Land Use and Energy Comparison of grid-connected Monocrystalline, and Heterojunction with Intrinsic Thin-layer Solar Technologies using advanced PVsyst Software (A Case Study in Kabul Province, Afghanistan)

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Abstract

This study aims to compare the performance and land use requirements of grid-connected monocrystalline and heterojunction with intrinsic thin-layer (HIT) solar technologies in Kabul Province, Afghanistan, using advanced PVsyst software. A 3 kWp PV system was designed and simulated for both technologies. The results show that HIT panels outperform monocrystalline panels in terms of annual energy production and performance ratio (PR). HIT panels generated 6108 kWh annually with a PR of 85.49%, while monocrystalline panels produced 5969.5 kWh with a PR of 83.56%. Additionally, HIT panels required approximately 8.1% less installation area compared to monocrystalline panels, making them more space-efficient. The findings suggest that the adoption of HIT solar technology can lead to improved energy output and more efficient use of available land, contributing to more sustainable and effective solar energy solutions in the region. Despite potentially higher initial costs, HIT panels can provide better long-term benefits through higher efficiency and lower land use requirements. Further research is recommended to explore the cost-benefit analysis, long-term performance evaluation, sensitivity analysis, grid

integration, and policy frameworks related to HIT solar technology in Afghanistan. By addressing these areas, a more comprehensive understanding of the practical implementation and long-term sustainability of HIT solar technology can be achieved, ultimately supporting the transition towards more efficient and environmentally-friendly renewable energy solutions in the country.

Keywords: Solar PV, Monocrystalline, Heterojunction with Intrinsic Thin-layer (HIT), PVsyst, Land Use, Energy Comparison, Afghanistan

1. Introduction

The key function for development and quality of life is energy (Kalogeria, 2009). Beside other factors life standards of any region are calculated by the rate of energy consumed by the population in that area (Abdullah, 2022). The utilization of solar energy for the advancement of humanity is currently experiencing a surge in popularity. Solar Photovoltaic (SPV) systems, functioning as decentralized power sources, offer a promising alternative due to a multitude of benefits such as their modular configuration, decreasing expenses, supportive governmental policies, minimal upkeep requirements, and environmentally friendly operation. The employment of SPV systems demonstrates significant potential in fulfilling energy demands economically through the implementation of efficient design tactics. Additionally, to ensure uninterrupted power generation from SPV sources, the incorporation of backup systems like battery storage is imperative.

The installation of Photovoltaic (PV) systems is playing a crucial role on a global scale as PV systems represent clean, eco-friendly, and secure energy sources. Nonetheless, a drawback of PV systems is the higher initial investment required compared to traditional energy sources. Presently, numerous research endeavors are concentrated on enhancing PV systems by determining the optimal quantity of PV modules, suitable storage battery capacity, appropriate inverter capacity, and ideal PV array tilt angles. The assistance of user-friendly software tools is essential to facilitate the determination of the optimal sizing for PV systems. Afghanistan does not have a reliable source of power, and people who live in cities do not have full access to electricity (Shirzad, Fazli, Zgham, & Fatemi, 2023). Most businesses heavily rely on a consistent and reliable supply of electricity to sustain their operations (Serat, Fatemi, & Shirzad, 2023).

A variety of software tools have been created to facilitate the efficient design of PV systems, as documented in (Kaldellis, 2004, El-Hefnawi, 1998, Soler-Bientz, Ricalde-Cab, & Solis-Rodriguez, 2006, Lalwani, Kothari, & Singh, 2010).

