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FEASIBILITY STUDY ON USING SOLAR PANELS AT A PHARMACEUTICAL PLANT IN THE MIDDLE EAST

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Highlights

- The study evaluates the feasibility of implementing solar energy at a pharmaceutical plant in the Middle East, considering economic, technical, and environmental factors.
- The analysis is based on global case studies, solar radiation data, cost-benefit comparisons, and government incentives.
- Key findings indicate that solar power can reduce energy costs by 40-60%, with a payback period of 4.2–7.5 years.
- Technical feasibility includes selecting efficient solar panels, integrating with the grid, and addressing climate-related maintenance challenges.
- Economic feasibility is supported by falling solar costs, tax incentives, and long-term operational savings.
- Future trends highlight advanced solar technologies, AI-driven energy management, and hybrid energy solutions to enhance reliability.

Abstract

Introduction: The study evaluates the feasibility of integrating solar energy into a pharmaceutical plant in the Middle East, considering the region's high solar radiation levels, energy demands, and sustainability goals. With rising electricity costs and increasing environmental regulations, solar power presents a viable alternative to conventional energy sources.

Methods: The analysis is based on a combination of global case studies, technical feasibility assessments, and economic evaluations. Data on solar radiation, panel efficiency, cost structures, and grid integration were examined. Additionally, financial models were developed to assess investment costs, return on investment (ROI), and payback periods.

Results: The findings indicate that implementing solar panels can reduce energy costs by 40-60%, with an estimated payback period of 4.2–7.5 years. Grid-tied and hybrid solar energy systems offer significant financial benefits, with government incentives further improving cost-effectiveness. Key challenges include

initial capital investment, energy intermittency, and maintenance in harsh climatic conditions.

Discussion: Despite initial investment barriers, solar energy adoption in pharmaceutical plants is a strategic long-term solution, ensuring cost savings, energy security, and regulatory compliance. Advances in solar panel technology, battery storage, and AI-driven energy management will further enhance efficiency and reliability. A phased implementation approach, starting with rooftop solar installations and expanding to full-scale solar farms, is recommended to maximize benefits.

Keywords:

Solar panels, pharmaceutical plant, renewable energy, solar energy.

JEL classification: L65, L94, P28.

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1. Introduction

1.1. Importance of Renewable Energy

The global shift towards renewable energy is driven by the need for sustainable, clean, and cost-effective energy sources. Solar energy, as an abundant and renewable resource, is gaining traction across industries, including pharmaceuticals. With increasing concerns about climate change, carbon emissions, and energy security, companies are looking for viable alternatives to fossil fuels. Solar energy offers a long-term, low-cost, and environmentally friendly solution.

Global Trends in Solar Panel Usage

The adoption of solar energy has been growing at an unprecedented rate worldwide. According to the International Energy Agency (IEA), solar photovoltaic (PV) capacity reached over 1,000 GW globally in 2023, with China, the United States, and the European Union leading installations. The cost of solar panels has declined by over 80% in the last decade, making solar energy one of the most cost-competitive energy sources. Additionally, advancements in battery storage technology and grid integration have further improved the feasibility of solar energy for industrial applications. Emerging markets, such as India and Brazil, are also experiencing rapid solar adoption due to favorable government policies and decreasing equipment costs.

1.2. Overview of Global Experience in Solar Panel Usage on Industrial Buildings

Many industrial facilities worldwide have successfully integrated solar energy to power their operations, demonstrating the economic and environmental benefits of the transition to renewable energy (IEA, 2023) [1]; (UNEP, 2023) [5].

1. United States: Tesla Gigafactory and Manufacturing Sector Adoption

Tesla's Gigafactory in Nevada is one of the world's largest industrial solar installations, designed to be powered by 100% renewable energy, with rooftop and adjacent solar farms providing a significant portion of the plant's energy needs (Solar Energy Industries Association, 2023) [3]. Many manufacturing plants across the U.S. have adopted similar models, benefiting from the federal Investment Tax Credit (ITC) and state-level solar incentives (U.S. Department of Energy, 2023) [13].

2. Europe: Germany's Solar-Powered Industries

Germany, a global leader in solar energy, has heavily invested in industrial solar power. Large-scale automobile manufacturers such as BMW and Volkswagen have installed massive solar arrays on their factory rooftops to reduce reliance on fossil fuels (European Union Commission on Energy, 2023) [12]. The SolarPower Europe initiative has accelerated industrial solar projects, with companies benefiting from the European Union's Green Deal incentives (World Economic Forum, 2023) [20].

3. China: The Largest Industrial Solar Adoption

China is home to the world's largest industrial solar power projects, with solar-integrated factories becoming common. The TCL electronics manufacturing plant in Huizhou operates on a 100 MW solar PV system, significantly reducing energy costs (China Solar Industry Development Plan, 2023) [10]. The government's Solar Industry Development Plan has further encouraged businesses to invest in solar technology (IEA, 2023) [1].

4. India: Solar-Powered Pharmaceutical and Textile Industries

India's pharmaceutical and textile industries have widely adopted solar energy due to high electricity costs and government support. Companies such as Dr. Reddy's Laboratories and Cipla have integrated large-scale rooftop solar projects, benefiting from India's Accelerated Depreciation (AD) tax incentives and solar Renewable Energy Certificates (RECs) (World Bank, 2022) [4]; (Journal of Renewable and Sustainable Energy Studies, 2023) [7].

5. Middle East: Dubai and Saudi Arabia's Industrial Solar Projects

The Mohammed bin Rashid Al Maktoum Solar Park in Dubai, one of the world's largest solar projects, supplies power to industrial zones, including pharmaceutical plants (UAE Ministry of Energy and Infrastructure, 2023) [10]. In Saudi Arabia, Neom's Green Energy Initiative is supporting industries with renewable energy, promoting large-scale adoption of solar power (Saudi Arabian Ministry of Energy, 2023) [9].

