington, DC.

# 7.3.2. California Solar Initiative

A landmark incentive that drove the massive success of solar in California was the California Solar Initiative (CSI) announced in 2006. The decade-long initiative was a \$3.3 billion project designed to expand the state's solar industry while reducing the cost enough to make it a mainstream source of energy. The CSI targeted to install 3 GW of additional solar power by 2016 which later expanded to 12 GW by 2020, helping consumers by lowering the cost of PV systems [97]. The program was so successful that it reached its goal of 3 GW solar installations 2 years earlier than its initial target. CSI initially offered an incentive of \$2.50/W on solar powered systems, which, combined with federal tax incentives, could deduct 50% of a solar power system's total cost. CSI provided more than \$2 billion worth of incentives to customers for adopting solar power systems. The substantial cost reduction is also apparent from Figure 23, which presents CSI as a driving factor behind the lowering cost of installed residential solar in California from \$10.69/W in 2006 (when the policy was launched) to \$5.32/W in June 2014 when the target was reached. Similar cost reductions of 51% was observed in the commercial sector, with prices dropping from \$8.86/W to \$4.32/W [98]. By the end of 2019, about 8.8 GW of solar capacity was installed in California alone, which exceeded the goal of Go Solar California by 293%. California's Million Solar Roofs Initiative was also one of the most ambitious targets set in the U.S., aiming to install one million solar homes in California alone, whereas the whole U.S. combined only reached 2 million installations by 2019 [47]. Amazingly enough, California actually reached 1 million solar installations at the end of 2019, marking an unprecedented milestone for any state or country in the world.



**Figure 23.** Massive success of California solar incentive (CSI) program in driving down the cost per watt of solar electricity by 45% in the residential sector and 51% in the commercial sector [98]. The million roofs target was reached in 2014, which is why the cost reduction has been plotted up to 2014. Further cost reductions are not directly associated with CSI.

# 7.3.3. Other State Level Incentives

Several state governments offer tax credits on the capital cost of installing solar power systems. They vary in amount in different states, but it usually allows a solar owner to deduct a percentage of the total cost of the system from annual tax liability. Most of the state-level tax credits have a maximum cap, with current caps varying between \$500 and \$5000, depending on the state. Massachusetts has devised an impressive solar incentive plan called the Solar Massachusetts Renewable Target (SMART) program which favors low-

income, small-scale, and community solar energy. For every kWh of solar energy produced with PV under 25 kW, a massive 230% factor is multiplied to the base compensation rate and offered as rebate under the SMART program. The program also accommodates up to 500 kW projects with the base compensation rate multiplied by a factor of 110%. New York offers a 25% solar tax credit on top of the 26% federal tax credit. The DOE has announced available incentives on Zero Energy Ready Home (ZERH) (not explicit to solar, but PV plays the main role) in states, such as Colorado, Connecticut, Delaware, Minnesota, New Jersey, Oregon, Pennsylvania, Rhode Island, Utah, and Virginia [85]. However, many states have not tapped into a substantial amount of solar resources. States with the highest solar potential, such as Arizona, Georgia, Utah, and New Mexico, lack policy incentives for driving solar adoption.

In terms of available incentives and policies, the highest incentives are provided by California (146), while the lowest number of incentives are offered in West Virginia (10) [85]. In March 2013, Lancaster, California, became the first U.S. city to mandate the inclusion of PV panels on new homes, calling for every new home to integrate an average 1 kW/house. This can bring about another solar revolution in California's already booming solar market. The mandate further expanded in January 2020, when California set a striking example of officially enforcing all new structures built in the state to come with solar panels. Minnesota has deployed the largest community solar garden in the U.S., allowing customers who are unable to buy solar power systems to benefit from centrally located PV systems that provide electricity to partaking subscribers. Feed in Tariffs (FiTs) for surplus energy compensation have proven to bring effective results in developing solar power in countries, such as Brazil, Chile, and Germany. However, it is not a popular incentive in the U.S., where the solar adoption has seen higher correlation with the ITC. Only six states have FiT incentives, and even those are not exclusive to solar. Net metering is also a state-level incentive, which has been discussed elaborately in Section 7.5.

#### 7.4. Distributed Generation

Small-scale renewable electricity generation and storage technologies used alongside traditional electric power systems to act as an alternative source of energy are known as distributed energy resources (DER). DER systems typically use RESs, including solar, wind, biomass, small hydro, and geothermal power, and currently play a significant role in the decentralization of power distribution system. DG refers to the generation of electricity in a decentralized manner where a variety of DERs are used to generate electricity at or near where it will be consumed. Connection to the distribution network is a key factor of DG, as local generation systems that are not connected to the grid is referred to as dispersed generation instead of distributed generation. DG brings the power source within a close proximity to the consumer, mitigating transmission and distribution losses, increased reliability (physical and cybersecurity), and sustainability by encouraging customer adaptation of RESs [99]. Microgrids can be referred to as a subsystem comprising of DG and associated loads. Rather than an individual or dispersed generation, microgrids utilize the emerging potential of DG by bringing it under an electric infrastructure. Microgrids have been discussed in Section 10 of this paper.

Solar energy is one of the key driving forces of DG. The 2019 Annual Energy Outlook Projections by EIA estimates more than 180 GW of solar DG installations by 2050. The leading reason for solar outgrowing wind is that small-scale wind DG has not experienced the rapid cost declines that solar has experienced. Small and midsize wind is only cost-effective in very windy locations, and more residents and businesses are located in regions that have better solar resources than onsite wind resources. Rooftop solar has been making inroads in the sunny states, propelled by various factors, such as the falling cost, attractive policies, various incentive programs with a carve-out for solar, etc. As the U.S. is transiting towards a cleaner and less centralized grid system, the significance of DG, such as rooftop solar, is becoming more prominent [100]. Figure 24 shows the vital role that solar will play in the upcoming DG markets. The PV, SHC, electric vehicle (EV) infrastructure, and

residential load management installations will account for more than 90% of DG installed between 2016–2025 [47]. As rates set for DG must take into account technical limitations and geographic considerations, state and local regulations would be more effective than federal jurisdiction. One such state-level policy is net-metering, which is one of the main drivers of DG.



**Figure 24.** Growth projections for distributed generation and the prominent role of solar energy in the DG market. Source: EIA Annual energy outlook 2019.

# 7.5. Net Metering

Net metering is a billing mechanism and one of the most popular state incentives through which domestic or commercial users of solar power systems can export their surplus energy back to the grid. Net energy metering (NEM) policies are schemes designed to remunerate the surplus electricity injected to the grid. This credit is used to deduct the amount of electricity that has been supplied to the grid from the amount of electricity that has been supplied to the grid for their net energy usage. On average, around 20–40% of a PV system's output remains unused and, therefore, is wasted if not utilized elsewhere. By exporting it to the grid, the electricity can be used to serve nearby customers. NEM works by utilizing a bidirectional energy meter to record energy flow to and from the grid. In recent years, NEM has been categorized into different types to cater to the needs of different niches of customers.

