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Reduction in Emissions by Massive Solar Plant Integration in the US Power Grid

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Abstract: Fossil fuels, the predominant energy source in the United States, have been identified as major contributors to environmental pollution through the release of harmful emissions. As a countermeasure, there has been an increasing focus on the exploration and development of cleaner energy alternatives to alleviate the environmental degradation caused by fossil fuels and to satisfy the growing energy needs. This study conducted scenario analyses to evaluate the impact of integrating solar energy into specific US power grids on reducing carbon emissions. The analysis encompassed electrical systems within California, New England, New York, and the Southwest, utilizing datasets from the Energy Information Administration and National Renewable Energy Laboratory. The Energy Information Administration dataset includes information on net generation according to each source and carbon emissions according to fuel type, whereas the National Renewable Energy Laboratory dataset provides hourly projections for 6000 theoretical photovoltaic installations and detailed solar energy output data every five minutes over a year. Our findings indicated a notable decrease in carbon dioxide emissions following the introduction of solar power facilities. The most significant reductions were observed in the Southwest and California, attributed to solar plant integration. Conversely, New York and New England were identified as regions requiring additional policy measures and incentives to meet the emission reduction goals.

Keywords: PV; photovoltaic; solar energy; electric vehicles; EV



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1. Introduction

In the US, fossil fuels are primarily responsible for providing energy. However, these fuels are cited as the major contributors to global warming [1], resulting in elevated risks of natural disasters [2,3]. Fossil fuels release pollutants (such as CO, CO₂, and NO₂) into the atmosphere that cause health hazards such as bronchitis, pneumonia, pulmonary edema, cardiovascular diseases, lung cancer, and death [4]. Plants are also affected, resulting in reduced agricultural yields especially due to the acidity of soils and water bodies caused by the pollutants [5].

Currently, only about 12% of the US energy consumed is generated by the various forms of renewable energy. Some examples are wind, solar, geothermal, biomass, landfill gas, and hydropower [6]. Biomass, which consists of biomass waste, biofuels, and wood, accounts for 40% of the renewable energy utilized in the US [7]. However, using biomass as fuel has environmental implications and can produce air pollutants equivalent to those produced by coal and natural gas [8]. Wind power, which produces the energy as air expands as it heats up and rises while being replaced by heavier, colder air, is the second most major renewable energy source (27%) [9]. Despite having no emissions, wind power

is an intermittent source and does not always produce energy when required. Rotor sounds, aesthetic effects, and animal hazards are some of the other issues [10]. The third place goes to hydropower, which produces energy by harnessing the force of flowing water (19%). The US coasts could potentially provide 66% of the power used annually, according to the EIA, using wave energy [11]. Despite this, hydropower is exceedingly expensive; it alters the natural environment, residents are forcibly evacuated owing to flood dangers, and energy generation is dependent on the amount of rainfall [12]. Another alternative is geothermal, which uses the heat produced by the Earth's crust to produce power [13]. Comparatively, geothermal has advantages over the other renewable sources due to its lower land requirements, reliability, and minimal water consumption. However, its drawbacks include a lower efficiency, the possibility of a hydrothermal eruption, and high initial investments [14].

Human behaviors can threaten the quality of our lives and natural resources. These threats may be evident in habitat loss and degradation, overexploitation, illegal wildlife trafficking, human–animal co-existence conflicts, and pollution [15]. The latter plays a significant part in our study, where the power demand rises more quickly than renewable energy uptake [16]. For this behavioral change to occur, education and environmental awareness are crucial. Studies show that increasing environmental knowledge dramatically impacts people's attitudes and behaviors about protecting the environment [17]. Some studies underline that environmental quality is significantly impacted by pro-environmental and climate-friendly actions [18]. However, there is currently insufficient awareness to create a quick and successful shift in behavior and routines [19]. The government can also pursue creating and implementing laws regulating the emissions produced [20]. Laws and regulations with incentive and punishment systems for industries can encourage carbon emission reductions [21].

The development of diverse vehicle types helps in reducing carbon emissions. These vehicles include BEVs, PHEVs, FCEVs, and HEVs [22]. BEVs are electric vehicles with batteries that are connected to a charging station to recharge the energy. BEVs are an alternative for reducing carbon emissions, but they have several disadvantages such as high costs, impacts on the grid, high electricity storage costs, and limited availability of charging stations [23]. FCEVs are zero-emission vehicles powered by hydrogen fuel cell technology [24]. Among the deficiencies of FCEVs are their high production cost and the scarcity of companies that produce hydrogen that can be adapted to these vehicles since it is an expensive process and requires further validation [25]. PHEVs, however, employ a battery system to power an electric motor and another fuel, such as gasoline, to power a combustion engine [26]. These vehicles are more expensive than HEVs, require double refueling stops (limited recharging stations and gas stops), and are in limited supply. HEVs work the same as PHEVs but without the ability to recharge the battery at a charging station, and instead use regenerative braking to charge the battery [27]. Although BEVs and PHEVs do not release emissions, many use grid-connected charging stations that generate a significant percentage of their energy from fossil fuels, which results in critical demand surges in the electrical system [28].

