Techno-economic performance comparison of crystalline and thin film PV panels under varying meteorological conditions: A high solar resource southern hemisphere case

George Alex Thopil[a],*, Christiaan Eddie Sachse[a], Jörg Lalk[a], Miriam Sara Thopil[b,c]

[a]Department of Engineering and Technology Management, University of Pretoria, South Africa
[b]Department of Electrical, Electronics and Computer Engineering, University of Pretoria, South Africa
[c]Aurecon South Africa, Tshwane Office, Pretoria, South Africa

*Corresponding author. george.alexthopil@up.ac.za

Highlights

•Financial performance comparison of 3 PV technologies are performed.
•Panel types include monocrystalline, polycrystalline and thin film CIGS.
•Comparison incorporates yield and meteorological data over two year period.
•CIGS panels outperform crystalline technologies across all financial indicators.
•CIGS perform better across all temperatures and are less sensitive to irradiation.

Abstract

Photovoltaic panel technologies have evolved considerably over a limited period. The most popular PV panel technologies can be divided into two main groups, the first being crystalline technologies and second, thin film technologies. This investigation compares the financial performance of three different photovoltaic (PV) panel technologies, namely, monocrystalline, polycrystalline and thin film copper indium gallium selenide (CIGS), based on measurements from a test facility and for varying meteorological conditions. The yield measurements of the panels from the site over a two-year period are used to develop the techno-economic indicator performance, for a proposed commercial installation. Measurements of solar irradiation and temperature are incorporated into a regression model for yield sensitivity analysis, which in turn is used to investigative the sensitivity of financial performance.

It was seen that CIGS panels delivered on average 11.6% more yield when compared to monocrystalline technologies per kWp, with sustained outputs even during relatively colder periods. The improved financial performance of CIGS panels over monocrystalline panels was seen via a 24% increase in discounted return on investment, 7.8% reduction in payback period and 21% improvement in net present value. The regression model indicates that CIGS panel yields are less sensitive to lower solar irradiation and more sensitive towards higher temperatures. Overall variation of financial indicators for a range of yield outputs, is lowest for CIGS panels compared to both types of crystalline panels. CIGS panels show lower variability in financial returns particularly in conditions with higher temperatures that makes the results valid in geographical locations with higher temperatures and higher solar irradiation. The findings are useful for multiple stakeholders within the PV industry who have an interest in sub-Saharan Africa and the southern hemisphere, where such investigations are limited though solar resource is abundant.

Keywords: Photovoltaic; Techno-economics; Crystalline; Thin film; Southern hemisphere; South Africa

1. Introduction

Increasing demands for energy and growing concerns for the environment have led to an urgent need for renewable energy [1], [2], with solar energy emerging globally as the renewable energy resource with the highest yearly energy potential [3]. The average annual growth rate for solar photovoltaic (PV) technology during the period 1990–2017 was recorded to be the highest at 37%, compared to other renewable energy technologies such as wind (23%), biogas (12%) and solar thermal (11%) [4].

Tapping into solar energy to generate electricity using PV cells is referred to as photovoltaic effect. The most popular PV panel technologies can be divided into two main groups, the first being crystalline technologies (which includes monocrystalline (Mono C-Si), polycrystalline (Poly C-Si), category III-V semiconductors and ribbon silicon) and the second, thin film technologies (which includes CIGS, cadmium telluride (CdTe) and amorphous thin-film silicon) [5], [6]. Crystalline PV technology has thus far been the dominating and preferred technology; however thin film technology such as CIGS is gaining popularity [7].

Studies that involve comparison of financial performance of multiple types of PV technologies using measured data are limited in the southern hemisphere, particularly in locations that receive high solar irradiation. Therefore, research conducted within this paper aims to investigate the performance of multiple commercial PV panel types under varying meteorological conditions in a location where high solar irradiation has been recorded. In order to achieve the stated aim, the performance of three types of PV panels, namely, monocrystalline, polycrystalline and thin film CIGS from a commercial test facility across a range of financial indicators are compared. The financial performance relating to return on investment (ROI), net present value (NPV), internal rate of return (IRR) and payback period, of three different PV panel technologies is evaluated. The study also aims to investigate the impact of meteorological variations in ambient temperature and solar irradiation on the financial performance of thin film CIGS compared to crystalline technologies.

The contributions of the investigation within this paper are dual in nature. The investigation primarily adds to the body of knowledge by providing measured evidence of the superior performance of thin film CIGS panels and secondly such investigations are limited in the southern hemisphere, particularly within sub Saharan Africa. The results of this investigation are novel, when considering the use of measured data from a commercial test facility from a high irradiation Southern hemisphere location. The results are useful for stakeholders who are involved in PV research and commercial PV installations, who have an interest in investing in PV technology in solar resource rich South Africa and southern Africa, and locations with similar meteorological conditions.

The market share of CIGS thin film technology annual production has increased from approximately 1% in 2007 to 2% in 2017 [7]. This can be attributed to increase in solar cell efficiency of thin film technology over the past fifteen years [7], [8], [9], [10]. The module efficiency of CIGS has been measured to be 10 to 14.5% compared to 15 to 20% efficiency of monocrystalline and 13 to 16% efficiency of polycrystalline technologies [11]. Furthermore, thin-film technology such as CIGS is more suited for PV panel applications in extreme heat because of its low temperature coefficient. CIGS also produce more energy than crystalline technologies in partially shadowed areas or during low-light conditions since they absorb light differently [11]. Within CIGS panels, panel cells have monolithic cell orientation, where cells are rectangularly oriented to improve output power whereas in crystalline panels if one cell is shadowed output power deteriorates owing to the series cell configuration [12].

The following section discusses literature related to the various PV panel technologies and their efficiencies. Section 3 presents the methodological framework used for the financial performance comparison of the three types of PV panels under consideration. Comparison of PV panel yields and financial models are presented in Section 4, followed by the discussion of yield and financial model analysis in Section 5, after which conclusions are provided in Section 6.

2. Background literature

Taking into consideration the amount of research being done in this field, such as – environmental impact study during life cycle of PV system [13], cost-benefit analysis for newer technologies such as reconfigurable PV modules [14], it is clear that PV industry is fast becoming one of the more popular forms of not just renewable energy but large scale energy production as well [15]. Recent studies have also delved into different PV panel technologies and how their performance, efficiency and yield vary, especially taking into consideration different meteorological conditions [16]. In Liu et al. [17], weather data is applied to neural networks to forecast PV output values and future trends. Kichou et al. [18] investigated the degradation of thin film (CdTe) and crystalline PV modules installed at Buštěhrad, Czech Republic while considering module temperature and solar irradiance. In Latin America, spectral impacts study on two PV systems using crystalline and thin film technologies in two climatically different areas in Brazil was performed by Braga et al. [19].

A meteorological study was conducted by Polo et al. [20] where an artificial typical meteorological year was created using seven-year spectral irradiance data. This information was applied to seven types of PV panel technologies to validate the methodology proposed; however, the paper does not delve into energy yield calculations that could have aided in a cost-perspective understanding.

In off-grid systems, there have been studies such as that by Diaf et al. [21] where a techno-economic optimisation was performed for different meteorological conditions. The optimal size of the off-grid renewable power supply, wind and PV in this case, which yields minimum levelized cost of energy (LCOE) at five different sites were calculated. Taking into account the decrease in PV module prices over the last eleven years since the study took place, with some data indicating a 90% drop in costs since 2009 [22], the results of Diaf et al. [21] can only be used as a reference or base point for current studies.

Cost-based studies from the perspective of residential consumers who install PV and storage systems were performed in Bertsch, Geldermann & Luhn [23]. The authors investigated the most profitable size of these systems, which can be installed in two countries – Germany and Ireland, considering subsidy, tariffs and other regulatory policies. A similar study was performed by Zhang et al. [24] where four commercial building networks in four different states in U.S. were studied and payback periods (while also considering local incentive policies) for PV and battery systems installed in these networks calculated. While these studies are important from an economical and policy perspective, it does not shed light on recommended PV technologies to use.

A study conducted in Brazil by Sorgato et al. [25] investigated technical and economic aspects of using thin film technology in building integrated PV systems in 6 different cities. However, the study does not go into an assessment of different PV technology types and considers only thin film CdTe due to the greater aesthetic value in building integrated PV systems. The study also does not look at real systems or test facilities, and approaches techno-economic analysis as a feasibility study. It can thus be concluded that far less research has been done regarding the differences between the true financial impact of various PV systems [26].

It is critical to include financial impacts when researching performance studies for the benefit of investors and stakeholders who are part of commercial as well as utility scale installations [27]. While PV systems use a free energy source (solar energy) to produce electricity, the technology to harvest this renewable energy comes at a price resulting in large upfront capital costs [28], [29] and lower operational costs [30]. Studies such as Perez et al. [31] are conducted on the assumption that operational costs for a PV system would amount to 1% of capital costs. As with any project, ROI and payback period are key financial indicators used to make decisions regarding PV project feasibility [32], [33].

Through the years, research in PV panel technologies has led to the use of newer and modern semi-conductor materials, all of which convert sunlight into electricity, varying slightly in the manner the conversion is done [34], [35], [36]. Different types of PV technologies as discussed in [37], [38], [39] are summarised in Table 1.