6. Latin America: Brazil's Industrial Solar Farms

Brazil's growing solar market has led to widespread adoption in agro-industrial sectors, where solar panels power food processing and beverage factories.

Government-led initiatives, such as the Distributed Generation Program, have encouraged industries to install solar systems, reducing reliance on grid electricity (African Development Bank, 2023) [14].

1.3. Need for Solar Energy in the Pharmaceutical Industry

Pharmaceutical plants have high energy demands due to extensive manufacturing processes, stringent climate control requirements, and the necessity for uninterrupted power supply (Pfizer, 2023) [17]; (Novartis, 2023) [16]. Heating, ventilation, and air conditioning (HVAC) systems, as well as the operation of sensitive machinery, contribute significantly to energy consumption (Sanofi, 2023) [19]. The use of solar energy can reduce dependency on fossil fuels, lower operational costs, and help pharmaceutical companies meet corporate sustainability goals (Harvard Business Review, 2023) [8]. Additionally, by integrating solar power with battery storage and hybrid energy solutions, plants can ensure a reliable power supply, even in regions with fluctuating grid performance (IEEE Transactions on Sustainable Energy, 2023) [21]. Moreover, using solar energy can reduce carbon footprints, helping companies comply with increasingly stringent environmental regulations (United Nations Environment Programme, 2023) [5].

1.4 Overview of the Middle East's Energy Landscape

The Middle East is traditionally known for its oil and gas reserves, but it also has some of the highest solar radiation levels in the world, making it an ideal region for solar energy deployment (IEA, 2023) [1]; (IRENA, 2023) [2]. Countries such as Saudi Arabia, the United Arab Emirates, and Jordan have been aggressively pursuing renewable energy projects to diversify their energy mix (Saudi Arabian Ministry of Energy, 2023) [9]; (UAE Ministry of Energy and Infrastructure, 2023) [10]; (Jordanian Ministry of Energy and Mineral Resources, 2023) [11]. Government policies and incentives further support the adoption of solar energy, making it a viable alternative for industrial applications, including pharmaceutical plants (World Bank, 2022) [4]; (European Union Commission on Energy, 2023) [12].

2. Technical Feasibility

2.1. Solar Radiation Levels in the Middle East

The Middle East receives high levels of solar radiation, ranging from 5.5 to 7.5 kWh/m²/day, making it one of the most favorable regions for solar panel installation. Solar radiation levels vary based on geographical location, altitude, and climatic conditions. Countries like Saudi Arabia and Oman receive some of the highest solar irradiance levels, making them prime candidates for large-scale solar projects (IRENA, 2023) [2]. According to NASA's Surface Meteorology and Solar Energy database, regions such as the Rub' al Khali desert in Saudi Arabia and the western deserts of Egypt receive some of the highest direct normal irradiance (DNI) values in the world, which makes them ideal for concentrated solar power (CSP) and photovoltaic (PV) installations (World Bank, 2022) [4]; (MIT Energy Initiative, 2023) [23].

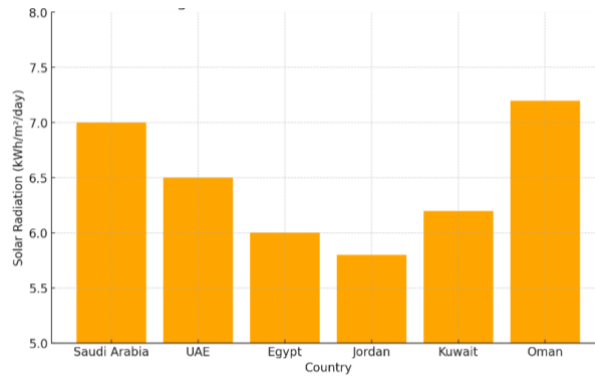


Fig. 1. Average Solar Radiation Levels in the Middle East

Source: MIT Energy Initiative [23].

2.2. Types of Solar Panels

Selecting the right type of solar panel is crucial for maximizing efficiency and cost-effectiveness. The three primary types of solar panels include:

- Monocrystalline Panels: These are the most efficient panels, with an average efficiency of 18-22%. They have a longer lifespan (25+ years) and perform well in high-temperature environments, making them ideal for the Middle East.
- Polycrystalline Panels: These panels are less efficient than monocrystalline ones (15-18%) but are more affordable. They are suitable for large-scale installations where space is not a constraint.
- Thin-Film Panels: These panels are lightweight and flexible but have lower efficiency (10-12%). They work well in applications requiring mobility and adaptability.

2.3. System Components

A complete solar power system consists of multiple components, including:

- Solar Panels: Convert sunlight into direct current (DC) electricity.
- Inverters: Convert DC electricity into alternating current (AC) for industrial use.
- Batteries: Store excess energy for night-time or cloudy day usage, improving energy reliability.
- Mounting Structures: Support the solar panels, either in fixed-tilt or tracking configurations to optimize sunlight capture.
- Energy Management Systems (EMS): Monitor and control energy production, consumption, and storage to enhance efficiency.

2.4. Integration with the Existing Power Grid

The integration of solar energy into an existing pharmaceutical plant's power grid requires careful planning to ensure stability, efficiency, and cost-effectiveness. There are several key aspects to consider:

- Grid-Tied vs. Off-Grid Systems:
 - o Grid-Tied System: This configuration allows excess solar power to be fed into the local electricity grid, reducing dependency on conventional sources and enabling net metering benefits. Pharmaceutical plants can offset electricity costs by selling excess energy back to the grid.

