Challenges in the Large-Scale Adoption of Solar Energy

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Abstract: ***Energy is one of the largest contributors to the climate crisis and the greenhouse gases responsible for global warning. Adopting renewable forms of energy seems the only way out of the deep crisis. However, all renewable forms are plagued by variables that often make them unpredictable and comparatively less cost efficient when compared to energy extracted from fossil fuels. Adoption of AI in this sector is increasingly acknowledged to be a game changing application. This paper discusses how AI could transform the renewable energy sector with special reference to solar energy.***

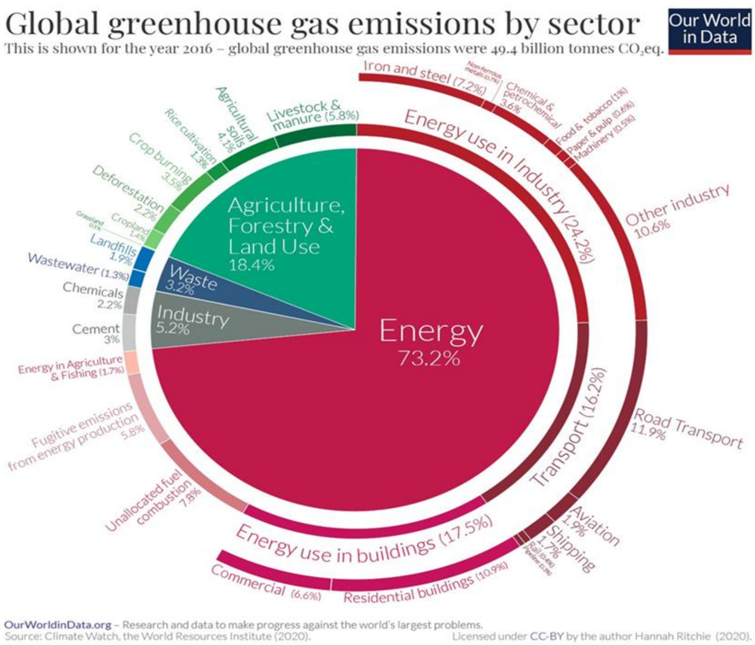
Keywords: solar energy, AI, efficiency, predictive analytics, efficiency, cost effectiveness

1. Introduction

The latest climate report by the United Nations Intergovernmental Panel on Climate Change (IPCC) has warned that "unless humans drastically reduce the use of coal, oil, and gas within the next 10 years, global temperatures will likely rise more than 1.5 degrees Celsius—surpassing the climate target in the international Paris Agreement—and cause irreversible and catastrophic damage". This stern warning has also led to an increasing interest in renewable energy sources as a viable alternative. Of all the renewable energy forms, solar energy is deemed the most promising given its all year-round availability, easier accessibility, and versatility. Easy accessibility makes solar a useful energy source in the underdeveloped regions with limited connectivity to traditional electricity sources or off-grid applications. Its versatility gives it a wide range of utility from solar powered hand devices to lighting transport, buildings, and satellites. It's easier installation makes it a very portable source of electricity allowing it to adapt to the demand of the consumer. Importantly, it is the cleanest form of energy available with the least carbon-intensive process for power generation. "Solar power produces no emissions during generation itself, and life-cycle assessments clearly demonstrate that it has a smaller carbon footprint from "cradle-to-grave" than fossil fuels" [2].

It is apparent from the figure below, that energy is the principal contributor of the Greenhouse gases and a shift to renewable energy could make a positive difference. Despite its popularity, solar energy has been plagued by various challenges including inefficient conversion efficiency which has a direct impact on its cost-competitiveness vis-à-vis the conventional sources of energy and the impact of variables regarding time of the day, weather, Wavelength, Recombination, Temperature etc which can make the source highly unpredictable.