This research builds upon previous studies conducted by the authors [29], extending the examination to the incorporation of solar power facilities within the US at the Balancing Authority level, and its effectiveness in diminishing emissions from fossil fuels. It specifically focuses on the main goal of reducing emissions from fossil fuels. This includes assessing the various degrees of solar energy penetration and its operation on an hourly basis. The guiding research question is as follows: How does the massive integration of solar power plants impact fossil fuel emission reductions in the US electrical system? By leveraging foundational work in grid disturbances and renewable energy integration [29], this study aims to provide new insights into the scalability and efficiency of solar power systems in reducing fossil fuel dependence.

2. Literature Review

2.1. US Electrical System

The electrical grid of the US represents one of the most intricate systems, utilizing a diverse array of energy sources such as nuclear power, coal, natural gas, and renewables [30]. According to the EIA, natural gas accounts for 38% of the energy generation in the United States, followed by coal (22%). Natural gas and coal represent around 60% of the energy generation in the US. Only 20% of total energy production comes from renewable sources. Wind is the largest renewable energy source, accounting for 9.2% of the total energy production, followed by hydroelectricity (6.3%) and solar energy (2.8%) [31].

The US's electrical system consists of three components that allow power to reach every corner of the country: generation, transmission, and distribution [32]. The generation process is where the plants produce electricity, whether from fossil fuels or renewable energy sources. The transmission process transports this high-voltage power over great distances. The distribution procedure allows electricity to reach each consumer at a low voltage. The US has three major interconnected systems that function independently of one another with minimal transfers. This system segmentation helps to maintain system dependability and prevent service interruptions [33]. The three interconnections that connect the US are the Eastern Interconnection, Western Interconnection, and Electric Reliability Council of Texas Interconnection [34].

The main challenges with the US electrical infrastructure that have made it vulnerable include the rise in user demand, decaying infrastructure, cybercrimes, terrorist attack targets, long lead times for replacing essential electrical components, and many supply disruptions for power plants [35]. A component as crucial as the electrical system's infrastructure is a target that would impact the nation's health, security, and economy. Reducing system centralization and distributing energy generation resources may result in greater cyberattack resilience [36]. The addition of solar energy to an electrical system may also cause disruptions due to irregular generation [37]. The US electrical system has numerous stakeholders (generators, suppliers, distributors, stakeholders involved in transmission, the US Department of Energy, regulators, and environmental and consumer advocacy organizations) and includes the regulated and deregulated energy markets based on state [38,39]. The regulated energy markets function as monopolies overseen by a government commission. The deregulated market is when electricity prices are set by the market and controlled by the federal government. The goal of the deregulated market is to increase competition and lower electricity costs [40].

2.2. US Initiatives to Reduce Emissions

Greenhouse gases are components of the Earth's atmosphere that capture infrared radiation and transfer it to more significant non-greenhouse gases [41]. The large percentages of non-greenhouse gases in the troposphere, such as nitrogen (78%) and oxygen (21%), cause the temperature in the troposphere to rise dramatically [42]. Even though this exchange is a natural cycle, humans have increased the intensity of these emissions, resulting in climate change and sea-level rise [43]. According to the EPA, carbon dioxide is responsible for 79 percent of greenhouse gas emissions. In 2020, electricity generation will be the second-largest source of carbon dioxide emissions, accounting for an estimated 32% of the total CO₂ emissions in the US [44].

Over the years, the US's position on reducing greenhouse gas emissions has been uncertain. In 1990, President George W. Bush signed the first amendment to the Clean Air Act in 30 years to decrease the health risks associated with urban air pollution and acid rain by controlling air pollutants [45]. In 1992, at the United Nations Framework Convention on Climate Change, President George H.W. Bush introduced a tax credit for renewable energy generation (Energy Policy Act) to stimulate the wind energy industry [46]. Later, in 2005, this was amended to include a fund for a tax credit for solar energy installation and renewable energy research [47]. The Kyoto Protocol was signed in 1997, claiming that humans were the primary cause of climate change and global warming. This protocol

aims to target greenhouse gas emissions in the atmosphere caused mainly by humans by implementing policies and restrictions. The US Senate decided not to participate in this agreement because of the economic consequences of enacting such legislation in the country [48].