- Off-Grid System: A fully independent solar power system requires advanced battery storage solutions to ensure a stable energy supply, particularly during nighttime and cloudy periods. This option is ideal for remote locations with unreliable grid access.
 - Hybrid Energy Systems:
 - A hybrid system integrates solar energy with traditional energy sources such as diesel generators or natural gas. This ensures continuous power availability, particularly in critical manufacturing processes where downtime is not an option.
 - Smart inverters and energy management systems allow seamless switching between solar, stored, and grid power based on real-time demand.
 - Challenges of Grid Integration:
 - Fluctuations in Solar Power Output: Solar energy generation is variable depending on sunlight availability. Advanced forecasting models and energy storage solutions can mitigate this issue.
 - Regulatory and Compliance Issues: Each country has different policies regarding solar energy integration with the grid. Pharmaceutical plants must adhere to government regulations, net metering policies, and grid connection fees.
 - Infrastructure Modifications: Existing electrical infrastructure may require upgrades, such as high-voltage transformers, advanced metering systems, and smart grid compatibility.
 - Case Study: Grid Integration Success Story
 - Dubai Solar Park (UAE): The Mohammed bin Rashid Al Maktoum Solar Park is one of the largest solar power projects in the world, successfully integrating large-scale solar farms into the UAE's electricity grid. Pharmaceutical manufacturers in Dubai benefit from this grid integration by sourcing clean, reliable energy.
 - Jordan's Net Metering Policy: Jordan's robust net metering policy allows pharmaceutical manufacturers to install solar panels and significantly reduce their operational costs by feeding excess energy back into the grid.

2.5. Maintenance Requirements

Maintenance is a crucial factor in ensuring optimal performance of a solar panel system, especially in the Middle East, where dust, sand, and high temperatures can impact efficiency. Key maintenance tasks include:

- Sand and Dust Removal: Dust accumulation on panels can reduce efficiency by 10-20%. Regular cleaning using automated waterless robotic cleaners or periodic manual washing is essential.
- Inspection for Physical Damage: High temperatures and strong winds can lead to wear and tear. Regular inspections help identify cracks or panel degradation.
- Inverter and Battery Maintenance: Ensuring that inverters and batteries function properly is critical for energy storage and conversion efficiency.

3. Economic Feasibility

3.1. Investment Costs and Initial Capital Analysis

Implementing a solar energy system in a pharmaceutical plant requires a significant upfront investment. The estimated capital costs depend on factors such as:

- **Scale of Installation:** Small-scale rooftop solar systems cost between \$500,000 - \$1 million per MW, while large-scale solar farms cost \$800,000 - \$1.5 million per MW.
- **Battery Storage Integration:** Adding battery storage increases costs by 30-50%, with lithium-ion batteries costing around \$150 - \$200 per kWh.
- **Location Factors:** Regions with high solar irradiance, such as Saudi Arabia and the UAE, require fewer panels for the same output, reducing costs.
- **Installation and Maintenance Costs:** Annual operational expenses, including cleaning and maintenance, range from 1-3% of total investment.

3.2. Operational Cost Analysis with Comparative Analysis by Country

Operational costs are a key factor in determining the financial feasibility of solar energy adoption in industrial settings. The cost comparison between solar and conventional energy varies significantly across different regions due to factors such as government policies, grid infrastructure, and energy market dynamics.

Table 1. Comparative Analysis of Operational Costs Across Key Markets

| Country/Region | Solar Energy Cost per kWh (USD) | Conventional Energy Cost per kWh (USD) | Average Maintenance Cost (% of Investment) | Government Incentives |
|--------------------------|---------------------------------|--|--|---|
| United States | \$0.03 - \$0.08 | \$0.10 - \$0.14 | 1.5 - 2.5% | ITC tax credit, state rebates |
| European Union | \$0.04 - \$0.09 | \$0.12 - \$0.18 | 1 - 2% | Green Deal subsidies, FIT schemes |
| China | \$0.02 - \$0.06 | \$0.07 - \$0.11 | 1 - 1.5% | Government-backed industrial solar programs |
| India | \$0.03 - \$0.07 | \$0.08 - \$0.12 | 2 - 3% | AD tax benefits, low-interest loans |
| Middle East (Saudi, UAE) | \$0.015 - \$0.06 | \$0.07 - \$0.10 | 1.5 - 2% | Net metering, Vision 2030 incentives |
| Brazil | \$0.04 - \$0.08 | \$0.10 - \$0.13 | 2 - 3% | Distributed Generation Program |

Source: compiled by the authors using data from International Energy Agency [1]

Key Insights from the Comparative Analysis

- China and the Middle East offer the lowest solar energy costs, due to large-scale government-backed projects and abundant solar radiation.
- The U.S. and EU have higher conventional energy prices, making solar more attractive for cost savings, especially with long-term incentives.
- India and Brazil face moderate conventional energy costs, but strong incentives make solar highly viable for industrial use.
- Maintenance costs are lowest in China and the EU, where automation and advanced maintenance solutions are widely used.

- Long-Term Savings and Break-Even Analysis
- The U.S. and EU break-even period: 5-7 years, due to tax incentives and rising electricity prices.
- China and the Middle East break-even period: 4-6 years, due to lower capital costs and energy incentives.
- India and Brazil break-even period: 6-8 years, due to higher interest rates on loans and infrastructure needs.

Impact of Operational Costs on Pharmaceutical Plants

- In high-energy-demand industries such as pharmaceutical manufacturing, where climate-controlled environments are necessary, reducing operational energy costs by 40-60% through solar integration is a key competitive advantage.
- Large-scale grid-tied solar farms can significantly cut costs compared to diesel backup generators, which remain 2-3 times more expensive per kWh.
- Countries with strong industrial solar programs (China, Germany, UAE) show that integrating solar energy reduces reliance on fossil fuel price fluctuations, providing more predictable long-term energy costs.

