



## Performance Comparison of Monocrystalline and Polycrystalline Photovoltaic Panels for Kabul City Based on PVsyst Simulation

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### Abstract

This study evaluates the performance of monocrystalline and polycrystalline photovoltaic (PV) technologies for a 5.9 kWp residential solar system in Kabul City using PVsyst simulation. The results indicate that monocrystalline modules achieve an annual energy yield of 11,295 kWh with a performance ratio (PR) of 71.1%, whereas polycrystalline modules generate 11,273 kWh with a PR of 70.9%. Although the difference in simulated annual energy production is only 22 kWh, equivalent to approximately 0.2%, monocrystalline technology demonstrates greater overall technical and economic suitability for Kabul's semi-arid urban environment. Experimental evidence further indicates that monocrystalline modules perform better under dusty conditions, experiencing only 14.1% power loss compared with 30.48% for polycrystalline modules under high-soiling conditions. This improved resistance to dust accumulation can contribute to more stable energy production and reduced maintenance requirements. In addition, monocrystalline panels require approximately 8.1% less installation area to provide the same system capacity, which is particularly advantageous for space-constrained residential rooftops in Kabul. Considering energy yield, soiling resistance, space utilization, and long-term operational performance, monocrystalline PV technology is therefore recommended for residential applications. The findings provide a practical and useful framework for homeowners, solar installers, and policymakers to make informed investment decisions and promote efficient solar energy deployment in semi-arid urban climates. These findings support careful technology selection and emphasize local climatic, environmental, and rooftop conditions when designing residential PV systems effectively.

### Keywords

A Monocrystallin; Polycrystallin; Climate Cange; Comparative Study; PVsyst Software

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## د کابل ښار لپاره د مونو کریستالین او پولی کریستالین لمريزو حجرو د فعالیت پرتله د PVsyst شبیه سازی پر بنسټ

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### چکیده

دا څېړنه د کابل ښار لپاره د ۵،۹ کیلوواټه پیک (5.9 kWp) استوګنیز لمريز سیستم کې د مونو کریستالین او پولی کریستالین فوتوولتایک (PV) ټکنالوژيو فعالیت د PVsyst سافټویر د سیمولیشن له لارې ارزوي. پایلې ښيي چې مونو کریستالین پینلونه په کال کې ۱۱،۲۹۵ کیلوواټه ساعت برېښنا تولیدوي او د فعالیت نسبت (PR) یې ۷۱،۱٪ دی، په داسې حال کې چې پولی کریستالین پینلونه ۱۱،۲۷۳ کیلوواټه ساعت برېښنا تولیدوي او د فعالیت نسبت یې ۷۰،۹٪ دی. که څه هم د دواړو ټکنالوژيو ترمنځ د کلي تولید توپیر یوازې ۲۲ کیلوواټه ساعت، یا نږدې ۰،۲٪ دی، خو مونو کریستالین ټکنالوژي د کابل د نیمه وچ ښاري اقلیم لپاره له تخنیکي او اقتصادي پلوه غوره ثابتېږي. تجربوي شواهد ښيي چې مونو کریستالین پینلونه د ښاري دوړو پر وړاندې ډېر مقاومت لري، ځکه د دوړو په سختو شرایطو کې یې د توان ضایع کېدل یوازې ۱۴،۱٪ دي، حال دا چې د پولی کریستالین پینلونو د توان ضایع کېدل ۳۰،۴۸٪ ته رسېږي. دا ځانګړتیا د انرژۍ د تولید ثبات زیاتوي او د ساتنې اړتیا کموي. سربېره پر دې، مونو کریستالین پینلونه د ورته ظرفیت د ترلاسه کولو لپاره شاوخوا ۸،۱٪ لږ نصبېدونکي ځای ته اړتیا لري، چې د کابل د محدود چټ لرونکو کورونو لپاره مهمه ګټه ګیل کېږي. د انرژۍ د تولید، د دوړو پر وړاندې د مقاومت، د ځای د اغېزمنې کارونې او اوږدمهاله عملياتي فعالیت له مخې، مونو کریستالین ټکنالوژي د استوګنیزو لمريزو سیستمونو لپاره غوره انتخاب بلل کېږي. د دې څېړنې موندنې د کورنیو، لمريز سیستم نصبونکو او پالیسي جوړونکو لپاره یو عملي چوکاټ وړاندې کوي ترڅو په نیمه وچو ښاري سیمو کې د لمريزې انرژۍ د پانګونې او ټکنالوژۍ د انتخاب په اړه اغېزمنې پرېکړې وکړي.

### تاریخچه

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### واژه‌های کلیدی

مونو کریستالین؛ پولی کریستالین؛ اقلیمي تغیرات؛ پرتله ایزه مطالعه؛ PVsyst سافټویر

## Introduction

الحمد لله رب العالمين والصلوة والسلام على سيد المرسلين وعلى آله وأصحابه أجمعين.

People's demand for energy is increasing daily to fulfill the material needs of human beings. On the other hand, fossil fuels are rapidly depleted and contribute to environmental pollution. This has led to the growing importance of renewable energy sources (Chatta et al., 2018). Researchers are trying to find alternative sources for obtaining energy instead of fossil fuels, because the rate of energy consumption is increasing by 1% per year in developed countries and by 5% in developing countries (Ettah et al., 2022). In 2020, despite the outbreak of the COVID-19 pandemic, global consumption of renewable energy continued to grow, increasing by 2.6% annually. The main reason for this growth was energy production from renewable sources, especially the record-level installation of solar and wind energy capacities. Additionally, the reduction in energy consumption during the pandemic contributed to a significant increase in the share of renewable energy in Total Final Energy Consumption (TFEC)—which is the core target of Sustainable Development Goal 7.2 (SDG7.2)—by 1.4%, reaching 19.1%. All of these factors made 2020 an exceptional year (IEA IRENA UNSD World Bank WHO, 2023). The consumption of renewable energy is shown in Figure (1) (IEA IRENA UNSD World Bank WHO, 2023).

