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From Energy Security to Water Stress: Implications of Pakistan's Solar Success

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Abstract. Pakistan has experienced an unprecedented expansion in solar photovoltaic (PV) deployment over the past three years, emerging as one of the world's fastest-growing solar adopter. This transformation has been driven by escalating electricity tariffs, declining PV and battery costs, and persistent grid unreliability. This paper provides an assessment of the structural drivers of decentralized solar adoption, evaluates its impact on the national energy system and consumer behavior, and analyzes the unintended consequences for groundwater sustainability. The findings highlight a critical challenge at the energy–water (and more broadly energy–water–food) nexus: that sustainability in one sector may induce unsustainable resource use in another. A simplified mathematical model for coupled analysis of energy-water system is also presented. The paper concludes with policy recommendations aimed at integrating energy and water governance to ensure long-term sustainability for both.

Key words. Solar Power, Energy-Water Nexus, Energy policy, Environment, Energy and Agriculture, Pakistan.

1. Introduction

In this paper we first give a brief background of the energy landscape in Pakistan over the last 30 years or so. This is followed by a discussion of the factors that led to the solar revolution. The consequences of this success and resulting challenges are discussed next, including the ever-shifting government policies. As Pakistan is among the leaders in solar adoption, lessons learned can help others avoid the same mistakes.

Electricity

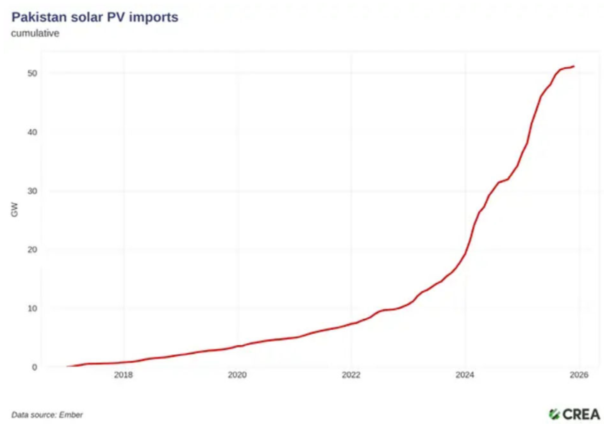
Over the past three years, Pakistan has undergone a rapid transformation in its energy landscape, emerging as one of the world's fastest-growing solar power markets. Driven by soaring electricity costs, worsening grid reliability, and sharply declining cost of solar photovoltaic (PV) panels, solar energy has surged from a peripheral role to become the most rapidly growing source of electricity [1,2].

Pakistan's electricity grid is now about 45GW. Note that production and distribution of electricity in Pakistan used to be entirely in the public sector. In the 1980s and 90s, increasing demand due to population growth as well as improving quality of life and corresponding use of large energy consuming items such as air conditioners and microwaves led to shortages and black and brown outs. This led successive governments to attract independent power producers (IPPs) with very lucrative power purchasing agreements to set up fossil plants. These agreements also included capacity payments. Mismanagement in the distribution networks has also led to privatization of distribution networks in some markets.

Electricity cost shot up by ~100-150% over the last three years. In affluent societies where the energy (electricity) bill is a small fraction of the household income, the demand curve is fairly inelastic – electricity demand remains what it is independent of the expected change in price over the typical range. However, in less affluent societies as the price of grid electricity goes up, the demand/use can go down. Often, countries like Pakistan introduce a tiered billing system, where the cost/kW-hr goes up with higher consumption, either stepwise or linearly. The jump from the cheapest rate for the first n units of electricity can be substantial, thus driving the consumer to stay below the threshold, or find alternate ways to keep electricity cost low. Enter the solar revolution!