- Conventional NEM, or individual NEM, connects a generating source to single netmeter, such as a home or building. This is also referred to as behind-the-meter (BTM) generation [101]. The recent update of net metering policies allow generation sources to be connected to more than one meter or property. This led to more NEM types and policies.
- Aggregate net metering (ANM) or NEM aggregation (NEMA) is a modified version
  of conventional NEM that enables a customer with multiple meters to offset electrical
  uses from his electrical meters for the purpose of NEM. ANM is supported by 17 states.
  ANM criteria varies regarding technology type, customer type, RES used, and the
  distance between the meters and source.
- Virtual net metering (VNM) or virtual net energy metering (VNEM) refers to a tariff arrangement that allows a customer with multi-meter properties to assign their energy credits to the tenants residing in his property. This allows customer niches who cannot afford solar power systems of their own to be benefitted from net metering [102]. Currently, only 25 states across the U.S. offer VNM. As of 2019, the total number of customers benefiting from NEM for virtual PV (under 1 MW) is 18,576, and, for virtual PV (1 MW and over), it is 8125.
- Remote Net Metering (RNM) is a system which allows farms and non-residential owners to gather the excess net metering credits from multiple generating equipment

in one location and credit it to other electric accounts owned by them. The account to which the RES is connected is called the host account. The account(s) that will receive the excess net metering credits are called the satellite account(s). Residential customers cannot take advantage of RNM as the host site, but a satellite account may be a residential account [103]. Until 2011, New York was the only state to implement RNM. Recently, in May 2018, New Jersey also passed an RMN bill.

The U.S. is the pioneer of NEM and the first country to implement it as a method to incentivize more integration of solar and wind into the electricity mix. As of 2021, 39 states and Washington, DC have mandated NEM rules for at least some utilities, and 8 states have alternative DG compensation mandates [85]. However, it is unlikely that all utilities actually compensate at full retail rates. Eligible generation sources for NEM vary across the states. With the massive uptake of solar in recent decades, state NEM policies have been erratic and uncertain in the face of adversities caused by utilities and regulators. Utilities have been trying aggressively to dismiss or limit state NEM policies by creating numerous regulatory, technical, and business hurdles. Many states that hit their DG solar caps refuse to mandate NEM facilities for new solar customers, while other states disregard the notion of NEM entirely. Lastly, certain states are renewing their state policies or offering alternative incentives, such as smart successor programs, to strike a balance between utility and solar DG in order to keep the trend of PV installations growing. Based on the NEM policies available, the 50 states have been categorized into three groups in Table 6. This gives an overview of the relative stance of a state's potential for new solar DG motivated by incentives. Typically, the best NEM/alternative state policies mandate retail rates for all utilities, the limited NEM/alternative state policies do not mandate such policies on utilities but still provide close to retail rates for surplus energy, and, finally, poor NEM/alternative policies give utilities the liberty of setting the rates and usually provide significantly less than retail prices.

Table 6. Current net metering policies adopted by state.

Net Metering Incentives	States
Best	California, Colorado, Connecticut, Delaware, Illinois, Iowa, Maine, Mas- sachusetts, Minnesota, New Hampshire, New Jersey, New Mexico, New York, Oregon, Pennsylvania, South Carolina, Vermont, Washington, West Virginia, Wyoming.
Limited	Alaska, Arizona, Arkansas, Florida, Hawaii, Maryland, Missouri, Mon- tana, Nebraska, Nevada, North Carolina, North Dakota, Ohio, Rhode Island, South Carolina, Texas, Utah, Wisconsin.
Poor or Zero	Alabama, Georgia, Idaho, Indiana, Kansas, Kentucky, Louisiana, Michi- gan, Mississippi, Oklahoma, South Dakota, Tennessee.

States, such as California, Florida, Massachusetts, Virginia, and North Carolina, imposed superior NEM programs which resulted in major residential PV installments in recent years. New Hampshire, Connecticut, Arkansas, Illinois, and Minnesota are rising states that came back with strong NEM or successor policies after phasing out. Many states do not mandate NEM or replace it with much lower successor tariffs. Arizona, Kentucky, Indiana, Michigan, and Louisiana fall short in providing strong NEM or alternative policies that drive the adaptation of solar. States that are constantly working to improve the existing or phased out NEM policies are expected to see the largest residential and commercial solar growth as investors will rush to reap the benefits of solar before it catches up with fossil fuels. However, it is expected that, once solar saturates the energy mix, NEM policies will eventually be laid off. When that happens, the next best option for solar owners will be to integrate storage with their solar power systems. Up to 2019, the number of people benefiting from NEM for PV are: 2,283,702 (residential), 86,552 (commercial), and 6499 (industrial).

# 7.6. Energy Storage Systems

Intermittency is the biggest drawback of solar as an electricity source. As mentioned previously, one way to mitigate this is by hybridizing solar plants with other sources that complement the availability of solar power. However, this only aids utility-scale solar projects, leaving a large sector of small-scale solar vulnerable to intermittency. This led to energy storage playing a key role in the further advancement of solar as a reliable DER alongside large-scale RES. Storing solar energy refers to capturing it during hours of availability and conserving it as some other form of energy, such as chemical, mechanical, thermal, etc., which can be used later. There are mainly two types of storage technologies that are coupled with solar generators: battery energy storage (BES) for PV and TES for CSP plants.

# 7.6.1. Battery Storage for PV

Batteries are electrochemical storage systems that are most commonly used in DG solar projects. A grid-connected storage device is sometimes referred to as a DER system, also known as a distributed energy storage system (DESS). The most common BESs are Li-ion batteries that can last up to 4 h, have a small footprint, can be installed anywhere, and are rapidly declining in costs. The price of Li-ion battery packs has fallen over almost 90% from \$1183/kWh in 2010 to \$156/kWh in 2020 and is projected to continue falling to around \$100/kWh by 2023, according to Bloomberg New Energy Finance (BNEF) [104]. According to Reference [105], DC-coupled systems can yield a 40% (\$158/kW) avoided cost in 2020, whereas AC-coupled systems can avoid 30% (\$118/kW). Lead-acid, Sodium, and Nickel-based batteries are some common BESs besides Li-ion. From 2008 to 2017, the U.S. was the top user of Li-ion BES with about 1 GWh of storage, 92% of which was deployed by utilities [106]. However, the large-scale adaptation of BESs with PV plants is often very expensive and economically unfavorable. The limited deployment of utility-scale PV-plus-storage is linked to technical and economic performance metrics for such systems not being well defined.

# 7.6.2. PV & Storage Plants in the U.S.

Until recently, one of the few utility-scale PVs paired with BES in the U.S. was the 13 MW AES Lawai Solar Project in Kauai, Hawaii, which is equipped with a 100 MWh, 5-h battery storage. However, in late 2020, the 230 MW Gateway Energy Storage project in San Diego, California, became the largest operating BES in the world. Soon after that, in December 2020, the U.S. broke the record once again for the largest BES with the 300 MW/1200 MWh Moss Landing Energy Storage Facility by Vista in Monterey County, California. The good news continue as some of the biggest BESs in the world have been announced inside the U.S., such as the 135 MWh battery announced by Arizona Public Service, Apple's 240 MWh storage in California, a pair of 100 MW batteries in Mason and Williamson counties, Texas, and many more medium-scale installations. The proposed Eland Solar & Storage Centre in Mojave, California, will have 400  $MW_{AC}$  PV and 300 MW (12,000 MWh) of storage when it becomes operational. As of April 2021, the two largest BESs announced in the U.S. are the 500 MW BES expected to supply inside the Electric Reliability Council of Texas (ERCOT) and the 409 MW BES which will be added to the existing 75 MW solar plant in Tampa, the largest solar plant in Florida. According to the interconnection queue data from EIA, independent system operators (ISO) and regional transmission organizations (RTO) in the interconnection queues estimate that 25% of all proposed solar projects are combined with BESs. In California, almost 67% of solar projects are proposed as hybrids.