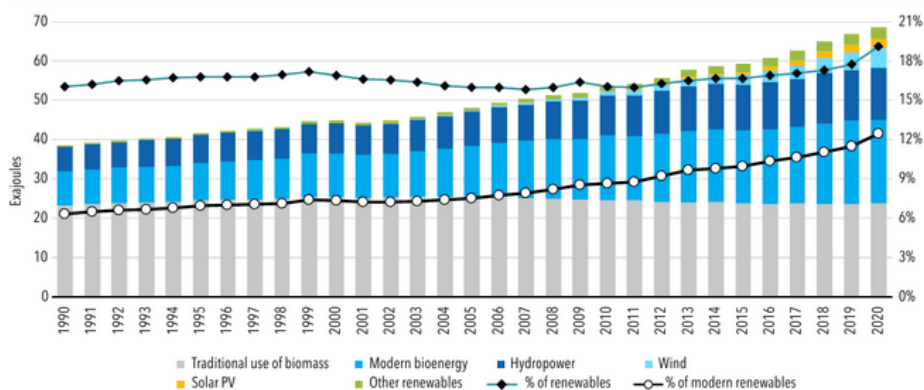


Figure 1: Renewable energy consumption and share in TFEC by technology, 1990–2020

Solar energy is one of the renewable energy sources, and its source is abundantly available in nature for free. This energy has many applications,

such as photovoltaics, solar thermal systems, and solar architecture technology has a simple and easy design, and it also requires little maintenance(Chatta et al., 2018). The advancement of technology, the reduction in material costs, and government support for renewable energy sources for electricity production have contributed to the rapid growth of solar panel (PV) technology in recent years. In 2010, solar panels with a capacity of 23.5 gigawatts (GW) were available worldwide, and they are increasing annually at a rate of 35 40%. In 2019, solar energy provided 3% of global electricity demand, and this share could reach up to 27% by 2050. In 2019, the solar photovoltaic (PV) market grew by approximately 12% and reached 115 gigawatts, while the total installed capacity of solar panels worldwide reached 627 gigawatts(Tyagi et al., 2013) . The figure(2) shows the installation of PV panels based on capacity from 2009 to 2019(Tyagi et al., 2013).

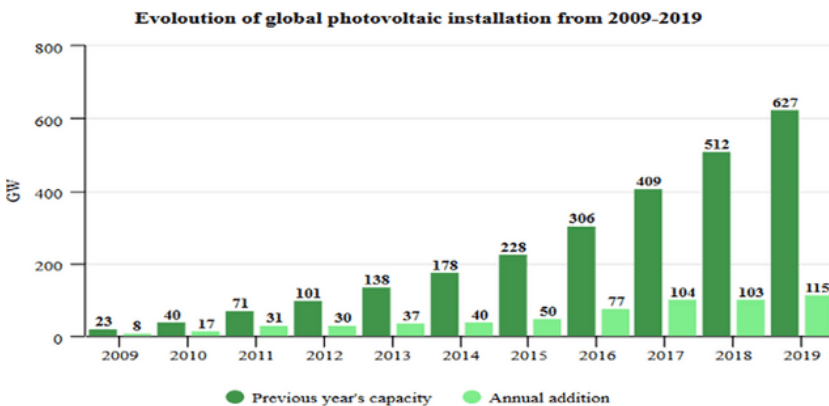


Figure 2: The evolution of PV installed capacity from 2009 to 2019

By the end of 2019, 18 countries had added around 1 gigawatt of capacity to the grid, while a total of 36 countries had installed capacities exceeding 1 gigawatt. Asia was the leading continent, accounting for more than half of the newly installed capacities. After Asia, Europe ranked second with 17%, followed by the Americas with 15% (IEA IRENA UNSD World Bank WHO, 2023). Figure (3) shows Leading countries with newly added solar PV installed capacity and their percentage share.(Mehrad, 2021)

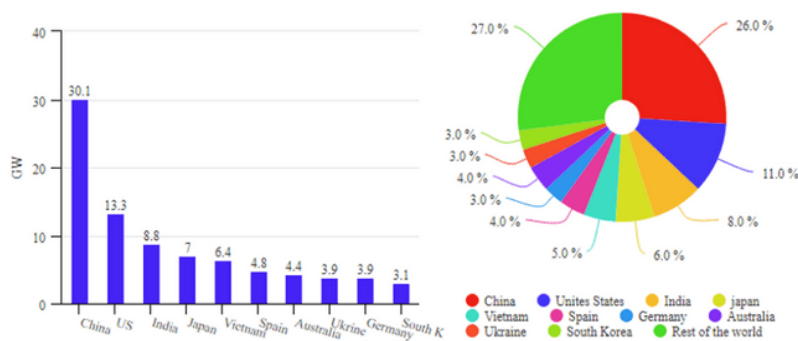


Figure 3: Leading countries with newly added solar PV installed capacity and their percentage share

A solar panel, also known as a PV (Photovoltaic) panel, is a semiconductor device that can directly convert solar energy into electrical energy. These panels are made from silicon crystal cells, which are installed in parallel or series in panels made of aluminum or stainless steel that are resistant to corrosion and protected by plastic or glass. When sunlight falls on these cells, the current is conducted by the depletion region between the cells. The amount of current depends on the amount of light energy reaching the silicon cells and also the surface area of the cells. All solar cells have at least two semiconductor layers, one with a positive charge and the other with a negative charge. When sunlight hits the semiconductor, electrons pass through the junction between the two layers, causing an electric current to flow (Mehrad, 2021). Figure (4) illustrates the photovoltaic effect in a solar cell (Hidayat et al., 2022)

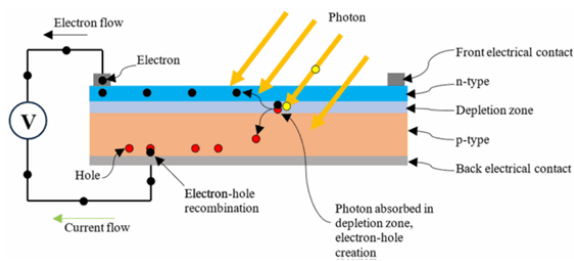


Figure 4: Photovoltaic effect

We can model a solar panel as a diode, where the current flows through the junction of the semiconductor layers. This current can be obtained through the following relation (Ettah et al., 2022).

$$I = I_o (\exp \frac{qv}{\eta KT} -1) .....(1)$$

The unique arrangement of atoms in crystals is called the crystal structure. The crystal structure is made up of a unit cell, which is a specific arrangement of atoms that repeats periodically in a crystal lattice. Solar cells come in two types: monocrystalline and polycrystalline. Polycrystalline solar cells are made of many solar cells, while monocrystalline solar cells are made of fewer solar cells (Supriyono et al., 2024). Figure (5) shows the crystal structure of monocrystalline and polycrystalline materials (Fitria Hidayanti, 2020).