The rapid adoption of solar reflects both push factors — such as escalating grid electricity tariffs and frequent outages prompting residential, commercial, agricultural, and industrial consumers to seek reliable alternatives — and pull factors — notably affordable Chinese PV modules and small battery storage systems that have lowered upfront costs and improved energy autonomy. This growth of distributed solar adoption taking place in both urban and rural sectors is not the result of centralized planning of large solar farms. Only role Pakistan government seem to have played is by not imposing an import duty on the solar panels, and establishing a net metering system. Since the introduction of net metering regulations in 2015, which incentivized households and businesses to install solar panels and to sell excess electricity back to the grid *at the same rate they pay*, Pakistan has experienced an unprecedented solar boom. Pakistan has imported solar panels over the last five to six years with a capacity of almost 45GW; ~20 gigawatts of solar panels in 2024 alone [3], more than double that in 2023, making it the world's third-biggest importer. Solar's share of electricity generation more than tripled in just three years, jumping up from about four percent in 2021 to about 14 percent in

2024. Net metering accounted for about 4 GW of electricity capacity on the grid in 2024 [1].



A graph showing solar PV imports in Pakistan. — via Centre for Research on Energy and Clean Air

Fig. 1. Growth in Pakistan solar PV imports [CREA]

These developments have significant implications for Pakistan's energy trajectory and its policy goals, including the government's target to source 60 % of electricity from renewables by 2030.

Water

Agriculture is a large fraction of Pakistan's economy. Network of rivers and canals formed the backbone of Pakistan's agriculture. However, ground water has been playing an increasingly larger role in recent years. Today roughly a quarter of cultivated land depends on surface water, quarter on groundwater, and the remaining half depends on both. There are ~2 million tubewells in the country, used to pump groundwater for agriculture. Vast majority of these have historically been run on diesel. Pumping such a large body of water takes energy. The total annual energy required for irrigation is estimated at ~100 PJ, with diesel-powered pumps consuming about three-quarter of this energy use, followed by electric pumps. As the water table drops, more power is needed. Energy requirements range from 7 to 2,260 kJ per cubic meter of water, depending on factors such as water source, pumping depth, and energy type [4]. With increasing cost of diesel and availability of cheap solar panels, many farmers have switched to solar power driven tubewells.

Energy Storage

With the increase in solar power's share in electricity and rapidly dropping battery prices, now reaching ~$100/kW-hr, a corresponding increase in battery was inevitable. Pakistan imported about 1.25 gigawatt-hours (GWh) of lithium-ion battery packs in 2024, and almost $95 million worth of batteries in a three-month period in 2025. The storage revolution is in its early stages, and battery imports are expected to rise even further. After discussing the challenges associated with unplanned solar power growth and water sustainability, we will speculate on challenges that may be in the offing if growth of energy storage is not better planned.

2. Challenges of Solar Success and Challenges at the Energy-Water Nexus

Growth of distributed solar power has led to two major challenges. The first challenge has already been noted in other markets that experienced significant solar penetration, and is not unique to Pakistan. This problem in Pakistan due to existing power purchase agreements and capacity payments is however even more acute. Moreover, in Pakistan there are two layers of this first challenge. The first sub-challenge is a direct consequence of distributing the non-power-related fixed cost of delivering power over an ever smaller amount of delivered energy that has disrupted the financial model of power utilities, which depend on selling electricity per unit (kW-hr) to recover both energy costs and fixed infrastructure expenses like transmission lines and substations. As more consumers generate their own power and rely less on the grid, utilities sell fewer units of electricity, yet their fixed costs remain unchanged, leading to rising tariffs for remaining users and increasing financial stress on distribution companies. This creates a feedback loop where higher tariffs push even more consumers toward solar, leaving utilities with "stranded assets" and worsening revenue losses [5].

A local resident transports a solar panel on his motorcycle in Karachi, on June 23, 2025. — AFP

Fig. 2. Solar panel being transported on a motorbike.

This is otherwise known as the "who-pays-to-maintain-the grid" problem, and has already led to significant changes in some societies in the way electricity is billed. In one variation of this change in some localities in the United States, the monthly electricity bill separates the charges for the total energy (kW-hr) from the charges associated with maintaining the grid, delivery, metering, billing, etc. This breakdown of the bill does not address the challenge, but at least spells out the source of the problem. When the power producer and distributor are two different entities, the consumer at least knows who is charging, how much is being charged and for what! The second layer of this challenge is a consequence of "net-metering", that was offered to the consumers in Pakistan to incentivize solar adoption. This is simply a promise by the government to buy the excess electricity produced by the consumer, and the problem it led to is a direct consequence of not recognizing the implications of the first sub-challenge. Not separating the cost-of-energy from the cost-of-delivery, the government promised households and businesses to buy excess electricity *at the same rate as consumers pay* for electricity, which is significantly higher than the worth of energy that the consumer adds to the grid. (In numbers as an example, the cost of the energy aspect of electricity in a market may be say, $0.06 per kW-hr; but when the cost of delivery and taxes etc are added, the consumer may be paying $0.15/kW-hr.) This has led to a serious crises leading to a mid-course change in government policy recently [xx]. The new model that replaces the old one, is called, "net-billing." In this model, the distributed solar power producer gets paid at the rate the government generates its own electricity or the rate at which it buys from the IPPs. This mid-course change in policy and rate is currently being litigated.

