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Evaluation of Solar and Wind Energy for Efficiency, Carbon Reduction, and Environmental Protection in Azerbaijan

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Abstract. As climate change intensifies, renewable energy sources such as solar and wind offer critical pathways to increase energy efficiency, reduce carbon emissions, and protect the environment. Globally, the cost of solar photovoltaic (PV) and wind power has plummeted in the past decade, making these technologies increasingly cost-competitive. Wind and solar generation produce virtually no greenhouse gases or air pollutants during operation, displacing dirtier fossil fuels and yielding substantial climate and health co-benefits. In Azerbaijan, an oil and gas-based economy with modest recent progress in renewables, the solar and wind potential is enormous. This article reviews recent scientific and policy literature (2015-2025) on alternative energy, focusing on solar and wind in Azerbaijan. Using a systematic analysis of publications and data sources, we assess technology performance, life-cycle emissions, and ecosystem impacts. The findings show that solar and wind power have far lower carbon footprints than coal or natural gas, and their deployment can sharply cut air pollution. Energy payback for PV occurs within a few years of operation. We also identify challenges such as land use, intermittency, and waste management, concluding that with supportive policies and grid planning, Azerbaijan can harness solar and wind to meet its energy needs more sustainably.

Keywords: renewable energy; energy efficiency; carbon footprint; solar power; wind energy

1. Introduction

Energy production and consumption account for the majority of global greenhouse gas (GHG) emissions and environmental impacts. In recent years the world has seen

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an unprecedented expansion of solar photovoltaic (PV) and wind power: costs have fallen dramatically and capacity has surged. Between 2010 and 2020, installed costs for utility-scale solar PV dropped by about 81%, and wind turbine costs also fell substantially, driving levelized cost of electricity (LCOE) declines of up to ~85% for solar and ~56% for onshore wind (IRENA, 2021). By 2020, renewables (including hydro) supplied roughly 29% of global electricity generation, up ~2% from the prior year (IEA, 2021). These market trends reflect technological learning curves (more efficient panels and turbines) and economies of scale. Equally important are environmental benefits: unlike coal or gas plants, solar and wind generation emit essentially no CO_2 or pollutants during operation (U.S. EIA, 2024; U.S. EIA, 2022). Consequently, adding renewables to a grid directly displaces combustion-based generation, yielding large avoided emissions and health benefits (Millstein et al., 2017). Analysis indicates that U.S. wind and solar growth since 2007 has prevented thousands of pollution-related deaths and delivered climate benefits on the order of billions of dollars (Millstein et al., 2017). In short, solar and wind are among the cleanest and fastest-deploying sources of electricity (DOE, 2017; Millstein et al., 2017).

Azerbaijan provides an instructive case study. Rich in oil and gas resources, the country's economy has long depended on hydrocarbon exports (roughly 87% of export earnings) and oil revenues (crudeaccountability.org, 2025). Domestic power generation is currently dominated by gas- and oil-fired plants. However, reserves are finite (BP's 2020 data suggest only ~24 years of oil and ~117 years of gas left at current production rates), and Azerbaijan is vulnerable to climate change impacts in the region. The government has recognized the need for diversification. In 2019 the Ministry of Energy and IRENA conducted a Renewables Readiness Assessment (RRA) for Azerbaijan, noting the country's *"excellent wind and solar resources"* and the socio-economic and low-carbon advantages of a renewable-based system (IRENA, 2019). Yet actual deployment has lagged: by 2014 only about 0.4 GW of wind capacity and a few dozen megawatts of solar PV were installed (Mustafayev et al., 2022). Domestic policies are evolving, but investor and bureaucratic barriers remain. Nonetheless, Azerbaijan has set goals (e.g. a 30% share of renewables in electricity by 2030) and announced projects (e.g. a 240 MW solar plant, and contracts totaling 6 GW of renewables by 2030 as per Aliyev, 2025) to tap its clean energy potential.

This review proceeds from general to specific. We first outline the fundamentals: solar and wind conversion efficiency, cost trends, and life-cycle carbon footprints, drawing on the latest literature. We then focus on Azerbaijan: assessing its solar insolation and wind resources, current energy mix, and national policies. The article draws on scientific studies, agency reports, and statutory data from the past decade (2015-2025) to ensure up-to-date analysis. By comparing renewable alternatives to conventional sources on efficiency (energy delivered per input), emissions (CO_2-

equivalent), and broader environmental impacts (water use, land use, pollution), we evaluate the potential benefits and constraints of a green energy transition in Azerbaijan.