As per (Kaldellis, 2004), the development of a software tool named "PHOTOV-III" aimed to ascertain the number of PV modules and battery capacity based on load demand for the optimal sizing of PV systems in Greece. The optimization process involves fixing the number of PV modules initially while adjusting the battery capacity in accordance with the load demand until zero load rejection is achieved. Subsequently, the number of PV modules is increased, and the simulation is reiterated. Throughout each simulation, PV sizing curves are generated under zero load rejection circumstances. However, this software solely produces the sizing curves without computing the specific dimensions of the PV system and does not account for the optimal inverter size or PV module tilt angle. As per (El-Hefnawi, 1998, Soler-Bientz), a software program coded in FORTRAN computes the minimum required PV array area based on a predefined weather profile and the minimum number of storage days for optimal PV system sizing. The drawback of the program lies in its lack of user-friendliness and its failure to calculate the inverter size or the PV module tilt angle. Another PV software tool was established to monitor the performance of a small PV system in a remote location (Soler-Bientz, Ricalde-Cab, & Solis-Rodriguez, 2006). This particular software monitors the performance of PV systems but does not determine the optimal sizing of such systems. Various commercially available software tools for simulating standalone and hybrid PV systems are cataloged in, (Lalwani, Kothari, & Singh, 2010). These commercial software tools consist of RETScreen, PV F-Chart, Solar DesignTool, INSEL, TRNSYS, NREL, among others. This study evaluates and compares the energy output of mono-crystalline and HIT solar photovoltaic (PV) technologies, under specific climatic conditions, with the help of advanced PVsyst software (Zgham, Shirzad, & Fatemi, 2024).

PVSYST is a computer software package meticulously designed for the examination, sizing, simulation, and data analysis of comprehensive PV systems (Worldwatch Institute, 2009). Developed by the energy institute of Geneva, PVSYST features all the necessary subprograms for the design, optimization, and simulation of PV systems, encompassing grid-connected, isolated, and pumping applications (International Energy Agency, 2009).This investigation employs PVSYST to conduct a comparative evaluation of PV cell performance for three distinct PV technologies under authentic operational conditions (PVSYST, n.d.).The utilization of solar energy for human welfare is currently experiencing an upsurge. Solar Photovoltaic (SPV) systems, serving as decentralized power sources, emerge as a promising option due to various advantages such as their modular configuration, decreasing expenses, supportive government regulations, minimal upkeep, and environmentally friendly functioning.

The utilization of SPV systems presents a substantial opportunity to fulfill energy requirements economically by employing efficient design approaches. Additionally, to ensure uninterrupted power generation from SPV sources, supplementary systems like battery storage are essential. The installation of Photovoltaic (PV) systems plays a vital role globally, showcasing the significant advantages of incorporating grid-connected PV systems to expand the current grid network.

This research endeavor aims to deliver a comprehensive evaluation of the efficiency and energy and land use implications of monocrystalline, HIT, solar technologies in Kabul Province, Afghanistan. In doing so, it aims to provide valuable insights into the most suitable PV technology for this specific region, taking into account its distinctive climatic and economic circumstances.

2. Materials and Method

This study focuses on Kabul Province, Afghanistan, which faces significant energy challenges, including limited access to electricity and high reliance on imported power. The region's climate and solar irradiance data were crucial for accurately simulating solar photovoltaic (PV) systems. The study compared two types of solar PV technologies:

2.1 Monocrystalline Panels

- Known for their high efficiency and long lifespan
- Widely used in various solar installations due to their reliability

2.2 HIT (Heterojunction with Intrinsic Thin-layer) Panels

- Combine the advantages of monocrystalline and thin-film technologies
- Offer higher efficiency and better performance in high-temperature conditions
- Require less installation area compared to traditional panels

The selection of these technologies was based on their efficiency and relevance to the renewable energy landscape in the region.

3. System Design

3.1 Site selection

Kabul, the capital city of Afghanistan, is located at a latitude of approximately 34.5553° N and a longitude of approximately 69.2075° E. Situated in the eastern part of the country, the city nestles in a narrow valley between the steep mountains of the Hindu Kush range at an altitude of about 1,800 meters (5,900 feet) above sea level. Covering an area of roughly 1,023 square kilometers (395 square miles), Kabul is traversed by the Kabul River, which provides a vital water source for the region. This high elevation contributes to its varied climate, with cold winters and hot summers. Despite facing numerous challenges, including conflict and political instability, the city retains its rich heritage and vibrant spirit. Figure -1 shows the map of Kabul (Valka.cz, n.d.).

