Design and Cost Analysis of Thin-Film Solar Energy Deployment in Tucson

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Abstract

This study presents a techno-economic assessment of a grid-connected thin-film photovoltaic (PV) system designed for deployment in Tucson, Arizona. The system comprises 700 First Solar FS-3100-Plus modules configured into five strings of 140 modules, paired with two Huawei SUN2000-30KTL-US inverters. The system yields an annual AC energy output of 18,894 kWh in its first year, with an energy yield of 270 kWh/kW and a DC capacity factor of 3.1%. Despite the relatively low performance ratio of 0.11, the financial evaluation demonstrates potential long-term value. The levelised cost of energy (LCOE) is estimated at 6.55 ¢/kWh (real), with Year 1 net savings of $2,097 and a net present value (NPV) of $3,290. The total installed cost of the system is $57,366.66, resulting in a unit cost of $0.82/Wdc, with the major expenses attributed to installation labour and overhead. A payback period of 15.8 years is projected, indicating the need for performance optimisations to improve return on investment. This analysis highlights the system's economic viability under Tucson's high solar irradiance and provides insights into cost distribution, efficiency potential, and long-term financial outcomes of thin-film PV systems in desert climates.

Introduction

Tucson, Arizona, is one of the most promising locations in the United States for solar energy development due to its high solar irradiance, receiving sunlight nearly 85% of the year [1]. This exceptional solar potential has made the region a key hub for testing and deploying solar technologies, including thin-film photovoltaic (PV) systems. Thin-film solar technologies, such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si), have garnered attention due to their low material usage, lightweight structure, and ability to perform well under diffuse light conditions [2], [3]. In Tucson, the University of Arizona Tech Park hosts the Solar Zone, a major facility dedicated to the demonstration and analysis of solar technologies under real-world desert conditions [4]. The Solar Zone includes projects such as Deriva Energy's thin-film panel installation, which spans approximately 37.4 acres and generates 6 megawatts (MW) of electricity—enough to power over 800 homes [5]. These installations provide invaluable data on energy output, panel degradation, and overall system reliability in arid environments [6]. Moreover, Tucson is home to Global Solar Energy (GSE), a leading manufacturer of CIGS thin-film PV modules. The company established a 40 MW production facility with an aim to expand significantly [7]. GSE also created one of the world's largest

CIGS installations at 750 kW, demonstrating both the manufacturing capability and real-world application potential of thin-film technology in the region [8], [9]. This vertically integrated model—from production to deployment—reinforces Tucson's role as a national leader in thin-film solar energy development. Thin-film panels deployed in Tucson have shown encouraging performance metrics in the face of challenging environmental conditions. Though early thin-film technologies suffered from higher degradation rates compared to crystalline silicon, newer modules—particularly CIGS—have achieved degradation rates of less than 1% per year after initial stabilization [10]. The arid and sunny environment of Tucson enables a high energy yield per module, which further improves the life-cycle performance and economic feasibility of thin-film solar projects [11].

Environmental life-cycle assessments (LCA) reveal that thin-film PV systems, especially CdTe and CIGS, offer significant reductions in greenhouse gas emissions and other environmental impacts when compared to conventional fossil-fuel-based energy sources [12], [13]. When deployed in high-irradiance regions like Tucson, these benefits are magnified due to increased energy generation efficiency over the system's lifespan. Studies show that thin-film technologies emit 90% less greenhouse gas over their life cycle compared to coal-based generation [14]. Tucson also supports ongoing academic and industry research into new generations of thin-film technologies. These include advanced material compositions, multijunction architectures, and flexible substrates aimed at expanding the applicability and efficiency of thin-film PV [15]. The combination of favourable environmental conditions, robust infrastructure, and industrial participation makes Tucson an ideal location for advancing thin-film solar energy.