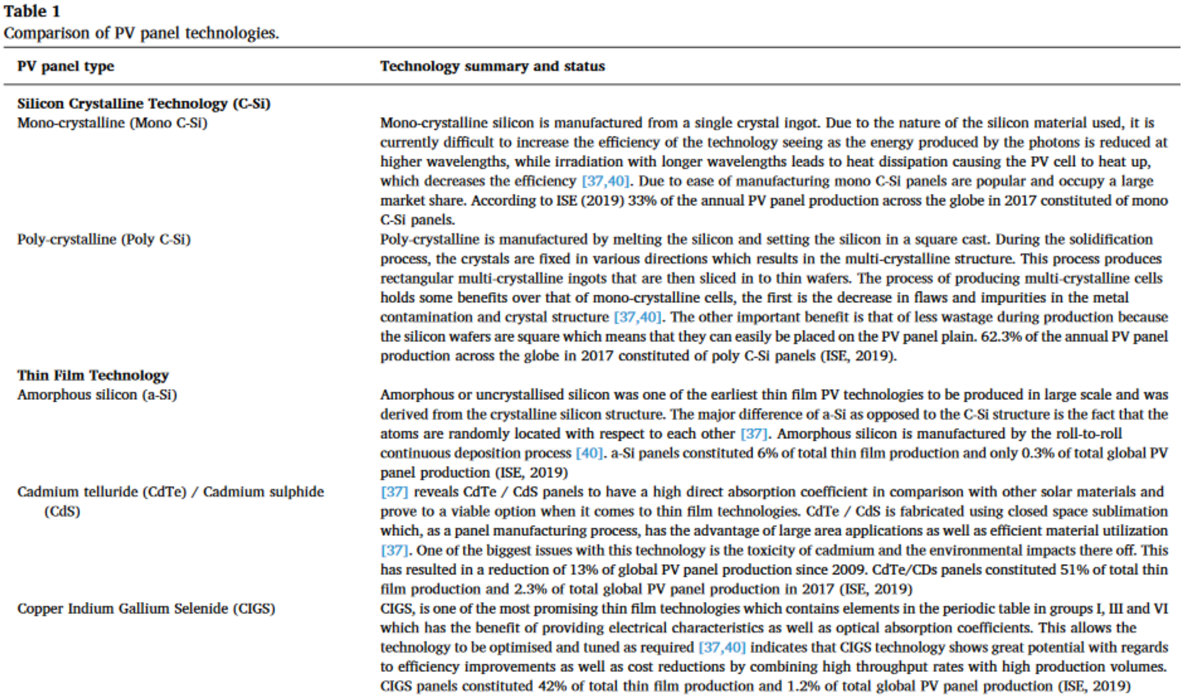


Table 1
Comparison of PV panel technologies.

PV panel type	Technology summary and status
Silicon Crystalline Technology (C-Si)	
Mono-crystalline (Mono C-Si)	Mono-crystalline silicon is manufactured from a single crystal ingot. Due to the nature of the silicon material used, it is currently difficult to increase the efficiency of the technology seeing as the energy produced by the photons is reduced at higher wavelengths, while irradiation with longer wavelengths leads to heat dissipation causing the PV cell to heat up, which decreases the efficiency [37,40]. Due to ease of manufacturing mono C-Si panels are popular and occupy a large market share. According to ISE (2019) 33% of the annual PV panel production across the globe in 2017 constituted of mono C-Si panels.
Poly-crystalline (Poly C-Si)	Poly-crystalline is manufactured by melting the silicon and setting the silicon in a square cast. During the solidification process, the crystals are fixed in various directions which results in the multi-crystalline structure. This process produces rectangular multi-crystalline ingots that are then sliced in to thin wafers. The process of producing multi-crystalline cells holds some benefits over that of mono-crystalline cells, the first is the decrease in flaws and impurities in the metal contamination and crystal structure [37,40]. The other important benefit is that of less wastage during production because the silicon wafers are square which means that they can easily be placed on the PV panel plain. 62.3% of the annual PV panel production across the globe in 2017 constituted of poly C-Si panels (ISE, 2019).
Thin Film Technology	
Amorphous silicon (a-Si)	Amorphous or uncrystallised silicon was one of the earliest thin film PV technologies to be produced in large scale and was derived from the crystalline silicon structure. The major difference of a-Si as opposed to the C-Si structure is the fact that the atoms are randomly located with respect to each other [37]. Amorphous silicon is manufactured by the roll-to-roll continuous deposition process [40]. a-Si panels constituted 6% of total thin film production and only 0.3% of total global PV panel production (ISE, 2019)
Cadmium telluride (CdTe) / Cadmium sulphide (CdS)	[37] reveals CdTe / CdS panels to have a high direct absorption coefficient in comparison with other solar materials and prove to a viable option when it comes to thin film technologies. CdTe / CdS is fabricated using closed space sublimation which, as a panel manufacturing process, has the advantage of large area applications as well as efficient material utilization [37]. One of the biggest issues with this technology is the toxicity of cadmium and the environmental impacts there off. This has resulted in a reduction of 13% of global PV panel production since 2009. CdTe/CDs panels constituted 51% of total thin film production and 2.3% of total global PV panel production in 2017 (ISE, 2019)
Copper Indium Gallium Selenide (CIGS)	CIGS, is one of the most promising thin film technologies which contains elements in the periodic table in groups I, III and VI which has the benefit of providing electrical characteristics as well as optical absorption coefficients. This allows the technology to be optimised and tuned as required [37,40] indicates that CIGS technology shows great potential with regards to efficiency improvements as well as cost reductions by combining high throughput rates with high production volumes. CIGS panels constituted 42% of total thin film production and 1.2% of total global PV panel production (ISE, 2019)

Based on the increased performance as well as the commercial availability of the CIGS technology amongst thin film technologies, it was decided to include CIGS panels as part of the comparison with crystalline panel technologies.

When sunlight (composed of photons) strikes the PV panel, photons are absorbed by the panel, and electrons are released resulting in flow of electric current. However, not all photons hitting the PV panel are absorbed; some are reflected while others pass through. Because of this effect, efficiency of a PV panel converting solar energy (measured in W/m^2) into DC electricity (measured in W) is relatively low [41]. Under ideal operating conditions, conversion efficiency of PV panels can be as low as 13% [42].

The highest lab efficiencies for a single PV cell and panel at the time of this study are shown in Table 2. These efficiencies are measured in a laboratory under Standard Test Conditions (STC). The STC parameters can be seen in Table 3.

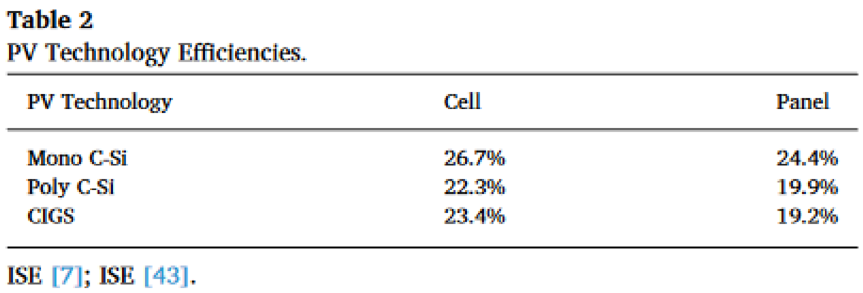


Table 2
PV Technology Efficiencies.

PV Technology	Cell	Panel
Mono C-Si	26.7%	24.4%
Poly C-Si	22.3%	19.9%
CIGS	23.4%	19.2%

ISE [7]; ISE [43].

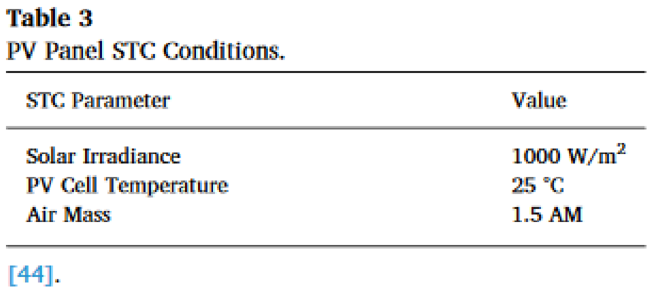


Table 3
PV Panel STC Conditions.

STC Parameter	Value
Solar Irradiance	1000 W/m^2
PV Cell Temperature	25 °C
Air Mass	1.5 AM

[44].

Kaldellis et al. [45] highlights the importance of testing efficiencies and power output of various technologies under operational module and ambient temperature and wind speeds. The study made use of two PV systems in Greece, both using Mono C-Si technology. Various authors, including but not limited to Guenounou et al. [46], Humada et al. [47], as well as Siddiqui et al. [44] indicates that actual performance and efficiencies of PV panels are far from the laboratory results shown in Table 3. This difference between laboratory results and actual performance of the system potentially has a large impact on the key financial indicators stated previously [48], [49].

3. Methodology

South Africa receives high levels of irradiation over most of the north western, central and northern parts of the country. Fig. 1 indicates the average Global Horizontal Irradiation (GHI) for South Africa over a 20-year period. In spite of high irradiations, techno-economic performances can be variant depending on PV panel technology type.

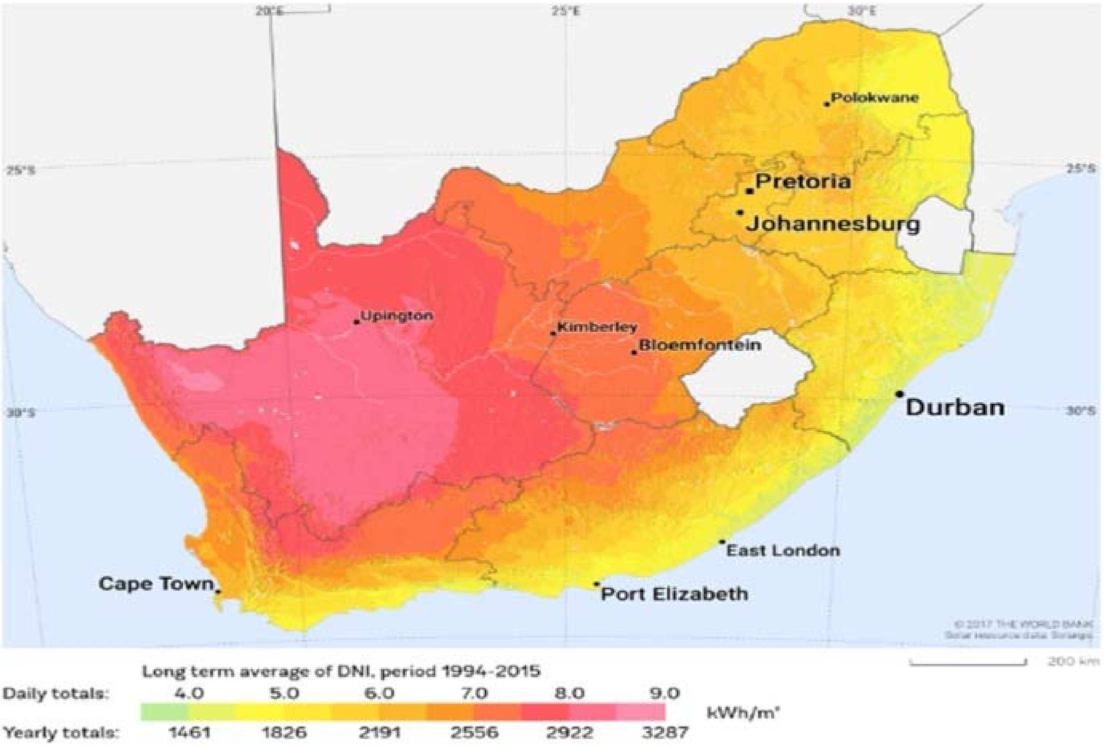


Fig. 1. Average GHI for South Africa [50].