2. Methodology

This study synthesizes findings from peer-reviewed publications, institutional assessments, and technical reports relevant to renewable energy performance and impacts. We conducted a literature review of scientific articles (2015-2025) on solar PV and wind technologies, energy efficiency, carbon emissions, and environmental effects. Key databases (Web of Science, Scopus) and agency websites (IRENA, IEA, EIA, etc.) were searched using combinations of terms such as “solar energy efficiency,” “wind carbon footprint,” and “renewable energy Azerbaijan.” Inclusion criteria emphasized recent data and relevance to energy generation and environmental metrics. For Azerbaijan-specific context, we analyzed national energy statistics (from the State Statistics Committee and Ministry of Energy) and country studies (e.g. IRENA’s RRA). Technical parameters—such as capacity factors, levelized costs, and life-cycle emissions—were extracted from review articles and reports (e.g. IRENA cost reports, IEA reviews, and systematic assessments).

To illustrate and compare resource availability, we tabulated technical potential estimates alongside current installed capacity. Table 1 (below) summarizes resource potentials from the IRENA (2019) assessment and other sources. We also compiled data on GHG emissions and pollutants by fuel type (from IPCC and national inventories) for comparison. Although this is not an experimental study, the methodology follows a systematic-review approach: qualitative synthesis supplemented by quantitative tables and examples. All values and claims are referenced to their original sources.

3. Findings

3.1. Energy Conversion Efficiency and System Performance

Solar PV and wind turbines convert natural inputs (sunlight, wind) directly into electricity without combustion. Typical modern PV panels achieve conversion efficiencies of ~15–22% under standard conditions, while large horizontal-axis wind turbines convert ~30–50% of wind kinetic energy into electricity (IEA, 2021). Although these percentages may seem modest, in practice solar and wind systems can operate more efficiently than many thermal plants because they avoid energy losses associated with heat engines. Furthermore, offshore wind turbines and large solar farms can achieve high capacity factors (actual output vs. maximum possible), especially in resource-rich sites. For example, sites in Azerbaijan's Caspian Sea region show mean annual wind speeds favorable for offshore projects (Azerbaijan RE Agency, 2025). Under such conditions, wind farms can supply power consistently, reducing the need for fuel.

Economically, solar and wind have become extremely efficient in cost terms. Global average LCOEs for solar PV and onshore wind are now often below those of new coal or gas plants (IRENA, 2021). This reflects sharp declines in equipment and installation costs: by 2020, utility-scale solar PV cost ~US$0.057/kWh and onshore wind ~US$0.039/kWh—85% and 56% below their 2010 levels, respectively (IRENA, 2021). In Azerbaijan's context, several large-scale solar and wind projects have been planned to leverage this cost parity. For example, current tenders and contracts signed by the Ministry of Energy include 760 MW of PV solar in Jabrayil and plans for wind farms (Touriño Jacobo, 2024). Efficient deployment also depends on grid integration; experts recommend upgrading transmission and adopting smart controls to accommodate variable renewables (IRENA, 2019).

3.2. Carbon Footprint and Emissions Reduction

The carbon footprint of energy sources is commonly assessed over their entire life cycle. By this metric, solar and wind power have extremely low GHG emissions per unit of electricity. A synthesis of multiple life-cycle studies by the IPCC (AR5, 2014) found that wind power typically emits on the order of 10–15 gCO_2-eq/kWh (median), and solar PV on the order of 40–50 gCO_2-eq/kWh (depending on technology and location), whereas coal and natural gas emit ~800–1000 and ~400–500 gCO_2-eq/kWh, respectively (IPCC, 2014 in Edenhofer et al., 2014). Recent analyses have reinforced that renewable technologies now stand at the bottom of the emissions chart. For instance, onshore wind turbines are often cited around 7–12 gCO_2/kWh and utility-scale PV around 40–60 gCO_2/kWh (Millstein et al., 2017; EIA, 2024).

In practical terms, using solar or wind in place of fossil generation cuts carbon output nearly one-to-one. During operation, solar panels and wind turbines emit virtually zero CO_2, methane, or other pollutants. As noted by the U.S. Energy Information Administration, *"Solar energy technologies and power plants do not produce air pollution or greenhouse gases when operating"* (EIA, 2024, p. 613). Similarly, *"Wind turbines do not release emissions that can pollute the air or water… and they do not require water for cooling. Wind turbines may also reduce electricity generation from fossil fuels, which results in lower total air pollution and carbon dioxide emissions"* (EIA, 2022, p. 615). These operational benefits accrue immediately: each kilowatt-hour from renewables directly offsets combustion of coal or gas and the associated CO_2.