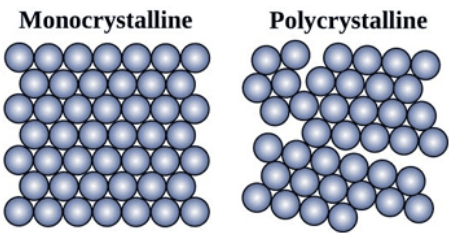


Figure 5: Crystal Structure of Monocrystalline and Polycrystalline

Monocrystalline silicon (Mono-Si) solar cells are manufactured from uniform cylindrical silicon ingots, where four sides are sliced to optimize efficiency and minimize wafer costs(Dhimish et al., 2021). Polycrystalline silicon (Poly-Si) panels are also highly prevalent, though Mono-Si generally provides higher baseline conversion efficiencies due to its single-crystal structure(Aedelia & Wijayanto©, 2025).

Solar module performance degrades as operating temperatures rise due to increased internal resistance and changes in the electrical properties of the semiconductor material(Mula, 2026). Artificial radiation testing under a 1000 W halogen lamp shows that Mono-Si possesses higher thermal stability, experiencing a thermal power degradation of 17.46% (with a temperature coefficient of -0.60%/°C) compared to a higher power loss of 23.53% (and a coefficient of -0.81%/°C) for Poly-Si(Mula, 2026).

Conversely, in the specific desert climate of El-Kharga Oasis, Egypt, field trials indicate that Poly-Si modules can be the superior choice(Galal et al., 2023). Under these hot desert conditions, Poly-Si exhibited a lower open-circuit voltage (Voc) drop of 0.075 V/°C (compared to 0.1666 V/°C for Mono-Si) and a smaller output power drop

of  $0.0514 \text{ W/}^\circ\text{C}$  (compared to  $0.0704 \text{ W/}^\circ\text{C}$  for Mono-Si)(Galal et al., 2023). The Polycrystalline and Monocrystalline Solar Cells are shown in figure (6)

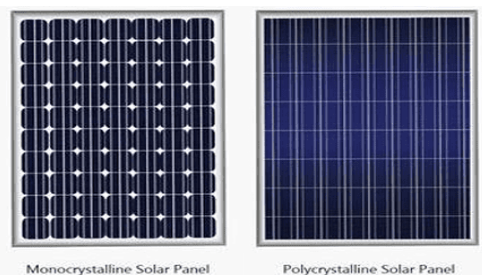


Figure 6: Polycrystalline and Monocrystalline Solar Cells

Environmental factors such as dust and cloud cover severely impair PV performance (Galal et al., 2023). Cloud cover results in an 80.503% power output loss for Poly-Si and a 79.240% loss for Mono-Si (Galal et al., 2023). Dust accumulation degrades power output by 41% for Poly-Si and 42% for Mono-Si, with dusty modules operating at higher temperatures than clean ones due to altered thermal exchange. Furthermore, during the initial hours of sunlight exposure, Mono-Si cells are more susceptible to Boron-Oxygen Light-Induced Degradation (LID) than Poly-Si cells, because Poly-Si cells inherently contain lower oxygen levels (Galal et al., 2023).

To counteract environmental losses, hardware and software optimization tracking solutions are deployed (Aedelia & Wijayanto©, 2025). Dual-axis solar tracking keeps modules optimally positioned to capture solar radiation (Aedelia & Wijayanto©, 2025). On the electrical side, the improved Incremental Conductance with Integral Regulator (IC-IR) MPPT algorithm eliminates steady-state tracking errors under dynamic conditions (Boniface & Kuşaf, 2025). Sizing simulations for a 120-kW grid-connected system demonstrate that IC-IR optimization extracts an additional 3.46 MWh of energy annually, yielding \$865 in annual savings with an extremely short payback period of 0.7 years (Boniface & Kuşaf, 2025).

Multi-site field data from 3,000 PV installations in the United Kingdom over an eight-year period revealed that Mono-Si degrades slower over time, with an annual degradation rate of  $-0.81\%/year$  compared to -

0.94%/year for Poly-Si. Mono-Si also achieved the highest monthly mean Performance Ratio (PR) of 87.97%, compared to Poly-Si's 85.08%.

Economic analysis for a residential load of 380W (consisting of 3 lights and 3 fans) over a 20-year lifespan in Dhaka shows that stand-alone systems with an inverter and battery require a total setup and maintenance cost of Tk 3,63,400 for Mono-Si and Tk 3,62,200 for Poly-Si (Boniface & Kuşaf, 2025). However, the 600W Mono-Si array extracts substantially more energy annually (1429.77 kWh) than the Poly-Si array (1031.58 kWh) (Boniface & Kuşaf, 2025). Consequently, the levelized cost of energy is significantly lower for Mono-Si (1.4688 Tk/kWh) than for Poly-Si (1.97755 Tk/kWh), establishing monocrystalline technology as the more cost-efficient option in the long term (Boniface & Kuşaf, 2025).