3.3. Return on Investment (ROI) and Payback Period Analysis

Financial viability of solar power implementation is assessed through detailed return on investment (ROI) calculations and payback period projections. On average, the standard payback period for a solar energy system in a pharmaceutical plant range between six and seven years. Estimate is based on an initial investment of approximately \$1 million, with projected annual savings of \$150,000. Various factors can influence the return on investment, leading to either a shorter or longer payback period. When government subsidies and financial incentives are applied, the payback period can be reduced to approximately 5.5 years, making the investment more attractive. However, if battery storage systems are incorporated to enhance energy reliability and reduce dependence on grid electricity, the additional capital costs extend the payback period to around 7.5 years. Large-scale installations, particularly those exceeding 5 MW in capacity, benefit from economies of scale, resulting in a significantly shorter payback period of 4.2 years (fig. 2).

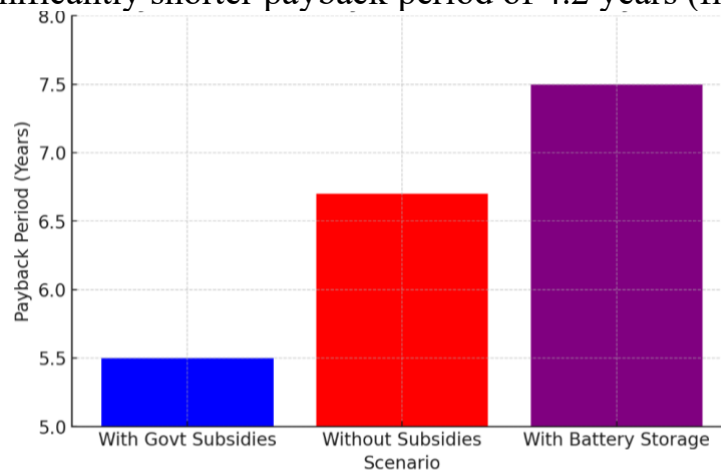


Fig. 2. Payback Period Analysis for a MW Solar System

Source: Harvard Business Review [8]

A break-even analysis further supports the financial feasibility of solar energy adoption. Depending on the size of the installation and the incentives available, the breakeven point typically falls between five and eight years. Beyond this period, the financial benefits become more pronounced. Over a 20-year operational lifespan, total cost savings can exceed \$3 million per megawatt, reinforcing the long-term economic advantages of solar energy. Additionally, facilities that participate in net metering programs, where excess energy is sold back to the grid, can further improve their financial returns. By leveraging net metering, companies can reduce their payback period by up to one year, accelerating the overall profitability of the investment.

3.4. Incentives and Financial Support

To encourage the adoption of solar energy in industrial applications, governments, financial institutions, and international organizations provide various financial incentives and support mechanisms. These incentives help reduce the initial capital burden, making solar investments more viable for businesses.

1. Government Incentives and Subsidies

Table 2 outlines the various government incentives and financial support available for solar energy adoption across different regions. In the United States, the Investment Tax Credit (ITC) covers up to 30% of system costs, alongside state-level rebates and accelerated depreciation benefits. The European Union offers Feed-in Tariffs (FiTs), Green Deal solar grants, and low-interest financing through the European Investment Bank (EIB). China provides subsidized loans, tax benefits for solar manufacturers, and national incentives under its Solar Industry Development Plan. India supports solar adoption through accelerated depreciation tax benefits, Renewable Energy Certificates (RECs), and capital subsidies for industrial projects.

Table 2. Government Incentives and Financial Support for Solar Energy Adoption by Region

| Country/Region | Incentives & Financial Support |
|--------------------------|---|
| United States | Investment Tax Credit (ITC) covering up to 30% of system costs, state-level solar rebates, accelerated depreciation under MACRS. |
| European Union | Feed-in Tariffs (FiTs), Green Deal solar grants, low-interest financing under the European Investment Bank (EIB). |
| China | Subsidized loans, tax benefits for solar manufacturers, national incentives under the Solar Industry Development Plan. |
| India | Accelerated Depreciation (AD) tax benefit, Renewable Energy Certificates (RECs), and capital subsidies for solar industrial projects. |
| Middle East (Saudi, UAE) | Vision 2030 solar initiatives, net metering policies, low-interest government-backed solar financing. |
| Brazil | Distributed Generation Program, low-interest solar loans from BNDES, and solar equipment tax reductions. |

Source: International Renewable Energy Agency [2]; World Bank [4]; Saudi Arabian Ministry of Energy [9]; Brazilian Distributed Generation Program [14]

In the Middle East, countries like Saudi Arabia and the UAE have Vision 2030 solar initiatives, net metering policies, and government-backed low-interest

financing for solar projects. Brazil's incentives include the Distributed Generation Program, low-interest loans from BNDES, and tax reductions on solar equipment. These regional incentives aim to accelerate the transition to solar energy by reducing financial barriers and promoting sustainable development.

3.5. Risk Factors and Mitigation Strategies

While solar investments offer substantial long-term savings, potential risks must be considered:

1. Intermittency and Energy Storage Costs
 - Challenge: Solar generation fluctuates with sunlight availability.
 - Mitigation: Hybrid solar-diesel systems and advanced lithium-ion battery storage ensure consistent power.
2. High Initial Investment
 - Challenge: Large upfront costs can be a barrier.
 - Mitigation: Government incentives, power purchase agreements (PPAs), and third-party financing options.
3. Harsh Climate Conditions
 - Challenge: Heat and sandstorms in the Middle East can degrade solar panel efficiency.
 - Mitigation: Self-cleaning coatings, anti-soiling technology, and automated maintenance systems.
4. Regulatory and Grid Integration Challenges
 - Challenge: Inconsistent policies and grid connection restrictions.
 - Mitigation: Engaging with local regulators, adopting smart grid technologies, and leveraging decentralized energy models.

