Comparative Analysis of the Performance of Four Different Photovoltaic-Thermal Modules

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Abstract

An experimental comparison between four different PVT modules is made, the modules being identical apart from their PV technology. Two experiments are run simultaneously comparing two sets of PVT and PV modules with the same solar cell technology. The passivated emitter and rear cell (PERC) technology with white back sheet is used as reference module, all the others are compared to it during one day of experimentation for each technology. For the thermal output of the PVT, the results show an improvement for the modules using PERC with black back sheet by more than 10 %, while there is no significant evidence of change for the silicon hetero-junction (SHJ) or tunnel oxide passivated contact (TOPCon) technologies. For the electrical output, none of the technologies outperforms the others in terms of performance ratio; but the PERC with black back sheet PVT-module sees a significant improvement of 2.5 % of its performance ratio compared to its PV counterpart.

Keywords: Photovoltaic-thermal, Comparative analysis, Performance Ratio, PERC, SHJ, TOPCon

1. Introduction

A photovoltaic-thermal (PVT) module gives the possibility to both extract thermal energy from photovoltaic cells, and cool them down, thus improving their electrical performance.

Several comparative analyses among PVT-modules or between PVT-modules and PV-modules have been performed. Han et al. (2021) show that a set of PVT modules combined with another set of solar thermal modules are outperforming PV and solar thermal combined when the ambient temperature tends to be high, the irradiance strong and/or the inlet temperature of the coolant lower. Carmona et al. (2021) compare a PVT-module with integrated phase change material (PCM) to a PV-module: an increase of AC output by 7.43 % is observed thanks to the cooling system. Good et al. (2015) compare PV+solar thermal, uncovered PVT, covered PVT+PV, and only PV for housing in Norway: the “only PV” configuration seems to get the closest to net zero energy balance when using energy for a building, but the result could be different by changing slightly the criteria of the comparison.

While these research works compare either PVT with PV or different PV technologies, there is little research about the comparative behavior of PVT equipped with different solar cell technologies. This article is a first attempt to fill the gap. In this article different PVT-modules equipped with the exact same cooling loop but with different solar cell technologies are compared: Si passivated emitter and rear cell with white back sheet (PERC white), Si passivated emitter and rear cell with black back sheet (PERC black), Si heterojunction with intrinsic thin layer (SHJ) and Si tunnel oxide passivated contact (TOPCon). All modules are having the same size and the same number of cells, the PV technologies differ by their electrical efficiencies and temperature coefficients.

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2. Experimental setup

2.1. Overview of the test platform

The test platform is situated at Kjeller, Norway at the following coordinates: N 59.9732, E 11.0537. It is made of four modules: one PV and one PVT module with PERC white (as PVT reference), one PVT and one PV module of another type (from left to right on Figure 1). The PVT module consists of a PV module mounted with a cooling system and a layer of insulation on its backside (cf. 2.3.). The setup allows direct comparisons between:

- Modules of identical PV technology with (PVT) and without (PV) cooling element
- Modules of different PV technology with cooling element
- Modules of different PV technology without cooling element

The irradiance I_{rr} (W/m^2) is measured via a calibrated thermopile pyranometer placed on the same test platform. The four panels tested at a given time are connected to an inverter. The electrical output of each module is recorded via the inverter (model QS1 from AP Systems) and a communication device about every 5 minutes.

Fig. 1: Experimental setup with PERC white (PV and PVT) and PERC black (PVT and PV) modules

2.2. Characteristics of the modules

All eight modules tested are initially characterized for their nominal power at STC P_{nom} under standard test conditions (STC) in a lab: irradiance G_{STC} = 1000 W/m^2 and corrected temperature T_{STC} = 25°C. The characteristics of the modules are indicated in Table 1, the temperature coefficient being taken from the manufactuer. All of them have the same geometry of cells: half-cells of M6 format wafers, 166 mm of side-length. All the modules have the same size: 1.04 m by 1.76 m. Each panel thus consists of 120 half-cells.