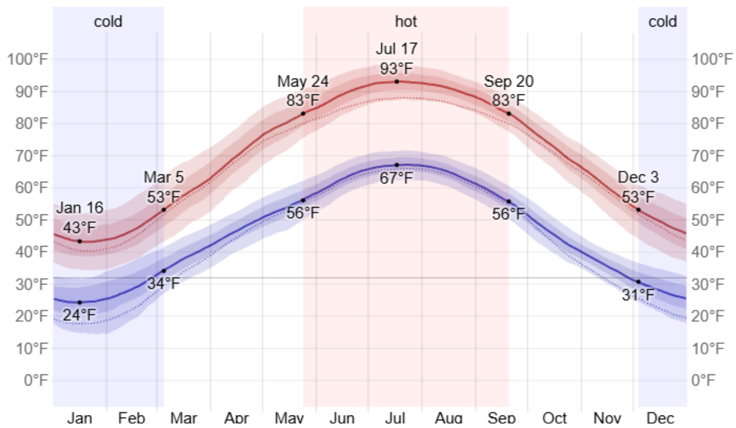
Figure-1: Map of the Kabul

3.2: Data Collection

3.2.1: weather data

Kabul, Afghanistan, experiences a diverse climate with distinct seasons. Figure-2shows During the summer months (June to August), the city is characterized by hot temperatures, ranging from 86°F (30°C) to 87.8°F (31°C), making it crucial to stay hydrated and seek shade. The nights remain relatively warm, with lows between 55.4°F (13°C) and 60.8°F (16°C). In contrast, the winter months (December to February) are cold and snowy, with daily high temperatures rarely exceeding 12°C (53°F). The coldest month is January, with an average low of -4°C (25°F) and a high of 7°C (44°F). The yearly temperature range varies from -4°C (24°F) to 34°C (93°F), with July being the hottest month (average high of 93°F and low of 67°F). and figure-2 shows the average temperature in Kabul (Weather Spark, n.d.).

Figure-2: Average High and Low Temperature in Kabul



Beside that figure-3, figure-4, figure-5, and figure-6 show the average hourly temperature in Kabul, cloud covered times, hours of daylight and average wind speed for the Kabul city respectively (Weather Spark, n.d.). That all these factors have their impacts on energy production of a solar PV system.