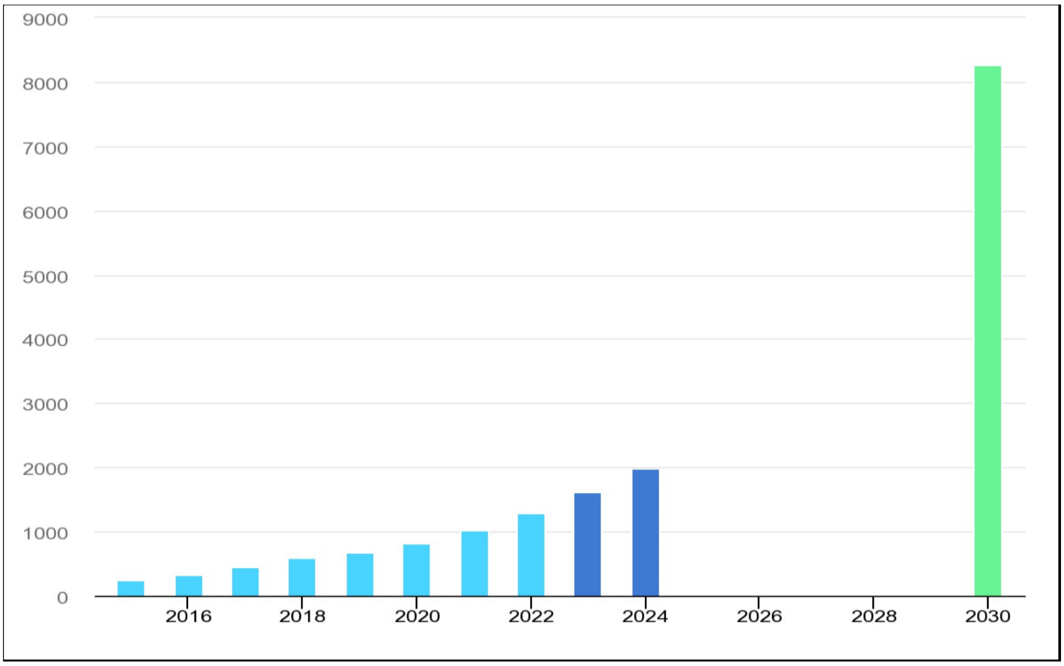
Studies have shown that "Transport accounted for around 23% of carbon emissions in 2013, which cannot be ignored in terms of global greenhouse gas (GHG) emissions and climate change" [3]. With increasing urbanisation and vehicular traffic, carbon emissions from the transport sector, is also projected to show positive growth. [4,5]. Given this high percentage, a shift to electric vehicles or hybrids powered by electricity generated from the sun can help mitigate carbon emissions to a great extent.



2. Challenges in the large-scale adoption of solar energy

The sun provides 1.7 x 1022 J of energy in 1.5 days [6]. This is equivalent to the energy generated by 3 trillion barrels fossil fuels. Another interesting fact is that according to studies the total annual energy consumption across the globe is approximately 4.6 x 1020 J. This energy is supplied by the sun in one hour [7]. Despite the abundance, easy accessibility and versatility of solar energy, it still hasn't become a major force to reckon with in terms of conversion to renewable energy despite pressure to make the change in light of the urgency to take action owing to climate change and to keep alive the goal of limiting global warming to 1.5°C.

Even though the Power generation from solar PV increased by a record 270 TWh in 2022, up by 26% on 2021, it accounted for only 4.5% of total global electricity generation [8]. This is the result despite such a huge focus on adoption of clean and affordable renewable energy emphasised in the UNSDG goals. The figure below clearly indicated that a lot more needs to be done is we are to achieve the energy goals set for 2030 to keep global temperature under check [9]. The latest report published by the International Energy Agency (IEA), the Renewable Energy Agency (IRENA), the United Nations Statistics Division, the World Bank, and the WHO titled 'The 2023 edition of Tracking SDG 7: The Energy Progress Report' warned that "current efforts were not enough to achieve the SDG 7 on time". [10]. Given that solar energy has a critical role to play in this conversion, it would be important to understand the challenges that are preventing its large-scale adoption globally.