President Barack Obama opted to join the Paris Agreement with China in 2016. These two countries are responsible for 38% of the global greenhouse gas emissions [49]. This agreement represents a significant step forward in collaborating with the great majority of countries in favor of global climate change solutions [50]. With the election of Donald Trump to the presidency of the US in 2017, Trump announced the withdrawal of the US from the Paris Agreement. His views and domestic policy primarily prompted this withdrawal [51]. President Trump imposed a 30% tax on solar imports made outside the US the following year, driven by rising military tensions with China. He was creating a barrier to advancing renewable energy in the US [52]. The US re-joined the Paris Agreement in 2021, following Joe Biden's election as President. As a result, the US will continue efforts to reduce greenhouse gas emissions [53]. The US's Mid-Century Strategy established a goal of achieving net-zero greenhouse gas emissions by 2050, and a goal to reduce greenhouse gas emissions by half by 2030 compared to 2005 [54].

In the US, household travel and residential energy account for 42% of total CO₂ emissions [55]. Alternative solutions have been put forth throughout time to reduce these emissions in the lives of each customer. When BEVs first appeared, many saw them as a potential solution to reducing GHG emissions. Although these cars have no emissions, the energy used to recharge them is provided mainly by the electrical system, which is powered by fossil fuels. This perception is detrimental because every HEV replaced with a BEV increases GHG emissions by 7% [56]. Another factor that can help reduce carbon emissions is the adoption of Smart Homes. Smart Homes would use sensors and meters in the home to make optimized decisions regarding energy use [57]. Developing habits in humans that consider the consumption of electricity is essential. These practices not only help the economy, but they also help to reduce carbon emissions [58].

2.3. Solar Energy Transition

Solar energy has both advantages and disadvantages. One of the advantages of using solar energy is that it does not emit carbon dioxide and has little environmental impact. The disadvantages include the fact that the solar energy produced is not continuous and depends on the place, time, season, and weather [59]. However, while economic and regulatory variables impact PV systems more, it is reasonably probable that solar and wind will account for 40% of the power generation by 2050 [60]. There is a general agreement that these renewable energy supplies cannot be incorporated in isolation, but instead, we need substantial infrastructure modifications in the electric grid, including meshed distribution lines and energy storage systems [61].

The United States has seen a substantial rise in solar energy installations in recent years, primarily due to state and federal incentives [62]. Due to changes in state subsidies, power rates, and solar insolation levels, solar PV system costs and financial returns heavily depend on each state [63]. The states of California and New York are two excellent examples of this. Both states have ambitious energy transition goals but have taken different approaches to using solar energy as a decentralization alternative [64]. Solar energy may be integrated through various ways and with various effective mechanisms for that area. Studies have demonstrated how the community choice mechanism has been more effective in California, and the shared solar mechanism has been more effective in New York. The community choice involves government organizations that protect consumer spending, allow customers to choose their electric providers, and offer more renewable energy options than other utility providers [65]. Because of this, community-based groups are crucial to the transition to renewable energy. The shared solar mechanism is a technique in which solar energy yields energy and/or economic gains to member owners [66].

California has the highest solar energy production in the United States, accounting for over 25% of the total electricity generation. Solar systems generate only 3.28% of the electricity generated in New York [67]. The success of California is a result of a combination of geographical and atmospheric conditions that are ideal for producing energy and laws and regulations that enable a more favorable development in this state. Compared to New York, California has higher levels of irradiance, more annual sunshine days, and fewer annual precipitation days [68]. Solar energy integration has various methods and mechanisms that are effective for each region. When discussing rules and regulations, we must include net metering legislation since it plays a critical role in the solar energy transition. Net metering allows the states to incentivize the use of renewable energy by exchanging utility credits for power injected into the grid [69]. The quantity of electricity authorized for exchange and the price at which that exchange of energy occurs determine the net metering efficiency [70].

3. Methods

3.1. Data Source Selection

The analysis leveraged data from both the National Renewable Energy Laboratory (NREL) and the EIA, with the NREL providing hourly outputs from theoretical solar installations and the EIA supplying data on hourly energy production by source and consumption. This evaluation includes a statistical comparison of the average outputs at varying solar penetration rates. Table 1 categorizes the EIA's statistics into 13 regions, detailing each region's code and share of solar power generation.

Table 1. Solar generation by US region [29].