Tab. 1: Module characteristics

Cell technology and application	Color of backsheet	Temperature coeff. (%/°C)	Power at STC, P_{nom} (W)	P_{nom} difference compared to PVT reference (%)
PERC PV	White	-0.38	347.3	-1.59
PERC PVT	White	-0.38	352.9	0
PERC PV	Black	-0.38	358.0	+1.45
PERC PVT	Black	-0.38	358.7	+1.64
SHJ PV	White	-0.26	362.4	+2.69
SHJ PVT	White	-0.26	354.5	+0.45
TOPCon PV	White	-0.31	364.4	+3.26
TOPCon PVT	White	-0.31	363.4	+2.98

2.3. Design of the cooling elements of the PVT modules

The cooling system is made of eight copper tubes, 1 cm external diameter, connected at the bottom and the top to two larger horizontal pipes. The system is insulated with a foam about 2 cm thick. The pipes are welded to an aluminum backplate itself in contact with the module. Figure 2 shows two views of the cooling configuration on the backside of the panel.

Fig. 2: Cooling loop design on the backside of the PVT module, and PVT module with insulation installed on the rack

2.4. Hydraulic loop

Each of the two PVT modules is connected to a hydraulic cooling loop (Figure 3). A pipe connects the PVT outlet to the top of a 200 l water tank; another pipe leaves the water tank close to its bottom to the PVT inlet, via a pump and a flow meter. The cooling loop is filled with water. Temperatures are recorded at the inlet and outlet of the PVT module. The pump is set constantly at its minimum power, equal to 50 % of its maximal power. The power consumption of the pump is about 21.5 W all along the experiments.

The recommendations of the norm for solar thermal collectors testing (ISO 9806:2017) are followed as closely as possible:

- The temperature probes are insulated and situated less than 200 mm from the inlet and outlet of each PVT-module
- The flow rate is maintained below 0.028 kg/(s·m^2), as close as possible to the norm: constant flow rate of 0.02 kg/(s·m^2)

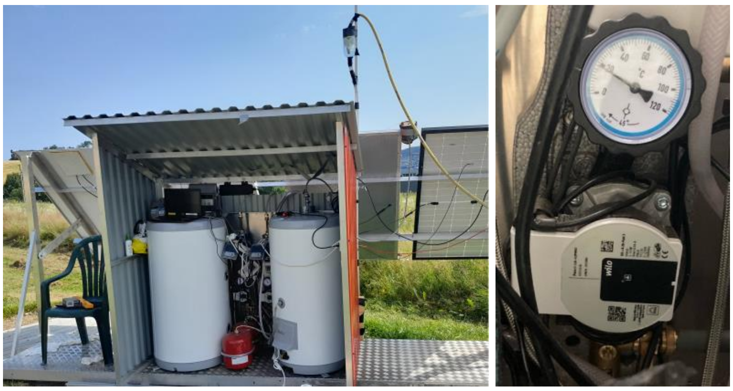


Fig. 3: Water tanks and hydraulic pump

2.5. Experiments

Four modules are tested simultaneously: the PERC white PV and PVT, and a set of PVT and PV modules of one of the other three technologies: PERC black, TOPCon and SHJ. Thermal and electrical outputs are measured.

Data is recorded every 10 seconds, except the electrical output of the modules recorded about every 5 minutes. The displayed data are computed using a moving average of 10 minutes.

The experiments are run during the days shown in Table 2 where the meteorological conditions are indicated together with the tested technologies. All technologies are tested with the PERC white as reference for both PVT and PV. On the 22nd of August, the reference PV module (PERC white) could not be connected and a comparison was made with the PERC black PV another day.

Tab. 2: Information on experiments

Date	Technology tested with reference	Weather
Aug. 22nd, 2022	PERC black	Sunny, up to 21°C
Aug. 23nd, 2022	SHJ	Sunny with sparse clouds, up to 22°C
Aug. 24nd, 2022	TOPCon	Mixed sunny-cloudy, up to 23°C

3. Energy analysis

3.1. Flow rate measurement and assumptions

Each loop is equipped with a flow meter. By controlling the flow manually on a regular basis, it is noted that only one flow meter is reliable. As the loops and pumps are nominally identical, the two flow rates are necessarily very similar and stable over time; however minor changes in the loop may slightly impact the flow rate at equal pumping power.