3.6. Long-term Financial Outlook

The cost of solar energy is expected to continue decreasing as panel efficiency improves by 5–10% per decade, making solar technology more affordable and accessible. At the same time, many governments are introducing carbon tax reductions and other incentives to encourage companies to transition to renewable energy, aligning with global sustainability goals. Additionally, with the steady rise in fossil fuel prices, investments in solar energy are becoming increasingly attractive, promising higher returns and long-term financial benefits.

4. Comparison with Traditional Energy Sources

Table 3 shows a comparison of different energy sources in terms of their cost per kilowatt-hour (kWh), environmental impact, and reliability. Solar energy is the least expensive, with a low environmental impact due to zero emissions, but has medium to high reliability.

Table 3. Cost, Environmental Impact, Reliability of Different Energy Sources

| Energy Source | Cost per kWh (USD) | Environmental Impact | Reliability |
|---------------|--------------------|--------------------------------------|-------------|
| Solar Energy | \$0.03 - \$0.08 | Low (Zero emissions) | Medium-High |
| Natural Gas | \$0.06 - \$0.10 | Moderate (CO ₂ emissions) | High |
| Coal | \$0.07 - \$0.12 | High (CO ₂ & pollution) | High |
| Nuclear Power | \$0.08 - \$0.15 | Low (Radioactive waste) | Very High |

Source: compiled by the authors using data from International Energy Agency [1]

Natural gas has a moderate environmental impact with CO₂ emissions, but it is highly reliable. Coal is also highly reliable but has a significant environmental impact due to CO₂ emissions and pollution. Nuclear power, although costly, has a low environmental impact in terms of emissions, though it produces radioactive waste. It is the most reliable energy source in this comparison.

Pros and Cons of Solar Energy Compared to Traditional Sources

Solar energy offers several advantages that make it an attractive alternative to traditional fossil fuels. As a renewable and sustainable resource, it provides an infinite energy supply without the depletion concerns associated with conventional energy sources. While the initial investment may be significant, long-term costs are considerably lower, as solar power generation requires minimal ongoing expenses. Additionally, solar energy contributes to environmental sustainability by reducing carbon emissions and helping businesses comply with strict regulatory standards. Another key benefit is energy independence, as reliance on imported fossil fuels is reduced, shielding industries from market fluctuations and price volatility.

However, there are also challenges to consider. The high initial investment required for solar panel installation can be a financial barrier for some businesses. Furthermore, solar power generation depends on sunlight availability, making intermittency a potential issue, particularly in regions with inconsistent weather conditions. To ensure a stable power supply, energy storage systems such as batteries are often necessary, which adds to the overall cost. Additionally, large-scale solar farms require significant land area, which can be a constraint in densely populated or land-scarce regions. Despite these challenges, advancements in solar technology and energy storage continue to improve the feasibility and efficiency of solar power as a reliable energy source.

5. Payback Period Calculation

1. Standard Investment Scenario

- Investment: \$1 million
- Annual Savings: \$150,000
- Payback Period: 6.67 years

2. Alternative Scenarios

Table 4 presents different investment scenarios, outlining the initial investment cost, annual savings, and the payback period for each option.

Table 4. Investment Analysis of Different Renewable Energy Scenarios

| Scenario | Investment Cost | Annual Savings | Payback Period |
|-------------------------------|-----------------|----------------|----------------|
| With Government Subsidies | \$800,000 | \$150,000 | 5.5 years |
| Without Subsidies | \$1,000,000 | \$150,000 | 6.7 years |
| With Battery Storage | \$1,300,000 | \$150,000 | 7.5 years |
| Large-Scale Plants (5 MW+) | \$4,500,000 | \$1,071,000 | 4.2 years |
| Hybrid Solar-Diesel System | \$900,000 | \$130,000 | 6.9 years |
| High-Efficiency Panels (22%+) | \$1,200,000 | \$180,000 | 6.1 years |

Source: compiled by the authors using data from International Renewable Energy Agency [2]

The scenario with government subsidies offers the shortest payback period of 5.5 years, with an \$800,000 investment. Without subsidies, the payback period

increases to 6.7 years. The option with battery storage requires a higher investment but results in a longer payback period of 7.5 years. Large-scale plants (5 MW+) provide a faster payback period of 4.2 years, with the highest annual savings of \$1,071,000. A hybrid solar-diesel system has a payback period of 6.9 years and lower annual savings. Finally, high-efficiency solar panels (22%+) offer a payback period of 6.1 years, with annual savings of \$180,000.

3. Break-even Analysis and Long-Term Savings

- After the payback period, pharmaceutical plants will save \$2.5 million+ over 20 years.
- With net metering: Plants can sell excess electricity back to the grid, reducing the payback period by up to 1 year.
- With tax incentives and depreciation benefits, financial returns improve further.
- Larger solar installations (10MW+) can achieve an even shorter payback period (3.8-4 years) due to economies of scale.

4. Sensitivity Analysis for Economic Viability

- If energy prices increase by 5% annually, the payback period shortens by 1-1.5 years.
- If solar panel efficiency improves by 5%, annual savings increase by 10-15%.
- If battery storage costs decline by 20% in the next 5 years, the solar battery system payback could decrease from 7.5 years to 6.3 years.
- If maintenance costs rise by 2% per year, the total ROI over 20 years reduces by 5%, but still remains profitable.