N	Code	Name	% Solar Generation
1	CAL	California	16.2%
2	SW	Southwest	3.2%
3	CAR	Carolinas	2.8%
4	NW	Northwest	1.9%
5	FLA	Florida	1.5%
6	SE	Southeast	1.1%
7	TEX	Texas	1.0%
8	MIDA	Mid-Atlantic	0.3%
9	TEN	Tennessee	0.3%
10	CENT	Central	0.2%
11	NE	New England	0.2%
12	MIDW	Midwest	0.1%
13	NY	New York	0.0%

This study conducted a comparative analysis of the electric grids in California, New England, New York, and the Southwest, examining the impact of integrating substantial utility-scale solar energy into the high-voltage transmission networks. The reason for selecting these four grids is as follows. California and the Southwest are noted for their high levels of utility-scale solar power production, in contrast to the relatively low levels observed in New England and New York. Notably, while California leads in solar energy production, which accounts for 16.2% of its energy mix, New York lacks utility-scale solar generation, as per the EIA data.

Through statistical analyses, the research assessed changes in fossil fuel-based electricity generation, solar power output, carbon dioxide emissions, and the net differences following the simulated introduction of solar facilities in the regions.

3.2. Data Collection

The EIA, a statistical and analytical arm of the US Department of Energy, provides comprehensive hourly data on the high-voltage electricity network across the 48 contiguous states, excluding Hawaii and Alaska. These data encompass a breakdown by fuel type (as

per EIA-930), including coal, nuclear, petroleum, natural gas, hydroelectric, solar, wind, and additional sources [71]. Included within this dataset are metrics on net electricity generation by source, overall carbon emissions, and emissions segmented by fuel type, specifically covering the period from 1 January to 31 December 2019. The NREL, renowned for its pioneering work in renewable energy research, plays a pivotal role in advancing the shift towards renewable energy sources [72]. NREL maintains a repository of data on theoretical PV solar installations, which are crucial for studies on renewable energy integration [73]. This repository offers daily hourly projections for approximately 6000 theoretical PV setups, along with data on solar energy production every five minutes over the span of a year. In our analysis, data synchronization was performed on an hourly basis, focusing solely on the day-ahead forecasts for energy production. Table 2 outlines the quantity of theoretical solar installations assessed within each region that were considered in this research.

Table 2. Quantity of hypothetical utility-level solar plants per region included in the study [29].

Region	Number of Solar Plants
California	167
Southwest	149
New England	68
New York	62

3.3. Data Analysis

The EIA-930 dataset served as the foundation for an updated hourly energy balance [71,72]. In this revised model, the integration of new solar power installations was given precedence over conventional fossil fuel-based generation facilities to meet the aggregate net production requirements. According to the EIA, each fossil fuel emits a varied quantity of carbon dioxide. The selection process for substituting fossil fuels with solar energy was guided by the carbon emissions attributed to each type of fuel [74]. In the regions of California and New York, coal-fired power stations were identified as the initial targets for replacement, followed by those burning petroleum products and, finally, natural gas facilities. Conversely, in the Southwest and New England, installations using petroleum products were prioritized for replacement, followed by coal and natural gas-fired plants. Furthermore, the investigation considered several different degrees of solar energy integration: 100%, 75%, 50%, and 25%. The statistical program RStudio was used to conduct the data analysis for this study.

Equation (1) represents the energy balance according to the EIA-930 data [71]:

$$NG = COL + NGA + NUC + PET + WAT + SUN + WND + OTH. \quad (1)$$

where

NG = Net generation

COL = Net generation from coal in MWh;

NGA = Net generation from natural gas in MWh;

NUC = Net generation from nuclear energy in MWh;

PET = Net generation from petroleum products in MWh;

WAT = Net generation from hydro in MWh;

SUN = Net generation from solar energy in MWh;

WND = Net generation from wind in MWh;

OTH = Net generation from other energy sources in MWh.

The EIA-930 dataset was utilized to update the hourly energy balance model. In this adjusted model, the incorporation of new solar energy installations took precedence over the continuation of fossil fuel-based power plants to fulfill the overall net generation needs. The EIA highlights that different fossil fuels are responsible for disparate amounts of carbon

dioxide emissions. The selection process for substituting fossil fuels with solar energy hinged on the carbon dioxide emission levels associated with each type of fuel.

$$NG(SUNFH) = DCOLFH + DNGAFH + NUC + DPETFH + WAT + SUN + WND + OTH + SUNFH \quad (2)$$

4. Results

4.1. 100% Solar Energy Penetration

Table 3 illustrates the effects on power generation resulting from the installation of theoretical solar plants at a 100% solar energy penetration rate. According to Table 1, the California area generates the most solar energy (16.2%), followed by the Southwest (3.2%). On the other hand, New York has the lowest solar energy generation rate at 0%, followed by New England at 0.2%. Natural gas and nuclear energy are the principal energy sources in New England, New York, and the Southwest. Coal and petroleum products are the energy generation sources with the most significant carbon emissions. The Southwest, with 14.7% coal-generated energy, is the area with the highest percentage of coal-generated energy. The states with the lowest percentages of generation using petroleum as a source of energy are California (0.3%), New England (0.2%), and the Southwest (0%).