Site selection

The climate data for Tucson's strong potential for solar energy generation. The annual average Global Horizontal Irradiance (GHI) of 5.84 kWh/m^2/day indicates a high level of solar resource availability, suitable for both flat-plate photovoltaic and thermal solar systems. Additionally, the Direct Normal Irradiance (DNI) value of 7.36 kWh/m^2/day is especially favourable for concentrating solar power (CSP) systems and high-efficiency tracking PV installations. The relatively low Diffuse Horizontal Irradiance (1.34 kWh/m^2/day) confirms that Tucson's skies are predominantly clear, which maximises the effectiveness of direct solar collection technologies. The average ambient temperature of 18.1°C further supports efficient solar panel operation, particularly for thin-film technologies like CIGS and CdTe that perform well in warmer conditions. High irradiance combined with moderate temperatures reduces thermal stress on PV modules and supports better long-term durability and lower degradation rates. This climate profile makes Tucson not only ideal for generating solar power but also an excellent testbed for evaluating thermal performance and real-world degradation of different panel types. Moreover, the average wind speed of 2.4 m/s suggests limited wind resource potential, reinforcing solar as the dominant renewable energy candidate in the region. However, the relatively low wind speeds also mean lower structural stress on PV systems, which can contribute to increased reliability and reduced maintenance costs. Collectively, this data reinforces Tucson's suitability as a prime location for large-scale deployment and field validation of solar technologies, particularly thin-film PV systems optimised for high irradiance and warm desert conditions.

Figure 1: Tuscan Solar Energy Project

Selected module

The selected module, First Solar Inc. FS-3100-Plus, is a thin-film photovoltaic panel designed for high-efficiency energy generation under standard test conditions. It comprises 146 cells and achieves a nominal efficiency of 13.91%, which is competitive for thin-film technology, especially in hot and sunny climates like Tucson. With a maximum power output (Pmp) of 100.152 Wdc, the module operates efficiently at a maximum voltage (Vmp) of 46.8 Vdc and a maximum current (Imp) of 2.1 A. The open circuit voltage (Voc) is 58.8 Vdc, and the short circuit current (Isc) is 2.3 A, reflecting a stable current–voltage relationship suitable for grid-tied and off-grid applications.

The temperature coefficients indicate that this module performs well in high-temperature environments. The power temperature coefficient of -0.249 %/°C and the voltage coefficient of -0.250 V/°C imply a relatively low loss in performance with rising temperature, which is especially beneficial in warm regions like Arizona. This thermal stability makes the FS-3100-Plus a strong candidate for deployment in hot desert areas, where traditional crystalline silicon panels may experience more pronounced efficiency drops. Additionally, the current temperature coefficient is minimal (0.039 A/°C), indicating consistent output under varying thermal loads.

While this module is not inherently bifacial, its design includes a bifaciality rating of 0.7 and a transmission fraction of 0.013, suggesting some capability to absorb reflected light from the rear side when elevated or installed above reflective surfaces. With a ground clearance height of 1 metre considered in the simulation, partial rear-side gain may still contribute to overall output. Taken together, the FS-3100-Plus module demonstrates robust performance and environmental adaptability, making it well-suited for utility-scale projects in sun-rich locations like Tucson, where thin-film modules benefit from high irradiance and lower temperature sensitivity.

Inverter selection

The selected inverter, Huawei SUN2000-30KTL-US [480V], is a high-performance, utility-interactive string inverter designed for medium to large-scale solar PV installations. It features a maximum AC output power of 30,000 Wac and a maximum DC input power of 30,562.3 Wdc, offering a close match between the input and output ratings, which helps maintain high operational efficiency. The CEC weighted efficiency is 98.14%, and the European weighted efficiency is 97.928%, indicating excellent performance across a wide range of irradiance conditions and load levels.

This inverter supports a nominal AC voltage of 480 Vac and a wide MPPT voltage range from 560 Vdc to 800 Vdc, enabling flexibility in PV array design. It is capable of handling a maximum DC voltage of 1,000 Vdc and a maximum DC current of 41.8662 A, making it suitable for pairing with high-current modules or multiple strings. With just one MPPT input, the design is optimised for systems with consistent shading and orientation across the array. This makes the inverter ideal for flat rooftops or ground-mounted systems where uniform conditions prevail.