Solar panels are seen installed on rooftops in a slum in Karachi, on June 24, 2025. — AFP

Fig. 3. Solar panels on rooftops.

The second challenge, and somewhat unique to this part of the world, is related to the impact of solar success on water sustainability. The title of a recent article in an English language daily newspaper, DAWN, summarizes it quite well: S*olar-powered farming is digging Pakistan into a water catastrophe* [6]. The rapid shift toward solar-powered irrigation in Pakistan—while solving energy problems for farmers—is unintentionally worsening groundwater depletion and creating a new environmental crisis. As electricity shortages and high diesel costs pushed farmers to adopt solar panels, many have begun using solar-powered tube wells to pump groundwater more easily and cheaply, allowing them to irrigate crops more frequently and with greater flexibility than before. Over a third of tubewells are now run on solar-powered motors. This has encouraged practices such as frequent "pulse irrigation" and a shift toward more water-intensive crops like rice, whose cultivated area has increased significantly in recent years, while less water-demanding crops such as maize have declined. At the same time, the widespread adoption of solar technology has dramatically reduced reliance on grid electricity in agriculture, with estimates suggesting that hundreds of thousands of tube wells have switched to solar and many new ones have been installed, meaning solar now powers a large portion of groundwater extraction in the country. However, because solar pumping removes the cost constraint associated with fuel or electricity, it has led to excessive and largely unregulated groundwater use, contributing to falling water tables—particularly in Punjab—according to official data and expert analysis.

Jamil et al [7] studied whether the availability of "free" solar energy leads to increased groundwater pumping. Using a matched-pair methodology, the authors compared 30 pairs of farmers operating under similar conditions—one using diesel pumps and the other solar pumps—by measuring flow rates, irrigation durations, and crop patterns, and estimating annual water extraction through validated models such as the Global Solar Atlas. The findings showed a statistically significant increase in groundwater extraction with solar pumps: on average, SOLAR-powered farms pumped about 20% more water annually compared to diesel-powered farms, and in about three-quarter of the cases, solar users extracted more water than their diesel counterparts, confirming concerns about potential over-extraction. The study also found that solar pumps generally have higher flow rates per unit power than diesel pumps, which contributes to increased annual water withdrawal despite their limited operating hours [7]. Similar impact of cheap or free electricity in eastern Punjab (in India) has been observed.

Fig. 4. Solar PV driven tubewell.

Data indicate that areas where the water table has fallen below critical thresholds (e.g., below 60 ft) have expanded by approximately 25 % between 2020 and 2024, while zones with depths beyond 80 ft have more than doubled in size, underscoring an accelerating aquifer depletion trend. What was once an energy solution has very quickly contributed to an emergent water crisis, as cheap solar energy removes previous economic constraints on groundwater extraction, exacerbating unsustainable trends in a water-stressed society already grappling with low surface storage and climatic variability.

[1/7] A worker installs a folding solar panel unit, to run a tube well, the motorised pump that taps groundwater, in a rice field in Muridke, Sheikhupura District in Punjab province, Pakistan August 12, 2025. REUTERS/Akhtar Soomro Purchase Licensing Rights

Fig. 5. Portable and foldable solar panels.

3. Conclusions and Recommendations

Pakistan's solar revolution represents a landmark shift in energy systems driven by market forces rather than centralized large-scale projects such as solar farms. The rapid adoption of solar PV has improved energy access, reduced costs, and accelerated decarbonization. However, it has also revealed critical interdependencies between energy and water systems. Pakistan's experience offers valuable lessons for other emerging economies undergoing rapid energy transitions.