## 7.6.3. Storage for CSP

TES has been mentioned previously in the discussion of CSP technologies in Section 3.5. Molten salt is a popular HTF for TES in many CSP mega-projects. A suitable HTF, often thermal oils or molten salts, can store thermal energy in an insulated tank which can be reused directly for SHC, or it can be used to generate electricity by turbines. Supercritical CO<sub>2</sub> is being explored as an HTF that is able to withstand higher temperatures which can reduce the size of generating plants [107]. Solar thermal storage (STS) are TES systems where the source of heat is provided by the solar field, collecting the excess energy that is not directly converted into power for later use. So, most TES technologies have been adopted in solar applications, particularly for power production. In addition, pumped hydro storage (PHS) and compressed air energy storage (CAES) may also be a viable pair-up with CSP plants. Though the round-trip efficiency of CSP with TES can be close to 100%, much higher than any electricity storage technology, TES can only store thermal energy produced from the solar field, as opposed to other storage technologies that can store electricity produced from any source.

# 7.6.4. Incentives for Energy Storage

Storage now plays a crucial part in taking solar energy to the next level. Other than addressing intermittency, it has numerous benefits for all PV system owners. For utility-scale projects, storage can provide utility stabilization, avoid over-generation, act as a back-up during electrical disruption, reduce grid management concerns, such as the duck curve, etc. The DOE explained that solar coupled with storage can alleviate, and possibly eliminate, the risk of over-generation. For DG projects, storage can help consumers to transition towards the time of use (TOU) pricing; TOU billing system allow customers to access the power from their own PV for more hours per day. Residential adaptation of storage is growing in popularity among homeowners who are living in states with little to no NEM incentives. Storage is an excellent way to make the best out of residential PV plants by bypassing low net-metering rates of utilities and reusing stored energy from one's own PV system. Storage integration is being encouraged by the government and solar companies by offering various incentives and rebates to incentivize self-consumption. An excellent step was to extend ITC to include solar storage as a part of eligible technologies for the tax credit, as long as the battery is exclusively charged by an on-site RES, such as solar [108]. Some states have also set storage goals and offer battery rebates, such as:

- Nine states have statewide targets for energy storage deployment- Oregon (10 MWh by 2020), California (1325 MW 2020), Nevada (1 GW by 2030), New York (3 GW by 2030), Maine (400 MW by 2030), Massachusetts (1000 MWh by 2025), Connecticut (1000 MW by 2030), New Jersey (2 GW by 2030), and Virginia (3.1 GW by 2035).
- Seven states have state level incentives for energy storage. Maryland offers state tax credit. Three utilities in Arizona, Nevada and Florida rebate programs for energy storage. California, Oregon, New Jersey, and Massachusetts have state grant and rebates.
- After reaching a million solar installations in California alone by the end of 2019, the state amazed the nation again by announcing their ambitious goal of installing one million solar-charged batteries by 2025.
- One of the best battery rebates are offered by California's Self Generation Incentive Program (SGIP) which significantly lowers the installation costs of adding a home battery system.
- Maryland offers an impressive battery incentive of 30% of the cost of installing the battery in the form of tax credit, up to \$5000 for homeowners and \$75,000 for commercial property owners.
- Solar battery incentive of up to \$4000 is available in Florida on qualified home or business battery system.
- In Arizona, BES rebates of up to \$3600 are available for the customers of Salt River Project.

- NV Energy from Nevada offers up to a maximum of \$3000 for installing storage, with higher payout for ToU.
- Connecticut, Massachusetts, and Rhode Island offer the Connected Solutions battery program from National Grid.
- The SMART solar program in Massachusetts offers incentives for battery systems.

More than 25% of all the BTM solar systems will come combined with storage by 2025, a significant increase from just 5% in 2019 [109]. About 20% contracted utility-scale projects now include solar storage system as a result of the recognition of the benefits of pairing solar with storage by utility-scale markets. Over 8 GW of commissioned work includes solar storage in its projects. According to BNEF, the energy storage market will double six times between 2016 and 2030, rising to a staggering 125 GW in capacity or 305 GWh in solar generation. The U.S. is expected to lead this growth by accounting for 25% of total deployments [110].

## 7.7. Solar Cost Reduction

The increasing deployment and decreasing cost of PV panels have a strong correlation. This relationship has been following a consistent pattern, which is described by Swanson's law (an industry-specific term for Wright's law that particularly applies to solar PV), named after the American solar manufacturer Richard Swanson. Swanson's law observes a 20% reduction in the average price of PV panels every time the global manufacturing capacity doubles. At present rates, costs go down 75% about every 10 years [111]. When solar panels were first deployed, it was far from affordable, costing \$1865/W in current price [112]. Between 2010 and 2020, there has been an 82% declination in the global utility-scale PV installation cost from around \$0.36 to \$0.94/kWh, the highest cost decline percentage among all RESs in less than a decade, which can be observed from Figure 25. The global average LCOE of CSP fell about 47% in the same period to 0.27/kWh [113]. Solar becoming more cost-effective has led to it directly competing with traditional generation sources. Taking into account the current growth rate of solar, extrapolations of Swanson's law estimates that solar panels can provide the world's current generation capacity at lower costs compared to fossil fuels, that, too, with a net gain in jobs by 2032 [114].



**Figure 25.** Exponential cost reduction with the increased installed solar capacity. The phenomenon can be explained through Swanson's law, which establishes a relation between cost reduction and global manufacturing capacity [115].

Grid parity is measured by the LCOE, which is a parameter to estimate the revenue needed to construct and operate a generator over a defined cost recovery period. The goal is to minimize cost of solar electricity until it falls into the territory of grid parity—below the LCOE for fossil-fired power and the price of wholesale power. LCOE is used to get a comparative overview of different electricity generation sources on a consistent basis. The general formula for calculating LCOE [116] is provided in Equation (5).

$$LCOE = \frac{Lifecycle\ cost\ (\$)}{Lifetime\ Energy\ Production\ (kWh)}.$$
(5)

In the U.S., the cost of installing solar power systems has cut back by more than 70% over the last decade. The price of an average residential system has decreased from \$40,000 in 2010 to about \$20,000 in 2020, while recent utility-scale prices span from \$16 to \$35/MWh. The price of crystalline Si has dropped down from \$76.67/W in 1977 to \$0.38/W in 2019 [117]. Between 2010 and 2016, California accounted for 40% of the global cost decline in the median residential PV system. At present, funds and incentives are being offered to aid the reduction of cost of solar power. The DOE announced a target to minimize the cost of solar electricity by 60% within this decade and \$128 million in funding initiatives to lower costs, increase efficiency, and ensure rapid deployment of solar technologies. The DOE (SETO) has recently announced the U.S.'s cost targets for solar energy:

- \$0.05/kWh for residential PV by 2030.
- \$0.04/kWh for commercial PV by 2030.
- \$0.03/kWh for 2025 and \$0.02/kWh by 2030.
- \$0.05/kWh for CSP plants by 2025.

For comparison, the current average retail price of electricity in the U.S. is \$0.11/kWh.

## 7.8. Solar Panel Manufacturing

US scientists and engineers have always led the way in solar innovation. The PV technology was invented in the U.S., first deployed in the U.S., and the most efficient solar cell technology to date has been developed in the U.S. However, the U.S. is struggling in the solar panel manufacturing market. Only one of the world's 10 largest makers of solar cells is American while seven of the top 11 solar panel manufacturers are now in mainland China. At present, China's global share of the solar cell manufacturing market is 80%. The U.S. was the largest importer of solar panels from China, until the U.S. imposed heavy tariffs on solar panels imported from China with the aim to incentivize domestic manufacturing. This drastically reduced the Chinese market in the U.S., while countries, such as Taiwan, and domestic manufacturers, such as Tesla, started setting up factories inside the U.S. In 2018, a further 30% tariff was imposed on all imported solar modules. Despite the target of increasing domestic manufactures, they fall short of the exponentially growing demand. The tariffs also dulled solar cost reductions in the U.S. compared to the steeper decreases observed in the global markets. Moreover, an analysis from SEIA found that the U.S. forfeited almost 62,000 jobs, \$19 billion in investment, and significant environmental impacts that would have resulted from additional the solar deployments had the tariffs not been imposed [118].