The efficiency curve reveals that the inverter operates above 95% efficiency even at low load levels (from 10% and up), maintaining nearly flat performance above 80% of rated power. This high and stable efficiency ensures minimal energy losses during DC to AC conversion, maximising the usable energy delivered to the grid. Furthermore, its low night-time power consumption of 1 W and modest operational power draw of 81.4585 Wdc contribute to its overall energy-saving design. These characteristics make the Huawei SUN2000-30KTL-US a strong choice for Tucson's high solar irradiance climate, ensuring reliable and efficient operation throughout the year.

System Design

The sizing summary for the proposed PV system illustrates a well-configured design using 700 thin-film modules arranged into 5 parallel strings, with each string containing 140 modules. This configuration results in a total nameplate DC capacity of 70.106 kWdc and a total AC capacity of 60.000 kWac, leading to a DC-to-AC ratio of 1.17, which is within the recommended range for ensuring inverter efficiency and system performance under high irradiance conditions. The system occupies a total module area of 504 m^2, indicating a substantial footprint suitable for commercial-scale or large institutional applications.

The electrical characteristics at reference conditions highlight that the open-circuit string voltage (Voc) reaches 8,232.0 V, while the maximum power point voltage (Vmp) is 6,552.0 V. These high voltages are typical of thin-film modules wired in large series strings and must be carefully matched with the inverter's maximum DC input ratings to avoid overvoltage issues. Since the string voltages exceed common inverter limits, it suggests that this simulation model might be conceptual, and voltage division through multiple MPPT inputs or voltage-limiting configurations would be necessary in practice.

The system uses 2 inverters to manage the DC input and convert it to AC output efficiently. With a total inverter DC capacity of 61.125 kWdc, the configuration ensures that each inverter handles roughly 30.56 kWdc, closely aligned with their rated capacity. This balance helps optimise inverter loading and efficiency. Overall, the system configuration appears to be robust and appropriately scaled for the Huawei SUN2000-30KTL inverter model used, provided that voltage compatibility and operational safety margins are confirmed during detailed design and installation phases.

Installation cost

The financial breakdown of the solar PV system shows a **total installed cost of $57,366.66**, resulting in a **cost per capacity of $0.82/Wdc**, which is highly competitive for a system of this scale. The **direct capital costs** make up the majority of the investment at **$48,625.80**, which includes modules, inverters, and key installation expenses. Notably, balance of system (BoS) equipment costs total **$10,515.96**, installation labour is **$12,619.15**, and installer margin and overhead reach **$17,526.60**. A 2% contingency adds a further **$953.45** to ensure project flexibility.

The **indirect capital costs** account for **$6,309.58**. These include permitting and environmental study costs at **$2,103.19**, engineering and developer overhead at **$701.06**, and grid interconnection expenses at **$3,505.32**. No land acquisition or preparation costs are included, as the land area used (0.415 acres) is assigned a cost of $0/acre, suggesting it is either pre-owned or otherwise exempt from purchase and prep expenses.

A **sales tax of 5%** applied to the direct capital cost results in **$2,431.29**. This relatively small proportion of the total cost contributes to a modest increase in final system cost. Overall, the system's pricing structure reflects a low-cost commercial solar deployment scenario, especially due to the zero-cost land use and optimised installation. This enhances the system's investment appeal despite its previously noted performance and payback challenges. Addressing underperformance could further increase the value delivered for this capital expenditure.