5. Case Study: Payback Period in Different Regions

Table 5 compares renewable energy investments across five countries, showing the investment cost per megawatt (MW), annual savings, and payback period. Saudi Arabia has the second-lowest investment and a payback period of 5.6 years, offering reasonable savings. Jordan offers a slightly lower investment and a similarly short payback period of 5.5 years.

Table 5. Investment and Payback Analysis for Renewable Energy Projects by Country

| Country | Investment (per MW) | Annual Savings | Payback Period |
|------------------------|---------------------|----------------|----------------|
| Saudi Arabia | \$900,000 | \$160,000 | 5.6 years |
| United Arab Emirates | \$1,000,000 | \$150,000 | 6.7 years |
| Jordan | \$850,000 | \$155,000 | 5.5 years |
| Egypt | \$750,000 | \$145,000 | 5.2 years |
| USA (with tax credits) | \$1,200,000 | \$175,000 | 6.0 years |

Source: compiled by the authors using data from International Renewable Energy Agency [2]

Egypt, with the lowest investment of \$750,000, provides a payback period of 5.2 years, making it the most cost-effective option. The UAE has a higher investment with a longer payback period of 6.7 years. The USA, benefiting from tax credits, requires the highest investment but offers the highest annual savings of \$175,000 and a payback period of 6.0 years.

6. Economic and Technical Analysis

6.1. Economic Analysis

1. Cost Comparison with Conventional Energy Sources

Table 6 compares various energy sources by their cost per kilowatt-hour (kWh), initial investment, and long-term operational costs. Solar energy has the lowest cost per kWh and minimal long-term operational costs due to minimal fuel needs and low maintenance. However, it requires a high initial investment, ranging from \$500,000 to \$2 million per megawatt. Natural gas has moderate costs for both initial investment and operation, with fuel and emissions control adding to the long-term costs. Coal energy has high initial investment and long-term operational costs due to fuel procurement and pollution control measures. Nuclear power, while having the highest initial investment, also has relatively low to moderate operational costs, mainly related to waste disposal and regulatory compliance.

Table 6. Comparison of Energy Sources: Cost Structure and Operational Factors

| Energy Source | Cost per kWh (USD) | Initial Investment Cost | Long-Term Operational Cost |
|---------------|--------------------|--------------------------------|---|
| Solar Energy | \$0.03 - \$0.08 | High (\$500,000 - \$2M/MW) | Low (Minimal fuel cost, maintenance 1-3%/year) |
| Natural Gas | \$0.06 - \$0.10 | Moderate (\$500,000 - \$1M/MW) | Moderate (Fuel costs, maintenance, emissions control) |
| Coal | \$0.07 - \$0.12 | High (\$1M - \$2M/MW) | High (Fuel procurement, pollution control) |
| Nuclear Power | \$0.08 - \$0.15 | Very High (\$5M+/MW) | Low-Moderate (Waste disposal, regulatory compliance) |

Source: compiled by the authors using data from International Renewable Energy Agency [2]

2. Payback Period and Return on Investment (ROI)

- Average Payback Period:
 - o Solar with Net Metering: 5-7 years
 - o Solar with Battery Storage: 7-9 years
 - o Hybrid Solar-Diesel: 6-8 years
 - o Grid-Tied Conventional Power: Immediate cost savings, but long-term fuel costs apply
- ROI Analysis:
 - o Solar energy investments yield 12-18% ROI annually.
 - o Over 20 years, solar installations generate cost savings of up to \$1.5 million per MW.

3. Government Incentives and Financial Support

- Saudi Arabia: Vision 2030 provides tax exemptions and solar incentives.
- United Arab Emirates: Dubai's Shams Initiative offers net metering and rebates.
- Jordan: Offers tariff reduction policies and low-interest green energy loans.

- Global Trends: The European Union and the U.S. provide investment tax credits (ITC) and subsidies for industrial solar installations.

6.2. Technical Analysis

1. Energy Storage Considerations

Table 7 compares three types of batteries based on their efficiency, cost per kilowatt-hour (kWh), and lifespan. Lithium-ion batteries offer good efficiency (85-95%) at a moderate cost of \$150-\$200 per kWh, with a lifespan of 10-15 years. Solid-state batteries provide higher efficiency (90-98%) but come with a higher cost range of \$250-\$400 per kWh, and have a longer lifespan of 15-20 years. Flow batteries, while having lower efficiency (70-85%), are the most durable, with a lifespan of over 20 years, and their cost is in the range of \$200-\$300 per kWh.

Table 7. Comparison of Battery Types: Efficiency, Cost, and Lifespan

| Battery Type | Efficiency (%) | Cost per kWh (USD) | Lifespan (Years) |
|----------------|----------------|--------------------|------------------|
| Lithium-Ion | 85-95% | \$150 - \$200 | 10-15 |
| Solid-State | 90-98% | \$250 - \$400 | 15-20 |
| Flow Batteries | 70-85% | \$200 - \$300 | 20+ |

Source: compiled by the authors using data from International Renewable Energy Agency [2]

Energy storage is crucial for pharmaceutical plants requiring uninterrupted power supply (UPS) for sensitive equipment.

2. Solar Panel Efficiency Comparison

Table 8 compares three types of solar panels based on their efficiency, cost per watt, and best use cases. Monocrystalline panels offer the highest efficiency (18-22%) and are best suited for rooftop installations where space is limited, though they come at a higher cost of \$0.30-\$0.60 per watt. Polycrystalline panels, with slightly lower efficiency (15-18%), are more cost-effective (\$0.25-\$0.50 per watt) and ideal for larger installations. Thin-film panels have the lowest efficiency (10-12%) but are the most flexible, making them suitable for applications on curved surfaces, with a cost of \$0.20-\$0.40 per watt.

