

Research Paper

Critical Review on How Solar Energy Can Replace Fossil Fuels and Nuclear Power

Abhinav Sharma^{1,*} and NFuse team²

¹Necrozma Labs, Project NFuse,

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Abstract

Solar energy has emerged as a leading contender in the global shift toward sustainable electricity generation. Unlike fossil fuels—which rely on burning coal, oil, or natural gas, producing significant greenhouse gas emissions—and nuclear power, which generates electricity through atom-splitting but creates long-lived radioactive waste, solar power harnesses sunlight to produce electricity or heat with minimal direct emissions. Over the past decade, solar technologies have advanced rapidly, making them more affordable and efficient. This paper offers a critical review of how solar energy could feasibly replace both fossil fuels and nuclear power on a large scale. We begin by explaining the fundamentals of each energy source—fossil fuels, nuclear power, and solar energy—in straightforward language. We then compare their environmental impacts, examine economic considerations, discuss technical challenges and potential solutions, and explore social and policy factors that influence large-scale adoption. Throughout, we aim to provide clarity on how solar energy could assume the primary role in meeting global energy needs, considering real-world examples and practical strategies for transition. Finally, we offer policy recommendations and identify future research directions.

KEYWORDS solar energy; energy transition; fossil fuels; nuclear power; renewable policy;

1. INTRODUCTION

Energy is a cornerstone of modern civilization. Every time we switch on a light, drive a car, or charge a phone, we rely on electricity or fuels that often come from fossil fuels—coal, oil, and natural gas—or from nuclear reactors. For centuries, we depended almost entirely on burning fossil fuels, which release carbon dioxide and other pollutants into the atmosphere. In the 20th century, nuclear power emerged as an alternative that generates large amounts of electricity with almost no direct carbon emissions. However, nuclear energy brings its own challenges: the risk of accidents, the problem of storing dangerous radioactive waste for thousands of years, and the high cost of building and maintaining nuclear plants.

In recent years, solar energy—harvesting sunlight to produce electricity or heat—has transformed from a niche tech-

TABLE 1. Common Acronyms and Abbreviations

Acronym	Meaning
PV	Photovoltaic
LCOE	Levelized Cost of Electricity
CO ₂	Carbon Dioxide
GWh	Gigawatt-hour
FIT	Feed-in Tariff
RPS	Renewable Portfolio Standard
VPP	Virtual Power Plant

nology to one of the fastest-growing energy sources worldwide. Solar power is clean, renewable (because the sun will shine for billions more years), and increasingly affordable. Yet solar energy also has limitations: it only produces power when sunlight is available, and it requires space for panels or mirrors. Despite these challenges, falling costs, improved efficiency, and better energy storage solutions mean solar energy could soon rival or surpass existing energy sources.

This paper explores whether—and how—solar energy could replace fossil fuels and nuclear power on a large scale. First, we describe each energy source in simple terms. Next, we compare their environmental footprints: greenhouse gas emissions, air and water pollution, and waste. We then examine economic factors such as costs, job creation, and long-term maintenance. Technical hurdles—like the intermittent nature of sunlight and the need for energy storage—are discussed along with promising solutions. We also look at social and policy issues, including how public opinion and government incentives shape the energy transition. By exploring case studies from countries such as Germany, China, and the United States, we illustrate concrete examples of rapid renewable adoption. Finally, we offer policy recommendations and outline future research priorities to help guide a transition toward a predominantly solar-powered world.

2. OVERVIEW OF ENERGY SOURCES

2.1 Fossil Fuels

Fossil fuels—coal, oil, and natural gas—formed hundreds of millions of years ago when plants and animals died, sank into swamps or ocean sediments, and were buried under layers of rock. Over eons, heat and pressure turned these remains into carbon-rich substances that we now extract by mining

(for coal) or drilling (for oil and natural gas). When burned, these fuels release energy that powers electricity plants, heat homes, and run engines.

Coal is primarily used to generate electricity. In large power stations, coal is burned to boil water, creating steam that spins turbines and drives generators. Oil, once refined into products like gasoline and diesel, powers most cars, trucks, and ships. Natural gas—on its own, a mixture of methane and other gases—burns more cleanly than coal or oil, and it is used for heating, electricity generation, and industrial processes.

While fossil fuels have powered industrial growth and modern conveniences, their environmental costs are steep. Burning coal releases large amounts of carbon dioxide, sulfur dioxide, nitrogen oxides, and particulate matter. These pollutants cause smog, acid rain, and respiratory illnesses. Oil combustion emits carbon dioxide and other toxins, contributing to global warming and health problems. Natural gas burns more cleanly than coal or oil but still emits carbon dioxide and, if leaked, potent methane—a greenhouse gas far stronger than carbon dioxide over short periods. Moreover, extracting fossil fuels often leads to habitat destruction, water contamination, and sometimes catastrophic spills. Because fossil fuel reserves are limited and concentrated in certain regions, their prices fluctuate and can be influenced by politics and conflicts.

2.2 Nuclear Power

Nuclear energy generates electricity through a process called fission, in which uranium atoms split apart inside a reactor, releasing a colossal amount of heat. This heat boils water into steam, which drives turbines to produce electricity. A single uranium pellet—about the size of a fingertip—contains as much energy as nearly a ton of coal. This high energy density means nuclear reactors can supply massive amounts of continuous, reliable electricity without burning fossil fuels during operation.

Despite producing almost no greenhouse gases while running, nuclear power has challenges. First, mining uranium and enriching it into fuel is energy-intensive and can produce greenhouse gases if fossil fuels power those processes. Second, nuclear plants are expensive and take a long time to build—often a decade or more—because of stringent safety regulations. Third, if something goes wrong (as happened at Chernobyl in 1986 or Fukushima in 2011), radioactive materials can escape, causing immediate and long-term health dangers. Even during normal operation, reactors produce spent fuel rods that remain dangerously radioactive for thousands of years. Finding safe, permanent storage solutions for this waste has proved politically and technically difficult.

Finally, because nuclear plants must operate under strict safety protocols, ongoing maintenance costs are high. When a plant reaches the end of its life—usually after 40 to 60 years—the decommissioning process to dismantle the reactor and handle radioactive materials can cost hundreds of millions of dollars and take decades to complete. Despite these hurdles, nuclear power plants do provide large baseload electricity supply, meaning they can run continuously at high capacity, which helps stabilize the grid.