To assess the variance in the techno-economic performance of different PV panel technologies, this investigation aims to answer two main questions:

1. Does choosing CIGS over Mono C-Si or Poly C-Si PV technology improve financial indicators relating to ROI, payback period, cost of energy and IRR of a PV system operating in South Africa and other countries with similar meteorological conditions?
2. Is the impact of change in module temperature and solar irradiation on the financial indicators lower when choosing CIGS thin film technology as opposed to Poly and Mono C-Si PV technology?

The data that was used in the study was obtained from a private test facility located in the Johannesburg area (26.19 S, 28.03 E) shown in Fig. 2a, Fig. 2b. The facility consists of;

- 3 kWp CIGS array connected to a 3 kWp Grid-Tie Inverter
- 3 kWp Mono C-Si array connected to a 3 kWp Grid-Tie Inverter
- 3 kWp Poly C-Si array connected to a 3 kWp Grid-Tie Inverter
- A Weather Station
- A logging system allowing information to be retrieved via internet

Fig. 2a. Private test facility PV panel and inverter setup.

Fig. 2b. Private test facility weather station setup.

Fig. 2a. shows the PV panel configuration and the inverter setup. Three panel arrays were installed on the roof top of a four storey building. All panels were setup at an inclination of 30° facing North. The panels were cleaned once a week during which cables and connections were also checked. Temperature sensors were mounted behind the centre of the array at the centre of the panels. The weather station (Fig. 2b) was mounted on a two meter pole at the same level as the panel arrays. The weather station comprised of sensors with the capability to measure ambient temperature, wind speed, solar irradiation and rainfall. In order to assess compare the yield of the panel technologies, data measured over a two year period (2016 and 2017) was used.

Energy generated over varying time periods is represented by E(x) in kilowatt hour (kWh), where x can be presented by an hourly – E(h), daily – E(d), monthly – E(m), or yearly – E(y) value. Eq. (1) shows the yearly energy generated by a specific system.

$$E_{AC}(y) = \sum_{m=1}^{m=12} E(m) \tag{1}$$

Where,

$E_{AC}(y)$: total yearly AC power output of the system (kWh).

m: month of the year.

E(m): total monthly AC power output of the system (kWh).

$E_{AC}(y)$ was then used to calculate the specific yield of each system, which is the annual amount of energy generated by a PV system per peak power (kWp) installed and is shown in Eq. (2).

$$Y_A\ (y) = \frac{E_{AC}(y)}{P_{PV}} \tag{2}$$

Where,

Y_A (y): annual specific yield of the given PV system (kWh/kWp/year)

P_{PV}: peak power of the PV system (kWp)

Eq. (3) is used to calculate the PV life cycle cost (PV_{LCC}) in Rands (R). The PV_{LCC} equation used includes the costs (C) in R associated with investment and maintenance costs [51].

$$PV_{LCC} = C_{system} + \sum_1^n C_{maintenance} \times R_{CW} + \sum_1^n C_{replacement} \times R_{CW} \tag{3}$$

Where,

PV_{LCC}: Life cycle cost of the PV system (R).

C_{system}: Capital cost associated with the PV system (R).

$C_{maintenance}$: Maintenance cost of the PV system during the life cycle (R).

$C_{replacement}$: Cost of replacing any PV system component during the life cycle (R).

R_{CW}: Discounting factor.

n: number of years representing life of project.

C_{system} comprises of all upfront costs associated with design of the system, site preparation, installation and cost of individual system components. C_{system} is calculated as shown in Eq. (4).

$$C_{system} = C_{design} + C_{site} + C_{install} + C_{components} \tag{4}$$

Where

C_{design}: Cost involving design of the PV system (R).

C_{site}: Cost involving preparation of site where PV system will be placed (R).

$C_{install}$: Installation cost of PV system (R).

$C_{components}$: Cost of each component of PV system such as panels, inverters, etc. (R).

$C_{maintenance}$ is an ongoing cost and normally lasts till end of project life. This cost is discounted at a certain rate in order to negate the effect of the time value of money.

Although most reputable PV module manufacturers have a 25-year linear performance guarantee which stipulates that the PV panel should not degrade by more than 20%, or should perform at 80% of the original efficiency after a period of 25 years [52], it is still necessary to add a replacement cost parameter ($C_{replace}$) to the equation.

The largest part of $C_{replace}$ would be the cost of replacing the PV inverter since most manufacturers grant a 5-year warranty on the product. Since $C_{replace}$ is also associated with a future cost, it is discounted using the same discounting factor as $C_{maintenance}$.

R_{CW} is calculated using future sum of money (F_{SM}) as indicated in Eq. (5).

$$R_{CW} = \frac{F_{SM}}{(1+I)^N} \qquad (5)$$

Where,

F_{SM}: Future sum of money (R).

I: discount rate.

N: period of discounting.

Once PV_{LCC} has been calculated, this value can be used to calculate the cost of energy production as shown in Eq. (6).

$$CE = \frac{PV_{LCC}}{\sum_1^n E_{AC}(y)} \qquad (6)$$

Where

CE : Cost of energy production (R/kWh).

n : number of years representing life of project.

Eq. (7) was adapted from Humada et al. [47] and indicates the payback period of the system.

$$Pay_{BP} = \frac{C_{system} + \sum_1^n C_{maintenace} \times R_{CW}}{E_{AC}(y) \times CE \times R_{CW}} \qquad (7)$$

Where

Pay_{BP}: Payback period of PV system (years).

The reason for not including $C_{replace}$ in Eq. (7) is that replacement cost normally comes into play during later stages of the project life cycle and does not have an impact on Pay_{BP}. Since PV_{LCC} is discounted to present-day value, NPV and PV_{LCC} can be seen as the same indicator.

The return on investment is calculated as shown in Eq. (8) from Humada et al. [47].

$$ROI = \frac{C_{recover} \times R_{CW} - C_{system} + \sum_1^n C_{maintenance} \times R_{CW} + \sum_1^n C_{replacement} \times R_{CW}}{C_{system} + \sum_1^n C_{maintenance} \times R_{CW} + \sum_1^n C_{replacement} \times R_{CW}} \quad (8)$$

Where

$C_{recover}$: Average income or savings achieved by the PV system (R).

The final financial indicator assessed is IRR, which indicates profitability of a potential investment, particularly with reference to different PV technologies. IRR is calculated by assigning NPV = PV_{LCC} = 0 in Eq. (3) and then solving Eq. (5), as shown in Eq. (9).

$$PV_{LCC} = 0 \text{ with } R_{CW} = \frac{F_{SM}}{(1+IRR)^N} \quad (9)$$

The calculated discount rate in Eq. (9) indicates the IRR for the particular project.

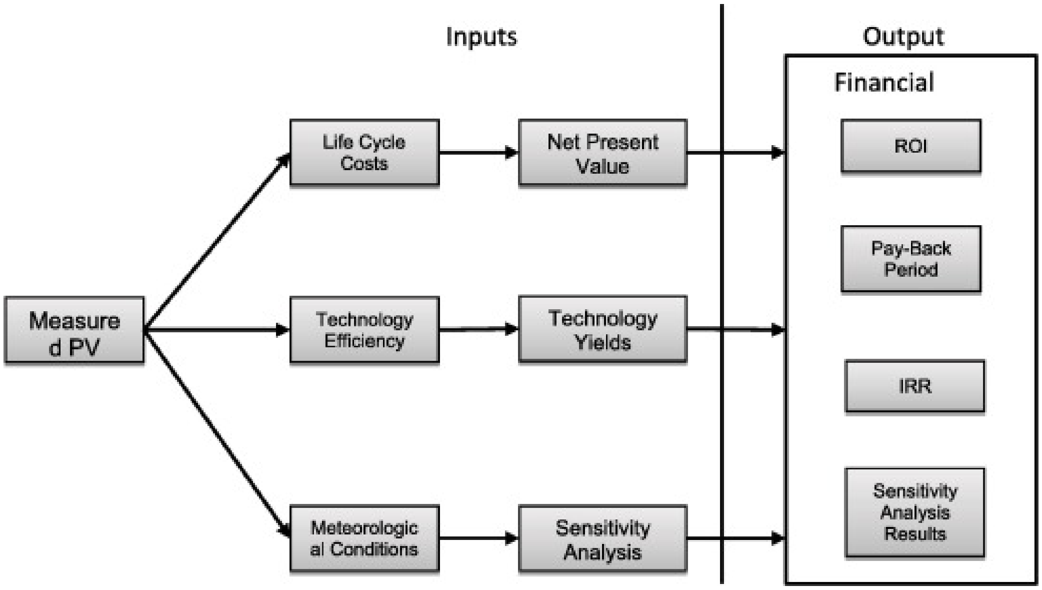


Fig. 3. Methodological framework.

The methodological framework used in this study is shown in Fig. 3. Using Eqs. (1), (2), (3), (4), (5), (6), (7), (8), (9), life cycle cost is calculated and used to determine NPV of the installed PV systems. The framework also considers energy yields of different PV technologies to perform a complete financial indicator analysis.