Moreover, beyond direct CO_2, reduced fossil use also means lower emissions of NOx, SO_2, and particulates, improving air quality (Millstein et al., 2017). DOE-funded analysis in the U.S. found that wind and solar deployment from 2007-2015 yielded cumulative public health savings of tens of billions of dollars and climate benefits in the multi-billion-dollar range, primarily by avoiding pollution (Millstein et al., 2017). In Azerbaijan, where fossil-based power emits substantial local pollutants (including methane from gas flaring, plus CO_2 from combustion), replacing even a portion of generation with solar and wind would meaningfully improve the carbon footprint of the energy sector. For example, a government analysis indicated that adding new solar projects (together producing ~268 million kWh/year) could save ~59 million m^3 of natural gas and avoid roughly 128,000 tonnes of CO_2 annually (Aliyev, 2025).

The construction and manufacturing phases of renewable plants do entail some emissions (steel, cement, silicon, etc.), but these are recovered quickly. The "energy payback" for PV systems—the time to generate as much energy as was used to build them—is typically 1-4 years (EIA, 2024). Over a 25-30 year lifetime, the net GHG impact remains minimal. In sum, solar and wind have orders of magnitude lower carbon footprints than conventional plants, making them excellent options for carbon reduction targets.

4. Environmental Impacts and Protection

Solar and wind also offer environmental advantages. Unlike coal or gas plants, neither solar fields nor wind farms require fuel extraction, water cooling, or fuel transportation once built, greatly reducing ecosystem disturbance and water use. The U.S. EIA notes that wind turbines use *"no water for cooling"* and have minimal landscape footprint per unit power (EIA, 2022, p. 615). Land-based wind farms do occupy land but typically allow dual use (e.g. grazing or even some agriculture under the turbines) and only about 1-2% of the area hosts physical infrastructure (DOE, 2017). Utility-scale solar farms require clearing of land but can be sited on degraded or low-value lands, and they often provide shade benefits or dual use (e.g. agrivoltaics).

Potential negative impacts of renewables are generally manageable. Solar panel manufacture involves some toxic chemicals, and blade and panel disposal pose issues (EIA, 2024). Wind turbines can cause bird or bat mortality and produce noise; however, these effects are relatively small compared to other anthropogenic threats (EIA, 2022). Both industries are investing in mitigation (recycling technology for blades and panels, bird-friendly site design). In contrast, fossil fuel extraction (drilling, mining, flaring) causes air and water pollution, land subsidence, and spills. By shifting away from oil and gas, Azerbaijan would also reduce hazards from its oil fields and gas flares. Ibadoghlu (2025) notes that a record volume of gas was flared at one terminal in 2024, emitting large quantities of CO_2 and methane. Solar and wind power would eliminate such flaring emissions entirely.

Overall, replacing a coal/gas plant with a solar or wind plant typically reduces local environmental stressors. The IRENA RRA for Azerbaijan concluded that a renewables-based system *"would offer socio-economic benefits, introduce innovative technologies, and provide viable low-carbon solutions"* (IRENA, 2019, p. 120). In other words, the combined effect of solar and wind deployment is markedly more benign on ecosystems than continuing heavy hydrocarbon dependence.

5. Azerbaijan-Specific Findings

Our synthesis indicates that Azerbaijan has particularly strong technical potential for solar and wind. The sunbelt of central Azerbaijan receives high insolation (akin to Mediterranean levels), making it suitable for PV farms. IRENA (2019) estimated the country's *technical* solar PV potential at ~23,040 MW and onshore wind at ~3,000 MW (Table 8, Mustafayev et al., 2022). Offshore, the Caspian Sea has vast wind resources: the Azerbaijani sector of the sea is preliminarily assessed to hold ~157,000 MW of wind potential (Azerbaijan Renewable Energy Agency, 2025). In Table 1 we summarize these figures alongside current capacities. Even conservative deployment of a few GW of renewables would dramatically cut fuel use and emissions.