The flow rate through the reference PVT module (PERC white) is therefore measured manually at the end of each day and the flow rate values during the day extrapolated from the flow meter values of the other PVT module. The flow difference between the two setups is between 0 and 3 % depending on the days. This method gives an additional uncertainty of ± 2 % for the flow rate of the reference PVT.

3.2. Calculation of efficiencies

The thermal and electrical energy outputs are correlated with the insolation reaching the module and displayed. The thermal efficiency is found using the following formula:

$$\eta_{th} = \frac{Q.\Delta t}{G.\Delta t} \quad \text{(eq. 1)}$$

where:
Q is the thermal power output of the module (W, cf. 3.3.);
G is the irradiance on the module (W) ;
Δt is the timestep (s);

while electrical efficiency is given by the following formula:

$$\eta_{el} = \frac{P_{AC}.\Delta t}{G.\Delta t} \quad \text{(eq. 2)}$$

where P_{AC} is the electrical power output (W).

3.3. Thermal analysis and assumptions

To calculate the thermal output the equation used is the following:

$$Q = \dot{m} \cdot C_p \cdot \Delta T \quad \text{(eq. 3)}$$

where:
$\dot{m}$ is the mass flow rate (kg/s);
C_p is the heat capacity of water, considered constant: 4180 J/(kg·°C);
ΔT is the temperature difference between the outlet and inlet of the PVT module (°C).

To effectively compare the modules, it is important to keep the inlet temperatures of water as close as possible to each other. This is not always possible, due to different starting temperatures, and different stratification behaviour of the two water tanks (despite being near identical).

To compensate for differences of temperature at the inlet, the following assumptions are made:

- The temperature difference between the two modules is equal to the one of the two water inlets
- The additional losses due to the temperature difference of the inlets are proportional to it
- The losses occur only on the front side of the PVT module
- The radiative emissivity of the modules is set at $\varepsilon = 0.7$ and the sky temperature at $T_{sky} = 0$°C, both used in radiative losses calculation
- The convective heat transfer coefficient is set to: $h = 6$ W/(m^2·°C) , used in convective losses calculation (typical for low wind velocity)

By calculating the difference of energy emitted by radiation (Stefan-Boltzmann equation) and lost by convection (Newton's law of cooling) between the two modules, we obtain the results shown in Table 3.

Tab. 3: Evolution of heat losses difference between two PVT modules for 1°C of difference at the inlet for cold, warm and hot inlet temperatures

Temperature at the inlets (°C)	**Difference in thermal losses (W/°C)**
15 and 16	17.5
25 and 26	18.3
35 and 36	19.1

From Table 3, it is possible to see that the difference of losses per °C of temperature difference at the inlet is rather constant. A value of $q_{dif} = 18$ W/°C is chosen for the rest of the study to account for additional thermal losses.

The additional thermal losses to compensate to get a proper comparison are equal to: $q_{dif}\Delta T_{in}$ (in W).

The rate of thermal energy conversion after electrical energy conversion (thermal energy converted divided by thermal energy available) is: $\frac{\eta_{th}}{1\text{-}\eta_{el}}$. Indeed, the rate must be calculated considering that a part of the solar energy has been converted to electricty before the thermal exchanges occur.

By multiplying the virtual additional heat available to the rate of thermal energy conversion A thermal output Q_{add} is thus added to Q for every timestep following this formula:

$$Q_{add} = \frac{q_{dif} \cdot \eta_{th}}{1-\eta_{el}} . \Delta T_{in} \qquad \text{(eq. 4)}$$

where:
ΔT_{in} is the temperature difference between the two inlets (°C).

A similar adjustment is made for the electrical output: the difference of temperature between modules is considered equal to the difference of temperature at the inlet of the hydraulic loop, and a term $P_{AC\text{-}add}$ is added to the electrical output P_{AC} when the temperature of a module is higher:

$$P_{AC-add} = P_{AC} \cdot TC \cdot \Delta T_{in} \quad \text{(eq. 5)}$$

where TC is the temperature coefficient (cf Table 1).