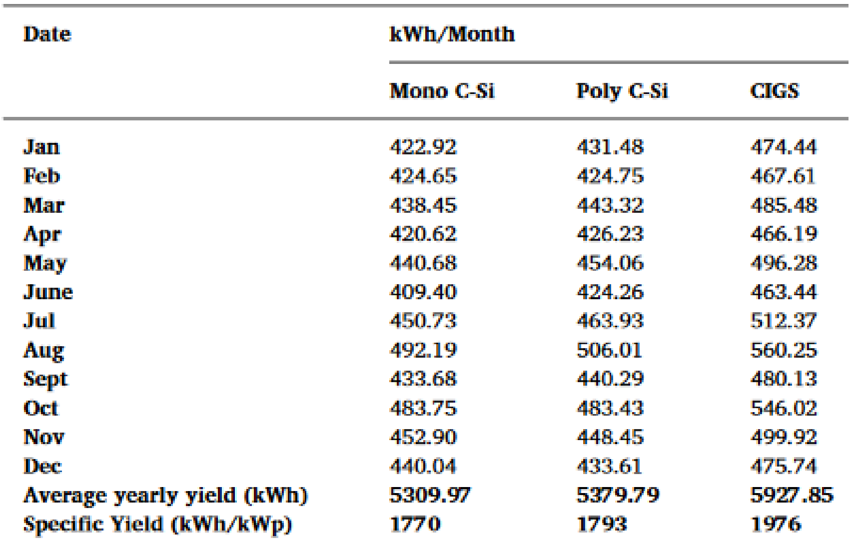
4. Results

The following section covers the yield variances, financial model as well as financial sensitivity analysis with respect to certain meteorological conditions of the three different panel technologies tested.

4.1. PV panel yield results

The yield analysis as indicated shownin Table 4 was measured over a period of two years, 2016 and 2017. To improve accuracy of the yield analysis and as well as the financial analysis it was decided to use the average monthly yield values. The installation facility measured hourly yield values, however in order to capture the effects of seasonal changes (and accompanying meteorological changes) on the performance of the panels, monthly averages were used. Table 4 shows the average month to month yield results for 2016 and 2017.

Table 4
Average Mono C-Si, Poly C-Si and CIGS Monthly Yield.



Date	kWh/Month		
	Mono C-Si	Poly C-Si	CIGS
Jan	422.92	431.48	474.44
Feb	424.65	424.75	467.61
Mar	438.45	443.32	485.48
Apr	420.62	426.23	466.19
May	440.68	454.06	496.28
June	409.40	424.26	463.44
Jul	450.73	463.93	512.37
Aug	492.19	506.01	560.25
Sept	433.68	440.29	480.13
Oct	483.75	483.43	546.02
Nov	452.90	448.45	499.92
Dec	440.04	433.61	475.74
Average yearly yield (kWh)	**5309.97**	**5379.79**	**5927.85**
Specific Yield (kWh/kWp)	**1770**	**1793**	**1976**

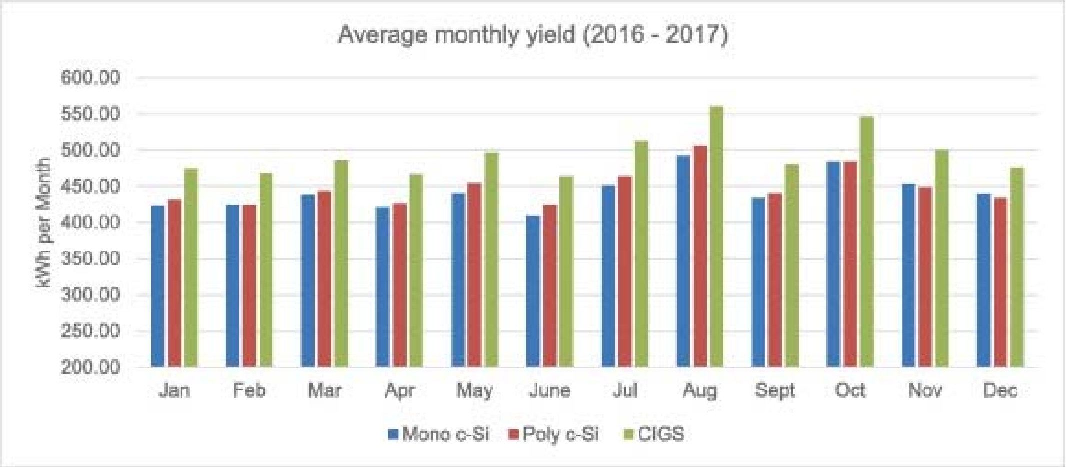


Fig. 4. Average Mono C-Si, Poly C-Si and CIGS Monthly Yield.

The average yearly yield for the 3 kWp installation (as shown in Fig. 2a) of monocrystalline, polycrystalline and CIGS thin film technology is 5309.97 kWh, 5379.79 kWh and 5927.85 respectively. These values indicate that the two crystalline technologies are very similar with respect to yearly yields, and their yields are less than that of CIGS technology. Fig. 4 gives a graphical representation of the monthly yield data as seen in Table 4.

Fig. 5 shows the average specific yield for all three technologies investigated. The results indicate that CIGS technology achieves an 11.64% increase in specific yield per kWp compared to monocrystalline panels, whereas polycrystalline panels have a modest specific yield increase of 1.31%.

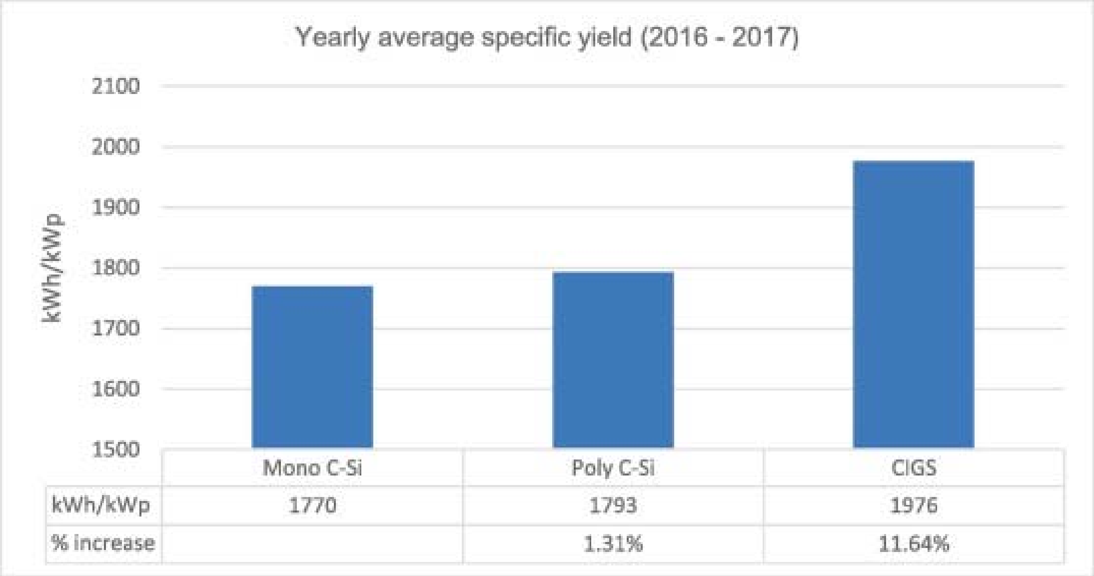


Fig. 5. Average Mono, Poly and CIGS yearly yield.

Fig. 6 indicates the differences in the monthly average yields. The Mono C-Si technology was used as the base line and the monthly average yield of the Poly C-Si and CIGS technologies were compared to the average monthly yield of the Mono C-Si technology. From the figure, it can be seen that Mono C-Si panels performed better than the Poly C-Si panels during the months of October, November and December and that there was an insignificant difference of 0.02% during February.

It is evident from Fig. 6 that CIGS technology as well as Poly C-Si technology are more efficient than Mono C-Si technology, especially during the colder months (May, June, July and August). Johannesburg has a subtropical climate with summer, during the months of October to February, and sunny dry winters from May to August. Due to the darker shade of Mono C-Si panels which leads to higher expected sensitivity to temperature, it can be expected that Mono C-Si panels will provide marginally higher yields compared to Poly C-Si panels, during summer. However high afternoon summer rainfall during the month of January, leading to lower temperatures, indicates a decrease in expected yield output of Mono C-Si panels. The higher contribution of temperature to yield performance for Mono C-Si panels compared to Poly C-Si panels is expected to be seen as part of the regression analysis (in Section 4.3).

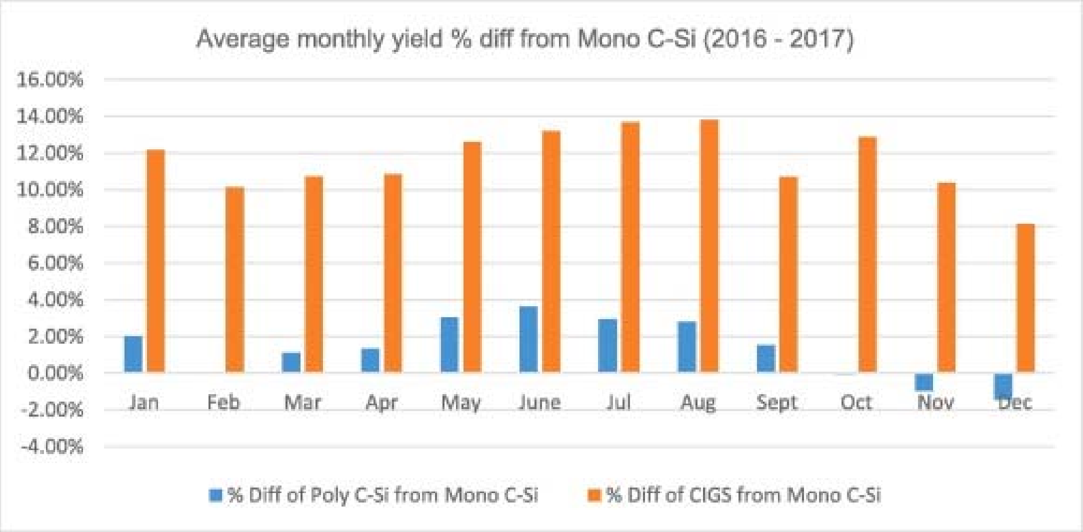


Fig. 6. Percentage difference in monthly average yields.