Table 1. Renewable resource potentials vs. installed capacity in Azerbaijan

Resource	Technical Potential (MW)	Current Installed (MW)
Solar PV (onshore)	23,040	~50 (solar PV, mostly small)
Wind (onshore)	3,000	~403 (by 2014, mostly Khizi)
Wind (offshore, Caspian)	157,000	0 (no offshore farms yet)
Biomass/Bio-waste	380	~0 (unused)
Small Hydropower	520	Minimal

Sources: IRENA (2019, via Mustafayev et al., 2022); Azerbaijan RE Agency (2025); national statistics.

Currently, Azerbaijan's power system (total ~8.4 GW as of 2024) derives only a small fraction from renewables. Aside from large hydro plants (e.g. 402 MW Shamkir HPP), the only solar/wind projects until recently were pilot and off-grid installations. For example, an onshore wind farm (Khizi) installed about 50 MW by 2013, and off-grid solar is on the order of tens of MW (Mustafayev et al., 2022). This is well below the potential. By contrast, government announcements indicate contracts for several gigawatts of new solar and wind by 2030 (Aliyev, 2025).

In terms of energy efficiency, integrating renewables can also indirectly improve system efficiency. Decentralized solar PV (e.g. rooftop, farms near load centers) reduces transmission losses. Less fuel combustion means less waste heat and lower thermal pollution. Moreover, renewables can complement efficiency measures: for instance, solar water heaters or wind-driven irrigation pumps reduce electricity needs from the grid. We found that technical studies in Azerbaijan emphasize hybridizing renewables with efficiency programs (Sagheb, 1994; Energy Agency reports). Although quantitative data on efficiency gains is limited, it is clear that switching to renewables allows more end-use energy to go into useful work (lighting, motors) rather than being lost as CO_2/heat.

Finally, the carbon reduction potential is stark. If Azerbaijan replaces even 10% of its electricity from gas with wind/solar, it would cut millions of tonnes of CO_2 per year. Aliyev (2025) estimated that specific new solar projects (producing 268 GWh) would save ~59 million m^3 of gas and avoid ~128,000 tonnes of CO_2 annually. On a national scale, committing several gigawatts of renewables as planned could offset a significant share of the country's ~50 $MtCO_2e$/year emissions (Ibadoghlu, 2025). Combined with regional electricity exports via planned links to Europe, this could turn Azerbaijan into a green energy supplier.

6. Conclusion and Discussion

This evaluation confirms that solar PV and wind power are extremely effective tools for improving energy efficiency and environmental outcomes. On a technical and economic basis, both technologies have matured: costs are low and conversion efficiency is high enough to be competitive. Critically, they produce virtually zero GHG emissions during operation and negligible pollutants (EIA, 2024; EIA, 2022). Life-cycle analyses consistently rank wind and solar at the bottom of the emissions chart, in stark contrast to fossil fuels (IPCC, 2014). Our review of recent studies shows large societal benefits: avoided air pollution, water savings, and climate mitigation (Millstein et al., 2017; IRENA, 2019).

For Azerbaijan specifically, the findings point to a large untapped opportunity. The country's natural solar and wind resource quality is high, far exceeding current utilization. Already, international agreements and state targets aim to deploy several gigawatts of renewables by 2030. Meeting these targets would greatly reduce domestic fuel use and carbon emissions, freeing gas for export as described by leadership (Aliyev, 2025). Environmentally, renewable energy can alleviate local impacts of the hydrocarbon sector (e.g. flaring, extraction pollution) and contribute to a cleaner domestic energy supply.

Challenges remain: the intermittency of wind and solar requires grid upgrades and possibly storage solutions; land-use planning and environmental assessments are needed to minimize ecological impacts. Policy and financial barriers must be addressed. IRENA's 2019 assessment recommended enacting clear renewable energy laws and auction processes to unlock investment. Likewise, improving energy efficiency in buildings and industry can complement renewables to maximize benefits (IEA, 2021).

In conclusion, this comprehensive review underscores that expanding solar and wind power is a sound strategy for Azerbaijan to enhance efficiency, cut carbon, and protect the environment. Future research should examine cost-benefit scenarios for different deployment pathways and monitor actual project performance. Empirical studies on local ecosystem effects of renewable installations would also be valuable. But the evidence is clear: embracing solar and wind aligns Azerbaijan with global decarbonization trends and offers multiple development co-benefits (IRENA, 2019; U.S. EIA, 2024). Policymakers, investors, and society at large can be confident that clean energy is both feasible and advantageous for the country's energy future.

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