The study, analysis and performance comparison of two emergent technologies of photovoltaic modules: HJT cells and PERC cells

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November 2022

Abstract

Renewable energy technologies have been increasingly important in the inevitable transition from our current level of dependence on fossil fuels. With the increasing installed capacity around the globe reducing the cost of photovoltaics, this energy conversion method is considered a mainstream technology fundamental to achieving carbon neutrality by 2050. In this regard, the Passivated Emitter and Rear Contact (PERC) cell, which by 2020 occupied 85% of the installed capacity worldwide [1], was studied and compared with the Heterojunction Technology (HJT).

Through the installation of these modules and an analysis of the output performance, it was possible to conclude that the HJT displayed an average of 1,88% more efficiency than the PERC technology. Despite this better performance, several installation simulations were computed to compare the optimal situation in which each technology should be implemented since these modules displayed different acquiring costs.

It was concluded that in cases in which there are constraints related to the installed power or there is a limited area, HJT modules should be installed. These will return more profit in the long run, despite both technologies becoming profitable in the short term. In cases where there is a limited budget, PERC modules should be installed. They will turn out a better investment independently of the time considered for the analysis.
Keywords: Passive Emitter and Rear Contact; Heterojunction Technology; performance; efficiency; costs; profit;

1. Introduction

With the continuous development of society, people consume more energy. As more attention has been drawn in recent years to environmental protection and adopting pollution-free energy conversion methods, solar has become increasingly important in the inevitable transition from our current dependence on fossil fuels.

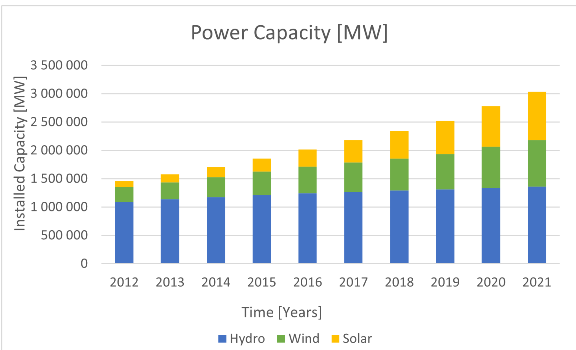

Figure 1: Power capacity distribution of the 3 biggest renewable sources per year [2].

As can be seen in Figure 1, solar power has been increasing significantly over the last years.

With higher development, costs have been reducing dramatically, as displayed in Figure 2.

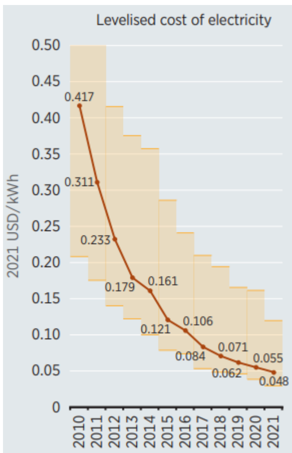

Figure 2: Levelised cost of electricity (LCOE) in USD/kWh [3].

2. Motivation

The performance of a photovoltaic (PV) module is strongly dependent on ambient conditions (e.g. irradiation, ambient temperature, wind, etc.) and different losses occurring in the solar cells. These losses are related to the increased temperature in the cell and associated to the recombination effect. Solar radiation is absorbed in the cell and increases the module temperature, reducing efficiency. In 2020, 85% of the market share was occupied by the passive emitter and rear contact (PERC) technology [1] due to the low cost of manufacture and high efficiency. However, this photovoltaic cell displays a high-temperature coefficient and light-induced degradation (LID). Interest has risen around the heterojunction (HJT) cell due to the lower temperature coefficient, lower recombination rates and the fact that it is a natural bi-facial cell.

3. High Efficiency Cells powered by Dielectric Layers

3.1. PERC

From an optical perspective, the power output is directly related to the amount of incident light absorbed by the cell. Silicon nitride acts as an anti-reflection coating, allowing more light to penetrate the cell, resulting in superior efficiency. Defects at the silicon surface are caused by the interruption of the crystal lattice periodicity, and as a result, unpaired electrons appear. These are called dangling bonds and generate a high local recombination rate. Passivation, i.e., minimizing surface recombination, is a prerequisite for achieving high-efficiency cells. This is achieved by combining two effective mechanisms: Chemical passivation by Intrinsic Hydrogen and Field-Effect passivation via fixed insulator charges [4].

Fixed negative charges present in the Al_2O_3 film are attracting holes to form an accumulation layer on p-type silicon. This positively charged layer acts as a barrier for electrons, resulting in a recombination decrease.