Fig. 7 shows the maximum monthly panel temperatures averaged over two years.

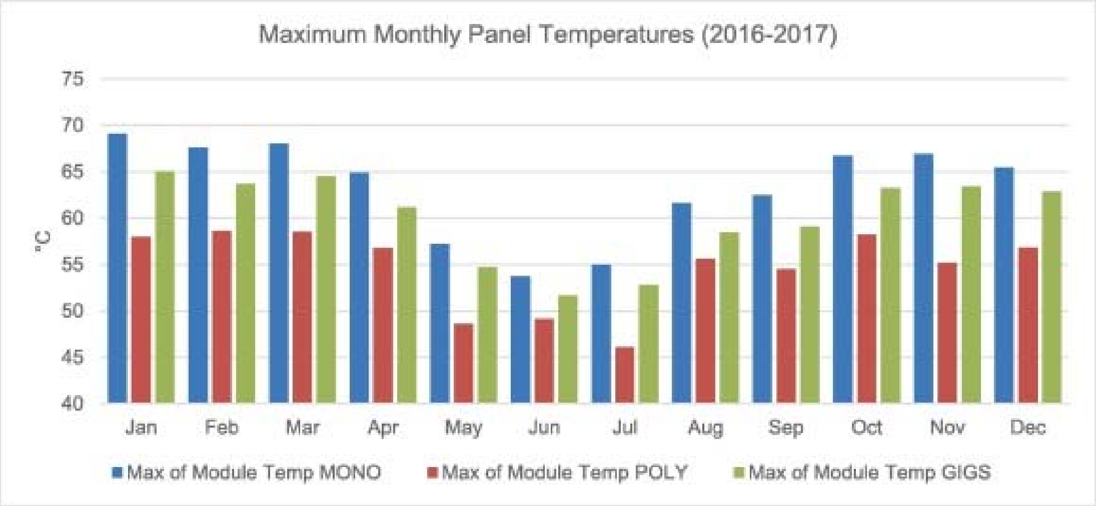


Fig. 7. Maximum Monthly Panel Temperatures.

Information in Fig. 7 shows that monocrystalline panels had the highest temperature followed by CiGS panels. This characteristic was expected owing to the darker shades of both types of panels. Fig. 8 indicates the maximum monthly solar irradiation averaged over a two year period. As expected solar irradiation is lowest during the winter months of June and July, and highest during the summer months of December, January and February.

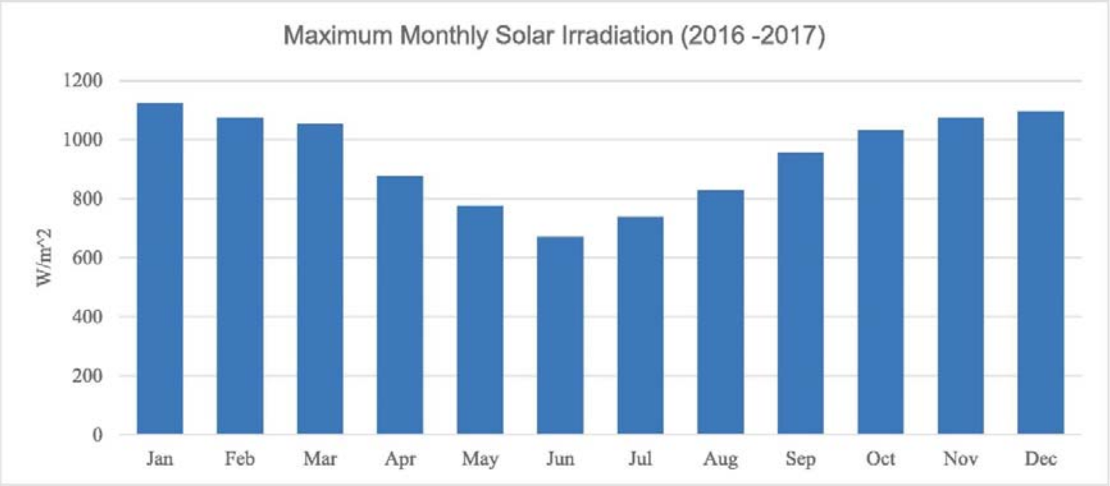


Fig. 8. Maximum Monthly Solar Irradiation for Johannesburg.

Taking into consideration the monthly yield data from Fig. 4, yearly specific yield data from Fig. 5 and the monthly yield variation in Fig. 6, it is clear that in a real-world environment the CIGS PV technology is more efficient than the Mono and Poly C-Si technologies especially at lower levels of solar irradiation. These specific yield results in Fig. 5, will be used in the financial modelling (Section 4.2) to calculate the key financial indicators relating to each PV panel technology, whereas the module temperature data from Fig. 7 and solar irradiation data from 8 will be used in the regression analysis (Section 4.3).

4.2. Financial model – Yield variance

To accurately assess each of the technologies financially, a discounted cash flow was created for each scenario. The discounted cash flow model is widely used when it comes to assessing various options relating to capital budgeting and long-term investments decisions [27], [32]. The discounted cash flow as well as the financial indicator calculations for each PV panel type uses Eqs. (1), (2), (3), (4), (5), (6), (7), (8), (9) from Section 3.

Table 5 shows the inputs used for the discounted cash flow relating to the Mono C-Si, Poly C-Si and CIGS panel technology. It is assumed that no loan is used to finance the systems. The inputs and assumptions are similar for Mono, Poly and CIGS technology and are listed in Table 5 and the following paragraph, respectively. To highlight the effect of variance in yield and specific yield of each technology, it was decided to keep the other input parameters constant. The only parameter that can potentially vary is the cost of the system. However, considering all the panels be approximately the same size and wattage, the balance of system (BOS), which includes everything except the panels and inverter, should be reasonably constant. Thus, the only variance could be the panel prices, and at the time this study was conducted, the panel prices were similar when considering panels of similar quality. In this context, similar quality links to the similar product guarantees (ten years), power tolerance ratings (0 to 5%) and degradation guarantees (0.8% per year) provided by the manufacturers. The specific yield used for each technology was as follows:

Mono 1770 kWh / kWp

Poly 1793 kWh / kWp

CIGS 1967 kWh / kWp

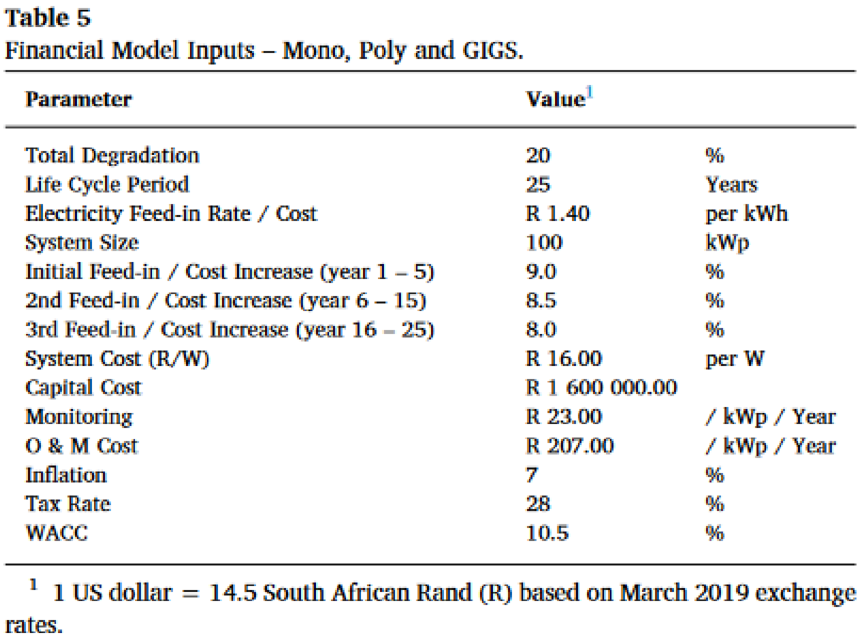


Table 5
Financial Model Inputs – Mono, Poly and GIGS.

Parameter	Value[1]	
Total Degradation	20	%
Life Cycle Period	25	Years
Electricity Feed-in Rate / Cost	R 1.40	per kWh
System Size	100	kWp
Initial Feed-in / Cost Increase (year 1 – 5)	9.0	%
2nd Feed-in / Cost Increase (year 6 – 15)	8.5	%
3rd Feed-in / Cost Increase (year 16 – 25)	8.0	%
System Cost (R/W)	R 16.00	per W
Capital Cost	R 1 600 000.00	
Monitoring	R 23.00	/ kWp / Year
O & M Cost	R 207.00	/ kWp / Year
Inflation	7	%
Tax Rate	28	%
WACC	10.5	%

[1] 1 US dollar = 14.5 South African Rand (R) based on March 2019 exchange rates.

1

The listed inputs and assumptions are explained in more detail:

- The total degradation is based on the maximum specification by the supplier.
- A financial life cycle of 25 years was selected since the panels each have a 25-year performance warranty.
- It is assumed that the energy produced by the system will either be used to offset the purchaser's current consumption or will be used in an area that makes use of net metering. In either case the price of energy produced / saved will be at the average municipal rate which was estimated at R 1.40 per kWh.
- The specific yield was obtained from the data analysed in Section 4.1
- Feed-in rate and increases are based on the national energy regulator prescription
- The system cost in Rand per watt is obtained from SAPVIA [53]. It was assumed that the R 16 per Watt includes all costs stated under capital cost, as well as extended warranty for the PV inverters.
- The monitoring, operating and maintenance (O&M) costs were also taken from the SAPVIA [53] study.
- It was assumed that weighted average cost of capital (WACC) for this project is equal to the prime lending rate of the South African Reserve Bank at the time analysis.

Once the specific yields were established, it was used as input to generate separate discounted cash flow models, to determine the financial indicators which in turn give insight into the profitability variances with respect to each technology. The resulting discounted yearly cash flows based on the financial model inputs in Table 5 and the respective specific yields, are presented in Appendix A for each of the panel technologies under consideration.