Figure-3: average hourly temperature

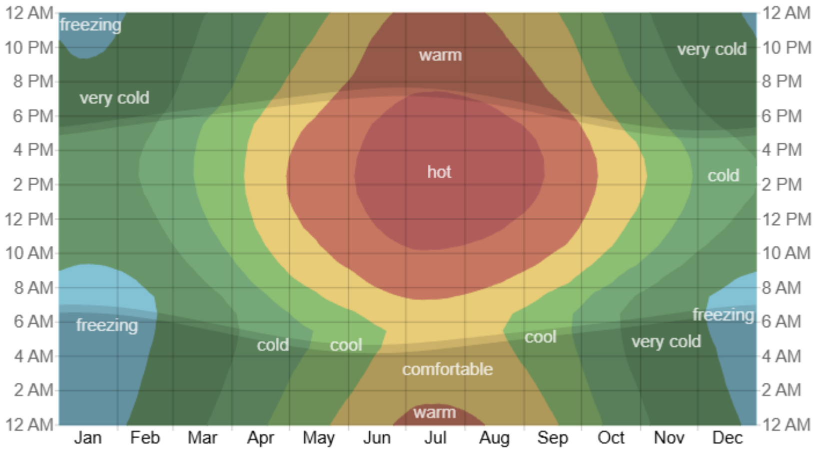


Figure-4: cloud covered times

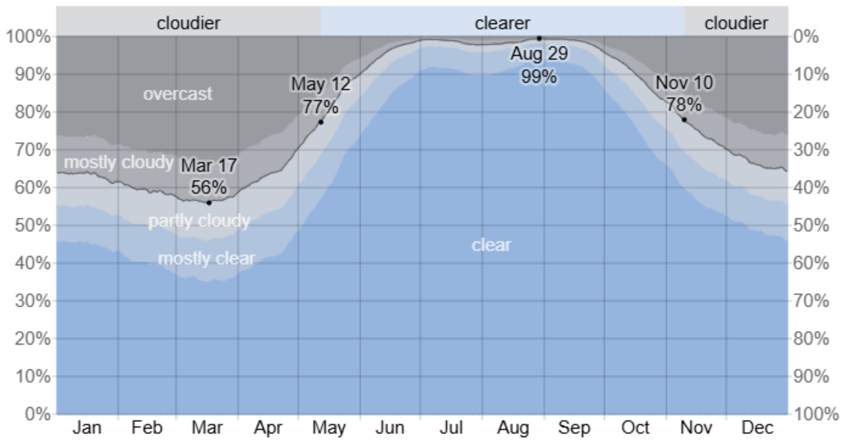
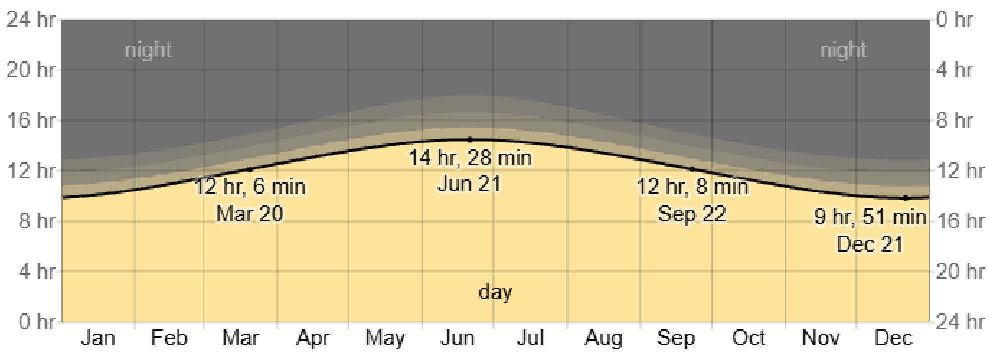


Figure-5: hours of daylight



In the following figures we see the average wind speed that has high impact in cooling of the panels, and requiring how strong fixtures would be required for fixing the panels in them.