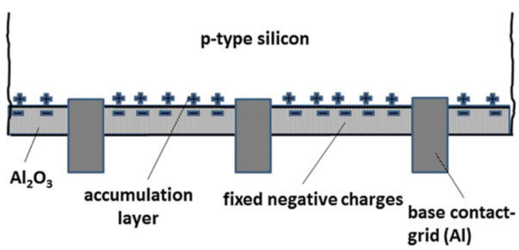

Figure 3: Rear Surface Passivation Scheme[5].

Due to the high refractive index and the superior surface passivation, Silicon nitride layers are applied in the use of silicon solar cells, as displayed in Figure 4.

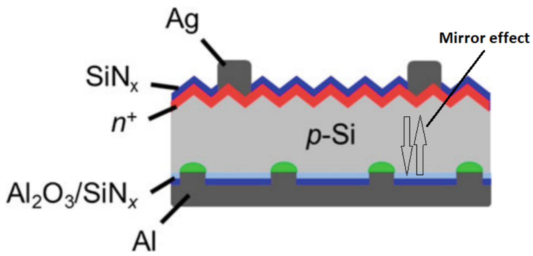

Figure 4: PERC cell scheme.

The combination of aluminium oxide and silicon nitrite provides passivation and creates a mirroring effect for incident light [6], enhancing its absorption within the solar cell.

3.2. HJT

Sanyo invented heterojunction with intrinsic thin layer (HIT) cell technology in the early 1990s and benefits from using intrinsic hydrogenated amorphous silicon layers to obtain higher efficiency.

The term heterojunction comes from the formation of the junction of semiconductors with different bandgaps. This is verified in the cross sectional view of SHJn, in Figure 5, where a n-type Silicon (c-Si(n)) is sandwiched between two amorphous Silicon intrinsic layers (a-Si:H(i)).

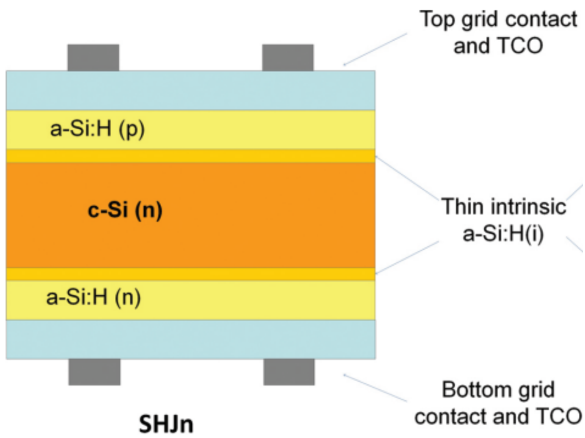

Figure 5: Cross sectional view of SHJn and SHJp[7].

Using the amorphous layers, surface recombination is suppressed by the chemical passivation of dangling bonds on c-Si wafer surface. This is possible due to the formation of Si-Si and Si-H bonds [8]. Amorphous silicon layers only provide passivation if they are in contact with intrinsic layers. Intrinsic means that the layers have not been doped intentionally.

Continuing the analysis of the SHJn cell, a p-type amorphous layer (a-Si:H(p)) is grown on the top, and on the bottom, n-type amorphous layers (n a-Si:H(n)) is deposited. These layers are then fully covered with a transparent conductive oxide (TCO), followed by screen-printing contact metal grids using low-temperature Ag conductive paste. TCO's are required to enhance the collection of the electron hole pair and are transparent to allow light to enter the cell.

This technology was commercialized by Sanyo under patented Heterojunction with Intrinsic thin layer (HIT). This patent expired in 2010 and opened the way for equipment suppliers and manufacturers to work with the technology and provide solutions to the market.

Meyer Burger is a Swiss company that used to manufacture machinery required to produce wafers in mass production. After 2010, they started working on the Heterojunction technology and present today HJT + SmartWire Connection Technology (SWCT®).

SWCT consists on the presence of small wire to replace busbars on top and bottom grid of the cell, as can be seen in Figure 6.

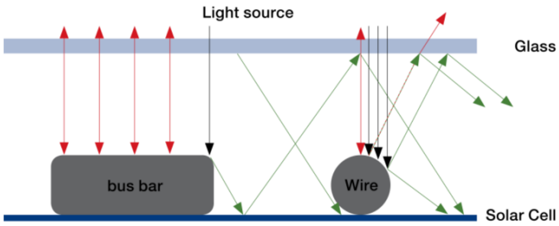

Figure 6: Busbar vs SWCT [9].

This technology can increase the efficiency of the HJT cell by 5,7% due to the reduced electrical losses and reduced optical losses (less shading) [9].

4. System-Design

4.1. PERC

The mono-crystalline 395 W panels with reference JAM54S31/MR/1000V from JASOLAR were chosen to study the PERC technology. These panels present a half-cell configuration, meaning that instead of having 1 circuit, the panel is divided into two parallel ones, halving the current values. Regarding the Joule loss effect, where the losses are related to the square value of the current, its values drop to 1/4.