Tariffs have had an indirect negative impact on the cost of solar modules, making them more expensive in the U.S. The local cost is around 79% higher than in major EU solar markets, 75% higher compared to Japan, and 85% higher compared to in China. Without the tariffs, the U.S. solar power system prices could be approximately 30% lower. With respect to the rest of the world, the U.S. share of solar PV module manufacturing has dropped to 1% [119]. Further impositions or expansions of tariffs could increase the price of solar modules inside the U.S. even more. Module imports from China have been on the rise since 2019, despite the triple tariffs currently imposed. Similar to mandatory NEM

policies, the import tariffs also have counterproductive results. So, it is very important for the government to carefully assess the long-term effects of their decisions.

A strong domestic solar manufacturing sector and supply chain supports the U.S. economy while meeting the rising domestic and global demand for affordable solar panels. According to SETO, the U.S. PV manufacturing industry has the capacity to produce enough PV modules to meet half of its domestic demand. SETO finances solar manufacturing research initiatives that will improve domestic manufacturing competitiveness and assist the U.S. to compete on a global scale by building commercialization paths for disruptive solar innovation. SETO's manufacturing funding programs include:

- Revitalizing the U.S. solar manufacturing industry through a series of contests with cash prizes ("American-Made Solar Prize" worth \$3 million)
- To encourage investments, patents, publications, and jobs, a funding program for developing prototypes to a pre-commercial level and removing business/market risks has been established (2020).
- Funding initiative for the development of resilient prototypes capable of demonstrating critical functions of final goods and attracting private-sector investment (2019).
- Funding program to research and test novel strategies to integrate emerging technology into the solar market quicker (2019).
- Small business innovation research and small business technology transfer to encourage U.S.-based small businesses to engage in high-risk, innovative research and technology development with the potential for commercialization in the future.
- DOE technology commercialization fund for R&D to develop promising energy technologies with high impact potential.

It should be kept in mind that the U.S. is already leading the innovation sector while countries like China and Japan are grabbing the global commercial market and establishing a supply chain. So, alongside funding that is heavily inclined towards R&D, comprehensive and concrete industrial development strategies should be adopted which focuses on commercialization of the existing technology.

#### 7.9. Socio-Economic Development

Due to the unemployment problem resulting from post-COVID economic descent and production management setback in many countries, social or socio-economic development can be acknowledged as one of the most important factors of sustainable development. The increasing solar market has proven to be an incubator for solar related job growth throughout the U.S. In the last ten years, there has been an astonishing 167% increase in the solar workforce [120]. In the last 5 years, the percentage was 44%, five times faster than the job growth rate in the overall U.S. economy [121]. As of 2019, there are 249,983 jobs created by the solar industry, with installation being the major (67%) job sector, followed by manufacturing (14%), sales and distribution (11%), and operation and maintenance (4%).

Between 2009 to 2019, tech giants, such as Apple, Amazon, Walmart, and Google, had a solar growth percentage of 39,830%, 36,900%, 2,316%, and 12,810%, respectively, which created a large number of job opportunities [122]. The solar industry also has a diverse workforce, as women constitute 26% of it. Moreover, 8% of solar jobs are held by veterans, a higher proportion than in any other sector of the overall economy. California is the largest solar job market employing almost 69,000 people. Florida, Texas, Massachusetts, and New York each have over 10,000 solar jobs. The job market is expected to grow exponentially in order to meet the most recent 2035 clean energy target. According to the U.S. Bureau of Labor Statistics, solar PV installer will be the third highest growing occupation between 2019 to 2029 with a rate of 51% in the U.S. [123]. An analysis by SEIA estimates that the solar industry in the U.S. will occupy 900,000 workers by 2035. The upcoming opportunities regarding of solar jobs will create more economic stability, and economic stability will create even more jobs. According to the IRENA job database, solar PV has the highest employment rate worldwide and the second highest employment in the U.S. among RESs. Apart from creating new jobs, there are several other key benefits of solar energy in socio-economic development. Bringing electricity to the rural areas, islands, or mountains, where construction of a functional power station may not be feasible is one of the biggest aspects of solar applications. Other than that, lowering the cost of electricity by creating competition in the electricity market, decentralizing utility dependence, and generating at the consumer end which reduces the transmission and distribution cost are also some of the numerous benefits of adopting solar.

## 7.10. Greenhouse Gas Abatement

One of the main reasons countries started shifting towards RESs to begin with was to decarbonize their electricity mix. Greenhouse gas (GHG), particularly CO<sub>2</sub> emissions, are the primary cause of climate change and global warming. Generation from RESs, such as solar, wind, and hydro, significantly reduces the amount of GHG compared to the same energy obtained through the combustion of fossil fuels [124]. According to EIA, approximately 1.72 billion metric tons of CO2 was released into the atmosphere from electricity generation in 2019, in particular, an average of 0.92 lb/kWh CO<sub>2</sub> emission from the power sector alone. Electricity generation accounted for 28% of total carbon emissions in the U.S., being the second largest emitter of GHG, following the transportation sector. In order to address the alarmingly rising rate of  $CO_2$  emission, on 12 December 2015, 200 countries signed the Paris agreement, whose long-term temperature goal is to limit the increase in global average temperature under 2 °C (3.6 °F) above the pre-industrial levels; and to make an effort to limit the increase within 1.5 °C (2.7 °F) [125]. In 2014, the U.S. pledged to reduce GHG emissions 26–28% below the 2005 level by the year 2025 [126]. Trying to meet the targets set by the Paris agreement was one of the main drives behind adopting solar, which will play a major role in decarbonizing the electricity mix. It is of key concern to the U.S. as it is the second largest emitter of  $CO_2$  in the world, following China.

It can be observed from Figure 26 that Spain has achieved exemplary reductions in their power sector emissions during 2019–2021. This coincides with their record installation of solar, where they added more solar power in the month of June 2019 alone, compared to the last seven years. This played a major role in reducing the emissions by 40%, more than four times that of the U.S. and the UK [127]. The steep fall in Spain's carbon reduction started in 2008, the same year they added five times more solar plants than what was installed in 2007 [128,129]. The drastic decarbonization of their power sector corresponded to a 14.1% decrease in their total CO<sub>2</sub> emissions in 2020. As a result, Spain experienced the highest reductions in their total  $CO_2$  emissions, indicating the significant impact of the power sector on the total emissions of a country. In the UK, U.S., Japan, France, and other countries, overall emissions reduced more than power sector emissions, mainly because of the transportation sector slowdown due to COVID-19 lockdown. Although China and India's emissions increased, it progressed much slower than what was previously calculated [130]. This might be due to major solar additions they have been making in recent years, along with several other factors. Increased power related emission from Russia also coincides with the country's passive solar additions. Brazil's case is an exception here, as the country has seen solar growth recently, but the increase in emission spike was mainly driven by excessive deforestation in the Amazon forest [131]. The U.S. experienced a 6.9% reduction in their power sector emissions corresponding to an 8.2% reduction in their overall emissions, securing third position for percentage of CO<sub>2</sub> emission reduction between 2019 and 2021.



Figure 26. Global variation in CO<sub>2</sub> emissions from the power sector between January 2019 and March 2021 [132].