Note that Q_{add} and $P_{AC\text{-}add}$ are introduced when normalizing the efficiencies to compare the energy outputs in part 4 (Figures 5, 7 and 9) and calculating the performance ratios in part 5.

4. Experimental results

4.1. PERC black PVT test

The evolution during the test of the electrical and thermal efficiencies for the PERC black and PERC white PVT modules are displayed in Figure 4. Due to the relatively stable irradiance, the efficiencies are also rather stable during the day. Comparing the electrical and thermal efficiencies of both modules will give a first insight on their relative performances. Figure 5 shows the evolution of the inlet temperatures, and the ratios of thermal and electrical outputs (output PERC black/output PERC white), both before and after the normalization described in 3.3: the large difference in inlet temperatures have a certain impact on the two ratios.

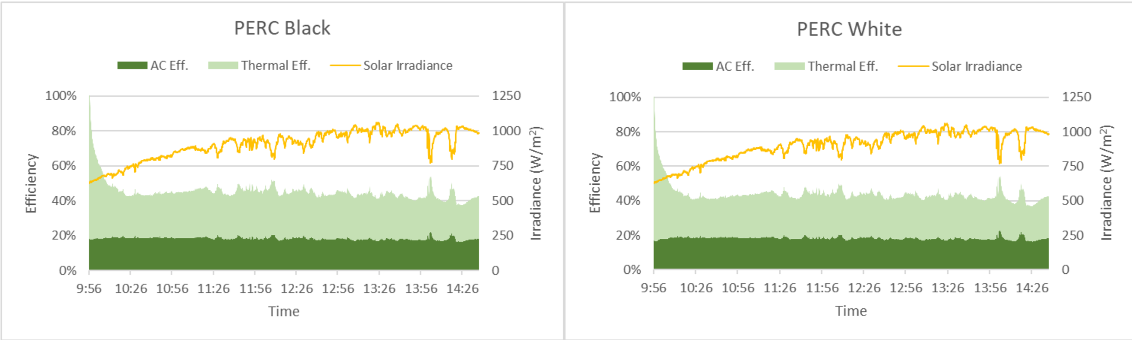


Fig. 4: Energy efficiencies for PERC black and PERC white – 22nd/08

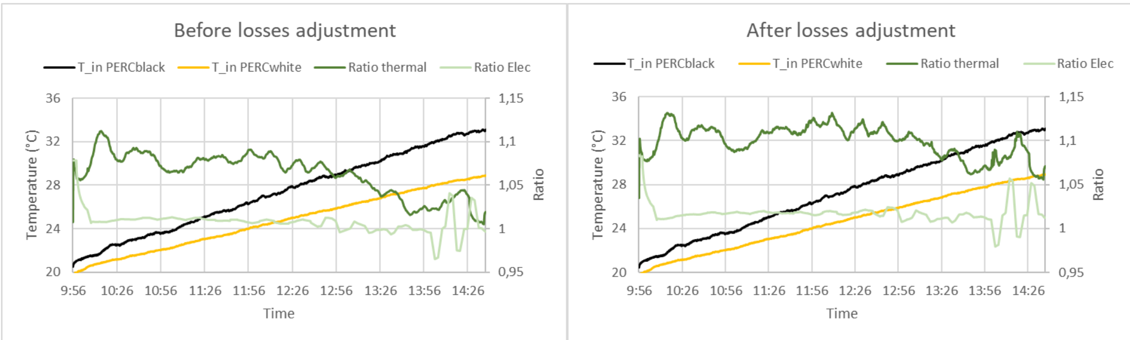


Fig. 5: Evolution of inlet temperatures and ratios of efficiencies before and after normalization – Aug. 22nd, 2022

4.2. SHJ PVT test

The evolution of the electrical and thermal efficiencies for the SHJ and PERC white PVT modules are displayed in Figure 6.