In Figure 7, the electrical parameters at standard test conditions are displayed.

ELECTRICAL PARAMETERS AT STC				
TYPE	JAM54S31 -380/MR/1000V	JAM54S31 -385/MR/1000V	JAM54S31 -390/MR/1000V	JAM54S31 -395/MR/1000V
Rated Maximum Power(Pmax) [W]	380	385	390	395
Open Circuit Voltage(Voc) [V]	36.58	36.71	36.85	36.98
Maximum Power Voltage(Vmp) [V]	30.28	30.46	30.64	30.84
Short Circuit Current(Isc) [A]	13.44	13.52	13.61	13.70
Maximum Power Current(Imp) [A]	12.55	12.64	12.73	12.81
Module Efficiency [%]	19.5	19.7	20.0	20.2
Power Tolerance	0~+5W			
Temperature Coefficient of Isc(α_Isc)	+0.045%°C			
Temperature Coefficient of Voc(β_Voc)	-0.275%/°C			
Temperature Coefficient of Pmax(γ_Pmp)	-0.350%/°C			
STC	Irradiance 1000W/m², cell temperature 25°C, AM1.5G			

Figure 7: PERC panel datasheet parameters.

Note the most relevant STC parameters: 395 W of maximum power, 20,2% module efficiency and temperature of coefficient of -0,350%/°C.

4.2. HJT

To study the HJT technology, the mono-crystalline Meyer Burger Glass Panels were chosen. It is important to note that the manufacturer offered this photovoltaic module to the university. It also presents a half-cell technology, meaning that the Joule loss effect is decreased to 1/4, and the panel gathers irradiance from both sides due to the its natural bi-facial configuration. In Figures 8 and 9, the electrical parameters at STC of the PV panel are displayed.

Power class in STC² [W_p]				370	
Minimum Performance (Power Tolerance –0 W/+5 W) [W_p]				STC	NMOT³
Minimum	Power at MPP	P_{mpp}	[W]	370	284
	Short Circuit Current	I_{sc}	[A]	10.4	8.4
	Open Circuit Voltage	V_{oc}	[V]	44.5	41.9
	Current at MPP	I_{mpp}	[A]	9.9	8.0
	Voltage at MPP	V_{mpp}	[V]	37.7	35.5
	Efficiency	η	[%]	20.6	

Figure 8: HJT datasheet parameters-1.

Temperature Coefficients			
Temperature Coefficient of I_{SC}	α	[%/°C]	+0.033
Temperature Coefficient of V_{OC}	β	[%/°C]	-0.234
Temperature Coefficient of P_{MPP}	γ	[%/°C]	-0.259
Nominal Module Operating Temperature	NMOT	[°C]	43±3

Figure 9: HJT datasheet parameters-2.

Note the most relevant STC parameters are: 370 W of maximum power, 20,6% module efficiency and temperature coefficient of -0,259%/°C.

4.3. Location and Connection

After arriving, the panels were mounted on University's rooftop. At the time, photovoltaic modules were very scarce worldwide, and JASOLAR PERC module suffered a delay of two months to arrive. To not delay even further the completion of this study, both modules were mounted horizontally. A basic structure to hold them to the ground was assembled, as seen in Figure 10.

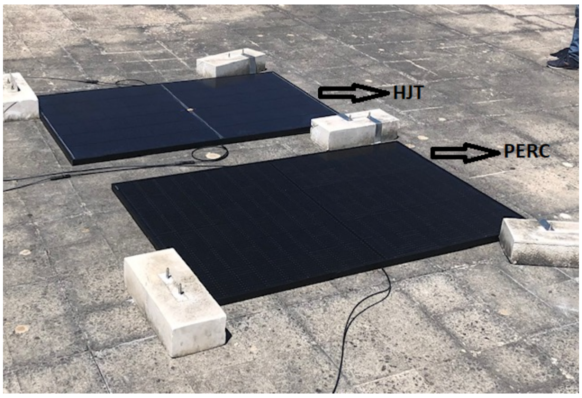

Figure 10: Panels displaced horizontally.

To connect the panels on the rooftop to the acquisition system, located four floors under, 50m of cables were used and passed through the air conduct. At the laboratory, the following setup was available to connect to the acquisition system.

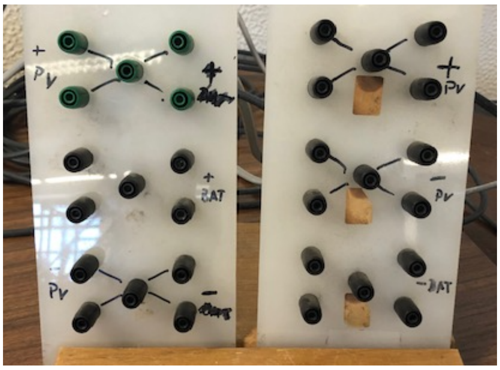
Figure 11: Available connection at the laboratory.