The sustainable economic and social development of a country is linked to the efficient management of its energy resources by its citizens. Although renewable energy sources are available worldwide, a large portion of energy is still derived from non-renewable resources, which play a major role in climate change and cause environmental issues that make living conditions more difficult. Non-renewable energy sources are responsible for 50% of global air pollution and 60% of the emission of greenhouse gases worldwide (Fitria Hidayanti, 2020). In 2023, electricity production in Afghanistan increased to 972.27 gigawatt-hours, compared to 967.43 gigawatt-hours in 2022. On average, electricity production in Afghanistan from 2008 to 2023 was 1002.42 gigawatt-hours. The highest level was recorded in 2019 at 1285.50 gigawatt-hours, while the lowest level was in 2008 at 827.10 gigawatt-hours (Slimankhil et al., 2020). Afghanistan holds a unique position among countries in terms of solar energy, with around 300 sunny days annually. In particular, the southern regions of Afghanistan are especially rich in solar energy potential (Economics, 2023). The map of Afghanistan is shown in figure (7) (Mehrad, 2021).

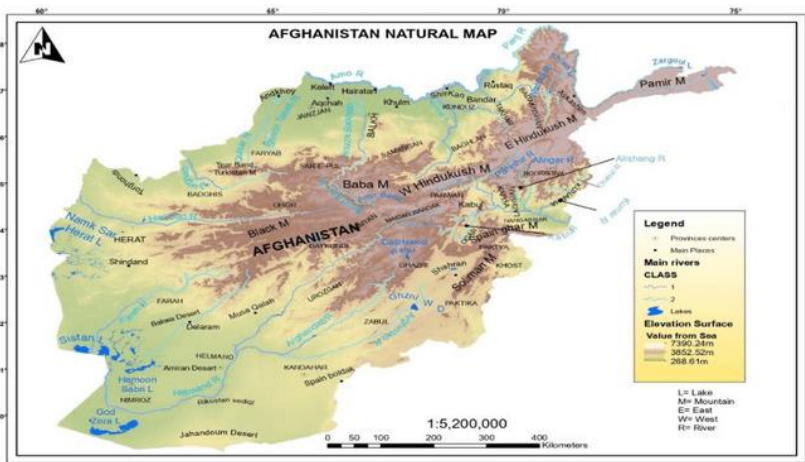


Figure 7: Natural map of Afghanistan

Kabul, the capital of Afghanistan, is a densely populated city where its residents face energy shortages throughout the year. This problem leads to the use of fuel sources (such as coal, gas, and oil) to meet energy demands, which in turn causes severe air pollution in the city. Kabul city, which frequently experiences electricity outages, has significant potential for solar energy. As a result, due to the instability of the electric grid, people have turned to solar power generation to meet their energy needs. Various types of solar panels are being used to produce electricity from solar energy.

While recent studies have explored solar PV performance in Afghanistan, a significant gap remains regarding localized assessments for Kabul City's residential sector. For instance, ( Shirzad et al., 2024) compared Monocrystalline with HIT technology in Kabul but focused on a small 3 kWp configuration. Similarly(Zgham et al., 2024) conducted a technical assessment of Mono-Si and Poly-Si modules, but their study was centered on the Ghazni region for a 10.23 kWp system. Furthermore, (Serat et al., 2026) evaluated PV performance across various climatic zones in Afghanistan, showing that Monocrystalline (m-Si) consistently yields higher performance ratios. This research distinguishes itself by focusing on a 5.9 kWp system, which is specifically tailored to meet the average electricity demand of a middle-income household in Kabul.

Article Objectives

Solar energy is one of the most sustainable and viable renewable energy sources, particularly in regions with high solar potential like Kabul City. However, the performance of solar panels is significantly influenced by environmental factors such as temperature, sunlight intensity, and dust accumulation. Monocrystalline and polycrystalline solar cells are the two most commonly used photovoltaic technologies, each with distinct efficiency levels, temperature coefficients cost considerations. The article's objectives are to compare the energy output and efficiency of monocrystalline and polycrystalline solar panels under the specific climatic conditions of Kabul City.

Methods and Materials

Site Selection

Kabul is located in the eastern part of Afghanistan, between 34°39' and 34°17' northern latitudes and 69°29' and 68°54' eastern longitudes, with an elevation of 1,798 meters above sea level. Kabul has an arid to semi-arid climate.(Akbari & Sharifi, 2024) Kabul city is divided into 22 administrative districts (Rashid A. Mushkani 1, 2021). Its population was estimated to be approximately 7 million in 2018 (Reshteen et al., 2024)Kabul map is shown in figure (8).

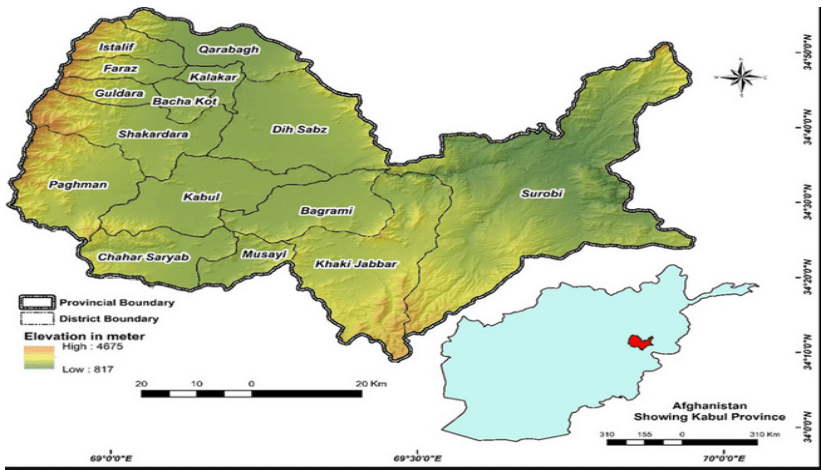


Figure 8: Kabul map

**Data Collection**

**Weather condition.** In Kabul, summers are usually hot and dry with clear skies, while winters are mostly very cold, snowy, or partly cloudy. Throughout the year, the temperature typically varies between  $-4^{\circ}\text{C}$  and  $34^{\circ}\text{C}$ , and it rarely drops below  $-10^{\circ}\text{C}$  or rises above  $37^{\circ}\text{C}$ . As shown in Figure (9), the hot season lasts for approximately 3.9 months, starting from May 25 and continuing until September 21. During this season, the average temperature is around  $28^{\circ}\text{C}$ , and the hottest day falls on July 18, with a temperature of  $34^{\circ}\text{C}$ . Likewise, Kabul’s cold season lasts for 3 months, from December 4 to March 6, with an average temperature of around  $12^{\circ}\text{C}$  during this period. The coldest day is January 19, when the temperature drops to around  $6^{\circ}\text{C}$ . Figures 9 and 10 graphically show the temperature levels of Kabul city(Weatherspark, 2023).