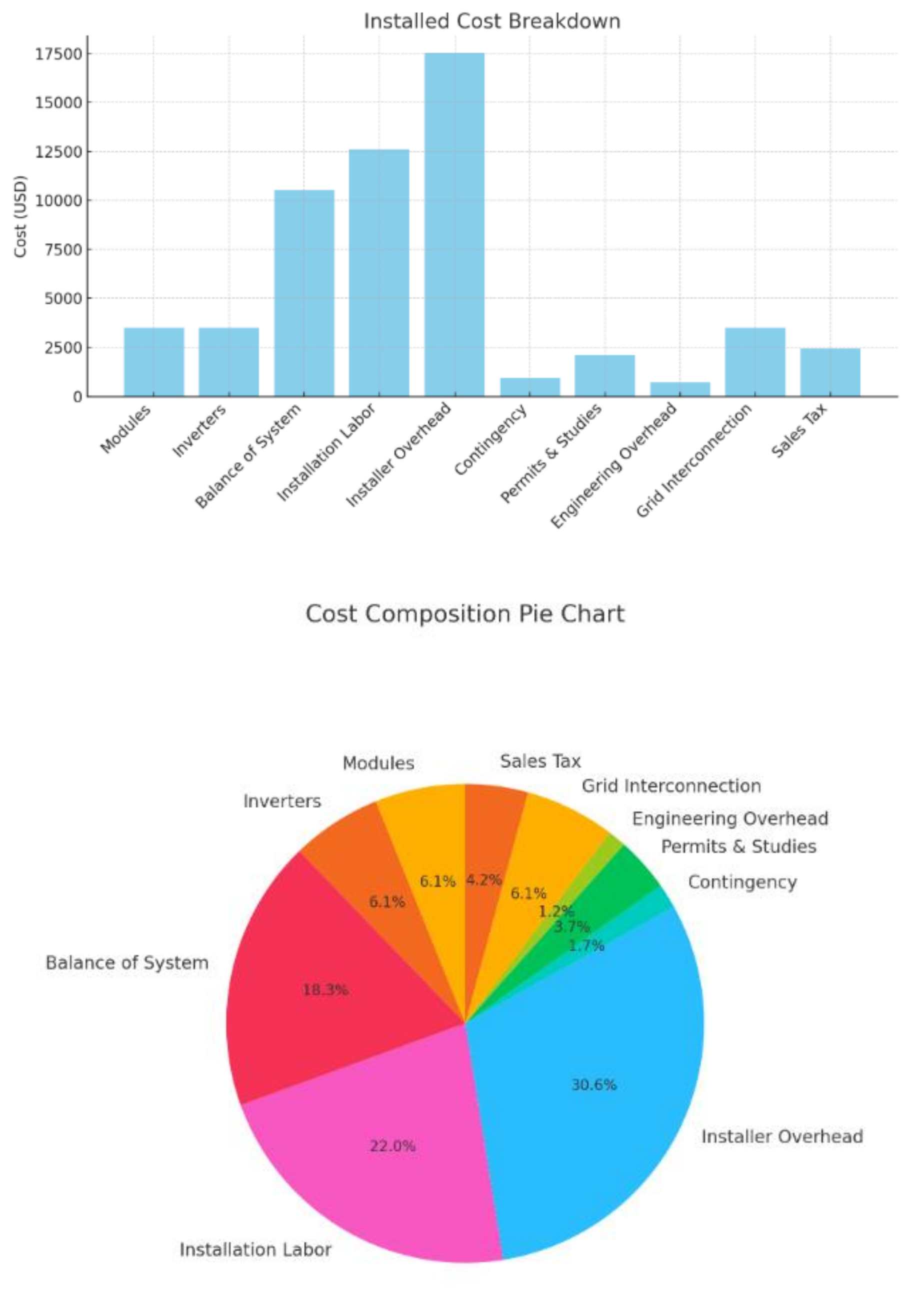

Figure 2: Cost Analysis

Discussion

The performance and financial analysis of the solar PV system indicates a Year 1 AC energy output of 18,894 kWh, which corresponds to an energy yield of 270 kWh/kW. However, the DC capacity factor is notably low at 3.1%, and the performance ratio is just 0.11, suggesting that the system may be significantly underperforming due to oversizing, high system losses, or unfavourable site conditions. These metrics should be closely examined as they directly affect system viability and energy generation effectiveness.

From a cost perspective, the Levelized Cost of Energy (LCOE) is 8.21 ¢/kWh nominal and 6.55 ¢/kWh real, which are competitive rates compared to grid electricity prices. The system results in Year 1 electricity bill savings of $2,097, reducing the annual bill from $104,614 to $102,518. This demonstrates that while the system offers savings, they are relatively modest in the initial year due to the limited performance, as reflected in the capacity factor and yield values.