4.4. Data acquisition

A variable resistor was connected directly to the panel, as displayed in Figure 12.


Figure 12: Final acquisition system used.

A power signal was obtained by visualising the voltage and current signals on the oscilloscope with probes and multiplying both signals. With the oscilloscope reading the signal during a time interval of 5 seconds, the resistor values were changed from the minimum, 1Ω, to the maximum, 9Ω. In between, the maximum power point would be visualized in the reading device, as seen in Figure 13.

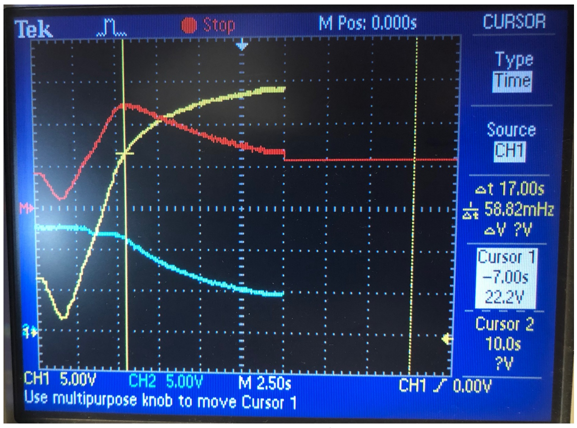

Figure 13: Visualization of the power signal.

4.5. Irradiance, Module temperature and Efficiency

Efficiency was the ratio of useful work chosen to analyze the performance of the photovoltaic modules. This decision was supported by the different sizes and power of the modules. This way, it is possible to compute the ratio of the output power of each module for the same area unit. To calculate module efficiency, the equation 1 was used.

$$\eta = \frac{P_{OUT}}{G \times A} \times 100[\%] \quad (1)$$

Where:

- P_{OUT} is the module output power, in W, read on the oscilloscope;
- G is the irradiance, in W/m^2, measured with the Pro Solar Power Meter ISM400, from RS;
- A is the panel's area. The HJT panel area equals 1,793 m^2 and PERC has an area of 1,953 m^2;

Temperature measurements were performed with the infrared camera FLIR E6-XT always on the same cell on each of the modules.

5. Experimental-Analysis

Data was collected in various weather to obtain a diversified set of samples and evaluate cell technology performance in different conditions. Analysis were perform during the 18th,19th,25th and 29th of August.

The first two days of measurements were characterized by the absence of clouds, resulting in the modules receiving direct radiation from the sun, present in Figures 14 and 15. The last two days of measurements presented clouds in the sky, as can be seen by the low irradiance values, later opening and turning into clear sky conditions, presented in Figures 16 and 17. It was required to gather all data that characterized the performance of the modules with irradiance above 250 W/m^2 in the same graph to understand the performance of the modules regarding temperature and irradiance for clear sky conditions. Figure 18 shows the temperature dependence of efficiency, Figure 19 displays the irradiance dependence of efficiency and Figure 20 shows the temperature dependence of the efficiency difference of the two modules.

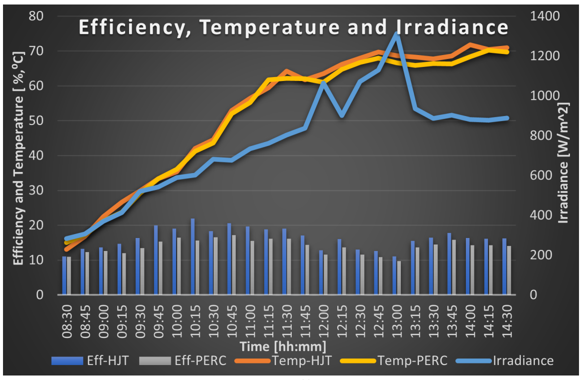

Figure 14: Irradiance, Module Efficiency and Module Temperature for 18/08/2022.

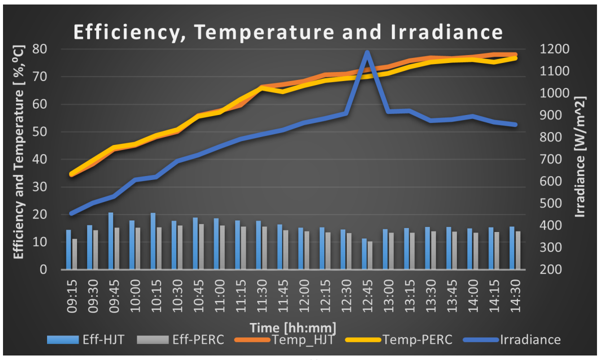

Figure 15: Irradiance, Module Efficiency and Module Temperature for 19/08/2022.