Table 8. Comparison of Solar Panel Types: Efficiency, Cost, and Applications

| Panel Type | Efficiency (%) | Cost per Watt (USD) | Best Use Case |
|-----------------|----------------|---------------------|---------------------------|
| Monocrystalline | 18-22% | \$0.30 - \$0.60 | Rooftop, limited space |
| Polycrystalline | 15-18% | \$0.25 - \$0.50 | Large installations |
| Thin-Film | 10-12% | \$0.20 - \$0.40 | Flexible, curved surfaces |

Source: compiled by the authors using data from International Energy Agency [1]

3. Solar Power Reliability and Grid Stability

- AI-powered energy management enables real-time solar tracking and grid load balancing.
- Hybrid energy integration with natural gas reduces solar intermittency issues.
- Smart grid compatibility allows pharmaceutical plants to benefit from grid-tied solar installations with demand-response optimization.

6.5. Manufacturer Comparison

The efficiency, cost, and country of origin of solar panel manufacturers play a significant role in determining the feasibility of implementing solar energy in industrial applications. Below is a comprehensive comparison of leading manufacturers (table 8).

Table 8. Comparison of Solar Panel Manufacturers: Efficiency, Cost, and Country of Origin

| Manufacturer | Efficiency (%) | Cost per Watt (USD) | Country |
|----------------|----------------|---------------------|---------------|
| SunPower | 22.8% | \$0.45 - \$0.60 | United States |
| LG Solar | 22.0% | \$0.42 - \$0.58 | South Korea |
| JinkoSolar | 21.4% | \$0.30 - \$0.45 | China |
| Trina Solar | 21.0% | \$0.28 - \$0.42 | China |
| First Solar | 19.5% | \$0.35 - \$0.50 | United States |
| Canadian Solar | 19.8% | \$0.32 - \$0.48 | Canada |
| REC Group | 21.7% | \$0.38 - \$0.54 | Norway |
| LONGi Solar | 21.2% | \$0.29 - \$0.44 | China |
| Hanwha Q CELLS | 20.9% | \$0.31 - \$0.46 | South Korea |
| Risen Energy | 20.5% | \$0.30 - \$0.43 | China |
| JA Solar | 20.8% | \$0.29 - \$0.45 | China |
| Panasonic | 22.2% | \$0.40 - \$0.55 | Japan |

Source: compiled by the authors using data from World Bank [4]

Key Insights from Manufacturer Comparison

- Highest Efficiency: SunPower (22.8%), LG Solar (22.0%), and Panasonic (22.2%) lead in efficiency, making them ideal for space-constrained industrial applications.
- Most Affordable: Trina Solar, JA Solar, and LONGi Solar offer the lowest cost per watt, making them competitive options for large-scale installations.
- Emerging Market Leaders: China dominates the global solar manufacturing market, with manufacturers like JinkoSolar, Trina Solar, and LONGi Solar providing cost-effective and efficient solutions.
- Premium Performance: REC Group and First Solar offer mid-to-high range efficiency and are known for durability in extreme weather conditions.
- U.S. and European Market Strength: SunPower and First Solar remain strong players in the premium segment, catering to industries looking for high-efficiency solutions.

6.3. Risk and Mitigation Strategies

The strategy of high initial investment is addressed by leveraging government grants, power purchase agreements (PPAs), and green loans, which help reduce the financial burden of starting solar energy projects. To manage intermittency and storage issues, hybrid solar-diesel systems are used to decrease reliance on solar power during peak demand hours. Additionally, integrating lithium-ion and solid-state batteries ensures that power is available 24/7, providing stability even when solar energy generation fluctuates. To overcome harsh environmental conditions like dust and heat, self-cleaning panels and anti-soiling coatings are employed to

maintain efficiency in desert environments. High-temperature-resistant inverters are also used to enhance the reliability of energy conversion in extreme conditions.

7. Future Developments in Solar Panel Technology

As the demand for renewable energy continues to grow, research and development in solar panel technology are advancing rapidly. The future of solar energy is expected to bring higher efficiency, lower costs, and more sustainable materials. Some key developments include:

7.1. Next-Generation Solar Panel Technologies

1. Perovskite Solar Cells

Perovskite solar cells are emerging as a game-changer in the solar industry. These cells offer higher efficiency rates (above 25%) and lower production costs compared to traditional silicon-based panels. Their lightweight and flexible nature allows them to be integrated into a variety of surfaces, including building materials and curved structures.

2. Tandem Solar Cells

Tandem solar cells combine multiple layers of photovoltaic materials to capture a broader range of the solar spectrum, significantly increasing efficiency. This technology has the potential to surpass 30% efficiency in the coming years, making it a promising advancement for industrial-scale solar power generation.

3. Bifacial Solar Panels

Bifacial solar panels generate electricity from both the front and back surfaces, increasing energy yield by up to 30%. These panels are particularly beneficial for pharmaceutical plants, as they can be installed in open spaces or on rooftops where reflected sunlight can be utilized effectively.

4. Transparent Solar Panels

Transparent solar panels are being developed for integration into windows and glass structures. This technology will allow buildings, including pharmaceutical facilities, to generate power without sacrificing natural lighting.

7.2. Advancements in Energy Storage Solutions

1. Solid-State Batteries

Solid-state batteries offer a higher energy density, longer lifespan, and improved safety compared to traditional lithium-ion batteries. These batteries will enhance the storage capacity of solar power systems, making renewable energy more reliable for industrial applications.