The U.S.'s total energy-related CO<sub>2</sub> emissions have gone down 15% since their 2007 peak, and the power sector, in particular, has witnessed a 33% reduction in the same time frame. For many years the power sector was the largest emitter of CO<sub>2</sub>, but the adoption of cleaner energy sources led to the gradual decrease in emissions. For the first time in 2016, the power sector dropped to second position and transportation became the largest sector for  $CO_2$  emissions marking a crowning achievement for RESs [133]. The power sector emitted around 1.9 billion tons of CO2 in 2017, compared to 2.6 billion tons in 2005 indicating a 28% reduction in a decade. This coincides with the reduction of coal's percentage in the electricity mix from 50% to 30% and the increase of RESs, such as solar and wind, from 2% to 10%, which also took place between 2005 and 2017 [126]. Unlike the desired continuous reduction, the CO<sub>2</sub> emission curve fluctuates each year. This is due to the fact that the power sector is the only sector that managed a momentum shift towards RESs with a sharp increase in wind and solar generation. It is observable from Figure 27 that, compared to the industries, transportation, residential, and commercial sectors, the emissions from the electric power sector achieved a significant reduction in CO<sub>2</sub> equivalent GHG emissions.



**Figure 27.** U.S.  $CO_2$  emissions by different sectors. Power sector was the largest emitter of  $CO_2$ , but mass uptake of RESs, such as wind and solar, resulted a gradual reduction of emission.

The U.S.'s current 108.7  $GW_{dc}$  (2021) solar capacity is enough to supply more than 18.9 million American homes and offset more than 110 million metric tons of CO<sub>2</sub> emissions. PV electricity emits 96–98% less GHGs than electricity generated from 100% coal [134]. Estimations state that it would require 2 billion trees to store the amount of carbon emissions mitigated by the U.S. solar industry [135]. At present, it is estimated that the U.S. is on track to reduce emissions by 17% within 2025, implying that there is still a large gap in reaching the target set during the Paris agreement [136]. Figure 28 demonstrates an interesting fact that the increment in the annual solar additions in the U.S. is coincided by a decrease in both the total CO<sub>2</sub> emission (such as transportation sector adopting electric vehicles and industries adopting SHIP), electricity generation will be the only sector that directly contributes to reduction of GHG and reaching the Paris agreement target. The only way to decarbonize the electricity mix is by introducing more solar power, whose rise directly coincides with the reduction of CO<sub>2</sub> from the power generation sector, along with other RESs.



**Figure 28.** Correlation between  $CO_2$  emission and solar deployment in the U.S. It is evident that clean energy sources, such as solar, can aid to decarbonizing the power sector, thus reducing overall emissions or at least decelerating the upward trend [133].

#### 7.11. Land Requirements

Solar energy comes with massive land requirements, as well as capital cost. As mentioned previously, utility-scale solar plant may require between 5 and 10 acres/MW (0.02–0.40 sq km/MW), depending on the type of technology. The largest solar power plant in the U.S., Solar Star, has around 1.7 million solar panels on over 13 square kilometers (sq km) of land located in California. That is nearly the size of 142 football fields, and the total project cost was \$1 billion. The Topaz solar farm, the second largest solar farm in the U.S., located in California, sits on more than 15 sq km of land costing \$2.4 billion. The Ivanpah Solar is the third-largest, sitting on an area of 14 sq km consisting of 300,000 solar panels and costing \$2.2 billion. The Agua Caliente Solar Project in Arizona cost \$1.8 billion and spans across 9.7 sq km. At 2.8 acres per GWh, 11.2 million acres or 5000 sq km would be required to power the entire U.S. with solar power. Although this appears as an insanely large area, this requirement could be met in numerous ways, including the use of disturbed or contaminated lands unsuitable for other purposes. Utility-scale solar plants are usually located in deserts and uninhabited areas. On top of that, a study by NREL concluded that, if rooftop PV is installed on all of the suitable commercial and residential rooftops, it would yield 1118 GW of solar power capacity. This means rooftops PVs alone (assumed solar panel efficiency of 16%) can power 39% of the total power used by the U.S. [137]. There are several studies outlining the land requirement and cost of solar projects in the U.S. [21,22,25,138].

## 8. Grid Integration of Solar Energy

If solar is to play its expected role in the energy mix, there is no alternative to connecting it to the utility grid. This comes with many challenges that need to be carefully assessed before injecting solar into grids that carry multiple generation sources. The stochastic nature of solar energy makes it a challenging task for grid integration. Solar electricity has power quality issues, such as frequency and voltage fluctuations, harmonic oscillation, and inconsistent power outputs (short-term and seasonal variation). Moreover, it needs an additional energy storage system for ancillary services, as well as protective devices for surges and current faults [139]. It also requires optimal placing and maximum power point tracking (MPPT) to ensure the system is operating at maximum efficiency. Designed for unidirectional flow, major modifications are needed in conventional grids to accommodate reverse power flow and create a bidirectional system. Most importantly, the protection and safety system must be robust to ensure the safety of the grid, as well as utility men who work with transmission lines. Relay desensitization, protection coordination, unintentional islanding, and increased wear and tear of equipment are some of the problems that need to be thoroughly assessed before proceeding with grid integration. Figure 29 portrays a basic schematic diagram of a grid integrated PV system involving an energy storage system and smart metering system. In case of CSP plants, the output power is readily produced as AC, but the output power must be synchronized to the grid before grid integration.

Currently, interconnection rules mostly encompass three types of interconnections: net metering, self-generation (non-exporting), and full-scale energy export. However, microgrids are a different type of interconnection which enables both grid-connected and islanded-mode operations. Microgrids have been discussed in Section 10 of this paper.



**Figure 29.** Basic model for grid integration of solar PV and energy storage system involving a smart metering system.

## Interconnection Policies

Interconnection is a critical process that needs to be backed by technical advancements, as well as strong policies facilitating the smooth integration of DERs. There are generally two objectives to interconnection rules: set and evaluate technical standards that ensure reliability, safety, and quality of the power system, and standard contractual agreements stipulating operational and cost responsibilities between DG owners and utility operators. The absence of interconnection standards has been one of the primary barriers to the deployment of DG in the U.S. Starting in the early 2000s, interconnection standards were governed by federal policy and overseen by the Federal Energy Regulatory Commission (FERC).

One of the technical standards is the PV hosting capacity, which is described as the maximum amount of PV generation that can be interconnected without imposing any changes to the existing infrastructure resulting in unacceptable power quality. It is a measure of the limit of PV generation that can be easily integrated and can be subjected to accelerated approval, but it is not a hard constraint that cannot be exceeded. Exceeding the hosting capacity require additional equipment and more in-depth analysis [140]. Calculating the hosting capacity is challenging as it is highly location dependent, varies with time and advancements in technology; and the absence of such data decelerates the entire interconnection process. In 2020, California, Connecticut, Maryland, Massachusetts, New York, Rhode Island, and Vermont created legal requirements that mandate utilities to share their data through hosting capacity analysis maps. These maps show where solar can be added on a distribution network without sustaining grid expenses. As of now, Alaska is the only state that does not have any state-level interconnection policies [85]. The particular case of Hawaii previously faced many difficulties while integrating mass solar deployments, due to the exponential growth of solar in Hawaii in early 2010s. Hawaii is not a significant producer of any fossil fuel, and it does not border any state, resulting in the highest cost of electricity in the U.S. and double the cost of the second highest rates in Alaska. On the other hand, it has one of the best solar resources in the country, making solar really extremely favorable. Hawaii started seeing so much residential PV installations that some utilities were forced to limit interconnection of RESs due to technical and financial difficulties. This scenario of limiting interconnection is highly unlikely for other states in the U.S. because all states share borders with other states that allow for import and

export of surplus energy and grid flexibility that enables routing surplus solar to areas that need it, unlike Hawaii, which is completely electrically isolated from the mainland. The limited interconnection ability of Hawaii's low inertia grids are being tackled by increased solar+storage projects that enable the island to be self-producers and self-consumers of their own electricity. This resulted in Hawaii having one of the highest solar penetrations in the U.S. The same mechanism of hybrid solar+storage can also be applied to electrically isolated islands and territories.