Table 3. Energy generation by region and sources before and after the integration of the hypothetical solar plants at 100% capacity [29].

		COL	NGA	NUC	PET	WAT	SUN	WND	OTH
California	Before	3.9%	42.4%	8.3%	0.3%	17.1%	16.2%	8.5%	3.2%
	After	2.2%	32.3%	8.3%	0.2%	16.4%	28.1%	8.5%	3.2%
New England	Before	0.5%	49.8%	31.2%	0.2%	8.4%	0.2%	3.6%	6.2%
	After	0.3%	46.2%	31.2%	0.1%	8.4%	4.0%	3.6%	6.2%
New York	Before	0.0%	34.7%	33.6%	2.9%	21.9%	0.0%	3.3%	3.5%
	After	0.0%	32.2%	33.6%	1.7%	22.0%	3.7%	3.3%	3.5%
Southwest	Before	14.7%	37.5%	39.3%	0.0%	3.2%	3.2%	1.9%	0.2%
	After	8.1%	28.4%	37.3%	0.0%	3.2%	18.9%	1.9%	0.2%

Table 3 shows the results of a 100% hypothetical solar energy penetration. The data are organized by source and penetration level for each region. The amount of solar energy produced in the California region increased from 16.2% to 28.1%. Solar energy climbed from 0.2% to 4% in New England. There was no solar energy generation in the New York region. However, after including 100% of the hypothetical solar plants, it achieved 3.7% solar generation. The Southwest had the second-highest solar generation, up from 3.2% to 18.9%. After installing all the potential solar plants, the Southwest area showed the most remarkable significant difference (+15%). This suggests that the Southwest may have massive potential for solar energy generation. Solar energy outperformed all other renewable energy sources (water and wind) in terms of utilization percentage in California and the Southwest.

After a thorough analysis of the hypothetical solar power plants, the utilization of the other energy sources that generate considerable quantities of carbon emissions was also affected. For California, natural gas consumption dropped from 42.4% to 32.3% (−10.1%), petroleum use dropped from 0.3% to 0.2% (−0.1%), and coal use fell from 3.9% to 2.2% (−1.7%). Natural gas showed the largest differences when this 100% solar energy penetration was implemented throughout all examined regions, with differences of −10.1% (California), −3.6% (New England), −2.5% (New York), and −9.1% (Southwest). Among the regions use coal, natural gas, and petroleum, it was possible to see that petroleum showed the lowest difference, at 0.1% (California and New England).

4.2. 75% Solar Energy Penetration

Table 4 shows how a hypothetical solar plant penetration of 75% affects the generation of different energy sources. When we look at the usage of solar energy in California, we can see that it is still the second-largest source of energy, at 26.1%, and the third-largest in the Southwest, at 15.9%. After implementing 75% of the hypothetical solar power plants, the Southwest (−12.7%) continued to have the biggest disparity between the 75% penetration scenario and the 0% penetration scenario. Even if that penetration rate was reduced to 75%, there was still a significant reduction in carbon dioxide emissions from energy sources. The most significant differences were observed in coal and natural gas. In California, coal fell from 3.9% to 2.2% (−1.7%), while natural gas fell from 42.4% to 34.4%. The Southwest cut coal generation from 14.7% to 8.3% (−6.4%) and natural gas generation from 37.5% to 31.2% (−6.3%). There were some reductions in New England and New York, but they were relatively small.

Table 4. Energy generation by region and sources before and after the integration of the hypothetical solar plants at 75% capacity [29].