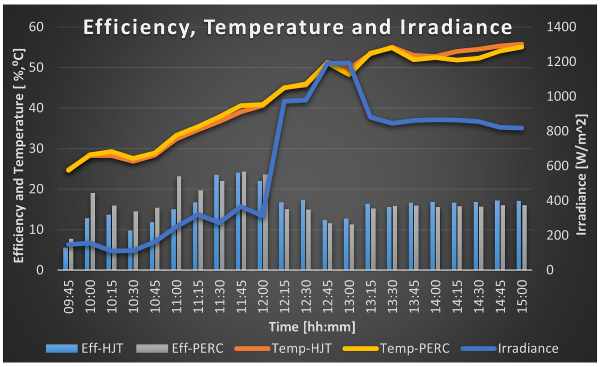

Figure 16: Irradiance, Module Efficiency and Module Temperature for 25/08/2022.

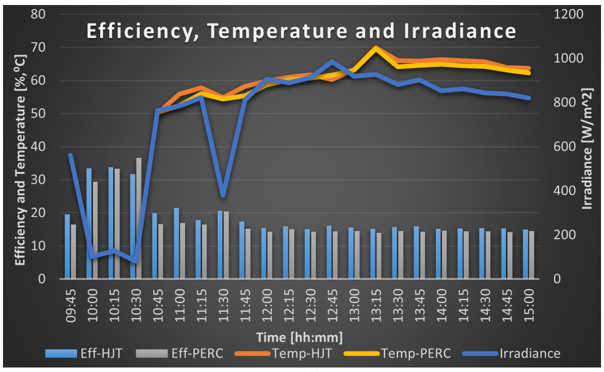

Figure 17: Irradiance, Module Efficiency and Module Temperature for 29/08/2022.

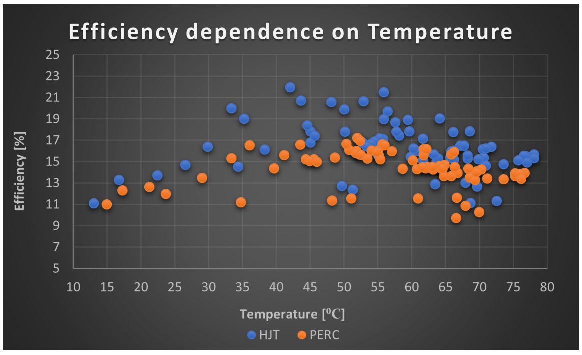

Figure 18: Efficiency dependence on temperature.

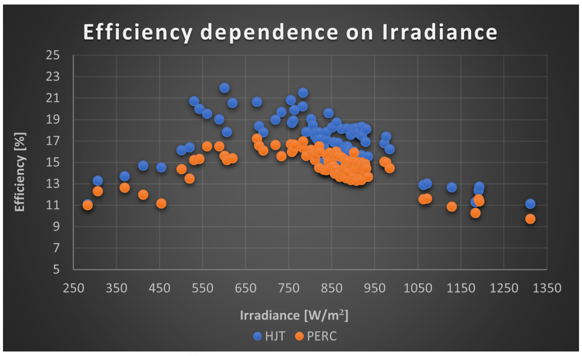

Figure 19: Efficiency dependence on irradiance.

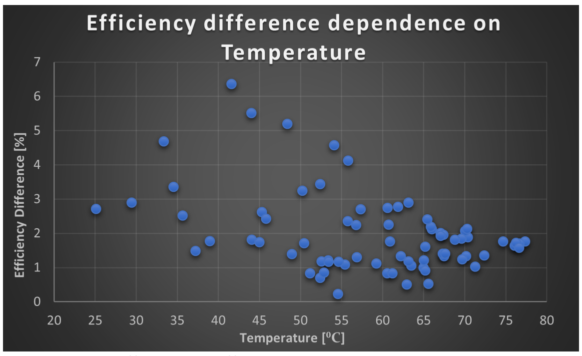

Figure 20: Efficiency difference dependence on temperature.

Analyzing five days of collected data, important information is gathered below:

- Under **clear sky conditions**, regarding efficiency, the **HJT outperformed the PERC module by an average of 1,88% abs**.
- Under cloudy conditions, regarding efficiency, the PERC module has displayed higher values than the HJT module in 71,4% of the measurements;
- Despite the PERC module presenting higher power output in STC conditions, experimentally, the HJT module outputs, almost every time, more power than the PERC module;
- **A sudden increase in irradiance negatively affects the efficiency, independently of the module temperature. Likewise, a sudden decrease in irradiance will increase module efficiency**;
- For the HJT module, maximum power was obtained with an average irradiance of 859,62W/m^2, an average efficiency of 18,78% and an average temperature of 58°C;
- For the PERC module, maximum power was obtained with an average irradiance of 866,26W/m^2, an average efficiency of 15,65%, and an average temperature of 60,03°C;
- **Despite the HJT module displaying a significantly better temperature coefficient, the efficiency difference is shortened when the modules present high working temperature**;
- Modules display better efficiency when working under the irradiance range [550W/m^2 ; 975W/m^2];
- Modules display better efficiency when working under the temperature range [35°C ; 55°C].