2.3 Solar Energy

Solar energy harnesses sunlight in two major ways. The first is solar photovoltaic (PV) technology, which uses panels made of semiconductor materials—most commonly silicon—to convert sunlight directly into electricity. When photons from sunlight hit a PV cell, they knock electrons loose from atoms, creating an electrical current that can be used immediately or sent to the grid. The second way is solar thermal technology, which concentrates sunlight with mirrors or lenses to heat a fluid—often a special oil or molten salt. This heated fluid produces steam that spins turbines, generating electricity. Solar thermal can also be used for direct heating, such as heating water for homes or industrial processes.

The sun delivers an enormous amount of energy to Earth—enough in one hour to meet the world's energy needs for an entire year. Unlike fossil fuels or uranium, sunlight will not run out on human timescales. Once solar panels are installed, they generate electricity without direct emissions of carbon dioxide, sulfur dioxide, or nitrogen oxides. Over their 25- to 30-year lifespans, modern solar panels require minimal maintenance—mostly occasional cleaning and inverter replacements—and no fuel costs, since sunlight is free.

However, solar energy is variable: it produces electricity only when the sun shines. Cloud cover, dust, and nighttime reduce or stop generation. To provide reliable power, solar systems often need batteries or other energy storage solutions to hold excess energy generated on sunny days for use at night or during cloudy periods. Solar thermal plants can store heat in materials like molten salt for 6–10 hours, allowing them to continue producing electricity after sunset. Additionally, solar installations require space—rooftops, desert land, or open fields. In dense urban areas or farmland, allocating large areas for solar panels may conflict with other land uses.

Over the past decade, the cost of solar PV has plummeted by more than 80 percent, making it one of the cheapest new sources of electricity in many parts of the world. This cost decline is largely due to improvements in manufacturing, economies of scale, and technological advances that have increased panel efficiency. As a result, solar energy is increasingly competing with, or even undercutting, the costs of fossil fuel-based electricity and nuclear power plants.

3. COMPARING ENVIRONMENTAL IMPACTS

3.1 Greenhouse Gas Emissions

When considering how solar energy stacks up against fossil fuels and nuclear power, the amount of greenhouse gases each produces over its lifetime is a key factor. Fossil fuels rank highest in carbon intensity. Burning coal produces roughly 2.2 pounds of carbon dioxide (CO₂) for every kilowatt-hour (kWh) of electricity generated. Natural gas is cleaner, releasing about 0.9 pounds of CO₂ per kWh. Oil, used mainly for transportation, emits around 1.5 pounds of CO₂ per kWh when converted to electricity, which is why burning oil for power is rare in many countries. These emissions trap heat in the atmosphere, driving global warming, changing weather patterns, causing sea levels to rise, and triggering more extreme storms. Beyond CO₂, burning coal also releases sulfur dioxide and nitrogen oxides, which form smog and acid rain, harming human health and ecosystems.

Nuclear power plants emit almost no CO₂ during operation, making them low-carbon electricity sources. However, small amounts of greenhouse gases are produced when mining uranium, enriching it, and constructing the plant. Taken over the full life cycle—from uranium mining to plant decommissioning—nuclear power typically emits about 0.02 pounds of CO₂ per kWh. While this is low compared to fossil fuels, it is still higher than solar or wind in many life-cycle analyses because mining and refining uranium, building massive containment structures, and managing long-term waste storage require energy—often from fossil fuels.

Solar PV systems emit no direct greenhouse gases when generating electricity. The main emissions occur during panel manufacturing and installation. Producing high-purity silicon for panels requires melting and refining processes, which historically used electricity from coal-fired or natural gas-fired power plants. As manufacturing gets cleaner—powered increasingly by renewable—solar's life-cycle emissions continue to drop. On average, a solar PV system produces around 0.15 to 0.3 pounds of CO₂ per kWh when accounting for manufacturing, transportation, installation, maintenance, and decommissioning. Solar thermal plants have similar life-cycle emissions, although exact numbers vary depending on the technology and local conditions. Once in place, solar systems operate without fuel and emit negligible greenhouse gases. This puts solar in the same low-emission category as nuclear, but with a slightly lower overall life-cycle carbon footprint in many analyses.

3.2 Air and Water Pollution

Beyond carbon, fossil fuels cause significant air pollution. Burning coal releases fine particulate matter (PM_{2.5}) that can penetrate deep into lungs, causing respiratory and cardiovascular diseases. Coal combustion also emits sulfur dioxide (SO₂) and nitrogen oxides (NO_x), which form smog and acid rain. Heavy metals like mercury and arsenic can enter waterways through coal ash waste, poisoning fish and making water unsafe to drink. Natural gas burns more cleanly, emitting less particulate matter and fewer sulfur compounds, but still produces NO_x, which contributes to smog. Extracting natural gas through hydraulic fracturing—or fracking—risks contaminating groundwater with chemicals and releasing methane, a short-lived but very potent greenhouse gas.

Nuclear power does not emit air pollutants during operation, but uranium mining can release radon gas—a radioactive cancer risk—in mining areas. Accidental releases of radioactive material, as seen at Chernobyl and Fukushima, had severe local impacts on air, water, and soil. Even routine nuclear plant operations require large volumes of water for cooling. This can warm nearby rivers or lakes, harming aquatic life and occasionally triggering thermal pollution events. Overall, nuclear power's air quality impacts are far lower than fossil fuels, but the risk of radioactive contamination and high water usage remain concerns.

Solar energy avoids most air and water pollution. Solar PV panels simply convert sunlight to electricity without burning any material. Generating electricity with solar has no direct emissions of particulates, sulfur, or nitrogen compounds. Solar thermal plants can require water to cool steam turbines, but many newer designs use dry-cooling systems

or hybrid approaches that dramatically reduce water consumption compared to conventional thermal power plants (coal, natural gas, or nuclear). The manufacturing of solar panels involves chemicals—such as silicon tetrachloride and other solvents—that can be toxic if not handled properly. However, strict manufacturing standards and recycling programs help minimize these risks. Land use is another consideration: large solar farms may cover many acres, which can disrupt habitats if placed on undeveloped land. Careful siting—such as using brownfields, deserts, or rooftops—can reduce these impacts.