Figure-6: average wind speed

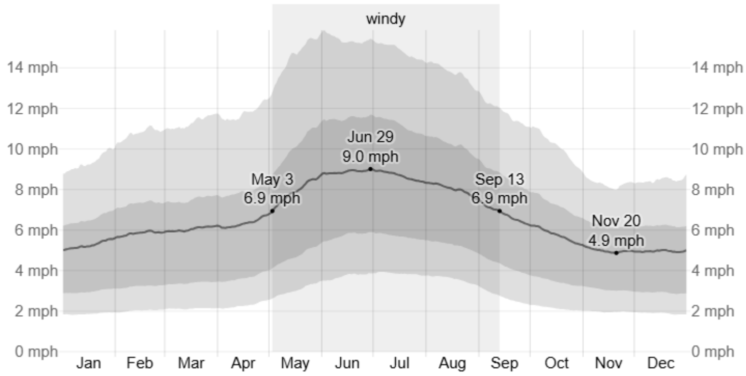


Figure-7: solar azimuth and azimuth in Kabul

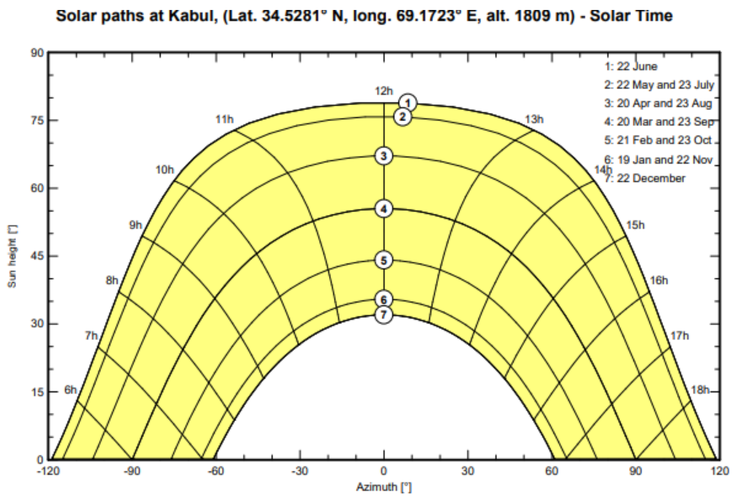
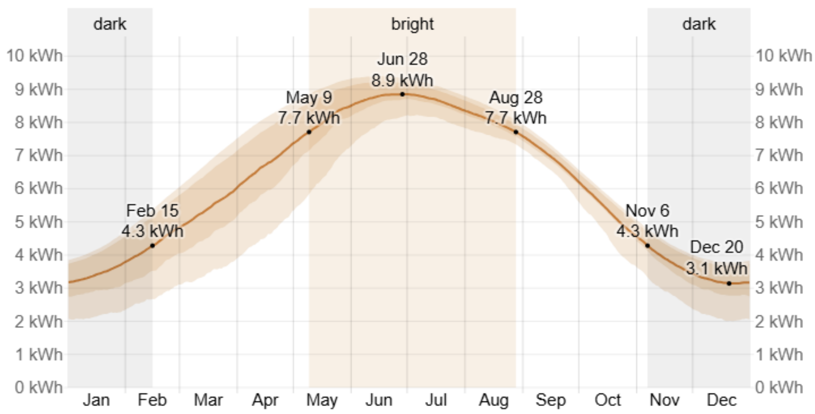


Figure-8: average daily incident solar shortwave for Kabul



C. Mismatch, whether inherent due to cell variations or induced by external factors, can impact the overall output of a PV array. A judiciously positioned PV array may experience a 1-3% reduction in DC power due to mismatch.

Space devoid of objects that cast shadows is ideal for PV panel installation. The selection of PV panels involved a comparative analysis of outcomes based on different manufacturing technologies. The specifications for panels and inverters were chosen from the PVSYST library.

4. Results and discussion

4.1. System Design and Configuration

A 3 kWp grid-connected photovoltaic (PV) system was designed and simulated using PVsyst software in Kabul Province, Afghanistan. The performance of monocrystalline and heterojunction with intrinsic thin-layer (HIT) solar technologies was compared, with the following key findings and it’s shown in figure-9, 10, 11, and 12 also:

Heterojunction with Intrinsic Thin-layer (HIT) Panels:

8 panels, each with 385 Wp capacity, 34 V voltage, and 11.32 A current

Annual energy production of 6108 kWh

Performance ratio (PR) of 85.49%

Required installation area of 14.8 m²

Figure-9: HIT PV Specification

General parameters

Grid-Connected System		**No 3D scene defined, no shadings**			
PV Field Orientation					
Orientation		**Sheds configuration**		**Models used**	
Fixed plane		No 3D scene defined		Transposition	Perez
Tilt/Azimuth	30 / 0 °			Diffuse	Perez, Meteonorm
				Circumsolar	separate
Horizon		**Near Shadings**		**User's needs**	
Free Horizon		No Shadings		Unlimited load (grid)	

PV Array Characteristics

PV module		**Inverter**	
Manufacturer	REC	Manufacturer	Canadian Solar Inc.
Model	REC385AA Pure	Model	CSI-3KTL1P-GI-FL
(Original PVsyst database)		(Original PVsyst database)	
Unit Nom. Power	385 Wp	Unit Nom. Power	3.00 kWac
Number of PV modules	8 units	Number of inverters	1 unit
Nominal (STC)	3080 Wp	Total power	3.0 kWac
Modules	1 strings x 8 In series	Operating voltage	80-500 V
At operating cond. (50°C)		Pnom ratio (DC:AC)	1.03
Pmpp	2882 Wp		
U mpp	300 V		
I mpp	9.6 A		
Total PV power		**Total inverter power**	
Nominal (STC)	3.08 kWp	Total power	3 kWac
Total	8 modules	Number of inverters	1 unit
Module area	14.8 m²	Pnom ratio	1.03