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2.1 Solar energy installation is expensive:

The high initial costs of installation are a huge deterrent particularly for families with moderate incomes. Combine this initial investment with unpredictability and dependence of weather condition, deters many people from making this investment. According to the Solar Energy Industries Association, the average cost of a house solar system is between $10,000 and $30,000, with the average installation costing approximately $18,000 [11]. This makes it attractive only for home owners who see the long term benefit in this investment on their properties. Rentals would not want to make this investment. Even though governments across the world are subsidising the initial investment through various monetary incentives, there is scepticism as the efficiency of the system cannot be guaranteed due to various variables associated with weather, direction of the installation etc. The solar cells of a panel are made of extremely refined silicon, manufactured complex process that demanding precision technology. Moreover an inverter has to be installed to transform the produced electricity into a usable form and storage needs expensive batteries, since they include rare minerals like lithium; all of which adds up to the cost. Any compromise on any of the above basic elements, would reduce the installations longevity and increase maintenance costs.

Even though the cost of solar power has dropped in the recent years due to industry expansion and generous tax credits and subsidies, the industry is not showing signs of being robust enough to function on its own merit. Thus, despite tax incentives, solar energy comprises a mere 2.3% of total energy consumption in the USA [12].

2.2 Conversion efficiency variables

Optically, reduced reflection and improved light trapping within the cell have had a large impact. Such features have increased silicon cell efficiency to a recently confirmed 24.7%. Recently, progress has been made in transferring some of the corresponding design improvements into production with commercial cells of 17–18% efficiency now available, world record values of a mere 15 years ago. The theory supporting these improvements in bulk cell efficiency

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shows that thin silicon layers, only a micron or so in thickness, are capable of comparably high efficiency.

The beat current technology available using single-crystal Si cells display an efficiency of about 20% [13]. In other words, they can convert only 20% of the incoming energy from sunlight into electric current. However, "for light-induced degradation (LID) losses only, within the hours of operation, the efficiency drops to 18%18%, which represents a 2%2% drop in total electric generation" [14]. This is the situation when we use the most efficient systems which are relatively more expensive as these Monocrystalline Si solar panels are produced from the highest-grade Si. Most deployment is of the cheaper polycrystalline or thin-film panels who have lower efficiencies in the range of 15–17% [12].

Besides we also must factor in the losses on account of the following:

1) Soiling losses is the caused by the Soiling losses refer to loss in power resulting from the accumulation of dust, dirt, snow and other contaminating that may cover the surface of the PV module and impact its efficiency. A lot of this fine dust comes from air pollution and vehicular movements among other weather and topographic conditions [15,16].
2) Shading losses happen when the PV modules do not receive the same levels of irradiance throughout the day which causes gross inefficiency. Shading can be dynamic like the ones caused by clouds, fog, mist etc while static shading could be cause by in situ obstructions like buildings, chimneys, trees etc [17].
3) The Angle dependence can have a major impact on the efficiency in photovoltaic. the incidence angle modifier or IAM helps determine optical losses that occur when the solar angle of incidence on the array surface is greater than zero in which case there can be energy loss due to reflection from the module surface materials [18].
4) Studies have shown that PID is caused "by an electrical potential difference between the front and back electrodes of the PV module and can be triggered by various factors such as humidity, high temperatures, and certain chemicals. PID can have a major impact on the overall performance and efficiency of PV systems, with some studies estimating that it can reduce power output by 30% or more" [19].
5) Temperature has a direct bearing on the output. Solar cells are made of semiconductor materials that are sensitive to temperature changes. Solar panels are manufactured to work at the optimum level temperature of 25 degrees Celsius or 77 degrees Fahrenheit as Standard Test Conditions (STC). Increase in temperature decrease the open circuit voltage of solar cells and their power output. A panel experiences an average decrease of 0.5% decrease in power for every degree above 25°C also referred to as the Temperature coefficient. This average varies depending on manufacturer, quality of material used etc. and will change depending on the quality, brand and type of panel. temperature losses [20].
6) PV yearly degradation or ageing varies between 0.6% and 0.7% per year [21,22]. This decline can happen due to various factors, climate, temperature fluctuations, humidity, rain, storms, wind laden dust, and corrosion from salt in coastal area's etc, the most significant factors being the exposure to sunlight.
7) Mismatch conditions alone were reported to cause up to 20 to 25% reduction in the output of the PV system [23]. Mismatch can be caused due to manufacturing or installation faults, Environmental conditions such as shading, soiling, snow, or temperature gradient [20], non-uniform degradation of the modules, shortened strings due to wear and tear and poor maintenance etc.
8) Since most defects in PV modules can't be detected with a naked eye, quality issues may sometimes go unnoticed effecting the efficiency. These flaws can arise during manufacturing, transportation, installation, degradation as discussed above etc.
9) Electrical losses include AC losses, inverter losses [25], and transformer losses [26].