3.3 Resource Availability and Waste

Fossil fuels and nuclear power rely on finite resources that must be extracted from the Earth. Coal, oil, and natural gas deposits formed over millions of years, and although current reserves are large, they will eventually deplete—raising extraction costs and environmental damage as easy-to-reach deposits dry up. Moreover, extracting these fuels often involves destructive practices: mountaintop removal mining for coal, offshore drilling risks, and fracking for natural gas, each of which can harm ecosystems, pollute waterways, and fracture communities.

Nuclear power depends on uranium, a metal found in limited concentrations in the Earth's crust. At current global consumption rates, known uranium reserves could last several decades to a century. However, if nuclear power expands rapidly, demand could rise faster than new reserves are found, pushing up prices. Spent nuclear fuel remains dangerously radioactive for thousands of years. While some countries reprocess spent fuel to recover usable uranium or plutonium, most store it in dry casks or pools, leaving societies with a long-term waste management challenge.

In contrast, solar energy relies on sunlight—a nearly infinite resource on human timescales. Panels and mirrors require materials such as silicon, aluminum, copper, silver, and, in some cases, rare earth elements. Silicon is abundant, but processing it into high-purity wafers requires energy. Silver, used as a conductor in many panels, is finite but used in small quantities per panel; innovations like copper-based contacts could reduce silver demand. Some thin-film solar technologies use rare materials like indium and gallium, which are less abundant, but those technologies make up a small fraction of the market.

When solar panels reach the end of their 25- to 30-year lifespans, they become electronic waste. Recycling infrastructure is growing, enabling recovery of glass (about 75 percent of a panel's mass), aluminum frames, and semiconductor materials. While recycling rates currently vary by region, many manufacturers and governments are setting up programs that will ensure panels are recycled rather than sent to landfills. This closed-loop approach—recovering valuable materials to make new panels—will help maintain solar's low environmental footprint over time.

4. ECONOMIC CONSIDERATIONS

4.1 Cost of Energy Production

The cost to produce electricity is a key factor in deciding which energy source to deploy. Economists often use the Levelized Cost of Electricity (LCOE) to compare different tech-

nologies; LCOE represents the average cost per unit of electricity over a plant's lifetime, accounting for construction, fuel, operation, maintenance, and decommissioning.

Fossil fuel plants have historically been inexpensive to build and operate, which helped them dominate the electricity market for decades. A new natural gas combined-cycle plant can cost USD 800 to USD 1,200 per kilowatt (kW) of capacity to build, and when fuel prices are low, operating costs remain competitive. Coal plants cost about USD 2,000 per kW to build, but stricter environmental regulations—such as installing scrubbers to remove sulfur dioxide—have increased costs. Fuel expenses (coal or gas purchases) and transportation add volatility: if global oil or gas prices spike, generating electricity becomes much more expensive, and those price spikes often get passed on to consumers.

Nuclear power plants are among the most expensive to build. A new reactor can cost 5,000 to 10,000 per kW of capacity, depending on local labor costs, regulatory processes, and financing rates. Construction delays and cost overruns are common, making nuclear projects risky for investors. Once built, however, nuclear plants have relatively low fuel costs—because uranium is energy-dense—and can run for decades at high capacity. Operating and maintenance costs for nuclear are higher than for most renewable, and decommissioning old reactors requires large sums of money. Couple these costs with the decades-long construction timeline, and nuclear often loses out to cheaper, quicker-to-build alternatives in many markets.

Solar PV has seen the steepest cost decline of any energy technology in recent years. Ten years ago, installing utility-scale solar cost around 4,000 per kW; today, that figure often falls below 1,000 per kW in sunny regions with strong manufacturing infrastructure. The LCOE of utility-scale solar PV has fallen into the 25–40 per megawatt-hour (MW h) range in many parts of the world. In comparison, new natural gas combined-cycle plants cost around 45–75/MW h (depending on fuel prices), new coal plants cost 60–110/MW h, and new nuclear plants often fall between 110–200/MW h. These figures vary by region and depend on local financing terms, labor costs, and regulatory environments, but the clear trend is that solar is now cheaper than most new fossil fuel or nuclear generation in many places.

Solar operating costs are extremely low. Sunlight costs zero, and maintenance—cleaning panels and replacing inverters every 10–15 years—amounts to a fraction of a plant's overall budget. Meanwhile, fossil fuel plants must continuously purchase fuel on volatile markets, and nuclear plants need expensive safety inspections and periodic fuel purchases. The only significant ongoing cost for solar is occasionally replacing inverters and sometimes redeploying panels if they degrade unevenly; otherwise, panels produce power for two to three decades with minimal intervention.

4.2 Job Creation and Economic Growth

Transitioning to solar energy can spur local job creation and economic growth. Solar industry jobs include manufacturing panels and inverters, installing and maintaining systems, and providing sales and administrative support. Because PV panels can be installed quickly—sometimes within months—

TABLE 2. Levelized cost of electricity (LCOE) by energy source, 2024 estimates.

Energy Source	LCOE (USD/MWh)
Solar PV (Utility-scale)	25–40
Wind (Onshore)	30–60
Natural Gas (Combined Cycle)	45–75
Coal (with scrubbers)	60–110
Nuclear	110–200

solar project development creates a spike in construction jobs. Once operational, solar farms require relatively few workers, but the installation and maintenance workforce remains in demand. According to global renewable energy reports, the solar sector employed over 4 million people worldwide at the end of 2024, with a significant share in installation, which tends to be local by nature.

In contrast, fossil fuel industries once employed large numbers—coal miners, oil rig workers, refinery staff—but automation and resource depletion have reduced workforce size over time. While fossil fuel jobs often pay well and require specialized skills, many are in rural areas where alternative employment opportunities are limited. As automation increases, even fewer workers are needed in extraction and processing. Nuclear power provides high-skilled jobs for engineers, technicians, and safety personnel, but building a nuclear plant takes years, and many of the required skills are highly specialized. Additionally, decommissioning an aging reactor can employ workers for decades in cleanup operations.