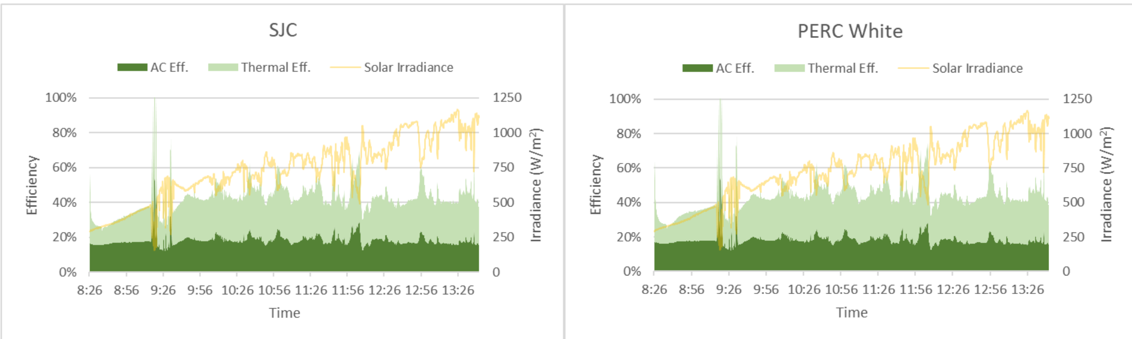


Fig. 6: Energy efficiencies for SHJ and PERC white – Aug. 23rd, 2022

The results are less regular due to the alternating bright and partially covered sun. The peaks in efficiency are due to the inertia of the thermal system and electrical recording. Figure 7 shows as Figure 5 the impact of the thermal loss correction on the ratios (output SHJ/output PERC white): the impact is much more modest here.

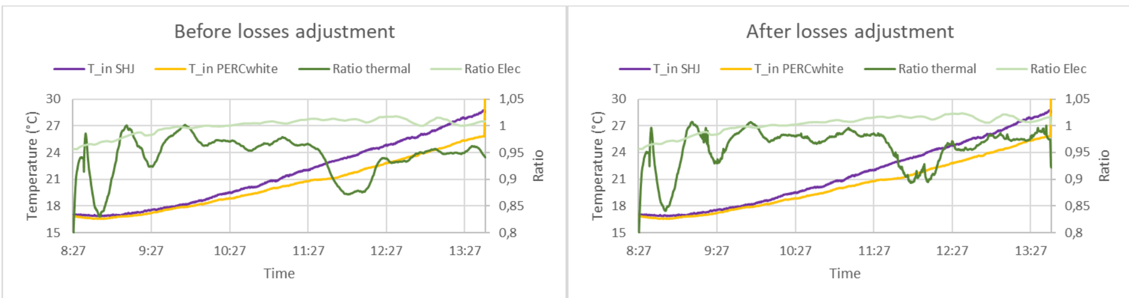


Fig. 7: Evolution of inlet temperatures and ratios of efficiencies before and after normalization – 23rd/08

4.3. TOPCon PVT test

The evolution of the electrical and thermal efficiencies for the TOPCon and PERC white PVT modules are displayed in Figure 8. This time, the results are very irregular due to the rapid alternation between sunny and cloudy weather. Figure 9 shows the influence of the correction to account for thermal losses on the ratios (output TOPCon/output PERC white), which is small here due to the reduced temperature difference between the two inlets.