6. Projects

A simulation of horizontal modules production was computed considering the annual irradiance for the university location with the help of PVGIS [10], displayed in Figure 21 and Table 1.

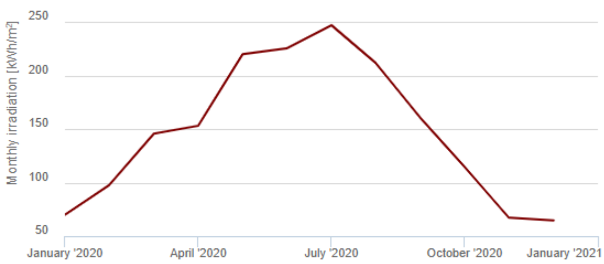

Figure 21: Monthly Irradiation during the 2020 year.

Month	HJT Output $[kWh]$	PERC Output $[kWh]$
January	20,71	19,98
February	29,00	27,99
March	43,15	41,66
April	45,34	43,76
May	65,14	62,88
June	66,78	64,47
July	73,16	70,62
August	62,70	60,52
September	47,54	45,89
October	33,96	32,79
November	19,90	19,21
December	19,17	18,51
Total	**526,56**	**508,28**

Table 1: Total energy conversion performed by the modules during one year.

Considering different energy suppliers in Portugal and presenting different costs of kWh, an average was computed, with a final value of 0,18424€/kWh. With the calculation of production parameters, five projects will be compared.

6.1. 4.5 kW Installation

An installation with 4.5 kW of nominal Power was considered. This translates to comparing a 13 HJT module system with 12 PERC modules. Efficiencies of the (modules+cables) were the values gathered during the experimental tests, 16,51% for HJT and 14,63% for PERC. Inverter efficiencies were computed according to each month, since it fluctuates with the amount of power that is displayed in the primary side of this device. The resulting inverter efficiencies are displayed in Table 2.

Efficiency	Efficiency for HJT [%]	Efficiency for PERC [%]
η at 25% of $P_{ac,r}$	95,50	95,13
η at 30% of $P_{ac,r}$	96,00	95,67
η at 50% of $P_{ac,r}$	96,80	96,67
η at 75% of $P_{ac,r}$	97,17	97,07

Table 2: Inverters efficiencies related to primary power and module technology.

It is now possible to compute the final energy produced for a whole year of each one of the systems.

Month	Energy Produced HJT [kWh]	Energy Produced PERC [kWh]
January	257,06	228,17
February	361,86	321,31
March	543,05	483,21
April	570,53	507,67
May	822,83	732,42
June	843,58	750,89
July	924,14	822,60
August	791,99	704,97
September	598,24	532,32
October	423,87	376,38
November	247,10	219,33
December	238,02	211,27
Annual	**6622,28**	**5890,55**

Table 3: Monthly and yearly energy produced by 13 HJT modules and 12 PERC modules.

Converting this energy value to €, it corresponds to a total annual production of 1220,09 € and

1085,27 € for the HJT and PERC system, respectively. Computing the system costs, modules display unitary prices of 271.385 € for the HJT and 154.16 € for the PERC technology. Since the nominal power of the modules correspond to different working power values, different inverters were used, with a cost of 1389.00€ for the HJT and 1314.99 € for the PERC. Cables were considered the same in both installations, with 200m of cables costing 280 €. An horizontal structure was considered, with unitary prices of 781.82 €. Finally, 1000 € worth of labour was considered to assemble the whole system. Total system costs are displayed in Figure 4.

Material	HJT [€]	PERC [€]
Modules	3528,01	1849.92
Inverters	1389,00	1314,99
Cables	280	280
Structure	781,82	781,82
Labour	1000	1000
Total	6978,83	5226,73

Table 4: HJT and PERC system costs for 4,5 kW system.

Accounting for the annual degradation that is guaranteed by the manufacturers of 0.2% for HJT modules and 0.55% for the PERC modules, the total profits of each system was computed over a period of 30 years and is displayed in Figure 22.

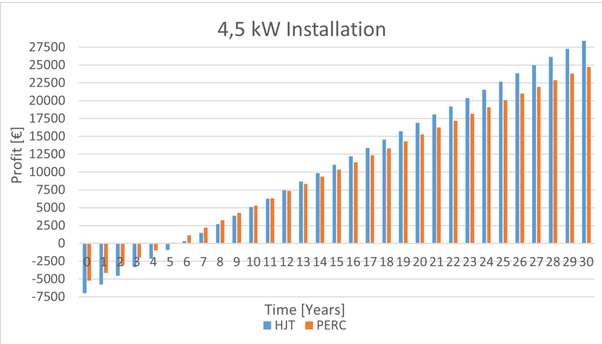

Figure 22: Cumulative profits of HJT and PERC systems over a period of 30 years-4,5 kW installation.