In economic terms, solar energy also reduces money spent on imported fuels. Countries that rely heavily on imported oil or natural gas spend large portions of their budgets on fuel purchases—money that leaves the local economy. By installing domestic solar farms and rooftop panels, nations can retain capital, improve energy security, and protect consumers from fuel price spikes. Moreover, as solar manufacturing expands—especially in countries that build panels—local economies benefit from factory jobs, research and development facilities, and supply chain growth.

However, transitioning to solar also means phasing out fossil fuel industries, which requires policies to help displaced workers. Retraining programs, early retirement packages, and local economic development initiatives—such as encouraging solar panel assembly plants in former coal-mining regions—can help communities adapt. Without such support, regions dependent on coal, oil, or natural gas may struggle economically, leading to social and political resistance to renewable energy policies.

5. TECHNICAL CHALLENGES AND SOLUTIONS

5.1 Intermittency and Grid Reliability

A major technical hurdle for solar energy is its intermittency: the sun does not shine at night, and cloudy or rainy days reduce power output. In contrast, coal, natural gas, and nuclear plants can run continuously, providing baseload power—electricity that is always there, rain or shine. Grid operators must balance electricity supply and demand in real time; too much supply can overload the grid, while too little

causes outages. If a region relies heavily on solar without adequate backup, cloudy days or long winter nights (in higher latitudes) can create gaps between generation and demand.

To address this, energy storage technologies store excess solar power when generation exceeds demand, then release it when generation falls short. Lithium-ion batteries are the most widespread solution today. Utility-scale battery installations—sometimes paired with solar farms—can store several hours of electricity. For example, on a sunny afternoon, a 100-megawatt-hour (MWh) battery might charge fully; if nightfall arrives, that stored energy can power homes and businesses until sunrise. Falling battery costs—down more than 80 percent since 2010—make this increasingly feasible.

However, batteries alone may not cover multi-day cloudy periods, especially in winter. That is where combining solar with other renewables, like wind or hydropower, helps. Wind often blows strongest at night or in different seasons than peak solar, so a mix of wind and solar can smooth overall generation. Hydropower plants with reservoirs can adjust output to fill gaps, acting as natural batteries—releasing stored water to generate electricity when needed. In regions where hydropower or wind resources are limited, long-duration storage solutions—such as flow batteries or hydrogen—are under development. Flow batteries use liquid electrolytes in tanks, offering longer lifespans and easier scaling than lithium-ion, though at lower energy density. Producing hydrogen via electrolysis—splitting water into hydrogen and oxygen—allows storing renewable energy in chemical form. Later, hydrogen can be converted back to electricity in fuel cells or burned to produce heat and power. While promising, hydrogen storage currently has lower round-trip efficiency than batteries and higher costs, but research is ongoing.

Another way to handle intermittency is demand response: encouraging consumers to shift usage to times when electricity is abundant. For instance, electric vehicle (EV) owners could program their cars to charge midday when solar output peaks, rather than overnight when solar is off-line. Smart thermostats can cool or heat buildings slightly more when solar is plentiful, reducing load later. By flattening peaks in demand to align with solar generation, the grid operator needs less standby capacity from fossil fuel plants.

5.2 Manufacturing and Material Constraints

Although solar energy relies on nearly limitless sunlight, producing solar panels requires raw materials and energy. The most common PV panels use crystalline silicon wafers. Producing high-grade silicon involves heating sand (silicon dioxide) to very high temperatures in electric arc furnaces. Historically, those furnaces were powered by electricity from coal or natural gas, which means solar panel manufacturing emitted greenhouse gases. As manufacturing shifts to regions where electricity comes from renewable—like hydropower in parts of China or wind and solar in other countries—these life cycle emissions decrease.

Silver, used as a conductive metal in many PV cells, is finite. While the amount of silver per panel is relatively small (often just grams), global demand for silver also comes from electronics, jewelry, and industrial applications. To reduce reliance on silver, manufacturers are developing copper-

based contacts, which are more abundant and cheaper but technically more challenging to apply at scale without compromising efficiency. Some thin-film solar technologies avoid silicon altogether, using materials such as cadmium telluride (CdTe) or copper indium gallium selenide (CIGS). While these can be more material-efficient, they rely on elements like indium or tellurium, which are rarer than silicon. Many thin-film companies focus on optimizing material usage and recycling to ensure sustainable supply chains.

Once panels reach their end of life—typically 25 to 30 years after installation—they must be recycled or disposed of. Currently, recycling rates vary widely by region. In the European Union, regulations require solar panel manufacturers to take responsibility for panel disposal and recycling, leading to well-established recycling systems. Recycled panels can return glass (about 75 percent of a panel's weight), aluminum frames, and semiconductor materials to the manufacturing supply chain. In regions without strong regulations, panels sometimes end up in landfills. Expanding recycling infrastructure worldwide will be crucial as early generations of PV panels retire in the 2030s and 2040s. Proper recycling reduces waste, recovers valuable materials, and lowers the overall carbon footprint of solar over its life cycle.

6. SOCIAL AND POLICY CONSIDERATIONS

6.1 Public Acceptance and Community Engagement

Large-scale deployment of solar installations often requires buy-in from local communities. A utility-scale solar farm might cover tens or hundreds of acres. If that land was previously used for agriculture or was open habitat, some residents may object, worrying about impacts on property values, local ecosystems, or changes to rural landscapes. However, when communities understand the environmental benefits—such as reduced air pollution and job creation—they are more likely to support solar projects. In many cases, solar developers work directly with landowners, leasing land that is less suitable for crops, such as arid or semi-arid areas. Dual-use strategies—like “agrivoltaics,” where solar panels sit above grazing animals or shade-sensitive crops—allow land to remain productive while generating clean energy. In urban settings, rooftop solar installations do not require extra land; instead, they turn otherwise unused spaces into productive energy generators. Community solar programs let residents who cannot install panels on their own roofs (renters, apartment dwellers) buy or subscribe to a portion of a larger solar installation. In return, they receive credits on their electricity bills. This approach shares the benefits of solar—lower energy bills and cleaner air—among a broader group of people.