		COL	NGA	NUC	PET	WAT	SUN	WND	OTH
California	Before	3.9%	42.4%	8.3%	0.3%	17.1%	16.2%	8.5%	3.2%
	After	2.2%	34.2%	8.3%	0.2%	17.1%	26.1%	8.5%	3.2%
New England	Before	0.5%	49.8%	31.2%	0.2%	8.4%	0.2%	3.6%	6.2%
	After	0.3%	47.2%	31.2%	0.1%	8.4%	3.0%	3.6%	6.2%
New York	Before	0.0%	34.7%	33.6%	2.9%	21.9%	0.0%	3.3%	3.5%
	After	0.0%	33.0%	33.6%	1.9%	21.9%	2.8%	3.3%	3.5%
Southwest	Before	14.7%	37.5%	39.3%	0.0%	3.2%	3.2%	1.9%	0.2%
	After	8.3%	31.2%	39.3%	0.0%	3.2%	15.9%	1.9%	0.2%

4.3. 50% Solar Energy Penetration

Table 5 shows the statistics by area, energy source, and the before-and-after results of implementing half of the hypothetical solar plants. Even with a 50% penetration rate, the Southwest and California continued to lead the way in solar energy production, while New York and New England had the lowest levels of solar energy output among the renewable energy sources (wind, solar, and water). When penetration approached 50%, it was evident that the supplies of fossil fuels were significantly reduced. This was true for coal in the Southwest, where it had fallen from 14.7% to 8.8% (−5.9%), and natural gas in California, where it had fallen from 42.4% to 37% (−5.4%).

Table 5. Energy generation by region and sources before and after the integration of the hypothetical solar plants at 50% capacity [29].

		COL	NGA	NUC	PET	WAT	SUN	WND	OTH
California	Before	3.9%	42.4%	8.3%	0.3%	17.1%	16.2%	8.5%	3.2%
	After	2.3%	37.0%	8.3%	0.2%	17.1%	23.4%	8.5%	3.2%
New England	Before	0.5%	49.8%	31.2%	0.2%	8.4%	0.2%	3.6%	6.2%
	After	0.3%	48.1%	31.2%	0.1%	8.4%	2.1%	3.6%	6.2%
New York	Before	0.0%	34.7%	33.6%	2.9%	21.9%	0.0%	3.3%	3.5%
	After	0.0%	33.7%	33.6%	2.0%	21.9%	1.8%	3.3%	3.5%
Southwest	Before	14.7%	37.5%	39.3%	0.0%	3.2%	3.2%	1.9%	0.2%
	After	8.8%	34.6%	39.3%	0.0%	3.2%	12.0%	1.9%	0.2%

4.4. 25% Solar Energy Penetration

Table 6 displays the energy generation by region and energy source if 25% of the hypothetical solar power plants were implemented. California and the Southwest continued

to have the most significant percentages of solar energy generation, at 20.2% and 7.8%, respectively. When this statistic from the California region is compared to the generation with a 100% penetration level, there was a 7.9 percent decline from 28.1% (100% penetration) to 20.2% (25%). Comparing the 100% and 25% penetration, the Southwest region's solar energy output decreased by 11.1%. At a 25% penetration level, the solar energy output in New England and New York was roughly 1%. This suggests that implementing these solar power plants will have a more significant impact on California and the Southwest than on New England and New York in terms of reducing the use of fossil fuels.

Table 6. Energy generation by region and sources before and after the integration of the hypothetical solar plants at 25% capacity [29].

		COL	NGA	NUC	PET	WAT	SUN	WND	OTH
California	Before	3.9%	42.4%	8.3%	0.3%	17.1%	16.2%	8.5%	3.2%
	After	2.3%	40.1%	8.3%	0.2%	17.1%	20.2%	8.5%	3.2%
New England	Before	0.5%	49.8%	31.2%	0.2%	8.4%	0.2%	3.6%	6.2%
	After	0.4%	48.9%	31.2%	0.1%	8.4%	1.2%	3.6%	6.2%
New York	Before	0.0%	34.7%	33.6%	2.9%	21.9%	0.0%	3.3%	3.5%
	After	0.0%	34.2%	33.6%	2.4%	21.9%	0.9%	3.3%	3.5%
Southwest	Before	14.7%	37.5%	39.3%	0.0%	3.2%	3.2%	1.9%	0.2%
	After	10.4%	37.2%	39.3%	0.0%	3.2%	7.8%	1.9%	0.2%

5. Discussion

Based on the given data, this study aimed to explain how solar energy integration might impact energy production-related emissions in the US. The preliminary findings indicate the following:

- (1) Introducing solar power plants at different levels of integration into the US electrical grid would reduce the carbon emissions associated with electricity generation;
- (2) California and the Southwest hold substantial promise in mitigating carbon emissions by fully integrating all available solar power plants, aiming to achieve the United States' carbon emission reduction goals for both 2025 and 2030;
- (3) New York, with a 100% implementation of the hypothetical solar plants, would only be able to achieve a 25% reduction by 2025;
- (4) New England would not be able to achieve any goals even with the full penetration of the hypothetical solar plants;
- (5) To reach their carbon emission targets, New York and New England would require aggressive policies, regulations, and incentives for renewable energy.