6.2. 3.5 kW Installation

For a 3.5 kW installation, the same components of the previous example were used, changing only the number of photovoltaic modules. 10 HJT and 9 PERC modules were considered. These systems presented costs displayed in Table 5.

Material	HJT [€]	PERC [€]
Modules	2713,85	1387,44
Inverters	1389,00	1314,99
Cables	280	280
Structure	781,82	781,82
Labour	1000	1000
Total	6164,67	4764,25

Table 5: HJT and PERC system costs for 3,5 kW system.

The total profits of each system is displayed in Figure 23.

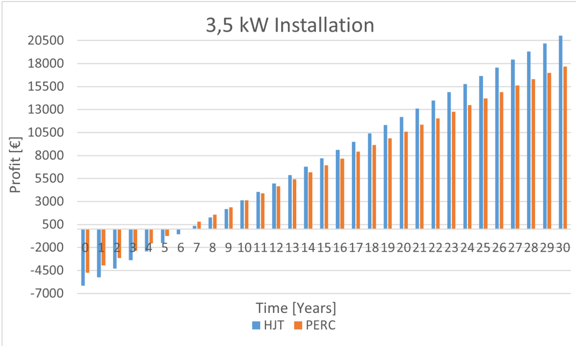

Figure 23: Cumulative profits of HJT and PERC systems over a period of 30 years-3,5 kW installation.

6.3. 2,5 kW Project

For a 2.5 kW installation, the same components of the previous example were used, changing only the number of photovoltaic modules. 7 HJT and 7 PERC modules were considered. These systems presented costs displayed in Table 6.

Material	HJT [€]	PERC [€]
Modules	1899,70	1079,12
Inverters	1389,00	1314,99
Cables	280	280
Structure	781,82	781,82
Labour	1000	1000
Total	5350,52	4455,93

Table 6: HJT and PERC system costs for 2,5 kW system.

The total profits of each system is displayed in Figure 24.

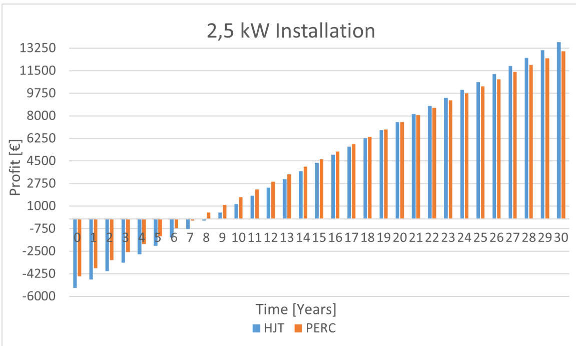

Figure 24: Cumulative profits of HJT and PERC systems over a period of 30 years-2,5 kW installation.

6.4. 5000 € Installation

An installation with a budget of 5000€ was considered and costs are displayed in Table 7.

Material	HJT [€]	PERC [€]
Modules	1356,93	1541,6
Inverters	1389,00	1314,99
Cables	280	280
Structure	781,82	781,82
Labour	1000	1000
Total	4807,75	4918,41

Table 7: HJT and PERC system costs for 5000€ installations.

The total profits of each system is displayed in Figure 25.

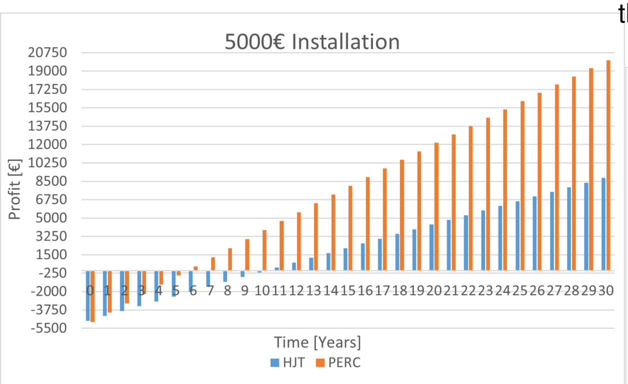

Figure 25: Cumulative profits of HJT and PERC systems over a period of 30 years- 5000€ installation.

6.5. 10000 € Installation

An installation with a budget of 10000€ was considered and costs are displayed in Table 8.

Material	HJT [€]	PERC [€]
Modules	1356,93	1541,6
Inverters	1389,00	1314,99
Cables	280	280
Structure	781,82	781,82
Labour	1000	1000
Total	4807,75	4918,41

Table 8: HJT and PERC system costs for 5000€ installations.