Perceptions of solar projects also hinge on aesthetics and wildlife concerns. Mounting panels slightly above ground allows native vegetation or grasses to grow underneath, preserving habitats for pollinators and small animals. In desert regions, careful siting of solar farms can avoid sensitive areas for threatened species, drawing on environmental impact assessments to guide placement. By involving local stakeholders early—through town hall meetings, transparent data sharing, and community benefit agreements—developers can address concerns and build trust, leading to smoother project approvals.

6.2 Policy Instruments and Incentives

Government policies and incentives have driven much of the world's shift toward solar energy. Feed-in tariffs (FITs), for example, guarantee a fixed, above-market price for electricity generated by solar for a set period (often 15–20 years). Early adopters in Germany saw generous FIT rates that made rooftop solar financially attractive, leading to rapid growth even in a country with only moderate sunlight. Those FITs gave small households and businesses a clear financial incentive to install panels; over time, as solar costs fell, FIT rates were gradually reduced, ensuring the market remained balanced.

Tax credits and rebates also lower upfront costs for solar installations. In the United States, the federal Investment Tax Credit (ITC) has offered a 26 percent tax credit for residential and commercial solar systems, substantially reducing the effective cost to consumers. Many states and local utilities add additional incentives—cash rebates or performance-based incentives—further cutting costs. Through net metering, residential solar owners can send excess electricity back to the grid and receive full retail value credits on their bills. This arrangement makes rooftop solar especially attractive, because households can offset electricity used at night or on cloudy days by banking credits earned during sunny afternoons. Some regions adjust net metering policies over time to reflect changing grid dynamics—reducing credit rates or capping enrollment—so policymakers must strike a balance between encouraging adoption and ensuring grid costs are fairly shared.

Renewable Portfolio Standards (RPS) require utilities to obtain a certain percentage of their electricity from renewable sources by specified deadlines. Utilities that miss those targets pay penalties or must purchase renewable energy credits (RECs). By setting progressive RPS targets—say, 30 percent renewable energy by 2030—governments create a steady demand for new solar and wind capacity. Another policy tool is carbon pricing—either through a carbon tax or cap-and-trade system. By putting an explicit price on carbon emissions, fossil fuel-based electricity becomes more expensive, making solar even more cost-competitive. Carbon pricing also encourages energy efficiency, electrification of transportation, and research into low-carbon technologies.

For solar to replace nuclear and fossil power, governments and regulators must design policies that level the playing field. That means placing realistic value on solar environmental benefits, ensuring fair compensation for grid services (such as voltage regulation), and removing subsidies that disproportionately favor fossil fuels. Transparency in permitting processes, streamlined interconnection rules, and standardized building codes for rooftop solar installations all help drive deployment by reducing bureaucratic hurdles and costs.

7. CASE STUDIES AND REGIONAL VARIATIONS

7.1 Germany's Solar Success

Despite receiving less sunshine than many regions, Germany became a global leader in solar energy over the past two decades. Beginning in 2000, Germany's renewable energy feed-in tariff (EEG) guaranteed homeowners and businesses a high, fixed payment for every kilowatt-hour of so-

lar electricity they generated. This stable, predictable incentive spurred massive investment in rooftop solar panels and small ground-mounted systems. By 2024, Germany had installed over 60 gigawatts (GW) of solar capacity—enough to supply more than 10 percent of its annual electricity demand. German households and citizen cooperatives played a major role, collectively owning a significant share of solar installations.

However, rapid growth presented challenges: the electric grid, originally designed for large power plants in fixed locations, struggled to handle sudden surges of solar power on sunny days. During spring weekends with mild temperatures and high sunlight, solar generation sometimes exceeded local demand, forcing grid operators to temporarily curtail (shut down) solar plants to maintain stability. To address this, Germany invested heavily in grid modernization—installing sensors, automated controls, and expanding interconnections with neighboring countries so excess solar power could flow to France, Austria, or the Czech Republic. Germany also increased incentives for battery storage, encouraging homeowners to pair solar panels with home batteries to use more of their own generation. Today, Germany's success demonstrates that even in less-than-ideal climates, strong policy support, community engagement, and grid upgrades can allow solar to flourish.

7.2 China's Manufacturing and Deployment Scale

China dominates global solar manufacturing, producing more than 70 percent of the world's solar panels as of 2024. Decades ago, the Chinese government directed resources toward building large-scale factories that benefit from economies of scale, resulting in extremely low panel costs—often 30–40 percent below those of competitors. At the same time, China's central and provincial governments offered subsidies, low-interest loans, and favorable land leases to developers to build utility-scale solar farms in sun-rich provinces such as Inner Mongolia, Xinjiang, and Qinghai. By 2024, China had installed over 350 GW of solar capacity—more than any other country. That accounts for around 10 percent of the country's electricity generation. In addition, China aggressively expanded its domestic manufacturing of batteries, inverters, and other solar components, creating a vertically integrated industry that lowered costs further.

However, China's rapid deployment occasionally outpaced grid expansion. In some sunny regions, transmission lines were insufficient to carry all solar power to eastern population centers. During peak production, installers reported "curtailment" rates of 10–15 percent—meaning that fraction of solar output was wasted because there was nowhere to send it. In response, China invested billions in ultra-high-voltage (UHV) transmission lines to connect western solar-rich provinces with eastern industrial hubs. Simultaneously, policies shifted to encourage distributed solar installations—rooftops on factories, schools, and homes—reducing the need for long-distance transmission. China's experience shows that while manufacturing scale can drive down global solar costs, matching that deployment with equally robust grid and storage investments is essential to minimize wasted energy.

7.3 United States: Diverse Policies and Growth

In the United States, solar adoption varies widely by state, driven by differences in state-level incentives, net metering rules, sunshine levels, and electricity prices. California, blessed with abundant sunshine and high electricity rates, leads the nation: by 2024, the state had over 40 GW of installed solar capacity, enough to generate about 25 percent of its electricity from solar during peak daytime hours. California’s success stems from a mix of strong state policies—such as a 50 percent Renewables Portfolio Standard by 2030—and generous net metering rules that credit rooftop solar owners at full retail rates. Texas, another solar leader, experienced rapid growth in recent years thanks to declining solar costs, high summertime electricity prices, and supportive competitive market structures for utilities. Meanwhile, states like Florida and North Carolina have seen growth driven by tax incentives and strong sunlight, though they often lag behind California in per-capita adoption.