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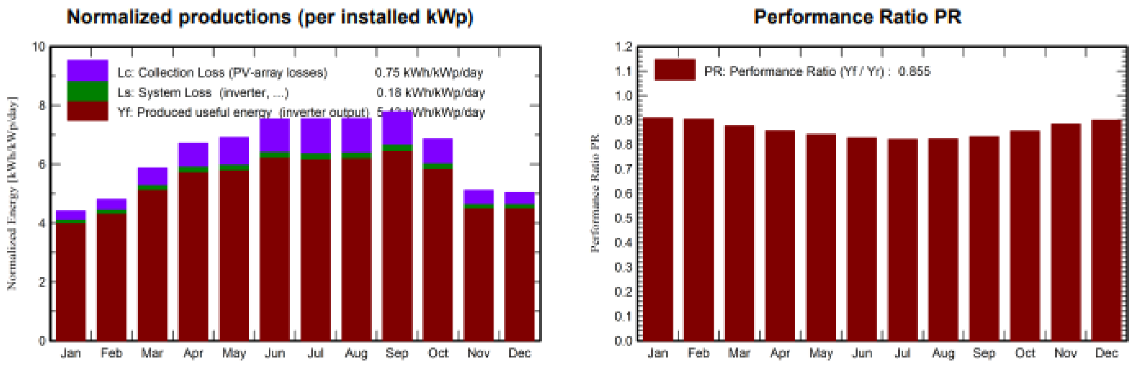
Figure-10: HIT PV Energy and PR simulation

System Production

Produced Energy	6108.00 kWh/year	Specific production	1983 kWh/kWp/year
		Perf. Ratio PR	85.49 %



Monocrystalline Panels

8 panels, each with 385 Wp capacity, 34 V voltage, and 11.32 A current

Annual energy production of 5969.5 kWh

Performance ratio (PR) of 83.56%

Required installation area of 16.1 m²

Figure-11: Monocrystalline PV specification

General parameters

Grid-Connected System	**No 3D scene defined, no shadings**	
PV Field Orientation		
Orientation	**Sheds configuration**	**Models used**
Fixed plane	No 3D scene defined	Transposition: Perez
Tilt/Azimuth: 30 / 0 °		Diffuse: Perez, Meteonorm
		Circumsolar: separate
Horizon	**Near Shadings**	**User's needs**
Free Horizon	No Shadings	Unlimited load (grid)