Based on the resultant cash flows, key financial indicators are calculated. Table 6 provides a summary and comparison of the key indicators for the three types of PV panels.

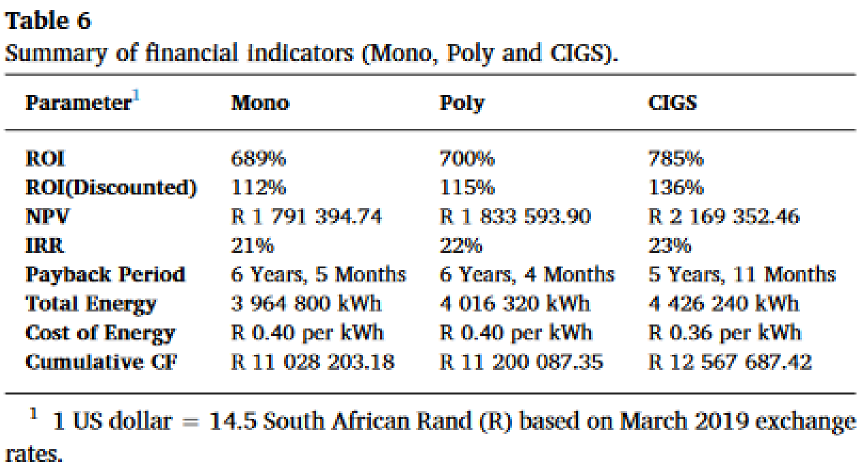


Table 6
Summary of financial indicators (Mono, Poly and CIGS).

Parameter[1]	**Mono**	**Poly**	**CIGS**
ROI	689%	700%	785%
ROI(Discounted)	112%	115%	136%
NPV	R 1 791 394.74	R 1 833 593.90	R 2 169 352.46
IRR	21%	22%	23%
Payback Period	6 Years, 5 Months	6 Years, 4 Months	5 Years, 11 Months
Total Energy	3 964 800 kWh	4 016 320 kWh	4 426 240 kWh
Cost of Energy	R 0.40 per kWh	R 0.40 per kWh	R 0.36 per kWh
Cumulative CF	R 11 028 203.18	R 11 200 087.35	R 12 567 687.42

[1] 1 US dollar = 14.5 South African Rand (R) based on March 2019 exchange rates.

The discounted return on investment, also known as the profitability index, only differs by 3% when comparing the Mono and Poly PV panels whereas it differs by 24% (in favour of the CIGS technology) when comparing the Mono and CIGS technology. All the results with regards to Mono- and Poly C-Si panels are within 3% over each other (except for the non-discounted ROI) which is in line with what was expected, when taking into account that the specific yields of the Mono and Poly technology only differs by approximate 1.3%. Due to the similarities between these two technologies, the rest of the results discussion will consist of a comparison between the results of the Mono C-Si technology and the CIGS technology.

The net present value results shown an increase of R 377 957.73 by selecting the CIGS technology when compared to the Mono technology. This is an increase of 21% which, as Gitman [32] indicates, is significant when it comes to making large capital decisions. The IRRs of each technology is close to each other with only 1% separating each technology, however looking at the IRR in correlation with the other results, it would still indicate that the CIGS technology would be the more profitable choice. The payback period of the CIGS technology is lower by approximately 7.8% when compared to the Mono technology.

Fig. 9 and Fig. 10 relates to cumulative yearly cash flow as well as the yearly cash flows indicating what the expected income would be with respects to each technology respectively. Fig. 10 indicates a large cash outflow at year zero which is attributed to the purchase of the system (the initial investment) followed by a larger cash inflow (more than the following year) which is due to the depreciation which is all allocated to year 1. This is possible due to a change in the section 12B of South African Tax act that allows a business to depreciate the entire value of the PV system within the first year. Previously the system had to be depreciated over a three-year period at 50% for the first year, 30% for the second year and 20% for the third year.

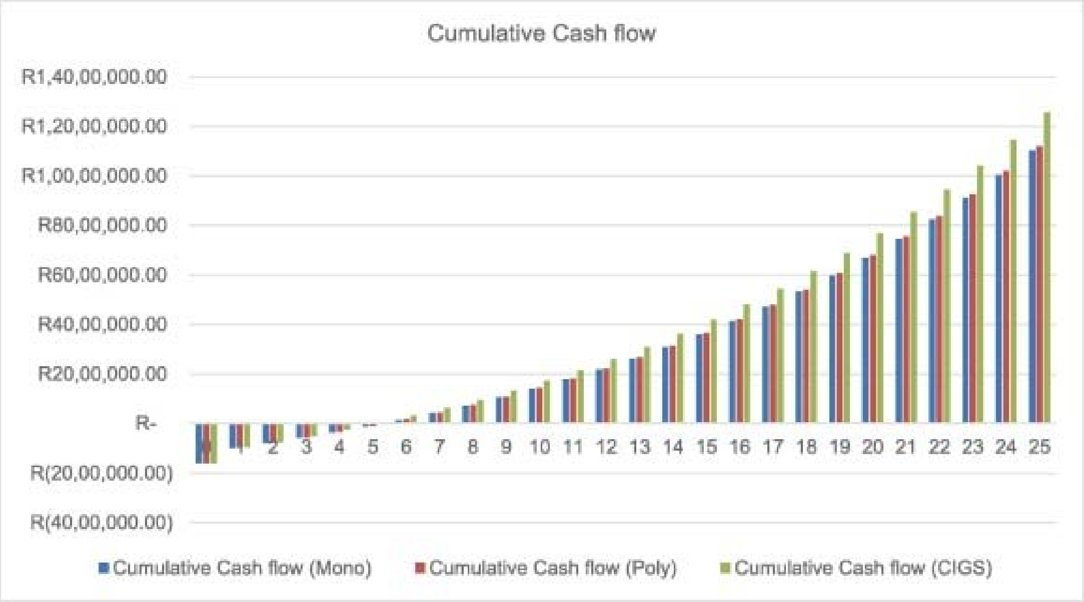


Fig. 9. Cumulative Cash flow (Mono, Poly and CIGS).

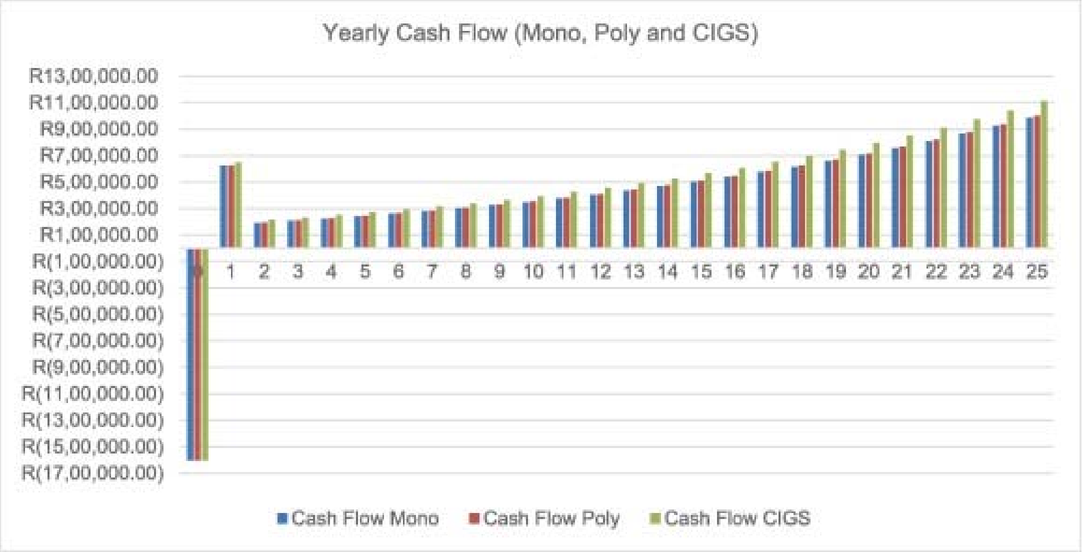


Fig. 10. Yearly Cash Flow (Mono, Poly and CIGS).

4.3. Regression analysis

In this section, regression analysis is conducted in order to analyse the effects of temperature and solar irradiation on the yield on of the technologies tested. While a number of parameters were measured using the weather station, the data sets that were used only included module tempertature and solar irradiation. The rationale for choosing module temperature is primarily because all three panel types are located at the same geographical location, therefore any change in meteorological conditions (such as ambient temperature, rainfall, humidity, wind speed, etc.) is the same across all three panel types. However the effect of the change will vary between panel types and is captured using module temperature as a proxy. A similar approach of assessing module temperature as a proxy for multiple meteorological parameters, even for panels located in different locations in South Korea is used by Kamuyu et al., [54]. It was seen that the error between measured and predicted module temperatures was less than 4% across all panel types. A study conducted in four different locations in Peru also found that module temperature closely tracked ambient temperature patterns for different panel types across all locations [55].

The results of the regression analysis for panel technologies investigated within the current study are provided in Appendix B. The independent variables used as part of the regression model are module temperature (MT) and solar irradiation (SR), whereas the dependant variable is the yield (Y) of the system. The data in Table B1, Table B2, Table B3 indicate that the yield is highly dependent on the combined effect of module temperature and solar irradiation, which can be observed via the high R square and adjusted R square values, for all three panel types. The overall significance of the regression model can be seen via that low overall significance value (as indicated by the significance F value), for all panel types. Module temperature was seen to have high significance for all three panel types while the effect of irradiation was lower (as seen in the P values). This relationship can be seen within regression coefficients as shown within the following equations:

$$Y_{Mono} = 0.2353MT_{Mono} + 0.0023SR \tag{10}$$

$$Y_{Poly} = 0.2090MT_{CIGS} + 0.0046SR \tag{11}$$

$$Y_{CIGS} = 0.3095MT_{CIGS} + 0.0013SR \tag{12}$$

Polycrystalline panel yield shows higher dependence on irradiation whereas CiGS panel yield shows least dependence. While this characteristic can be seen within the coefficients of the regression model it can also be observed within the line fit plots of module temperature and solar irradiation (as shown in Appendix B; Fig. B1, Fig. B2, Fig. B3, Fig. B4, Fig. B5, Fig. B6). The line fit plots of module temperature indicate a tighter fit for all three panel types, with CIGS panels showing the tightest fit (Fig. B.5). However the irradiation fit is the least for CIGS panels (Fig. B.6) compared to the other panel types.