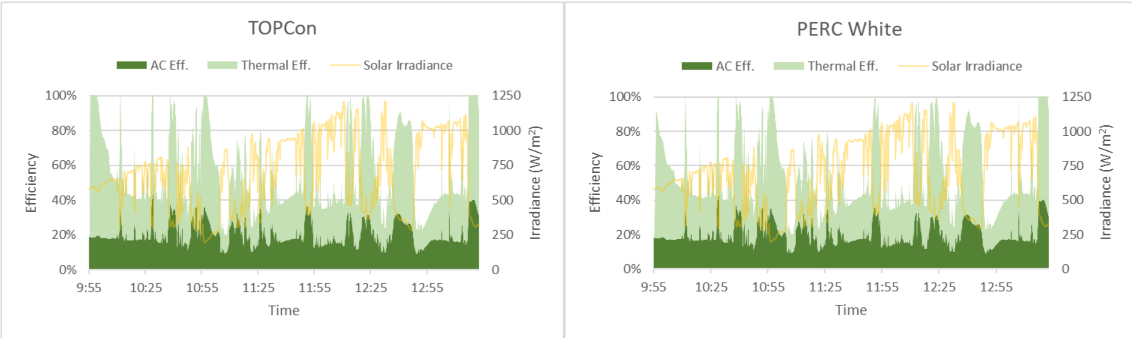


Fig. 8: Energy efficiencies for TOPCon and PERC white – 24th/08

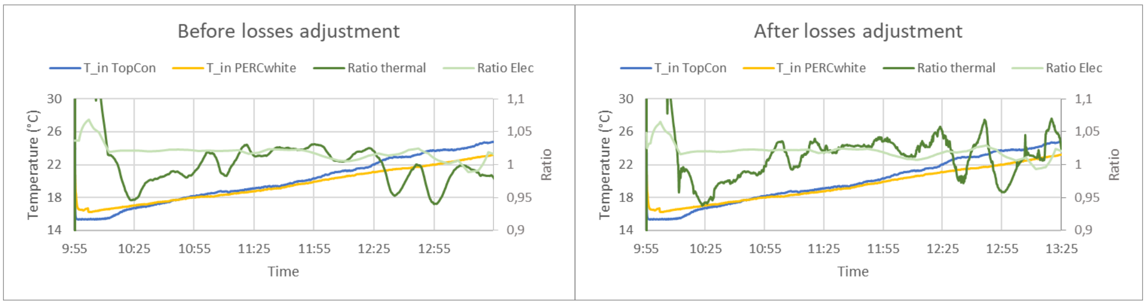
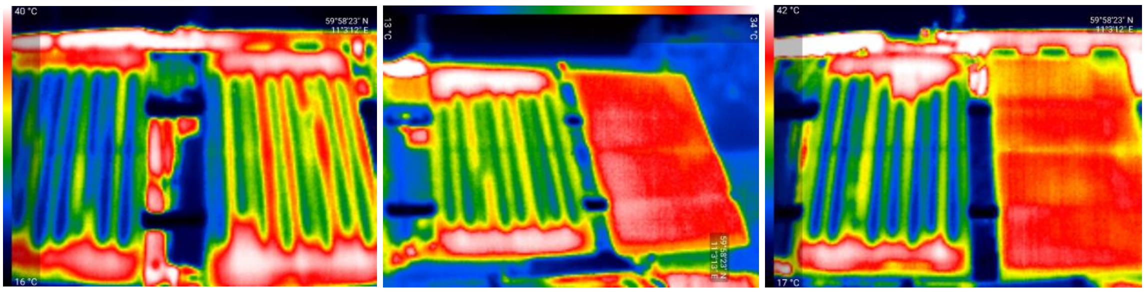


Fig. 9: Evolution of inlet temperatures and ratios of efficiencies before and after normalization – 24th/08

4.4. Infrared imaging

Infrared (IR) pictures have been taken during all experiments to identify any malfunction of the cooling loop, with color scales indicated on the side.



A B C

Fig. 10: IR imaging of PVT modules - A: PERC white (left) and black (right) PVT - B: SHJ PVT (left) and PV (right) - C: TOPCon PVT (left) and PV (right)

Figure 10 shows slight imperfections on the panels. Both modules on picture A (PERC white and black) seem to behave as expected, the black one being hotter. Picture B shows the SHJ PVT and PV modules: there is apparently a non-optimal heat exchange on the PVT for one of the channels. Likewise, picture C shows the TOPCon PVT and PV, and the contact of one of the channels on the PVT seems questionable. These pictures may help to give a different perspective on the interpretation of the data. Furthermore, the color scale helps to estimate the temperature difference between the PV and the coldest point of the PVT: potentially more than 10°C.

5. Comparative analysis and interpretation

5.1. Energy outputs compared to the reference PVT

Each PVT module performance is compared to the reference PVT module during the same day. The electrical and thermal performance of the reference is set at 100 % for each day and the performance of the other technologies are calculate relative to this. Figure 11 shows that the difference in electricity production is small, from 0 to 2 % increase compared to PERC white depending on the technology. Concerning the thermal output, the PERC black produces about 7 % more, the SHJ 8 % less and the TOPCon 4 % less than the reference. It is now important to adjust the data to ensure that the trends are not biased due to inlet temperature differences.