2.3 Challenges of Grid integration

Operational uncertainties in conventional electricity gris arise due to variations on the demand side. Whereas, in the case of solar energy these come from both the demand and the supply side, making integration challenging. [27]. Solar energy is "characterized by randomness, indirectness, and volatility that poses operational challenges for PV integration into the grid" [28]. This load demand and supply/generation mismatch leads to frequent fluctuations in the system and could cause breakdowns in the entire system leading to partial or total loss of electrical supply. [29] studies have shown that increased PV share accelerated the rate of change of frequency (ROCOF) and could be the most probable of a system collapse during natural overloads [30] and that more than 40% penetration of solar PV generation leads to the collapse of the systems during the worst contingency case due to the loss of inertia [31].

2.4 Space requirement for installation:

Space requirement can be a challenge for the installation of solar panels, particularly in clustered urban areas which need it the most due to heavy pollution statistics. Even where space is available it might not provide ideal sunlight or the right angle and might have buildings around it serve as obstructions to uninterrupted sunlight through the day.

2.5 Challenges of Storage

Due to the intermittent generation of solar energy, storage during high generation during peak sunlight hours can make up for the lack of it during periods of low or no sunlight. The current technology available for storage are expensive, have limited capacity and can't scale their storage. Most importantly they themselves are not good for the environment once they age and become ineffective.

This storage is mainly of the following types:

1) Mechanical energy storage. This includes pumped storage, compressed-air energy storage and flywheel energy storage. While pump storage has the advantage of large capacity, long service lifespan and low unit cost, it requires a large investment. The compressed-air

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energy storage has similar advantages but has lower efficiency. And its complex system requires some key location parameters which may not be easy to find. The flywheel energy storage has the advantages of high efficiency, fast response, long service lifespan, less demands on operation and maintenance, good stability, short construction period, small footprint, and no pollution, but the energy density is low, easy to be self-discharge which is only suitable for short time applications [32-35].

2) Heat storage Heat storage technologies are categorized into sensible heat storage and latent heat storage. The sensible heat storage uses water, oil, air, rock bed, sand, soil, etc as the heat storage medium. Whereas the latent heat storage is done by changing the phase of storage material in this case normally between solid and liquid phase. The materials used for this purpose are salt hydrates, polymers, water, etc. which are expensive and make the process less cost efficient and there is also the problem of corrosion and high maintenance [36,37].
3) Electrochemical energy storage is done in lead-acid, lithium-ion, sodium-sulphur and redox flow batteries. The traditional lead-acid battery technology is cost effective and easy to maintain but its capacity is known to decline under fast and high-power discharge and has less shelf life and causes environmental pollution that renewable energies are being adopted to mitigate to begin with. Lithium batteries are efficient, stable and have a longer life cycle but expensive. Redox flow battery mainly includes vanadium redox flow battery, zinc bromine flow battery has a longer shelf life but show slow response and provide low energy and average power density. The Sodium sulphur battery has advantages of high energy density, and longer shelf life, but the use of the inflammable metal sodium material can posea safety risk [38].
4) Electromagnetic energy storage uses super capacitor and superconducting magnetic energy storage. This storage system can discharge almost all the energy stored in the system with a high power output in a very short time, have higher capacitance, transient voltage dip improvement, faster charging and the advantage of lower maintenance. The primary disadvantage is the high cost of refrigeration and the material of the superconducting coil. [39].
5) Chemical energy storage is an energy carrier mechanism using hydrogen or synthetic gas. In this mechanism Solar power is stored in the chemical bonds in new fuels that can be combusted to provide energy. the most common practice is of using hydrogen, produced by separating it from the oxygen in water, and methane, produced by combining hydrogen and carbon dioxide. This Methane is then utilised for electricity production. This process needs great deal of refinement and is marked by low energy conversion efficiency in the range of 40%–50% which doesn't make it very cost efficient [40].