The total profits of each system is displayed in Figure 26.

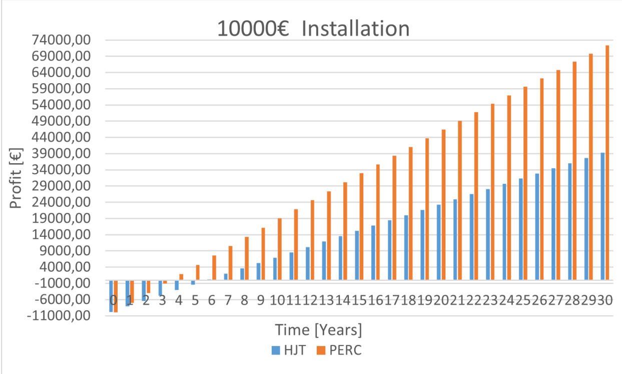

Figure 26: Cumulative profits of HJT and PERC systems over a period of 30 years- 10000€ installation.

6.6. 10000 € Installation + Out of Warranty Modules Replacement

Due to the different modules warranty of 12 years for the PERC and 30 years for the HJT technology, it is important to compute the effects in profits in the worst case scenario, where all PERC modules require replacement every 12 years. The profits of these systems are displayed in Figure 27.

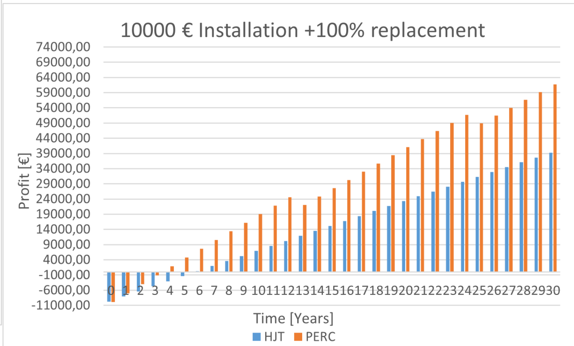

Figure 27: Cumulative profits of HJT and PERC systems over a period of 30 years- 10000€ installation with module replacements at year 13 and 25.

6.7. 5000 € Installation + Out of Warranty Modules Replacement

Computing a similar situation on the 5000 € installations, the new profits of both systems are displayed in Figure 28.

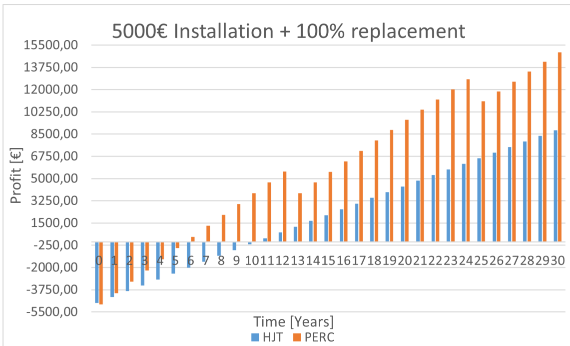

Figure 28: Cumulative profits of HJT and PERC systems over a period of 30 years- 5000€ installation with module replacements at year 13 and 25.

7. Conclusions

Analyzing the experimental and simulated data, it was concluded that:

- **Both modules are profitable** and when installed in these simulated systems, they reach the **break-even point before the 10 year mar**;
- **HJT modules are best suited for installations when there is a constraint of power or installation area**. Since this limit of module quantity will be reflected in approximately the same number of modules in both technologies, the HJT technology will surpass the profits of the PERC technology in the long run, due to the higher efficiency.
- **PERC modules are best suited for installations when there is a budget constraint**. For the same investment, PERC system will be composed of higher number of modules due to the lower unitary cost. This higher number will represent more profit even in the worst-case scenario, where all modules need replacement as soon as the warranty expire.

7.1. Difficulties encountered

- Modules suffered a delay of 2 months to arrive, due to the pandemic situation. Not to delay the work even further, an horizontal structure was assembled instead of an optimised structure that could tilt the modules directly to the sun. This analysis did not take into account the bifaciality of the HJT module;
- Due to the malfunctioning of the inverters, it was required a manual process that needed to be performed every 15 minutes instead of having two sensors for voltage and current and the Arduino UNO collecting data continuously;

7.2. Future work

- Installation of new inverters that store the data that characterizes the performance of the modules;
- Installation of the modules oriented directly to the sun to optimize exposure and increase output power, and the HJT module can receive irradiance from both sides, increasing its efficiency;
- Compare HJT technology with other technologies that have been raising interest over the last years, such as Interdigitated Back Contact (IBC) cells and tunnel oxide passivated contact (TOPcon) cells;
- Introduce cooling techniques to understand the effect of temperature in a module with the same irradiance and study the economic feasibility of this new project;

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