# 9. Challenges of Solar Technologies and Proposed Solutions

Despite the numerous benefits of solar energy, such as abundant supply, low lifetime costs, absence of harmful emissions, and so on, there are also some challenges that impede the growth of solar energy technologies. Some of such challenges are described in Table 7, and their impacts are scaled on a score of 1 to 5. Alongside, the probable solutions to those challenges are also included in the table, with similar scores of the level of the impact of the solution. From 1 through 5, the scores indicate very low, low, moderate, high, and very high impact, respectively. The scoring criterion for the challenges considered several factors. The consideration included whether it is an ongoing challenge directly impeding deployment or an immediate threat, or whether it might cause problems in the distant future, how much it hampers the efficiency or reliability, and how severe the long time consequences are. The solutions are also scored in a similar manner, taking into consideration the extent to which the problem can be mitigated, and the pace of ongoing research which can come up with better alternatives in the near future. In addition, the technological readiness level (TRL) of each challenge is assigned, based on the maturity of the suggested solution.

Challenge	Impact of the Challenge	Level of Impact	Solution	Level of Impact	TRL of Solu- tion
Land	Solar power requires a large land area for considerable energy outputs. So, utility-scale solar farms are located in the desert or uninhabited areas, or result in loss of cultivable land.	3	Many alternatives to large-scale solar plants can be implemented, such as FPV, rooftop PV and SHC, transpired collectors, solar wall, flexible solar panels, road solar, etc.	4	9
requirements [141]	In the U.S., an area larger than Texas will be impacted by energy developments, including solar by 2040.	3	In 2050, ground-based solar technologies require a maximum land area equivalent to 0.5% of the contiguous U.S. surface area. This requirement could be met in numerous ways, including the use of disturbed or contaminated lands unsuitable for other purposes.	5	8
	The average lifespan of most solar panels is 25 years. Less than 11% of a panel is salvageable as metals, and, currently, there is limited research on the EOL disposal.	3	The positive panel terminals are made of silver, which has recycling value, and there are numerous other valuable elements, including indium, gallium, and germanium within the components.	3	5
End of life (EOL) disposal [142–144]	Harmful emission and release of solvent during the recycling process	2	Using activated carbon fiber adsorption as a condensation device and a de-watering and refining device, the organic gas produced can be transformed into a highly pure liquid organic solvent at the end of recycling.	5	3
	By 2035, the discarded panels will outweigh new units by a factor of 2.56, and cost of recycling a single PV panel by then will reach \$20–30, which would increase the LCOE of PV by a factor 4.	5	None are taking responsibility of setting up recycling plans for solar wastes. First Solar is the only U.S. panel manufacturer with a running recycling initiative. Government subsidies are crucial to quickly develop capacity commensurate to the magnitude of the looming waste problem.	3	1
	Europe is on its way to deploying a successful recycling program, but, in the U.S., it is an unregulated market. Similar legislation is underway in Japan, India, and Australia.	5	SEIA has a national recycling program, in partnership with First Solar, Cleanlites Recycling, ECS Refining, and Green Century Recycling. Policies, such as the Extended Producer Responsibility (EPR), need to be implemented hold PV manufacturers responsible for the lifecycle impacts of their products. Takeback programs are also useful.	3	6
Manufacturing	Though solar energy generation does not emit CO <sub>2</sub> , the process manufacturing, mining, and industrial process to make conversion technologies still produce some CO <sub>2</sub> .	2	Although emissions from solar panel production is comparatively low, it can be addressed by low concentration carbon capture methods, such as sorbent-based adsorption, aqueous amine, etc.	4	8
waste materials [143,145]	During the process of polycrystalline production, 68% of the Si feedstock is lost during the production steps in the form of Si waste, such as liquid Si tetra-chloride, which is a harmful byproduct.	2	The sludge is potential Si feedstock, since the quality of this Si at the beginning was up to the standards of solar panel requirements. SoG Si feedstock can be produced using pre-purification techniques. Plasma purification along with slagging, acid leaching, alloying process, directional solidification, and gas blowing can be starting points for recycling byproducts.	5	3
Endangering biodiversity [146,147]	Mega-projects, such as the one in Mojave Desert, have caused destruction and fragmentation of natural habitat to more than 29 species and subspecies, and may increase the possibility of fires, endangering more wildlife.	3	Mitigation-driven translocations on sensitive species can temporarily solve endangered individuals. However, long-term effectiveness can be assured if proper monitoring and breeding can be assured at the site of relocation.	5	5

# Table 7. Challenges and probable solutions of solar technologies.

Challenge	Impact of the Challenge	Level of Impact	Solution	Level of Impact	TRL of Solu- tion
Low energy return	EROI is very low for solar, typically in the range of 4–10%.		Cheaper solar panels should be made available either by increasing domestic production or easing tariffs on imported panels.	5	6
on investment (EORI) [148,149]			Incentives and policies, such as ITC, RPS, CSI, MACRS, etc., are advancing the solar industry by eliminating cost limitations. Research funding also helps lower the solar cost.	4	8
Intermittency	Intermittency causes uncertainty in generation. Utilities generate and purchase power according to the load forecasts. Predictability of energy generation is necessary to prevent blackouts or over-generation.	5	Usage of various sophisticated forecasting methods will help the grid operators to better schedule for extreme high or low generation. Sky images, satellite images, hourly forecasting using time series can be used to predict the variables for the next few hours.	4	7
	Stochastic generation nature resulting in inconsistent power outputs.	5	Power output irregularity can be addressed by integrating energy storage technologies. Storage price has started going down as the market is becoming more competitive.	4	9
Unavailability	Solar energy is completely unavailable at night and can be obstructed by overcast clouds.	5	TES and hybrid plants best compensate the unavailable hours of solar. Off-grid corporate buildings that mostly consumes during the day can best utilize solar in this regard.	5	6
Shading	Shading of PV panels by nearby tall objects, self-shading, or panel disorientation can significantly lower the output power.	5	Setting the PV panel in a place with adequate exposure to sunlight, and possibly add a tracking mechanism to follow the sun.	5	8
Low efficiency [34,150]	Modern PV cells are only 13–16% efficient.	3	Modern solar cells have reached efficiencies approaching 50%. Methods, such as enhancing low-bandgap polymer solar cells by using alkane dithiols, and photon induced transitions at intermediate levels, are being studies. The next step is commercialization.	4	5
HTF water in deserts [151]	CSP using wet cooling consumes 2x more water per MWh than fossil fuels, thermal/biomass/geothermal, and 4x more than NGCC or ISCC power plants.	3	Dry cooling can reduce water consumption by 10x but requires a reduction in energy generation. Freshwater footprint can be reduced by utilizing alternative water sources, such as water with impaired quality or saline water.	5	4
Dust accumulation [152,153]	Dust accumulation on curved mirrors or solar collectors installed at different slopes is a big issue for CSP, even more challenging in desert areas with water scarcity.	3	Hydrophobic coatings, such as poly (p-phenylene butylene), on the surface of the mirrors use the concept of lotus effect for self-cleaning and anti-contamination. Hydrophobic functionalized nano-silica materials and polymer binders have been assessed for low cost anti-dust coating.	5	2

Table 7. Cont.