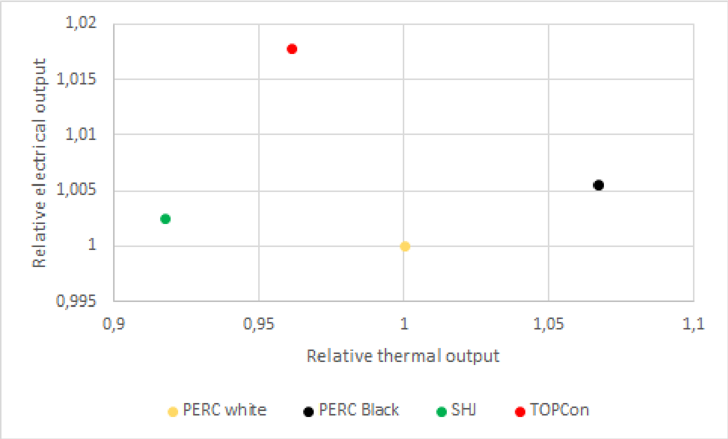


Fig. 11: AC and thermal output compared to PERC white

5.2. Normalized energy outputs compared to the reference

The difference in inlet temperatures biases the results in favour of the PVT module with the coldest inlet temperature (generally the PERC white, reference module), both for thermal and electrical outputs. The adjustments described in 3.3 are applied to get a normalized comparison to the reference if the conditions at the inlet were the same (Figure 12). Note that the normalization adjusts for differences due to temperature, but not due to differences in P_{nom}, this adjustment will be considered when performing the performance ratio analysis.

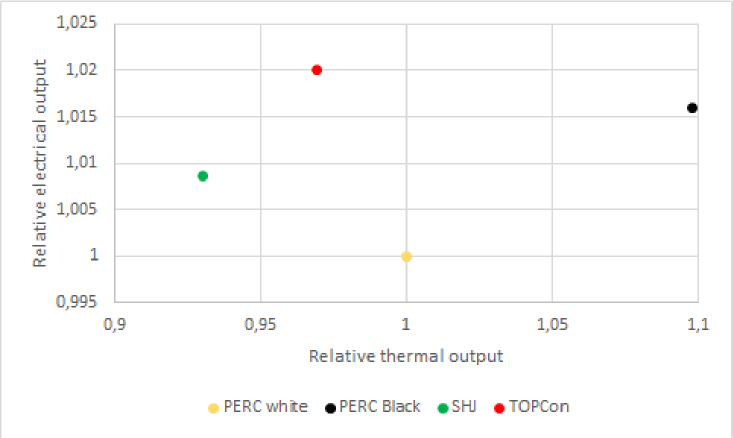


Fig. 12: Corrected AC and thermal output compared to PERC white

After the adjustments, the trend of the thermal outputs are confirmed. The black module produces over 10 % more thermal power: it can be explained by the black back sheet absorbing more radiation with its higher absorptivity. The SHJ underperforms thermally by about 6 % and the TOPCon by 3 % compared to the reference. The imperfections from Figure 10 may explain the lower thermal output for SHJ and TOPCon; also their higher electrical output may impact negatively but marginally the thermal output. There is thus no major evidence of differences of behavior for SHJ, TOPCon and PERC white for the thermal energy extracted.

In terms of electrical output, the PERC black and TOPCon modules produce less than 2 %, and SHJ less than 1 %, more compared to PERC white. Note that the nominal power of all the other panels are significantly higher than PERC white, it is thus relevant to perform an analysis of the performance ratios.