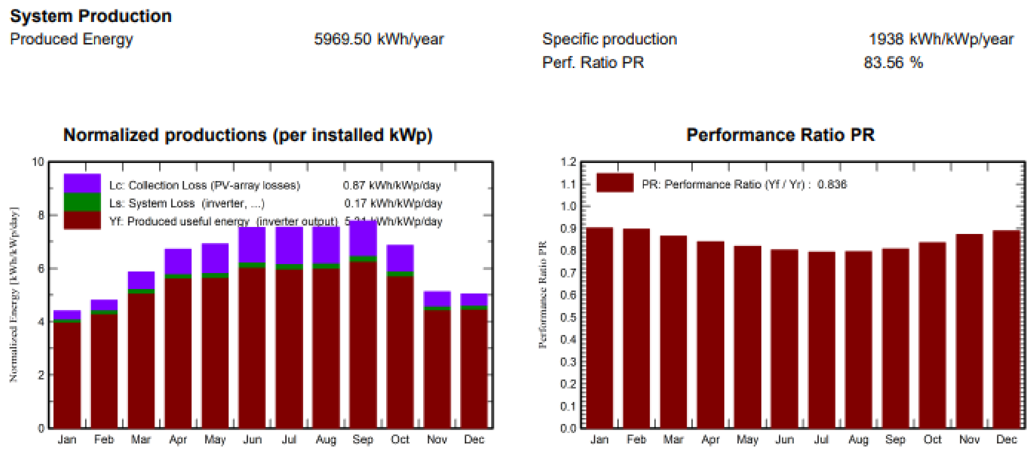
PV Array Characteristics

PV module		**Inverter**	
Manufacturer	REC	Manufacturer	Canadian Solar Inc.
Model	REC 385TP3SM 72	Model	CSI-3KTL1P-GI-FL
(Original PVsyst database)		(Original PVsyst database)	
Unit Nom. Power	385 Wp	Unit Nom. Power	3.00 kWac
Number of PV modules	8 units	Number of inverters	1 unit
Nominal (STC)	3080 Wp	Total power	3.0 kWac
Modules	1 strings x 8 In series	Operating voltage	80-500 V
At operating cond. (50°C)		Pnom ratio (DC:AC)	1.03
Pmpp	2827 Wp		
U mpp	288 V		
I mpp	9.8 A		
Total PV power		**Total inverter power**	
Nominal (STC)	3.08 kWp	Total power	3 kWac
Total	8 modules	Number of inverters	1 unit
Module area	16.1 m²	Pnom ratio	1.03
Cell area	14.5 m²		

4.2. Energy Production and Efficiency

HIT panels demonstrated a 2.3% higher annual energy output compared to monocrystalline panels. The performance ratio was also higher for HIT panels at 85.49%, indicating better overall system efficiency.

Figure-12: Energy production of monocrystalline after simulation



4.3. Land Use

HIT panels required approximately 8.1% less installation area compared to monocrystalline panels for the same system capacity, making them more space-efficient.

4.4. Comparative Analysis

The study found that HIT technology offers superior performance in terms of energy production and land use efficiency compared to monocrystalline panels. Despite potentially higher initial costs, HIT panels can provide better long-term benefits through higher efficiency and lower land use requirements, making them a viable option for grid-connected PV systems in regions like Kabul Province. The adoption of HIT solar technology could lead to improved energy production and more efficient use of space, contributing to more sustainable and effective solar energy solutions in the region. Further research on cost-benefit aspects and long-term performance could provide additional insights into the practical implementation of these technologies

5. Conclusion and Future scope

The comparative analysis of monocrystalline and heterojunction with intrinsic thin-layer (HIT) solar technologies in this study has demonstrated the superior performance of HIT panels in the context of Kabul Province, Afghanistan. The key findings are:

- HIT panels achieved a 2.3% higher annual energy production compared to monocrystalline panels.
- The performance ratio (PR) of HIT panels was 85.49%, which is higher than the 83.56% PR of monocrystalline panels, indicating better overall system efficiency.
- HIT panels required approximately 8.1% less installation area compared to monocrystalline panels for the same system capacity, making them more space-efficient.

These results suggest that the adoption of HIT solar technology can lead to improved energy output and more efficient use of available land, contributing to more sustainable and effective solar energy solutions in the region.

5.1. Future Scope

While this study has provided valuable insights into the comparative performance of HIT and monocrystalline solar technologies, further research and analysis could explore the following areas:

1. Investigate the long-term economic viability of HIT panels, considering factors such as initial investment, operational costs, and potential savings from higher energy yields and reduced land requirements.
2. Assess the durability and reliability of HIT panels over an extended period, including their degradation rates and maintenance requirements, to better understand their suitability for long-term deployment.
3. Explore the impact of various environmental and climatic factors, such as temperature, humidity, and dust accumulation, on the performance of HIT and monocrystalline panels in the specific context of Kabul Province.
4. Investigate the challenges and opportunities associated with integrating HIT-based PV systems into the existing grid infrastructure, including grid stability, power quality, and potential grid upgrades required.
5. Analyze the current policy and regulatory environment in Afghanistan and identify potential incentives, subsidies, or other support mechanisms that could encourage the widespread adoption of HIT solar technology.

By addressing these future research areas, a more comprehensive understanding of the practical implementation and long-term sustainability of HIT solar technology in Kabul Province, and similar regions can be achieved, ultimately supporting the transition towards more efficient and environmentally-friendly renewable energy solutions.

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