Federal incentives also play a role. The U.S. Investment Tax Credit (ITC) offers a 26 percent tax credit for residential and commercial solar installations through 2024, stepping down to 22 percent in 2025. This policy encourages homeowners and businesses to invest in solar, but because it is tied to federal tax liability, low-income households with little tax liability may receive less benefit. That is why many states and utilities supplement the ITC with rebates or performance-based incentives to ensure broad access.

Grid integration strategies differ as well. California’s “duck curve” phenomenon—where midday solar surges are followed by steep ramps in late afternoon as solar output drops—is managed through a combination of utility-scale battery deployment, demand response programs (incentivizing customers to shift usage toward midday), and flexible gas-fired plants that can ramp output quickly. In contrast, the U.S. Midwest, with relatively low solar adoption, relies more on wind power for daytime generation and thus sees less extreme swings. Across the country, pilot programs for virtual power plants—aggregating home solar and battery systems into a coordinated network—are beginning to emerge. These VPPs can sell energy or grid services back to utilities, helping stabilize supply and potentially earning revenue for homeowners.

Together, these case studies underscore that while solar energy can scale rapidly under supportive policies, each region must address technical, economic, and social factors tailored to local conditions. No one-size-fits-all solution exists, but common themes—strong policy incentives, grid upgrades, storage integration, and community engagement—recur in successful solar markets.

8. FEASIBILITY OF A LARGE-SCALE TRANSITION

8.1 Scenarios for Replacing Fossil Fuels and Nuclear

Researchers have modeled scenarios in which solar energy, combined with other renewables, displaces fossil fuels and nuclear power by mid-century. One ambitious scenario envisions that by 2050, the global electricity system relies predominantly on solar photovoltaic and solar thermal plants, backed by wind power, hydropower, geothermal, and substantial energy storage. Key assumptions in these models include continued rapid declines in solar and battery costs,

TABLE 3. Global solar deployment overview in selected countries (2024).

Country	Installed Capacity (GW)	Key Policies	Challenges
Germany	60	Feed-in Tariffs, Net Metering	Grid saturation, seasonal mismatch
China	350+	Subsidies, manufacturing incentives	Curtailement, transmission limits
United States	120+	Investment Tax Credit, RPS targets	Uneven policy, “duck curve” issues

large-scale grid expansion to connect sunny regions with demand centers, and significant policy support—carbon pricing, renewable mandates, and RD funding.

In such a scenario, land requirements for solar panels are often cited. Estimates suggest that covering roughly 0.3 percent of the world’s land surface with solar arrays could generate enough electricity to meet current global demand. While 0.3 percent seems small, that still translates to many millions of acres. In practice, much of this land could come from deserts, brownfields (old industrial sites), rooftops, and other underutilized areas. Siting solar on already disturbed or marginal lands—rather than cutting down forests or converting prime farmland—reduces ecological impacts. Moreover, agrivoltaic systems, which combine agriculture and solar (for example, raising sheep or planting shade-tolerant crops under panels), can make dual use of land, improving land productivity without sacrificing food production.

Large-scale storage is another necessity. To cover nights, multi-day cloudy spells, and seasonal variations, models often assume hundreds of gigawatt-hours (GWh) of battery storage capacity and thousands of GWh of long-duration storage by 2050. While lithium-ion batteries will cover much of short-duration needs (4–10 hours), flow batteries and hydrogen storage are projected to fill longer gaps. For hydrogen, excess solar electricity powers electrolyzers that split water into hydrogen and oxygen. The hydrogen is stored—either as compressed gas, liquid, or bound into ammonia—and can later be used in fuel cells or burned in turbines to generate electricity. Although round-trip efficiency (electricity-to-hydrogen-to-electricity) is lower than batteries, hydrogen is well suited for seasonal storage because it can be stored in salt caverns or large tanks at relatively low cost per unit of energy compared to batteries.

Grid upgrades are central to any large-scale transition. Today’s electric grids, especially in developing countries, often struggle with integrating variable renewable. In advanced economies, grids typically run on a top-down model: large centralized power plants (coal, natural gas, nuclear) send electricity through high-voltage transmission lines to substations, then distribution lines, and finally to homes and businesses. A solar-dominated grid flips this model: countless small-scale systems (rooftop solar, small community solar arrays) plus large utility-scale farms all feed into the grid in a more distributed fashion. To manage this complexity, grid operators need advanced sensors, real-time communication systems, and automated controls—collectively known as a “smart grid.” Smart inverters on solar installations can

help regulate voltage and frequency, smoothing out fluctuations. Advanced forecasting—predicting solar and wind outputs hours or days ahead—gives grid operators more time to plan dispatch, reducing reliance on fossil fuel peaker plants.

8.2 Mixed Renewable Portfolios

Rather than relying entirely on solar, many experts argue that the most feasible path to a low-carbon electricity system is a diverse renewable portfolio. Each renewable source brings a different generation profile: solar peaks at midday and in summer; wind often generates more at night and can be stronger in winter; hydropower is dispatchable but limited by rainfall and reservoir levels; geothermal can supply steady baseload; bioenergy is flexible but faces competition with food production for land. By blending these sources, the need for storage and backup can be significantly reduced.

For instance, in parts of the United States, a combination of solar, wind, hydropower, and battery storage can meet over 90 percent of electricity demand reliably. Wind often picks up when solar declines in the evening. Hydropower reservoirs can be managed to fill short-term gaps. Geothermal plants, though small in capacity compared to solar or wind, provide steady power. Bioenergy can run on demand to cover unexpected dips. This diversified approach minimizes the vulnerability to weather patterns or seasons. Regions with less hydropower potential but strong wind resources (such as the Great Plains or northern Europe) can pair wind and solar more heavily, while tropical regions may rely more on solar and hydropower.

A fully 100 percent solar grid by 2050 is technically possible in some regions—especially those with extremely high solar potential and vast areas of unpopulated land, such as parts of North Africa, the Middle East, or Australia—transmitting power via high-voltage transmission lines to population centers. But most studies agree that a combination of solar plus wind, hydro, geothermal, and effective storage is more practical and cost-effective. For example, a 2023 study by a leading energy research institute modeled Australia's grid if 95 percent of electricity came from renewables: 60 percent solar, 30 percent wind, and 5 percent hydro—with batteries and pumped hydro filling gaps. The study found that total system costs were similar to those of continuing to run coal and gas plants with carbon capture, but with much lower emissions and health costs.