Financially, the net present value (NPV) of the system is $3,290, indicating a positive return on investment over the system's life. However, the simple payback period of 15.8 years is quite long and exceeds the typical 10–12 year threshold preferred for most commercial projects. This extended payback may be attributed to the system's low efficiency or high upfront costs. To improve economic viability, system design adjustments or operational improvements should be explored—such as optimising tilt, reducing shading, or refining the inverter-to-array ratio.

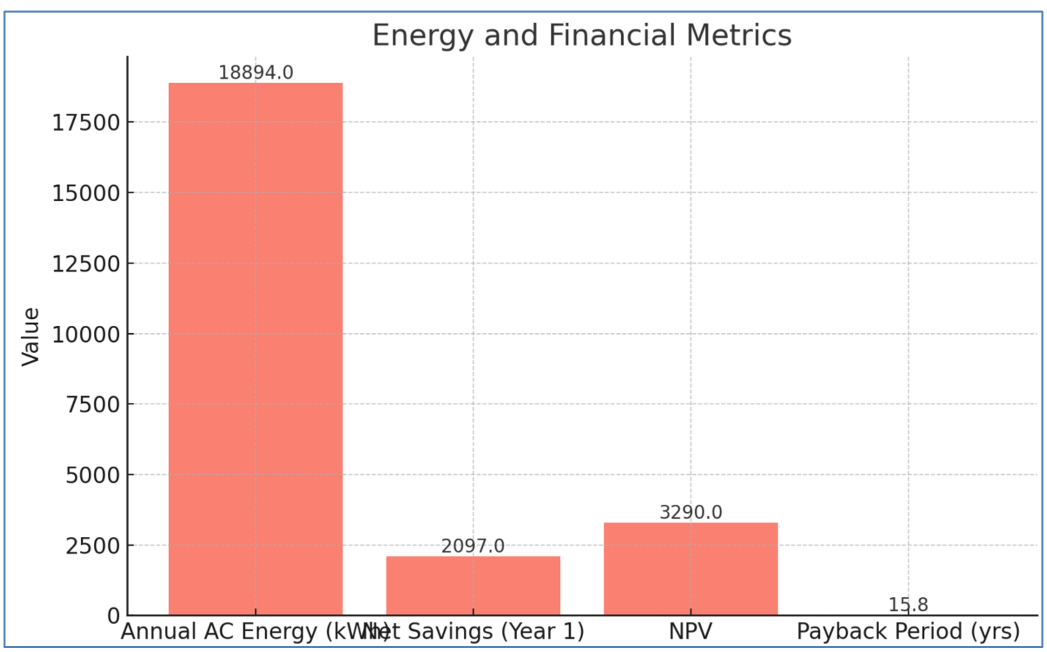

Figure 3: Energy and Financial Metrics

Conclusions

The analysis of the proposed thin-film photovoltaic (PV) system in Tucson demonstrates the feasibility of deploying large-scale solar power under high irradiance and moderate temperature conditions. While the system shows a relatively low performance ratio and capacity factor, it still achieves an annual AC energy output of 18,894 kWh and delivers consistent energy savings from the first year of operation. The financial assessment reveals a competitive levelised cost of energy (LCOE) at 6.55 ¢/kWh (real) and a reasonable net present value of $3,290, despite the extended simple payback period of 15.8 years.

The total installed cost of $57,366.66, equivalent to $0.82/Wdc, is considered cost-effective, especially with optimised installation and zero land acquisition expenses. The majority of the costs are concentrated in labour and installer overhead, indicating opportunities for cost reduction through improved logistics or local workforce development. Additionally, the inclusion of high-efficiency Huawei inverters ensures that system losses are minimised, further supporting long-term performance.

In conclusion, the system is technically viable and financially justifiable over the long term, particularly in sunny regions like Tucson. However, to enhance economic returns and reduce the payback period, further optimisation of array layout, shading analysis, and energy output per installed watt is recommended. This study confirms the potential of thin-film PV technologies for scalable and sustainable solar energy deployment in arid environments.

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