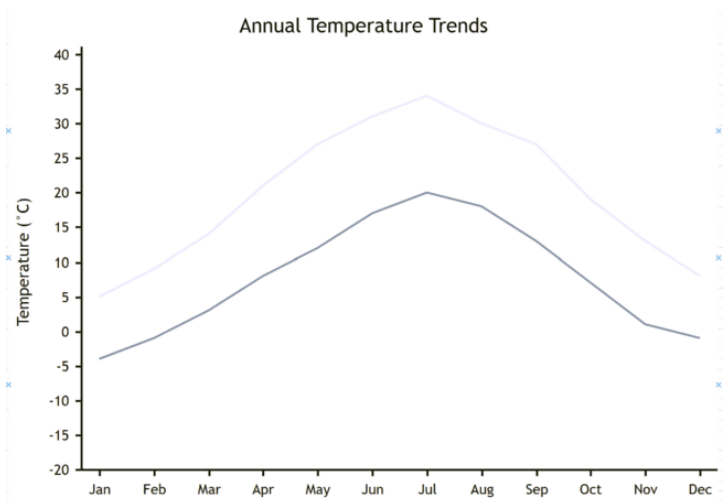


Figure 9: Average High and Low Temperatures in Kabul

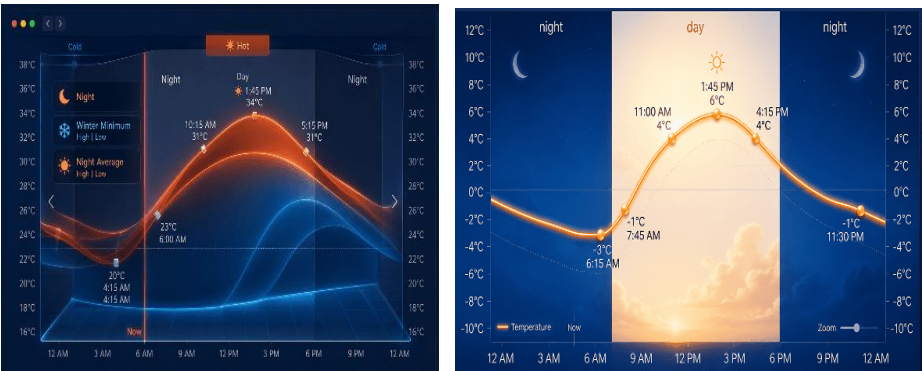


Figure 10: Average Temperature on January 19 and July 18 in Kabul

The shortest day of the year in Kabul city is December 21, with a duration of daylight lasting 9 hours and 51 minutes. The longest day of the year is July 21, with a duration of 14 hours and 28 minutes. Figure 11 shows the hours of daylight and twilight in Kabul city(Weatherspark, 2023).

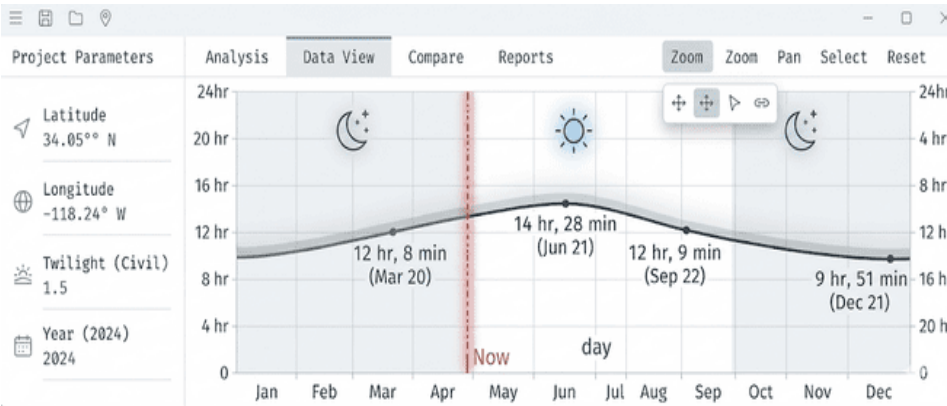


Figure 11: Hours of Daylight and Twilight in Kabul

Similarly, sunrise times also vary throughout the year. As shown in Figure 12. The earliest sunrise occurs on June 13 at 4:40 AM, while the latest sunrise takes place on January 7 at 7:00 AM. Likewise, the earliest sunset of the year happens on December 5 at 4:42 PM, and the latest sunset occurs on June 29 at 7:10 PM(Weatherspark, 2023) .