9. ADVANTAGES AND LIMITATIONS OF REPLACING FOSSIL AND NUCLEAR

9.1 Advantages of Solar Over Fossil Fuels

Solar energy offers several clear benefits compared to fossil fuels. First, it drastically reduces greenhouse gas emissions; after panels are manufactured and installed, the electricity they generate has almost zero carbon footprint. This mitigates climate change, which is already causing more extreme weather, sea-level rise, and biodiversity loss. Second, solar power improves local air quality: no sulfur dioxide, nitrogen oxides, or fine particulates are emitted during operation, reducing respiratory illnesses and healthcare costs. Third, because sunlight is freely available nearly everywhere, countries can reduce dependence on imported fuels. This enhances energy security and shields consumers from

volatile fossil fuel prices, which can spike due to geopolitical tensions or natural disasters. Solar also hedges against fuel price volatility: once a panel is installed, there is no fuel cost—unlike coal or natural gas plants, which must continuously purchase fuel on international markets. Finally, solar systems can be deployed incrementally: homeowners, businesses, or communities can install small rooftop systems, gradually adding capacity without the need for large centralized projects.

9.2 Advantages of Solar Over Nuclear

While both solar and nuclear power produce minimal operational emissions, solar holds advantages in terms of safety, waste, deployment speed, and scalability. Nuclear reactors carry the risk—albeit small—of catastrophic accidents. Even highly regulated plants can suffer unforeseen problems, such as equipment malfunctions or natural disasters. Solar panels pose no risk of radiation release. In terms of waste, nuclear reactors produce spent fuel that remains dangerously radioactive for thousands of years. Managing and storing this waste safely is a political and technical challenge; many countries have yet to establish long-term repositories. In contrast, end-of-life solar panels contain no radioactive material. Though they require recycling to manage materials—and recycling systems must still expand—solar panels do not pose a hazard to communities.

Deployment speed is another important difference. Building a large nuclear power plant can take a decade or more, requiring billions of dollars in financing, extensive regulatory reviews, and long construction times. A utility-scale solar farm can often be built in under a year, depending on permitting. Rooftop solar installations can be completed in weeks. This speed makes solar an attractive option for rapidly scaling clean energy, particularly in regions where immediate reductions in emissions are needed for air quality or climate goals. Solar is also highly scalable: it can be installed at many scales, from small off-grid systems in remote villages to massive desert farms that supply electricity to entire cities. Nuclear power, by contrast, is inherently large-scale—reactors typically generate hundreds to thousands of megawatts each, which may be too much for smaller grids or remote communities.

9.3 Limitations and Concerns

Despite its many advantages, solar energy faces limitations. The most commonly cited is intermittency: solar only generates electricity when the sun shines. While energy storage and diversified renewable mixes help mitigate this, they add complexity and additional costs. In regions with long, dark winters (such as Northern Europe or high-latitude North America), solar output drops significantly for months at a time, making it harder to rely on solar as a primary source without massive storage or import capacity.

Land use is another concern. Utility-scale solar farms covering thousands of acres can compete with agriculture, natural habitats, or recreational areas. Strategically, most large solar projects are sited on deserts, brownfields, or marginal cropland to minimize conflicts. Rooftop solar, while mitigating land concerns, is limited by roof orientation, shading, and available area. Not every building has a suitable roof

TABLE 4. Comparison of solar PV, fossil fuels, and nuclear energy across major criteria.

Criteria	Solar PV	Fossil Fuels / Nuclear
Lifecycle Emissions (gCO ₂ e/kWh)	20–60	450–820 (Fossil), ~12 (Nuclear)
Fuel Cost	None (sunlight is free)	High (fossil), Low (nuclear)
Deployment Time	Months (scalable)	1–3 years (fossil), 10+ years (nuclear)
Waste Profile	Low; recyclable	Toxic (fossil), radioactive (nuclear)
Safety Risk	Negligible	Pollution (fossil), radiation (nuclear)
Scalability	High (modular)	Medium to low

for solar, and urban density can constrain rooftop potential.

Material supply and manufacturing capacity also pose challenges. Producing the billions of panels needed to replace fossil and nuclear capacity requires vast quantities of silicon, glass, aluminum, and sometimes rare elements like silver, indium, or tellurium. While silicon is abundant, refining it into purified wafers is energy-intensive. Taller supply chain bottlenecks—shortages of polysilicon, shipping delays, or trade restrictions—could slow deployment. Addressing these concerns involves diversifying supply chains, investing in new manufacturing facilities, and developing recycling programs to recover materials from decommissioned panels.

Upfront costs remain a barrier in many developing countries. Even though solar's leveled cost is low, installing a system requires paying 100 percent of the capital cost upfront or securing a loan. Low-income households and communities may lack access to financing or face high interest rates, preventing broader adoption. International development agencies and multilateral banks can help by providing low-cost loans or grants to establish solar capacity in regions without reliable electricity. Innovative business models, such as pay-as-you-go solar and solar leasing, also help low-income customers access solar without large upfront payments.

10. POLICY RECOMMENDATIONS AND STRATEGIES

Drawing on the environmental, economic, technical, and social analyses above, we offer the following policy recommendations and strategies to facilitate the transition from fossil fuels and nuclear power to solar energy:

Prioritize Continued Cost Reductions and Technological Innovation

Governments, academic institutions, and private companies should sustain and increase funding for research and development focused on solar cell materials, panel efficiency, and manufacturing processes. Simplifying permitting for new factories, supporting pilot projects for advanced technologies (perovskite cells, multijunction cells, next-generation inverters), and encouraging public-private partnerships will help drive breakthroughs that lower costs and increase performance. Bulk procurement and standardization of solar equipment can also help reduce prices by creating economies of scale.

Expand Energy Storage and Grid Infrastructure

To address solar's intermittent nature, policymakers must support both short-duration (batteries) and long-duration (flow batteries, pumped hydro, hydrogen) storage solutions. This can include grants, low-interest loans, or tax credits for utility-scale and behind-the-meter storage installations. Simultaneously, investment in smart grid technologies—advanced sensors, automated controls, real-time communication networks—will allow operators to balance variable solar and wind inputs more effectively. In regions with high solar potential in remote areas, building high-voltage transmission lines ensures that generated electricity can reach population centers. Interregional and international grid interconnections also help balance supply and demand across wider geographic areas.