2.6 Environmental impact

It is ironical that while solar energy is seen as a clean source of energy that could help reverse climate change, the manufacturing process and the materials used in solar panels are potentially harmful to the environment. Proper recycling and disposal measures need to be in place to mitigate the environmental impact of solar panel waste.

Solar energy systems use materials, such as metals and glass, have energy intensive production processes. Moreover, hazardous chemicals used to make photovoltaic (PV) cells, panels and storage batteries can harm the environment once they are discarded. Some solar thermal systems use potentially hazardous fluids to transfer heat, and leaks of these materials could also cause great harm. This is why the U.S. Department of Energy is supporting various efforts to address *end-of-life* issues related to solar energy technologies, including the recovery and recycling of the materials used to manufacture PV cells and panels [41]. Studies are also showing that construction of power plant may have long-term effects on the local biodiversity and ecosystems; a factor that cannot be ignored as the world looks towards using more and more of this renewable energy.

3. Conclusion

Given the enormity of environmental challenges being faced by our planet and the large role played by fossil fuel usage in causing them, adoption of renewable sources of energy is no longer a matter of choice but of dire necessity. Solar energy become the front runner as it is most readily and abundantly available. "Solarenergyoftenoffersseveraladvantagesover fossil fuels like coal and oil since it cleans the air, emits fewer greenhouse gases, and can be produced again during our lives" [42]. While the large-scale adoption of solar energy comes with its fair share of challenges, its advantages far outweigh its weaknesses. Hence, concerted efforts to improve the technology that will make its large scale adoption easier and cost effective at the same time are what the world should focus on.

The current research on achieving both these goals through the anti-solar cell concept is a step in the right direction. This alternative photovoltaic concept uses the earth as a heat source and the night sky as a heat sink, resulting in a "nighttime photovoltaic cell" that employs thermoradiative photovoltaics and concepts from the advancing field of radiative cooling. The device would work during the day as well, if you took steps to either block direct sunlight or pointed it away from the sun. Because this new type of solar cell could potentially operate around the clock, it is an intriguing option to balance the power grid over the day-night cycle [43]. This technology is already being pitted as a game changer for the future.

Another improvement in Solar energy efficacy can be brought in using Artificial Intelligence. AI and its powered predictive analytics can reduce the intermittency, chaos, and randomness properties of renewable energy make it possible to affect the stability and reliability of the power system when it is integrated into the distribution network on a large scale (Frias-Paredes et al., 2017) [44]. The latest trends in **Smart grid ecosystem** which introduced a new entity of 'prosumers,' or those who simultaneously produce, buy, and sell energy, thus altering the traditional dynamics of the power grid has been quite a game changer. These

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smart grids allow a closer and accounted real-time interaction between producers and consumers which enables more reliable data collection and dissemination. This data is used through an AI drawn analytics system that allows producers to regulate their electricity generation based on forecasted demand. At the consumer end, it facilitates better energy management and a more regulated usage both for personal and industrial use [45].

It is imperative that these solutions are refined to resolve all the bottlenecks that we face today to ensure large scale adoption. Let's not forget, that solar energy is not only a very readily available renewable energy source with the ability to lowergreenhouse gas emissions, it also has the potential to "stabilizing degraded land, create jobs, accelerate rural electrification, and raise living standards in developing nations [46].

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