Previous studies have shown similar results, with California placing first in the solar market and second in growth projections and ranking for the next five years [67]. Other studies showed that California and the Southwest benefit from geographical and atmospheric advantages that put them in a better position to generate more solar energy than other regions. Among these advantages are high irradiance levels, many average annual sunny days, and low yearly precipitation levels [68]. Other studies showed that this success is a result of a combination of the significant potential for solar energy generation in this state, as well as the fact that this state has one of the highest electricity costs in the United States, which can be reduced by the adoption of PV systems. Additionally, California has been quite aggressive in adopting incentives and programs to reduce carbon emissions both at the state and federal level. Some examples include the California Solar Initiative (CSI), net metering incentives, the Solar Investment Tax Credit (ITC), Disadvantaged Communities-Single-Family Solar Homes (DAC-SASH), and local solar rebates [67,75,76]. Some studies suggested that without rebates like those offered by the California Solar Initiative, there would be 53% fewer PV system installations [77].

This research study evaluated the influence of solar plant integration on carbon emission reductions within four distinct regions of the United States' power grid: New England, California, New York and the Southwest. It analyzed the solar energy output from theoretical solar installations, drawing upon NREL research, and juxtaposed this against the output from major carbon-dioxide-emitting sources such as oil, natural gas, and coal. Figure 1 presents a breakdown of the power generation by source and region, both before and after the full integration of the solar installations. This information highlights the impact of solar energy adoption on the consumption of fossil fuels within the US electrical network.

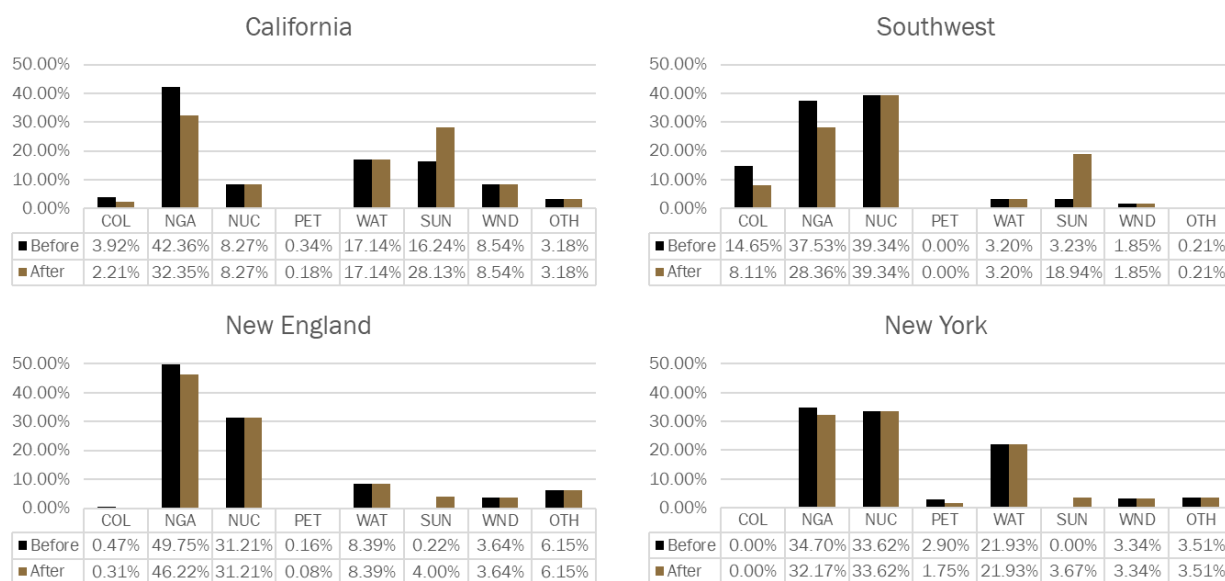


Figure 1. Solar energy output by region before and after the 100% solar penetration [29].

As a comparative framework, the reduction percentages of each region were compared to the carbon emission reduction percentages specified by the United States as goals for 2025 and 2030. The US plans to cut carbon emissions by 26% by 2025 and 50% by 2030. California and the Southwest were the only regions evaluated with a high probability of meeting the 2025 and 2030 goals by building 100% of the NREL's hypothetical solar plants. The New York region would only meet the 2025 objective, while New England would not meet any goal.