Reform Market and Regulatory Structures

Policymakers should design electricity markets that reward flexibility and clean energy. This includes time-of-use pricing (charging more for electricity during peak demand and less during surplus solar generation), fair compensation for grid services that solar and storage can provide (frequency regulation, voltage support), and carbon pricing to internalize the external costs of fossil fuel pollution. Reforming net metering policies to reflect the evolving value of distributed solar—while maintaining incentives for residential owners—will help maintain grid cost recovery and fairness. Renewable Portfolio Standards (RPS) or clean energy standards mandating that utilities source a specific percentage of power from renewables—ideally with gradually increasing targets—provide long-term market certainty for investors.

Promote Social Equity and Workforce Transition

As fossil fuel plants and nuclear reactors retire, investments must be made in “just transition” programs to retrain and place displaced workers into solar, storage, and grid modernization jobs. These programs can include vocational training, apprenticeships in solar installation and maintenance, and relocation assistance. To ensure low-income households benefit from solar, governments can provide targeted incentives—such as grants or low-interest loans—for rooftop installations, or support community solar projects where participants pay minimal upfront costs and receive electricity bill credits. Engaging local communities early in project planning—through town halls, stakeholder committees, and transparent environmental assessments—helps build trust and avoids conflict. Revenue-sharing models, where a portion of solar farm profits return to local governments or community funds, can further increase support.

11. FUTURE DIRECTIONS AND RESEARCH NEEDS

Advanced Solar Cell Materials

Perovskite solar cells have shown lab efficiencies above 25 percent, rivaling crystalline silicon. However, they currently face stability issues (degrading after a few years) and concerns about lead content. Research should focus on improving durability, developing lead-free perovskites, and scaling manufacturing. Multijunction cells—stacking layers of different materials to capture more of the solar spectrum—offer

higher efficiencies but at greater complexity and cost. Continued work on making these cells cost-competitive could open new markets, such as space-based solar or specialized applications.

Long-Duration Energy Storage

As solar expands, the need for months-long storage—bridging seasonal variations—becomes more pressing. Hydrogen produced via electrolysis is a leading candidate, but current technology has round-trip efficiency of only 30–40 percent (electricity-to-hydrogen-to-electricity). Research to improve electrolyzer and fuel cell efficiency, reduce costs, and develop safe, large-scale hydrogen storage (such as underground salt caverns) will be crucial. Other technologies—like advanced flow batteries using organic or aqueous chemistries—could offer longer cycle life and lower costs for multi-day storage. Continued demonstration projects at utility scale will drive down costs and improve reliability.

Grid-Scale Innovation

As distributed solar grows, virtual power plants (VPPs) and microgrids become essential. A VPP aggregates many small resources—rooftop solar, home batteries, electric vehicles—into a coordinated portfolio that can bid into wholesale markets or provide grid services such as frequency regulation. Pilot projects in several U.S. states and Europe have shown that VPPs can help balance supply and demand and defer costly transmission upgrades. Microgrids—self-contained localized energy systems—can provide resilience for hospitals, military bases, or remote communities, operating independently of the main grid during outages. Research into the economics, control algorithms, and policy frameworks for VPPs and microgrids will help scale these innovations.

12. CONCLUSION

Solar energy stands out as a transformative technology that can significantly reduce reliance on fossil fuels and nuclear power. By tapping into the sun's virtually limitless energy, solar photovoltaic and solar thermal systems generate electricity with minimal greenhouse gas emissions, no air pollution during operation, and no long-lived radioactive waste. Over the past decade, rapid cost declines have made solar one of the most competitive sources of new electricity, frequently undercutting the costs of building and operating new coal, natural gas, or nuclear plants. Additionally, solar installations create local jobs in manufacturing, installation, and maintenance, while decentralizing electricity generation—empowering homeowners, businesses, and remote communities to produce their own power.

However, replacing fossil fuels and nuclear with solar requires overcoming several challenges. Solar's intermittent nature demands robust energy storage solutions and grid modernization. Land-use concerns and supply chain constraints—especially for materials like silicon, silver, and specialized semiconductors—necessitate careful planning, innovative manufacturing, and recycling programs. Upfront financing barriers must be addressed through incentives, low-interest loans, and community solar models that broaden access. Policymakers must implement clear, long-

term strategies: carbon pricing, renewable portfolio standards, feed-in tariffs or tax credits, and reforms to net metering and interconnection rules. These policies should be designed to ensure social equity, helping displaced workers from declining fossil fuel or nuclear sectors transition to careers in solar and storage.

Case studies from Germany, China, and the United States demonstrate that when strong policies, community engagement, and grid investments align, solar energy can scale rapidly—even in regions with moderate sunlight. A complete 100 percent solar grid may be most feasible in areas with vast unoccupied land and high solar irradiance. In most regions, however, a diverse renewable portfolio—combining solar with wind, hydropower, geothermal, and long-duration storage—offers the most reliable and cost-effective path to a low-carbon electricity system.

Looking ahead, continued research and development in advanced solar materials, long-duration storage (such as hydrogen and flow batteries), grid-scale innovations like virtual power plants and microgrids, and socioeconomic studies to ensure equitable transitions will pave the way for a solar-driven future. By integrating these technological advances with thoughtful policies and financing mechanisms, the world can achieve a sustainable energy system that meets growing demand while drastically cutting emissions. In doing so, solar energy can replace the polluting legacy of fossil fuels and address the safety and waste concerns of nuclear power—offering cleaner air, a healthier climate, and lasting economic benefits for communities worldwide.

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Competing Interests

The author, Abhinav Sharma, declares that there are no financial, professional, or personal relationships that could be perceived as potential competing interests relevant to the submitted work. The research conducted under **Project NFuse** was carried out independently, with no external financial backing or collaboration that would influence the design, data collection, analysis, or manuscript writing process. There are no conflicts of interest with any funding organizations, publishers, or other entities associated with this work. Should any competing interests arise in the future, the author is committed to updating this declaration in accordance

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