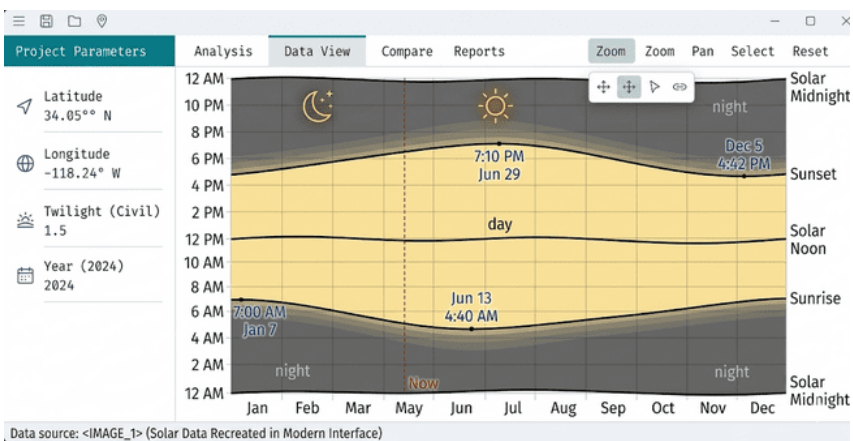


Figure 12: Sunrise & Sunset with Twilight in Kabul

Wind also has an impact on solar systems. If a solar plant is built in an area where there is no wind or where the wind speed is so low that it has no significant effect, the temperature of the solar panels will increase. This, in turn, leads to higher energy losses(Kaldellis et al., 2014). However, if the wind speed is high, it also impacts the project's economy, because in the case of increased wind speed, we are forced to use stronger structures for the installation of the solar panels(Zgham et al., 2024). As shown in Figure 13, winds last for about 4.3 months throughout the year, starting from May 4 and continuing until September 14, with an average speed of 3.1 meters per second. The windiest month of the year is June, with a wind speed of 4 meters per second. The calmest period of the year lasts for about 7.7 months, starting from September 14 and continuing until May 4. The calmest month of the year is December, with an average wind speed of 2.2 meters per second(Weatherspark, 2023).

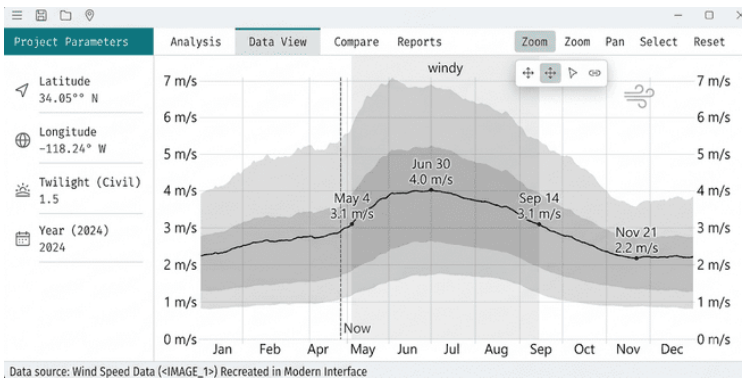


Figure 13: Average Wind Speed in Kabul

**Solar insolation.** From May 10 to August 29, over 3.6 months, is the brightest period of the year. During this period, the average shortwave solar radiation energy per square meter is 7.7 kWh. June is the brightest month of the year, with an average brightness of 8.8 kWh. The dark period in Kabul lasts for 3.2 months, starting from November 7 and continuing until February 15. During this time, the average daily shortwave solar radiation energy per square meter is less than 4.3 kWh. December is the darkest month of the year, with an average energy of 3.2 kWh per square meter. Figure 14 shows the average daily incident shortwave solar energy in Kabul(Weatherspark, 2023).

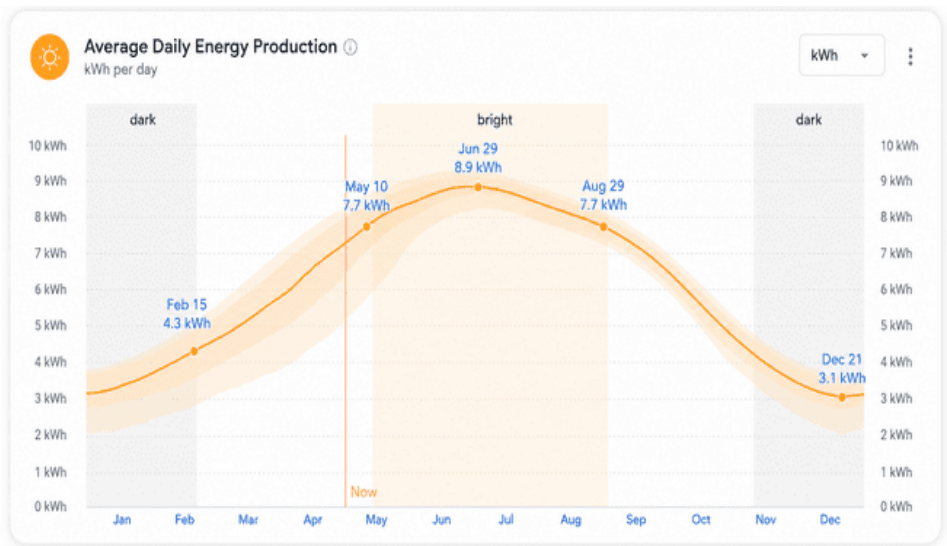


Figure 14: Average Daily Incident Shortwave Solar Energy in Kabul

In Table 1, the global horizontal irradiance, the diffuse horizontal irradiance, and the ambient temperature for Kabul are shown for all months of the year, as well as the annual values of these parameters (Goel, 2007).

Table 1: Monthly Global Horizontal Irradiations, Horizontal diffuse irradiations, and ambient temperature in Kabul

| Months | GlobHor KWh/m2 | DiffHor KWh/m2 | T_Amb °C |
|--------|----------------|----------------|----------|
| Jan    | 88             | 30.5           | 0.5      |
| Feb    | 98.1           | 38.5           | 2.7      |
| Mar    | 150.6          | 51.1           | 9.4      |
| Apr    | 190.6          | 58             | 14.5     |
| May    | 222.7          | 62.1           | 20       |
| Jun    | 248.1          | 53.2           | 24.8     |
| Jul    | 250.6          | 54.7           | 27.7     |
| Aug    | 229.2          | 52.5           | 26.3     |
| Sep    | 199.7          | 38.9           | 21.8     |
| Oct    | 156.4          | 33.2           | 15.4     |
| Nov    | 100.8          | 29             | 8.1      |
| Dec    | 93             | 24.5           | 3.2      |
| Year   | 2027.9         | 526.1          | 14.5     |

**System Design**

The research is based on system design according to capacity, and a fixed-capacity system was chosen for the study. This was done to provide a standard comparison between monocrystalline and polycrystalline PV technologies. The selection of this fixed capacity was made to eliminate the effects of capacity-related variations and to prevent any form of inequality, ensuring that fair conditions for the comparison and analysis of both technologies are established.