4.4. Specific yield sensitivity analysis

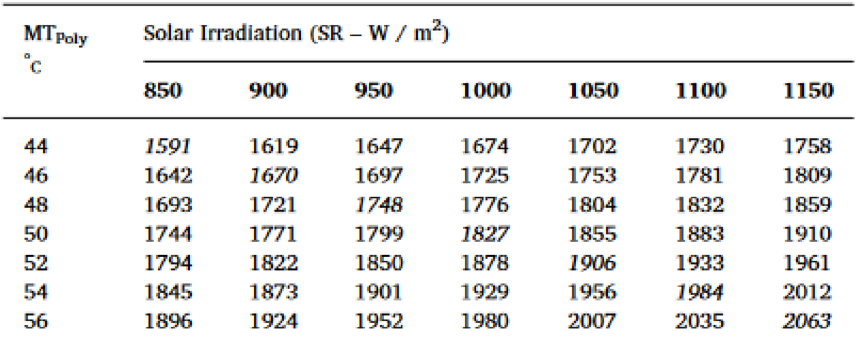
The Eqs. (10), (11), (12) derived in the previous section were used to conduct the sensitivity analysis for the three PV panel types.

Table 7
Specific Yield (kWh/kWp) Sensitivity Analysis - Mono.

MT_{Mono} °C	Solar Irradiation (SR – W / m^2)						
	850	**900**	**950**	**1000**	**1050**	**1100**	**1150**
44	*1502*	1516	1530	1544	1559	1573	1587
46	1559	*1573*	1587	1602	1616	1630	1644
48	1616	1630	*1645*	1659	1673	1687	1702
50	1673	1688	1702	*1716*	1730	1745	1759
52	1731	1745	1759	1773	*1788*	1802	1816
54	1788	1802	1816	1831	1845	*1859*	1873
56	1845	1859	1874	1888	1902	1916	*1931*

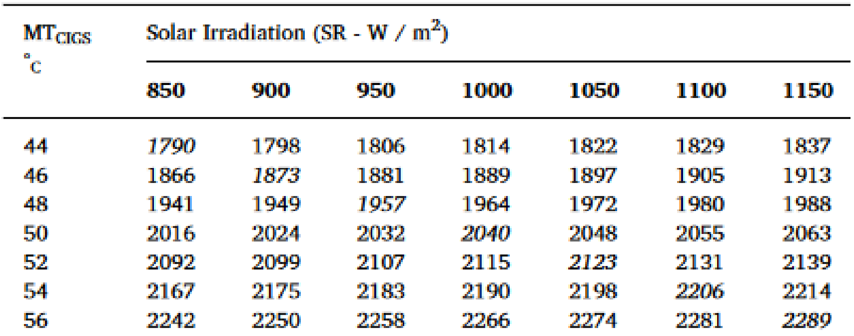
The temperature and solar irradiation range was selected by taking note of the minimum, maximum and average values of the data set as well as the regression analysis in order to ensure minimal error. Table 7, Table 8, Table 9 show the results from the specific yield analysis relating to the Mono, Poly and GIGS technology, respectively.

Table 8
Specific Yield (kWh/kWp) Sensitivity Analysis - Poly.



MT_{Poly} °C	Solar Irradiation (SR – W / m^2)						
	850	900	950	1000	1050	1100	1150
44	*1591*	1619	1647	1674	1702	1730	1758
46	1642	*1670*	1697	1725	1753	1781	1809
48	1693	1721	*1748*	1776	1804	1832	1859
50	1744	1771	1799	*1827*	1855	1883	1910
52	1794	1822	1850	1878	*1906*	1933	1961
54	1845	1873	1901	1929	1956	*1984*	2012
56	1896	1924	1952	1980	2007	2035	*2063*

Table 9
Specific Yield (kWh/kWp) Sensitivity Analysis - CIGS.



MT_{CIGS} °C	Solar Irradiation (SR - W / m^2)						
	850	900	950	1000	1050	1100	1150
44	*1790*	1798	1806	1814	1822	1829	1837
46	1866	*1873*	1881	1889	1897	1905	1913
48	1941	1949	*1957*	1964	1972	1980	1988
50	2016	2024	2032	*2040*	2048	2055	2063
52	2092	2099	2107	2115	*2123*	2131	2139
54	2167	2175	2183	2190	2198	*2206*	2214
56	2242	2250	2258	2266	2274	2281	*2289*

Comparing the sensitivity analysis of the Mono and Poly technology it can be seen that the specific yields are fairly close. The specific yield between the Mono and Poly technology differ by up to 6–7%. When comparing the specific yield at the lowest temperature and solar irradiation to that of the highest temperature and solar irradiation for both the Mono- and Poly C-Si technology a difference of approximate 28–30% is observed for both technologies. As expected, the overall specific yield of the GIGS technology is higher than that of the Mono and Poly technology.

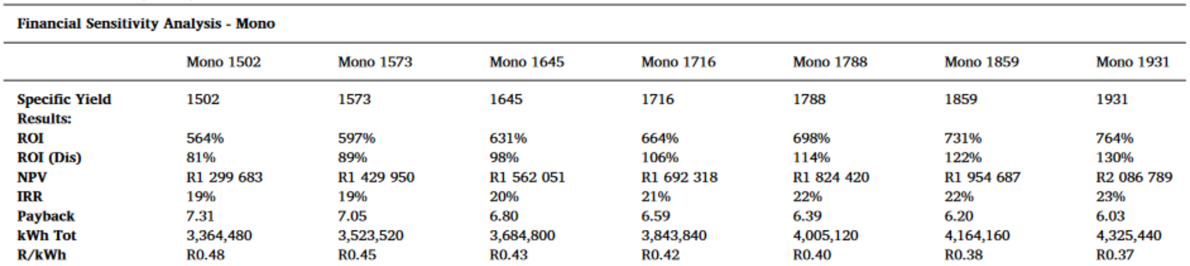
4.5. Financial sensitivity analysis

4.5.1. Monocrystalline sensitivity analysis

The financial sensitivity analysis was conducted by selecting the specific yields that coincide with the lowest temperature and the lowest solar irradiation up towards the highest temperature and highest solar irradiation. In other words, specific yields along the diagonal (in italics and shaded) in Table 7 were chosen for the sensitivity analysis. These values were selected due to the fact that the levels of solar irradiation and temperature tend to directly relate to each other, thus if the temperature tends to increase so does the solar irradiation.

Table 10 shows the results with regards to the financial sensitivity analysis conducted for the Mono C-Si PV panel technology. The specific yield associated with each of the scenarios is shown in the top section of the table and range from 1502 kWh/kWp to 1931 kWh/kWp.

Table 10
Financial Sensitivity Analysis - Mono.



Financial Sensitivity Analysis - Mono

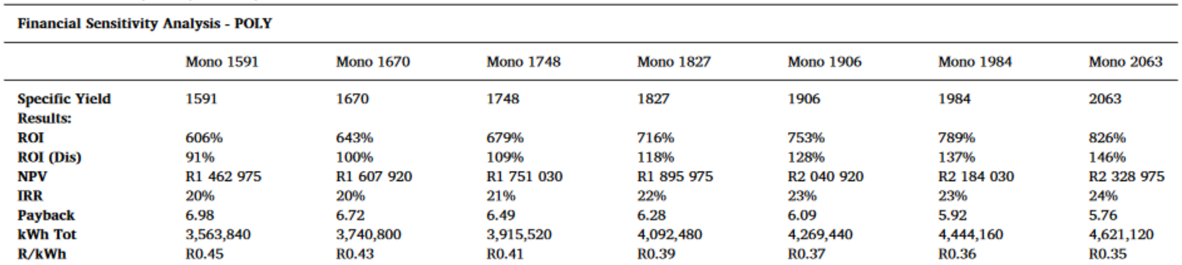
	Mono 1502	Mono 1573	Mono 1645	Mono 1716	Mono 1788	Mono 1859	Mono 1931
Specific Yield	1502	1573	1645	1716	1788	1859	1931
Results:							
ROI	564%	597%	631%	664%	698%	731%	764%
ROI (Dis)	81%	89%	98%	106%	114%	122%	130%
NPV	R1 299 683	R1 429 950	R1 562 051	R1 692 318	R1 824 420	R1 954 687	R2 086 789
IRR	19%	19%	20%	21%	22%	22%	23%
Payback	7.31	7.05	6.80	6.59	6.39	6.20	6.03
kWh Tot	3,364,480	3,523,520	3,684,800	3,843,840	4,005,120	4,164,160	4,325,440
R/kWh	R0.48	R0.45	R0.43	R0.42	R0.40	R0.38	R0.37

The discounted return on investment (ROI Dis) increased by 49% and the net present value (NPV) increased by 60% over the full range of the sensitivity analysis. The IRR increased by 4% whereas the payback period and cost of energy (R/kWh) decreased by 17.5% and 22.9% respectively.

4.5.2. Polycrystalline sensitivity analysis

Table 11 shows the results relating to the financial sensitivity analysis conducted with respect to the polycrystalline PV panel technology. The specific yield ranged from 1591 kWh/kWp to 2063 kWh/kWp. The discounted return on investment increased with 55% and the net present value increased by 60% when considering the minimum and maximum specific yield values. The IRR increased by 4% which is similar to that of the Mono C-Si scenario.

Table 11
Financial Sensitivity Analysis - Poly.