Table 7. Cont.					
Challenge	Impact of the Challenge	Level of Impact	Solution	Level of Impact	TRL of Solu- tion
FPV impact on water body [154,155]	Heat dissipation from cables and components may hamper fauna and flora, water resource usage, depletion, or pollution.	2	FPVs can function as artificial reef for many small species to settle on, or as stepping stones to colonize expanded areas or as breeding ground. They are also used by fish living in larger water columns. If long term harmful effects are confirmed, then relocation might be the best option.	5	4
PV heat island effect [156]	Large-scale PV plants are responsible for creating a heat island by raising the surrounding air temperature and increasing heat absorption and re-radiation.	3	Targeted revegetation could reintroduce latent energy fluxes.	4	2
Threatened resilience and reliability	If solar energy, which is an inertia-less source, dominates the energy mix, the grid resilience and reliability might be threatened.	5	A complementing hybrid energy mix is necessary wherein other RESs are equally contributing. Energy storage systems, particularly chemical energy storage, may also be a feasible solution to enhance the grid flexibility.	5	9

#### 10. Alternative Applications of Solar Energy

So far, this paper has addressed applications of solar energy in the electricity mix and SHC sector. These are the most common and conventional applications of solar at present; however, solar has the potential to achieve much more. Keeping up with the new technologies being designed every year, the integration of solar is also fast adapting to the changes. Some alternative applications of solar are presented briefly in this section.

#### 10.1. Transportation Sector

The upcoming market of EV and plug-in hybrid vehicles (PHV) have opened up opportunities to incorporate solar into both the running and charging of such vehicles. Incorporating solar power into mobile vehicles can be unprecedented application of solar which other RESs, such as wind and hydro, are not applicable for, since solar energy is available almost everywhere and capable of small-scale integration. This specific sector will play a role in directly reducing the emission from the transportation sector, the largest emitter and slowest progressor at present. Solar can be integrated into a myriad of automobile applications, such as car-roof PV, high performance solar-engine car, circulating or storing surplus solar energy specially during parking mode, etc. [157]. Research by Masuda et al. exclaimed the possibility of cars covering less than 30 km per day can rely on solar energy without charging with electricity and gas [158]. Charging of EV and PHV using solar energy is being looked into more aggressively, as a significant objective of EV is reducing the emissions from the transportation sector, the charging system should also consume electricity that is not being fueled by emissive sources.

#### 10.2. Agriculture Sector

Agricultural sector is one of the most primitive sectors that can use simple technologies to integrate solar energy to assist in improving the product quality and quantity and make more efficient use of resources. Solar water pumping systems, such as solar irrigation system [159], and solar thermal pumping system have no cost for fuel, no noise, and no pollution, and have relatively simple designs, which have been reviewed in Reference [160]. Storage and refrigeration play a crucial role in maintaining quality of agricultural produce. Some of the applications of solar in the cooling and refrigeration of agriculture are PV refrigerator, solar thermal refrigerator, thermo-mechanical refrigerator, and sorption refrigerators. These also help to mitigate the harmful GHG emissions of refrigerants that are depleting the ozone layer [160]. Drying is another preservation method which is fairly common in the countryside with conventional dehydration methods. Improved solar dryers can facilitate drying industrial quantities in a shorter time span while preserving organoleptic characteristics and nutritional quality. Bennamoun et al. presented a solar batch dryer for agricultural produce and summarized other works in the field [161]. The U.S. Department of Agriculture (USDA) has published an overview of the solar technologies and policies that are currently deployed in the U.S. [162]. Widespread utilization of solar in such sectors can prove to be more efficient and environment-friendly than the conventional methods.

#### 10.3. Water Desalination

By 2050, the exponential rise in freshwater demand and consumption is projected to exceed the safe limit for Earth's stability. A survey conducted by the U.S. Government Accountability Office stated that 42 out of 50 state water managers expect freshwater shortages in the following 10–20 years under normal weather conditions. Utilization of the sea as a viable source of water can help to meet the expected water demand [163]. However, seawater is not widely adopted as a water source for portable water in the U.S. The primary reason behind this is the enormous energy consumption per unit of product water required to process seawater. Desalination of seawater has been one of the most expensive methods of producing drinkable water. The U.S. started constructing desalination plants in the 1960s to simultaneously meet the rising demand of water and tackle the steady decline in surface water and groundwater resources. The U.S. is currently among the top contenders

in the desalination market with daily production capacity of 2 billion gallons per day and around 2000 operational desalination plants. Each year, an estimated 8.78 million tons of oil is globally used to produce 1 million m<sup>3</sup> of fresh water per day through desalination process [164]. So, utilizing RESs, such as solar, can greatly aid the desalination process while reducing the carbon footprints associated with it. Studies suggest that solar-assisted desalination is becoming increasingly viable, despite its high capital cost [164]. Between 1974 and 2009, 131 RES desalination plants were operational globally, out of which 36% was powered by STE and 34% by PV [165]. C. Li et al. [164] present a concise summary of the solar desalination processes that are currently in use. Other solar technologies, such as solar collectors (ETC, PTC, CPC, FPC, SD, LFR, ST) or solar ponds, can be utilized to produce electricity, as well as heat, and, thus, combined with most types of desalination technology.

#### 10.4. Microgrid and Load Balancing

The most advanced form of PV grid integration is the implementation of microgrids [166]. Microgrids combine PV systems with other DERs (such as DG, storage, controllable loads, etc.). They are considered to be the building blocks of smart grids and come with benefits, such as system flexibility, increased electricity integration through DER and storage, support grid stability (voltage or frequency), and uninterrupted supply to isolated loads, in case of grid failure. During grid-tied mode, it operates in parallel with the grid and acts as a self-consumption unit, exporting only the surplus energy. In the case of islanded mode, the PV system is completely detached from the grid, and its main function is to control the local frequency and voltage parameters. Microgrids can be AC or DC, incorporating AC, DC, and hybrid control strategies. To integrate solar PV to DC power lines or DC microgrids, DC-DC converters are required instead of DC-AC converters. An in-depth analysis of DC-DC converters has been presented in Reference [167] which reviews different DC-DC converter topologies. Microgrids are a modern concept, so there are a number of challenges that are still not fully addressed. Supply-demand mismatch in conventional grids has been mitigated by load curtailment techniques, such as demand response. However, there are a number of other net-load balancing components in smart grids with high penetration of PV, which cannot be mitigated using simple demand response techniques [168]. Mechanisms, such as voltage var optimization (VVO), are required to tackle the over-generation of solar, which is occurring more frequently in California. A net-load balancing framework that can address both supply and demand curtailment at less computational cost compared to VVO has been proposed in Reference [168].

#### 11. Outcome of the Study

This is a complete review on the particularities of the solar power industry in the U.S., the second largest solar market in the world. This paper is a compilation of statistical and empirical information of the U.S. solar market, its trends, available incentives and policies, and future growth projections which will work as a useful tool for anyone who is interested in the booming market of solar energy. It will also work as a compact overview of the U.S. solar industry for conducting comparison analyses with other countries. To summarize, the outcomes of this review paper are delineated as follows.

#### 11.1. General Outcomes

- Solar energy has been the fastest growing RES for 4 consecutive years and is expected to account for 48% of global RE generation in 2050.
- At present, the U.S. has 108.7 GW<sub>dc</sub> (2021) of installed solar capacity, making it the second largest producer of solar in the world. However, the local solar penetration is only 3% of the total electricity mix.
- California is the solar capital of the U.S. with 31 GW of solar capacity installed, which accounts for 33% of the U.S.'s total solar installations, three times more than the second highest state, Texas.