The expansion of solar-powered irrigation has removed economic constraints on groundwater extraction, contributing to unsustainable depletion. This underscores the importance of adopting a systems-based approach to energy transition planning. While efforts such as aquifer recharge pilots and irrigation reforms are underway, the current lack of comprehensive groundwater monitoring and regulatory frameworks poses a major governance challenge. A more cautious and regulated approach, including limiting pump capacity, introducing monitoring systems, developing spatial suitability maps, and aligning solar deployment with groundwater sustainability considerations is recommended.

To address the challenges stemming from net-metering, policymakers are shifting from net-metering to lower compensation schemes (net-billing), which would reduce payments for excess solar electricity exported to the grid. While this may ease pressure on utilities, it could also slow new solar adoption. If the rate offered under the net-billing model is significantly less than that offered under the net-metering model, it may yet lead to interesting consumer behavior especially when storage or other uses of electricity are available.

Future strategies must integrate energy, water, and agricultural policies to ensure that sustainability gains in one sector do not create vulnerabilities in another [8-10]. The future of Pakistan's solar transition lies in integrating technologies like battery storage and developing smarter, more flexible grids. Solar-plus-storage systems could allow users to store excess daytime energy and use it during peak demand hours, reducing strain on the grid. Additionally, reforms such as time-of-use tariffs, demand-response systems, and grid modernization may better align costs, improve efficiency, and support renewable integration.

It is easy to foresee the implications of the impending "storage revolution," which on one hand can make the "who-pays-for-the-grid" problem even worse, but also stands to make Pakistan a true example of a forward looking paradigm for electricity generation, storage, and distribution, including local micro-grids and local "electricity banks." Introduce largescale cheap EVs from China, which has begun, or indigenous production of cheap EVs (with their own need for power as well as storage capabilities) into the mix, and achieving multi-sector sustainability goals can become even more challenging. For example, consider how cheap EVs and nearly-free and non-polluting electricity may stress the transportation/road network.

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APPENDIX: Analytical Framework

We here summarize a set of simple models that can be used to develop an integrated energy-water assessment. This simplified model can be used for quantitative assessment to evaluate energy and water production and usage and cross-sectoral impacts. The model is structured around three primary components: energy system modeling, solar adoption estimation, and groundwater extraction analysis. The methodology incorporates approaches to model demand, resource flows, and trade-offs, and establishes "interactive" and "connected" links between water and energy systems, such as energy used for water pumping and water used in electricity generation.

Symbols:

C_{grid}	installed grid capacity
$C_{required}$	required capacity for reliability
C_{solar}	cumulative installed distributed solar capacity
CF_{solar}	capacity factor (~0.2)
D_{gross}	gross demand
D_{net}	net demand
D_{peak}	peak demand
E_{solar}	annual solar generation
E_w	Energy required to pump water
h	depth of water table
P_e	marginal energy cost
PRM	planning reserve margin (PRM; ~1.15)
Q	extraction volume
Q_w	groundwater extraction volume

Annual solar generation can be approximated as:

$$E_{solar} = C_{solar} \times CF_{solar} \times 8760$$

$$C_{required} = PRM \times D_{peak}$$

Distributed solar reduces daytime grid demand by:

$$D_{net}(t) = D_{gross}(t) - G_{solar}(t)$$

Groundwater extraction is modeled as a function of energy cost:

$$Q_w = f(P_e^{-1})$$

The demand curve for electricity as a function of cost is interesting. Because of the ability to diversify the source of electricity from the grid to distributed and local solar, the demand curve should be made explicit for electricity-from-the-grid vs the cost of grid-electricity. There can be a separate demand curve for off-grid electricity which can be for local and distributed electricity generation capacity or maybe for electricity from a local, micro-grid which runs somewhat independently from the main grid. The quantification of the solar revolution in Pakistan, and possibly in other similar economies, should take these two demand curves into account. What complicates the matter even further is the hard-to-quantify "unreliability" of the grid electricity that further pushes consumers toward local solutions.

Electricity demand response to price increases can be expressed as:

$$\epsilon = \frac{\frac{\Delta Q}{Q}}{\frac{\Delta P}{P}}$$

In Pakistan's case, instead of reducing consumption, consumers substituted grid electricity with self-generation. This indicates a cross-elasticity effect, where solar becomes a substitute good.

Energy–Water Coupling

Water extraction energy requirement:

$$E_w = \rho g h Q$$

As the water table drops, the energy required to pump water increases linearly.