**PVsyst Simulation**

PVsyst is considered one of the most standard simulation software tools that is widely used nowadays. This software was designed and developed by Swiss scientist Andre Mermaid and his collaborators. It is used by numerous engineers around the world because it can quickly provide results and also generate production reports with high accuracy(Anurag Shrivastava, Rajneesh Sharma, 2023). The PVsyst software provides design capabilities at different levels. These levels allow users to understand the size of the system or its potential energy production without needing to enter into detailed specifications. The pre-sized level quickly assesses the dimensions and components of a system, as well as evaluates the system's production. The Design level offers a complete and detailed design of a project, where the system is thoroughly planned with all

necessary specifications. PVsyst also contains extensive solar radiation data for many cities, which it obtains from sources such as NASA, SSE, and RETScreen databases.(Muñoz et al., 2016). For this research as well, the PVsyst software was used in order to accurately compare monocrystalline and polycrystalline solar panels and to determine which type of solar panel is more suitable for the city of Kabul.

Here are the step-by-step PVsyst simulation stages:

- **Project Initialization:** The simulation began by creating a new project within the PVsyst software, specifically selecting the "Off-Grid " system type to align with the research objectives.
- **Geographical Site and Meteorological Data Selection** The study site was defined as Kabul, Afghanistan (Latitude: 34.5° N, Longitude: 69.2° E). To ensure high simulation accuracy, hourly meteorological data, including global horizontal irradiation and ambient temperature, were obtained from the NASA-SSE database and imported into the software.
- **Orientation Settings:** To maximize solar energy capture at Kabul's latitude, the PV panels were configured with a fixed tilt angle of 30°. The orientation was set to South-facing with an Azimuth of 0°.
- **System Definition and Component Selection:** The total system capacity was set to 5.9 kWp, chosen to reflect the average residential load in Kabul. Two separate configurations were modeled: one using Monocrystalline modules and the other using Polycrystalline modules. A compatible inverter was selected from the PVsyst database to match the specified system capacity for both scenarios.
- **Loss Parameter Calculations:** Specific loss factors were integrated to reflect Kabul's unique urban environment. A 5% soiling loss was applied to account for high dust levels. Additionally, the simulation incorporated thermal losses (based on temperature coefficients), wiring (ohmic) losses, and inverter efficiency losses to ensure a realistic energy yield prediction.
- **Running the Simulation:** After all technical parameters were set, the software performed an hourly simulation for a full calendar year. This process calculated the total energy injected into the grid (kWh) and the system's Performance Ratio (PR).

- 7. Report Generation and Results Extraction. In the final stage, comprehensive simulation reports were generated for both technologies. These reports provided the data required for the comparative analysis of monthly and annual energy production presented in the Results section of this study

Findings

The comparison of poly-crystalline and mono-crystalline solar panels for Kabul city was carried out using PVsyst software, and the results are summarized in Table 2. Table 2 presents the monthly output energy and the performance ratio of both solar technologies for a fixed-capacity 5.9 kW system. The annual output energy of the poly-crystalline solar panel system is 11273 kWh, whereas the annual output energy of the mono-crystalline solar panel system is 11295 kWh, which clearly indicates that mono-crystalline solar panels perform better than poly-crystalline ones. Additionally, the annual performance ratio for poly-crystalline solar panels is 0.709, while this parameter for mono-crystalline solar panels is 0.711, and these values are also higher for mono-crystalline panels. This further demonstrates that monocrystalline solar panels have better performance compared to polycrystalline solar panels.

Table 2: Monthly output energy and performance ratio for both mono and poly (5.9 kWp) solar PV systems

| Output Power from (5.9kW) System |       |       | Performance Ratio of (5.9kW) System |       |
|----------------------------------|-------|-------|-------------------------------------|-------|
| Months                           | Mono  | Poly  | Mono                                | Poly  |
| Jan                              | 836   | 832   | 0.974                               | 0.872 |
| Feb                              | 812   | 807   | 0.917                               | 0.911 |
| Mar                              | 984   | 991   | 0.746                               | 0.755 |
| Apr                              | 1003  | 1005  | 0.693                               | 0.693 |
| May                              | 989   | 989   | 0.68                                | 0.68  |
| Jun                              | 956   | 955   | 0.627                               | 0.627 |
| Jul                              | 983   | 983   | 0.624                               | 0.624 |
| Aug                              | 983   | 981   | 0.618                               | 0.618 |
| Sep                              | 954   | 954   | 0.593                               | 0.593 |
| Oct                              | 984   | 979   | 0.665                               | 0.665 |
| Nov                              | 867   | 863   | 0.849                               | 0.852 |
| Dec                              | 944   | 934   | 0.885                               | 0.857 |
| Year                             | 11295 | 11273 | 0.711                               | 0.701 |

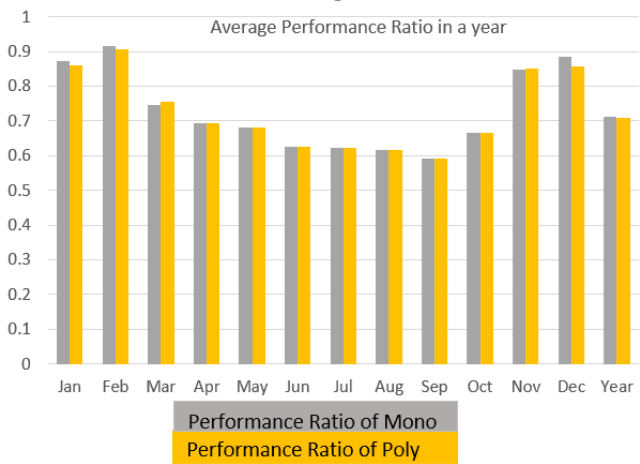


Figure15: Comparison of monthly performance ratio for both mono and poly solar PV (5.9 kWp) systems

Figure 15 shows the performance of both technologies from January to December. It can be observed that the system performance for both technologies is higher in January, February, March, November, and December, while from April to September, due to the hot weather, the performance decreases. Figure 16 graphically shows a comparison of the monthly output energy of mono-crystalline and poly-crystalline solar panels (5.9 kWh).