- Federal policies, such as the ITC, MACRS, and the Sunshot initiative, are key drivers of the solar industry.
- State-level policies can also significantly boost regional solar adoption, such as the case in California's Million Solar Roof Initiative.
- The average cost of installing a residential PV system has gone down from \$40,000 to \$20,000 at present.
- The solar industry will employ close to a million people on its way to reach the 2035 target.

# 11.2. Technical Outcomes

- The major solar harnessing technologies are PV, CSP, and SHC. Applications range from residential to utility-scale, off-grid, FPV, and expand to numerous alternative applications.
- The CSP market of the U.S. is not living up to its legacy. However, the situation might change, depending on the successful deployment of CSP plants that have been announced recently.
- A large portion of the niche markets, such as FPV, SHC, SWHS, and SHIP, are still unexplored for solar applications.
- HPP is one of the best ways to increase a plant's reliability and incorporating multiple RESs. In the future, RESs will operate complementing each other in HPPs to ensure seamless power supply.
- Storage will play the next big role in solar uptake. Solar incentives are being expanded to include storage as a qualifying technology.
- The main purpose of shifting towards RES is reducing harmful emissions to comply with the target set by the Paris Agreement. Solar energy has shown positive correlation with a country's carbon emission abatement.
- Interconnection is crucial to allow solar to become a conventional energy source. Interconnection policies should be outlined as soon as possible.

# 11.3. Analysis Outcomes

- Solar growth projections in the next decade suggest that predominant growth will be observed in the Southwestern states, with scattered growth in some northeast states.
- According to Wright's law, cost of solar energy is expected to reduce to \$10.5/MWh by 2031, indicating an approximate 77% drop in the next decade.
- Current research is focused on mitigating existing limitations, and the proposed solutions have been rated based on their TRL.

# 11.4. Research Gaps

- Research on Generation 3 solar-thermal or CSP power plants has been encouraged by the DOE. The upcoming CSP market requires extensive technical, economic and feasibility assessments. Latest research should also expand towards commercializing thin-film and perovskite solar cells.
- Solar energy is such a versatile resource that it can complement other energy sources very efficiently. Hybrid energy systems should be paid more attention to properly utilize the merits of all energy sources.
- BESs and storage will be crucial to make up for the intermittency of solar energy, so it is important to commercialize more efficient, affordable, and durable storage systems.
- Alternative applications, microgrids, existing challenges and recycling of solar panel waste are areas that still need in-depth R&D.

# 11.5. Policy Implications

• Alongside the existing R&D investment, low-interest loans to businesses in the solar sector should be provided according to the needs of economic plans.

- Auctions for long-term PPA should be arranged to encourage investment in CSP and other industrial projects.
- ITCs delineate energy sources by broad categories like solar. Higher incentives can be offered for higher efficiency, less commercialized alternatives, such as thin-film, CSP or perovskites.
- Smart successor programs of the existing ITC and NEM policies should be planned, so that solar adoption does not decline during or after phase out.
- All states should be encouraged to adopt RPSs.
- Domestic manufacturing of solar panels and peripherals need to be escalated to match the upcoming exponential demand and to mitigate the slowdown in solar uptake due to heavy tariffs imposed on imported panels. Manufacturing tax credit should be introduced.
- GHG emission programs with carbon taxes or carbon credits for zero-emission technologies can help further levelize the cost of solar power.

#### 12. Conclusions

This paper has presented a data-driven analysis of the key aspects driving the solar upsurge. A state categorization has been carried out for the U.S. based on a state's potential for solar growth in the next 10 years, considering 18 factors in total. States that are expected to witness the highest growth are predominantly located in the Southwestern region, in addition to some scattered growth in the Northeast. Besides, the price of solar technologies in the U.S. has been predicted using Wright's law to drop down to \$10.5/MWh within the next 10 years. Finally, the paper has also looked into possible reasons behind solar energy not being as dominant as other energy sources and rated plausible solutions to its limitations based on the TRL. The final outcome has argued that, with the right strategies, solar does possess the potential to be the largest energy source in the U.S.'s ambitious target to reach a carbon-free power sector by 2035 and a net-zero emission economy by 2050.

Future work can further explore the solar generation potential of each region of the U.S. with similar geographical characteristics in consideration of the factors discussed in this paper, and carry out an assessment of the gap between the solar potential and generation in order to maximize solar exploitation and meet the 2035 target of carbon-free power sector. It can also look into other RESs that can play a supporting role to solar in the clean energy outlook.

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# Abbreviations

RE	Renewable energy
RES	Renewable energy sources
EIA	Energy Information and Administration
AHP	Analytical hierarchy process
CSP	Concentrated solar power
PV	Photovoltaic
STE	Solar thermal energy

NREL	National Renewable Energy Laboratory
DSSC	Dve-sensitized solar cell
SHC	Solar home systems
IRENA	International Renewable Energy Agency
PTC	Parabolic trough collectors
LFF	Linear Fresnel reflectors
ST	Solar towers
SD	Solar dish
UTE	Heat transfor fluid
DC	Distributed generation
DG	Thermal energy storage
	Compact linear Freenal reflectors
	Compact linear Fresher reliectors
5WH5	Solar water neating systems
DSHWS	Domestic solar hot water system
FPC	Flat-plate collectors
EIC	Evacuated-tube collectors
HVAC	Heating, ventilation and air conditioning
SHIP	Solar heat for industrial processes
LCOE	Levelized cost of energy
FPV	Floating photovoltaic
GHI	Global horizontal irradiation
DNI	Direct normal irradiation
NCC	Net capital cost
DOE	Department of Energy
SETO	Solar Energy Technologies Office
R&D	Research and Development
HPP	Hybrid power plant
CF	Capacity factor
MWh	Megawatt-hour
DEWA	Dubai Electricity & Water Authority
ISCC	Integrated solar combined cycle
NGCC	Natural gas-fired combined cycle
CCUS	Carbon capture, usage and sequestration
ITC	Investment tax credit
RECAI	Renewable Energy Country Attractiveness Index
RECAL	Renewable Energy Country Attractiveness Index
sa km	Square Kilometer
RPS	Renewable portfolio standards
LFFD	Leadership in energy and environmental design
CHP	Combined heat and power
ICT	Joint Committee on Taxation
SHC	Energy credit tax expenditure
MACRS	Modified accelerated cost recovery system
SPEC	Solar renowable energy cortificates
CSI	California Salar Initiativo
SMAPT	Callor Massachusetts renewable target
ZEDLI	Zara anargy ready home
	Zero energy ready nome
F11 DED	Feed in tariffs
DEK	Distributed energy resources
EV	Electric vehicle
NEM	Net energy metering
BIM	Behind-the-meter
ANM	Aggregate net metering
NEMA	NEM aggregation
KNM	Remote Net Metering
BES	Battery energy storage
DESS	Distributed energy storage system

BNEM	Bloomberg New Energy Finance
ERCOT	Electric Reliability Council of Texas
RTO	Regional transmission organizations
PHS	Pumped hydro storage
CAES	Compressed air energy storage
TOU	time of use
SGIP	Self generation incentive program
SEIA	Solar Energy Industries Association
GHG	Greenhouse gas
MPPT	Maximum power point tracking
FERC	Federal Energy Regulatory Commission
TRL	Technological readiness level
EOL	End of life
EPR	Extended producer responsibility
EROI	Energy returned on invested
PHV	Hybrid electric vehicles
USDA	US Department of Agriculture
VVO	Voltage var optimization

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