Financial Sensitivity Analysis - POLY

	Mono 1591	Mono 1670	Mono 1748	Mono 1827	Mono 1906	Mono 1984	Mono 2063
Specific Yield	1591	1670	1748	1827	1906	1984	2063
Results:							
ROI	606%	643%	679%	716%	753%	789%	826%
ROI (Dis)	91%	100%	109%	118%	128%	137%	146%
NPV	R1 462 975	R1 607 920	R1 751 030	R1 895 975	R2 040 920	R2 184 030	R2 328 975
IRR	20%	20%	21%	22%	23%	23%	24%
Payback	6.98	6.72	6.49	6.28	6.09	5.92	5.76
kWh Tot	3,563,840	3,740,800	3,915,520	4,092,480	4,269,440	4,444,160	4,621,120
R/kWh	R0.45	R0.43	R0.41	R0.39	R0.37	R0.36	R0.35

The payback period decreased by 17.5% and the cost of energy (R/kWh) decreased by 22.5%. Over all, the Poly panels performed marginally better at the high temperatures and high solar irradiation considering a 6% increase in discounted ROI with respect to the Mono panels (55% compared to 49%).

4.5.3. CIGS sensitivity analysis

Table 12 shows the results with regards to the financial sensitivity analysis conducted with respect to the CIGS technology. The specific yield ranged from 1790 kWh/kWp to 2289 kWh/kWp which is considerably higher than that of the other two panel technologies.

Table 12
Financial Sensitivity Analysis – CIGS.

Financial Sensitivity Analysis - CIGS							
	CIGS 1790	CIGS 1873	CIGS 1957	CIGS 2040	CIGS 2123	CIGS 2206	CIGS 2289
Specific Yield	1790	1873	1957	2040	2123	2206	2289
Results:							
ROI	699%	737%	777%	815%	854%	893%	932%
ROI (Dis)	114%	124%	133%	143%	152%	162%	171%
NPV	R1 828 090	R1 980 374	R2 134 492	R2 286 776	R2 439 060	R2 591 344	R2 743 628
IRR	22%	22%	23%	24%	25%	25%	26%
Payback	6.41	6.18	5.97	5.79	5.62	5.46	5.31
kWh Tot	4,009,600	4,195,520	4,383,680	4,569,600	4,755,520	4,941,440	5,127,360
R/kWh	R0.40	R0.38	R0.36	R0.35	R0.34	R0.32	R0.31

The discounted return on investment and net present value increased by 57% and 50% respectively when comparing the low temperature and solar irradiation with that of the high temperature and solar irradiation. The IRR increased by 4%. The payback period and cost of energy (R/kWh) decreased by 17.2% and 22.5% respectively.

The data indicates that the CIGS technology is more efficient and provides better yields than Mono C-Si and Poly C-Si technologies especially at high temperatures and high levels of solar irradiation. The difference between the discounted ROI of the CIGS technology and that of the Mono- and Poly technology is 41% and 25% respectively considering the scenario with the highest temperatures and solar irradiation. This also shows that the Poly technology is more efficient than the Mono technology at high temperatures.

5. Discussion

This research sought to assess the financial impact of using various PV panel technologies (monocrystalline, polycrystalline and CIGS). The investigation also looked at how specific meteorological conditions (solar irradiation and temperature) affect the specific yield performance of the panels and in turn how varying specific yield impacts financial indicators.

The research was also performed to confirm the findings in other investigations such as, Guenounou et al. [46] and Carra & Pryorb [56] stating that certain thin film PV panel technologies have a higher average yield compared to crystalline PV technologies when operating in countries with relatively high average temperatures.

5.1. Yield analysis

The yield analysis done in Section 4.1 looked at the yield data relating to the three PV panel technologies namely Mono C-Si, Poly C-Si and CIGS for a period of two years (2016 and 2017). It is clear from the results that the CIGS technology is more efficient and produces more energy when compared to that of the monocrystalline and polycrystalline technologies. The results show that the worst performing technology, given the meteorological and geographical conditions, was the Mono technology. On average, the CIGS technology produced 11.64% more power than the Mono technology and 10.19% more power than the Poly technology.

Looking at Fig. 6, it is evident that the CIGS technology as well as the Poly C-Si technologies are more efficient than the Mono C-Si technology especially during the colder months (May, June, July and August). The maximum variance in the module temperature between summer and winter is 21% whereas the maximum change in solar irradiation is 40%. Taking into consideration the fact that the highest yield variation between the CIGS technology and the Mono technology is during the period of low solar irradiation, it is clear that in a real-world environment the CIGS PV technology is more efficient than the Mono- and Poly C-Si technologies especially at lower levels of solar irradiation as well as at elevated temperatures.

The results from this section are in line with the results of Carr and Pryor [56] where it was shown that CIGS technology delivered on average 11.5% more yield when compared to crystalline technologies. The results are also in line with studies done by Guenounou et al. [46] and Humada et al. [47].

5.2. Financial models

The key financial indicators in Section 4.2 indicate that the CIGS technology delivers superior economic and financial results and results in the best return on investment. The total energy that a CIGS panel system can produce (4426.4 MWh) compared to a Mono panel system (3964.8 MWh) is roughly 11.6% higher whereas the cost of energy that the CIGS system needs to demand (0.36 R/kWh) is 10% lower than that of the Mono technology (0.4 R/kWh). This correlates to the higher yield and higher specific yield of (11.6%) the CIGS technology when compared to the Mono technology as per the previous section.

Based on the comparisons in Table 6 and the earlier discussion, it can be validated that choosing CIGS thin film PV panel technology over crystalline-silicon (Mono & Poly) PV technology does improve the financial indicators relating to discounted return on investment (24%), payback period (7.8%), cost of energy (10%) and internal rate of return (2%) of a PV system, operating within South Africa as well as other countries with similar meteorological conditions.

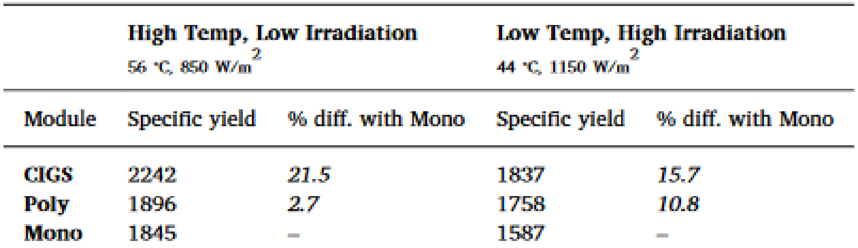
5.3. Sensitivity analysis

The sensitivity analysis conducted in Section 4.5 looked at the sensitivity of the key financial indicators of each technology whilst varying the solar irradiation levels as well as PV panel temperatures (Table 7, Table 8, Table 9). This was achieved by first developing a regression model to link the effect of measured temperature and solar irradiation with the specific yield. Using the model, the effect of the changes in specific yield to varying range of temperature and solar irradiation were analysed after which the effect on the key financial indicators were analysed.

The results indicate that CIGS technology is still overall more profitable when compared to the Poly and Mono technologies. It can also be noted that the gap in economic and financial performance between the CIGS and crystalline technologies increases (in favour of the CIGS technology) as the temperature and solar irradiation increases. Looking at the highest levels of temperature and solar irradiation evaluated, the discounted return on investment of the CIGS technology is 25% higher than that of the polycrystalline technology and 41% higher than that of the monocrystalline technology. It is also notable that the polycrystalline technology out performs the monocrystalline technology (by 15%, discounted ROI) at high levels of solar irradiation and temperature.

Therefore, it is clear that the impact on the economic and financial indicators of a PV system with respect to change in ambient temperature and solar irradiation is lesser when choosing CIGS thin film technology as opposed to Poly and Mono C-Si PV technology. However, it should be noted that the difference in specific yield between CIGS panels and Mono/Poly panels (Table 7, Table 8, Table 9) varies more at high temperatures and lower levels of solar irradiation with lesser variation at low temperatures and high levels of irradiation, as summarised in Table 13.

Table 13
Variation in specific yield outputs.



	High Temp, Low Irradiation 56 °C, 850 W/m^2		**Low Temp, High Irradiation** 44 °C, 1150 W/m^2	
Module	Specific yield	% diff. with Mono	Specific yield	% diff. with Mono
CIGS	2242	*21.5*	1837	*15.7*
Poly	1896	*2.7*	1758	*10.8*
Mono	1845	–	1587	–

6. Conclusion

By means of the techno-economic model and the sensitivity analysis framework used in this study, the variation in financial performance of the various PV panels when considering different technologies as well as varying meteorological conditions can be assessed. Based on the results and discussion, it can be concluded that a PV system or plant operating in South Africa and other geographical locations with similar meteorological conditions will have an improved yield of roughly 11.6% and financial performance (24% increase in discounted return on investment, 7.8% reduction in payback period and 21% improvement in net present value), should CIGS PV panel technology be used instead of monocrystalline and polycrystalline PV panel technology. CIGS panels also show least sensitivity in yield output during low irradiation, when compared to both crystalline technologies.

The findings are critical when considering commercial and utility scale installations. To date, operational utility scale installations in South Africa are dominated by crystalline panels (1180 MW) compared to thin film panels (294 MW), despite the improved financial performance [57]. The findings are also useful for industry practitioners and stakeholders for whom improved technical and financial analysis relating to commercial and utility scale solar PV installations are critical. In practice, the research also contributes to more accurate energy planning with regards to improved yield forecasting. More importantly, such investigations are limited in sub-Saharan Africa and the southern hemisphere that is rich in solar irradiation.

To expand on the research done in this study, as well as to improve on the accuracy and the generalisability of the models developed, a number of improvements can be brought about. The ambient temperature in addition to the module temperature can be used as part of the regression model. Another possible improvement would be to increase the number of geographical locations across the globe in order to obtain data from a larger range of geographical and meteorological conditions. An aspect of variation can be brought about by measuring the solar irradiation perpendicular to the PV panel plane to more accurately assess the influence of solar irradiation on the financial model. Finally, a mathematical model that equates the solar irradiation perpendicular to the PV panel plane to global horizontal irradiation, can be incorporated into the model, in order to make the model more generalised and easier to use with existing irradiation data.

CRediT authorship contribution statement

George Alex Thopil: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing - review & editing, Supervision, Project administration. **Christiaan Eddie Sachse:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Project administration. **Jörg Lalk:** Conceptualization, Writing - review & editing, Supervision. **Miriam Sara Thopil:** Investigation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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