5.3. Performance ratio analysis

The performance ratio formula is the following (IEA-PVPS report, 2021), based on the AC power instead of DC:

$$PR = \frac{E.G_{STC}}{P_{nom}.H_{POA}} \qquad \text{(eq. 6)}$$

where:

E is the AC energy produced over a given time (J)
H_{POA} is the plane-of-array irradiation over the same given time (J/m^2)

Ratios of PR are calculated. A PR analysis can bring help in comparing the electrical performance of different systems. First, the PR of each setup for each experimental day is estimated from experimental data, including the normalization described in 3.3 when applicable (Table 4). Then, the ratio of the PR of the PVT module tested a given day to the PR of the reference module (PERC white) the same day is calculated and displayed in Table 5.

Tab. 4: PV performance ratios of all the modules PVT and PV tested

Performance Ratios of the modules					
22.08.2022		**23.08.2022**		**24.08.2022**	
PERC White		**PERC White**		**PERC White**	
PV	PVT	PV	PVT	PV	PVT
No Data	0.942	0.991	0.981	0.967	0.951
PERC Black		**SHJ**		**TOPCon**	
PV	PVT	PV	PVT	PV	PVT
0.919	0.932	1.006	0.978	0.938	0.930

Tab. 5: Ratios of PR of PVT modules by PR of the reference

Technology	$PR_{PVT}/PR_{PVT\text{-}PERCwhite}$
PERC Black	0.999
SHJ	1.004
TOPCon	0.991

The results show that the PRs remain very close to each other. It is important to remember that these values are calculated including the thermal losses normalization, and this model may have its limits and margin of errors. Only the TOPCon gives a slightly lower ratio, but it is also the one having the smallest correction due to thermal losses. Therefore there is no evidence of major improvement or deterioration of PR of the PV element when changing the technology.

Tab. 6: Ratios of PR of PVT modules by PR of PV modules of the same technology

Technology	PR_{PVT}/PR_{PV}
PERC White 23rd/08	0.989
PERC White 24th/08	0.983
PERC Black	1.025
SHJ	0.979
TOPCon	1.004

Finally, Table 6 compares the PR of the PVT to the PR of the same PV under the same conditions. Note that only two measurements are displayed for the reference module, as explained in 2.5. The PR of PERC White and SHJ are slightly larger in their PV version, while the TOPCon gets identical PR for PVT and PV, and the PERC black gets a larger PR when used on PVT configuration. It is important to interpret these results with care due to the use of the thermal loss correction; however the PERC black improvement (2.5 %) is larger than the improvement due to this correction (which is about 1 %). Also, a better design of the cooling on the backside may have a positive impact on the PR_{PVT}.

The quality of the thermal contact for the SHJ and TOPCon PVT modules being under question, it could have an influence on the ratios in Table 5 and 6 for these two technologies, which may be higher with a standard contact.

6. Conclusion

Three experiments comparing couples of PV and PVT modules of a given solar cell technology are run.

Concerning the thermal output:

- The PERC black outperforms the other three technologies by 10 %, the black color giving a certain advantage for solar radiation collection.
- Among PERC white, TOPCon and SHJ, there is no evidence of superiority of one of these technologies over the other: the margin of errors and imperfections of the backside can explain the differences observed and more advanced experiments are needed before concluding.

Concerning the electrical output:

- There is no evidence of major differences on the other, the performance ratios remain very similar for all PVT modules. The questions about quality of thermal contact keep the discussion open.
- The PERC black PVT gets a slightly better performance ratio than its PV counterpart; while PERC white and SHJ PVT do not match the performance ratio of the corresponding PV.

From these experiments, the PERC black seems to be the most competitive configuration, by having both the best increase in thermal output and in PV performance ratio.

The differences between setups are small: the uncertainties concerning flow measurements, different weather conditions for different experiments (cells can be more effective under certain conditions), difference of quality among cooling setups and limitation of the thermal loss model must be underlined. It is likely that their cumulated impact remains small, but it may limit the breadth of the conclusions.

A deeper analysis on the influence of temperatures on all the PV and PVT modules must be done on the current set of data to sharpen the understanding and will be likely discussed in future research works.

The following recommendations are listed for future experiments:

- Extended testing in parallel during a larger period of time
- Improved cooling structure, both in design, quality, and consistency between modules
- More advanced equipment: control on the inlet temperature, accuracy of flow rate measurement

7. Acknowledgments

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