Compared to California, New York's situation is a little different. Furthermore, New York has had success with options like shared solar while California has not; California has been prosperous in areas like community choice while New York has not [64]. Natural gas, nuclear power, and hydropower produce 90% of New York's electricity [78]. Due to the global COVID-19 emergency, which impacts the data for the years 2020 and 2021, this research collected data between 1 January and 31 December 2019. Although these studies were conducted in 2019, it is worthwhile to replicate them using more recent data and in a condition of standard power generation and demand. This is important to note since a quarter of New York's utility-scale solar power came online between January 2020 and June 2021. New York will have 2700 megawatts of solar energy by the middle of 2021. According to one study, New York is a less effective locale than California and the Southwest due to lower irradiance, fewer sunny days per year, and more yearly precipitation [68]. However, New York has actively promoted the use of solar energy through grants and tax benefits. Additionally, they have put in place the Renewable Portfolio Standard (RPS), which mandates that utilities acquire a specific amount of their energy from renewable sources. Because mixed results have been found in RPS efficiency, some research suggests that RPS efficiency is dependent on the implementation in each state [79,80]. Some studies attribute the reduction in solar investments to the Value of Distributed Energy Resources

(VDER). To compensate prosumers for sending power to the grid, the VDER was the option that took the role of net metering. People who oppose the VDER believe it does not adequately reward prosumers and impacts the return on investment [81].

Massachusetts, Connecticut, Rhode Island, Maine, and New Hampshire comprise the New England region. The weather in the New England region is not as good for solar energy as it is in California and the Southwest, with less irradiance, fewer sunny days per year, and higher average annual rainfall [68]. Net metering regulations and a renewable portfolio are used to control the market in Massachusetts, which ranks ninth in the nation for the quantity of power produced by solar systems [82]. In 2020, Massachusetts had an increase in net generation from solar systems, which reached 20% of the state's total net generation [83]. The amount of power used and produced in 2020 was twice as much. Solar Massachusetts Renewable Target (SMART) programs have pushed the adoption of solar electricity in this state [82]. To further understand the current state of renewable energy in New England and New York, as well as the unique requirements of each area, further research on these two examples are required. This will make it possible to utilize each region's resources to their fullest potential to reduce carbon emissions.

6. Conclusions

This study offers several practical implications with respect to diminishing carbon emissions within the United States' electrical grid by advocating for the extensive deployment of solar energy across different regions of the nation. The degree of carbon emission reduction increased as the percentage of solar plant penetration increased. Although the costs of purchasing a PV system have fallen, many consumers still face economic challenges. There are some solutions to this problem. First, more rebates, tax credits, and incentives must be established to encourage the use of solar power, especially for low-income persons with financial constraints that restrict them from accessing solar systems. Second, net metering regulations and incentives must be revived. Net metering is a mechanism whose efficiency has been reduced due to various barriers imposed on it, making it an unfavorable alternative for prosumers. Third, incentives must be developed to encourage the use of electric cars while also including renewable energy-generating systems to recharge them. For example, credits or subsidies can be granted to purchase a PV system when purchasing an electric car, just as credits or subsidies can be supplied to purchase an electric vehicle when purchasing a PV system. This will allow these cars to be recharged using renewable energy while having no influence on the demand for the electrical grid, which is mainly powered by fossil fuels. Fourth, integrating energy storage systems (e.g., batteries) can expand the potential of solar energy. Fifth, to decide how to deploy solar energy or other renewable energies effectively, it is essential to analyze each region's features, constraints, advantages, and needs.

There are several opportunities for future research. First, future research should be conducted to promote generalizability by replicating the study across additional regions within the US. Second, future research should be performed outside the US to examine the effects of integrating solar and other renewable energy sources on reducing carbon emissions within other countries' electrical systems. Third, future research should investigate which renewable energy or renewable energy combinations are the most efficient. Fourth, future research should explore the influence of EV integration on the power grid to better understand the effects of supply and demand changes on the electrical system, and the indirect carbon emissions that would be produced. Fifth, the application of carbon emission reduction in other sectors of the utility business, and the implementation of utility-level peer-to-peer (P2P) energy trading business models can be other avenues of research to pursue; this approach has much potential for solar energy exchange, which would influence the adoption of solar systems, but it currently has no regulations and security for extensive application.

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Abbreviations

US	United States
NREL	National Renewable Energy Laboratory
EIA	Energy Information Administration
PV	Photovoltaic
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
NO	Nitrogen Dioxide
BEVs	Battery Electric Vehicles
PHEVs	Plug-In Hybrid Electric Vehicles
FCEVs	Fuel Cell Electric Vehicles
HEVs	Hybrid Electric Vehicles
EPA	Environmental Protection Agency

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