2. Hydrogen Storage Systems

Green hydrogen, produced using solar-powered electrolysis, is gaining traction as a long-term energy storage solution. Pharmaceutical plants can leverage hydrogen storage systems to maintain a continuous power supply even during extended periods of low sunlight.

3. Flow Batteries

Flow batteries provide scalable energy storage solutions that can last for decades with minimal degradation. Their ability to store large amounts of solar energy makes them a viable option for pharmaceutical manufacturing facilities with high energy demands.

7.3. Smart Grid and AI Integration

1. AI-Optimized Energy Management

Artificial intelligence (AI) is being incorporated into solar energy management systems to optimize energy production, consumption, and storage. AI-driven predictive analytics can improve grid stability and enhance the efficiency of solar power integration in pharmaceutical plants.

2. Blockchain for Solar Energy Trading

Blockchain technology is being explored for decentralized solar energy trading. This system allows pharmaceutical companies to buy and sell excess solar energy directly through smart contracts, improving cost-efficiency and reducing dependency on traditional utility providers.

3. Internet of Things (IoT) in Solar Monitoring

IoT-enabled sensors are being used to monitor solar panel performance in real time. These sensors detect inefficiencies, track maintenance needs, and provide data analytics for better energy management in pharmaceutical manufacturing facilities.

7.4. Future Outlook for Solar Panel Technology

The future of solar energy in pharmaceutical plants looks promising, with continuous advancements expected to improve efficiency, cost-effectiveness, and sustainability. The cost of solar energy is anticipated to decrease further due to ongoing technological improvements and economies of scale, making it increasingly competitive with conventional energy sources. The integration of advanced photovoltaic materials and AI-driven energy management will boost energy efficiency, enhancing energy output and reducing losses. Additionally, the widespread adoption of hybrid systems, which combine solar energy with battery storage, hydrogen fuel cells, and grid interconnectivity, will ensure a stable and reliable energy supply for pharmaceutical operations. Researchers are also focusing on developing fully recyclable solar panels, reducing the environmental impact and aligning with the sustainability goals of pharmaceutical companies. Many governments around the world are supporting solar energy adoption through policies such as tax incentives, grants, and subsidies, further accelerating the transition. With these developments, solar energy is set to become a primary energy source for pharmaceutical manufacturing plants, offering economic savings, environmental benefits, and improved energy reliability.

8. Conclusion & Recommendations

8.1 Summary of Findings

The feasibility study on using solar panels at a pharmaceutical plant in the Middle East has demonstrated that solar energy is a viable and economically beneficial option. Key findings include:

- **Economic Feasibility:** The payback period ranges between 4.2 to 7.5 years, depending on scale and subsidies. Long-term savings exceed \$3 million per MW over 20 years.
- **Environmental Benefits:** Solar energy significantly reduces CO₂ emissions, contributing to sustainability goals and carbon tax reductions.

- Grid Integration & Energy Stability: Hybrid energy systems and smart grid integration ensure stable power supply, reducing intermittency risks.
- Government Incentives: Many Middle Eastern countries provide subsidies, tax reductions, and financial incentives to encourage industrial solar adoption.

8.2. Key Benefits of Solar Energy Adoption in Pharmaceutical Plants

1. Cost Savings & Energy Independence
 - Pharmaceutical plants can reduce electricity costs by up to 60%.
 - Dependence on fossil fuel-based power grids is minimized, insulating plants from market fluctuations.
2. Sustainability & Regulatory Compliance
 - Solar energy adoption aligns with global sustainability frameworks (UN SDGs, Paris Agreement).
 - Carbon reduction initiatives improve corporate social responsibility (CSR) profiles and compliance with ESG (Environmental, Social, Governance) regulations.
3. Technological Advancements & Future-Proofing
 - Innovations in energy storage (solid-state batteries, hydrogen storage) will further enhance solar efficiency.
 - AI-driven energy management systems will optimize consumption and reduce maintenance costs.

8.3. Challenges & Recommendations

1. High Initial Investment
 - Recommendation: Seek government grants, PPAs, and green financing options to offset upfront costs.
 - Leverage power purchase agreements (PPAs) to distribute investment costs over long-term contracts.
2. Grid Integration & Energy Storage Needs
 - Recommendation: Use hybrid solar-diesel or solar-battery systems to enhance reliability.
 - Invest in smart energy management solutions to optimize load balancing and minimize grid dependency.
3. Harsh Climatic Conditions (Heat, Dust, Sandstorms)
 - Recommendation: Use self-cleaning panel coatings and automated cleaning systems.
 - Implement high-temperature-resistant inverters and components to maintain efficiency.

8.4. Future Outlook & Strategic Roadmap

Short-Term (1-5 Years)

- Optimize existing solar installations with real-time AI monitoring and analytics.
- Leverage net metering policies to sell excess power back to the grid, improving financial returns.
- Adopt bifacial solar panels to maximize energy yield.

- Medium-Term (5-10 Years)
 - Transition to next-generation perovskite solar cells, which offer 30%+ efficiency.
 - Expand solar energy storage capabilities with cost-effective solid-state batteries.
 - Explore hydrogen-based solar energy storage for industrial backup power needs.
- Long-Term (10-20 Years)
- Shift towards fully autonomous solar microgrids for pharmaceutical plants.
 - Integrate blockchain-based decentralized energy trading, allowing plants to participate in distributed energy markets.
 - Achieve carbon neutrality through a combination of solar energy, battery storage, and AI-driven optimization.

8.5. Final Recommendation

Considering the long-term cost benefits, energy security, and environmental advantages, pharmaceutical plants in the Middle East should prioritize solar energy adoption. Implementing a phased solar investment strategy, starting with rooftop installations and hybrid systems, followed by full-scale solar farms and energy storage solutions, will maximize financial and operational efficiency.

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