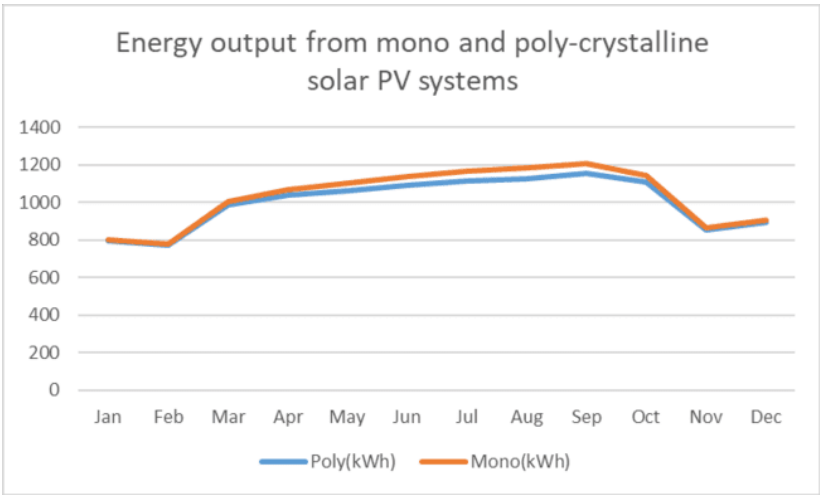


Figure 15: comparison of the monthly output energy of mono-crystalline and poly-crystalline solar panels (5.9 kWh).

Based on the above comparisons and analysis, it is concluded that monocrystalline solar panels have better performance compared to polycrystalline solar panels. This is evident as the monthly output power and performance ratio of mono-crystalline solar panels are higher than those of poly-crystalline solar panels.

## **Discussion**

The simulation results for a 5.9 kWp system in Kabul reveal a technical energy yield difference of only 0.2% (11,295 kWh for Monocrystalline vs. 11,273 kWh for Polycrystalline). While this margin appears statistically minimal, it does not fully reflect the dynamic environmental challenges of Kabul's urban micro-climate, such as extreme seasonal temperature fluctuations and high atmospheric soiling.

### ***Impact of Urban Soiling (Dust Accumulation)***

The primary justification for preferring Monocrystalline technology in Kabul lies in its superior resilience to dust. Although the PVsyst simulation applied a uniform soiling loss, experimental research indicates that dust accumulation affects module types differently. According to Geetha et al. (2025), the accumulation of dust leads to a significantly higher power decline in Polycrystalline modules (30.48%) compared to Monocrystalline modules (14.1%)(Geetha et al., 2025). This discrepancy is attributed to the surface characteristics of Polycrystalline cells, which attract and retain particulate matter more readily than smoother Monocrystalline surfaces. In Kabul's semi-arid environment, where winter air pollution and dust are prevalent, the actual performance gap is expected to widen far beyond the simulated 0.2%(Geetha et al., 2025).

### ***Thermal Stability and Degradation***

Kabul experiences high solar irradiance and elevated temperatures during the summer months. Monocrystalline modules generally exhibit better thermal stability. Furthermore, field studies across Afghanistan's climatic zones confirm that Monocrystalline (m-Si) technology consistently maintains a higher performance ratio, ranging from 81.8% to 88.9% across various regions(Serat et al., 2026). Over a standard 25-year operational lifespan, the annual degradation rate for Monocrystalline is typically lower than that of Polycrystalline, ensuring a higher cumulative lifetime energy

yield and a more favorable Levelized Cost of Energy (LCOE)(Serat et al., 2026).

### ***Space Efficiency and Urban Constraints***

In the densely populated urban districts of Kabul, where rooftop space is limited, the higher efficiency per square meter of Monocrystalline modules is a critical factor. Research indicates that advanced Monocrystalline technologies can require approximately 8.1% less installation area than traditional alternatives for the same capacity(Shirzad et al., 2024). This reduction in footprint effectively minimizes the balance-of-system (BOS) costs and allows residents to maximize energy production within constrained areas(Shirzad et al., 2024). Therefore, despite the marginal simulated difference, Monocrystalline technology is the more sustainable and economically sound choice for Kabul's residential sector

### **Conclusion**

This study provided a techno-economic comparative analysis of Monocrystalline and Polycrystalline PV technologies for a 5.9 kWp residential system in Kabul City using PVsyst simulation. The results indicate that Monocrystalline panels generate an annual energy yield of 11,295 kWh with a Performance Ratio (PR) of 71.1%, while Polycrystalline panels produce 11,273 kWh with a PR of 70.9%. While the simulated performance difference is a marginal 0.2% (22 kWh/year), this study concludes that Monocrystalline technology is the technically and economically superior choice for Kabul's urban environment for several reasons. First, experimental data suggest that Monocrystalline modules are significantly more resilient to urban soiling, experiencing only a 14.1% power decline compared to 30.48% for Polycrystalline modules in high-dust conditions. Second, the superior temperature coefficient and lower annual degradation rate of Monocrystalline panels ensure a higher energy harvest over a 25-year lifespan, leading to a more favorable Levelized Cost of Energy (LCOE). Finally, Monocrystalline panels require approximately 8.1% less installation area, which is a critical advantage for the space-constrained rooftops of Kabul.

### ***Study Limitations***

The primary limitation of this research is its reliance on simulation-based data with a uniform soiling factor. Real-world performance in Kabul may vary due to extreme seasonal air pollution and localized shading from rapid urban expansion, which may not be fully captured in standard meteorological databases.

### **Recommendations**

#### ***For Residents and Investors***

Monocrystalline panels are recommended for residential installations in Kabul to maximize energy density on limited roof spaces and ensure better performance during dusty winter months.

#### ***For Policy Makers***

The Afghan energy sector should incentivize the import of high-efficiency PV technologies to improve urban energy self-sufficiency and reduce reliance on imported power.

#### ***For Future Research***

Future studies should focus on long-term on-site experimental validation to measure the precise impact of Kabul's unique particulate matter on various PV coatings and cleaning cycles.

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