PHOSTER FIELD TESTS MONITORING

Contents

I. Introduction

This report aims to give an overview of the performance of photovoltaic modules developed in the frame of PHOSTER project. Firstly, testing locations at Haironville and Liège will be presented, as well as the module types included in the benchmark. Then, production in Haironville will be laid out per kilowatt-peak to compare PHOSTER CIGS modules with the selected reference, mono-crystalline silicon modules.

It is important to note that field tests were replicated after the project to bigger ones that the ones installed in the frame of the project: the power performance of the field tests installed during PHOSTER project in Haironville and Liège were respectively 0.3kW and 0.2kW: new installations are 1.23 kW and 4.86 kW. Monitoring performed on these new installations allows better understanding of modules behavior while using more conventional inverters.

Location	During Phoster		After Phoster	
	Installed power [W]	Inverter type (and numbers)	Installed power [W]	Inverter type (and numbers)
Liège	200	Micro (1)	1229	String (1)
Haironville	300	Micro (1)	4862	String (2)

Two locations are currently available for field tests:

- The ArcelorMittal's field tests at Haironville;
- The roof of CRM's extension of building 2, in Liège, which constitutes a new field test with a significant size realized after Phoster project.

II. Field tests

A. Haironville, ArcelorMittal location

FIGURE 1 : SATELLITE VIEW OF ARCELORMITTAL'S HAIRONVILLE SITE, WITH THE FIELD TESTS AREA OUTLINED.

FIGURE 2 : (FOREGROUND) PVSTEEL MS GEN0.2 MODULES, WITH (BACKGROUND) CRYSTALLINE MODULES

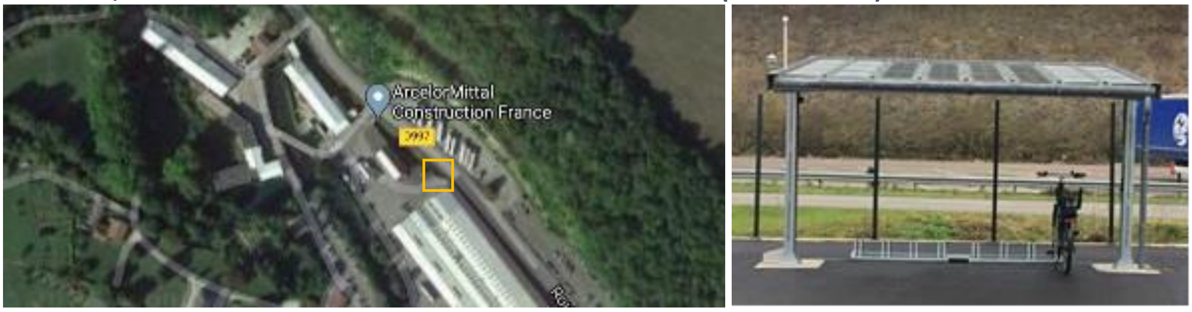

FIGURE 3 : (LEFT) SATELLITE VIEW OF ARCELORMITTAL'S HAIRONVILLE SITE WITH THE BIKE PORT LOCATION OUTLINED, AND (RIGHT) SAID BIKE PORT.

B. Liège, CRM location

FIGURE 4 : SATELLITE VIEW OF CRM SITE, WITH THE CRM2 NEW EXTENSION OUTLINED.

FIGURE 5 : AERIAL PICTURE VIEW OF CRM2 FIELD TEST.

FIGURE 6 : PICTURE OF CRM2 EXTENSION BUILDING, WITH SOLAR PANELS ON ITS ROOF.

C. Installed power and references

Details on the installed modules in Haironville and Liège are listed in Table 1. Are listed, per module, their name, material type (silicon or CIGS), their location, manufacturer's temperature coefficients, and power installed per MPPT. The station is also equipped with a pyranometer and an ambient thermometer.

To summarize, as of June 2020, 5.46 kW_p mono-crystalline silicon (c-Si) panels and 1.229 kW_p PHOSTER CIGS modules are installed in Haironville. CRM2 field test consists of double skin roof with 11.192 kW_p CIGS reference modules and 4.862 kW_p PHOSTER modules.

This report focuses on Haironville's data.

Location		**Haironville**		**CRM2**	
Name		**c-Si reference**	**PHOSTER**	**CIGS reference**	**PHOSTER**
Absorber material		mSi	CIGS	CIGS	CIGS
Installation date		2018-11-12	2019-01-10	2020-05-14	2020-05-14
Mounted on...		structure	structure	roof	roof
Structure		steel profile	steel profile	double skin panel	~80mm air gap + double skin panel
Foam thickness [mm]		—	—	170-180	170-180
Foam type		—	—	PUR	PUR
kW_{peak}		5.460	1.229	11.192	4.862
Temp. Coeff.	**Current α**	0.045		0.008	
	Voltage β	-0.34		-0.28	
	Power γ	-0.47		-0.38	

TABLE 1 : INPUT DATA FOR DATA ANALYSIS. EMPTY VALUES DENOTE MISSING DATA; COEFFICIENTS ARE GIVEN IN %/°C.

III. Data analysis for Haironville's field test

A. Distribution of the production, from raw data

Here we will show and analyze the raw data taken from the irradiance sensor at Haironville. This data covers dates from 2019-01-30 to 2020-09-30, during daytime, when irradiance is strictly positive.

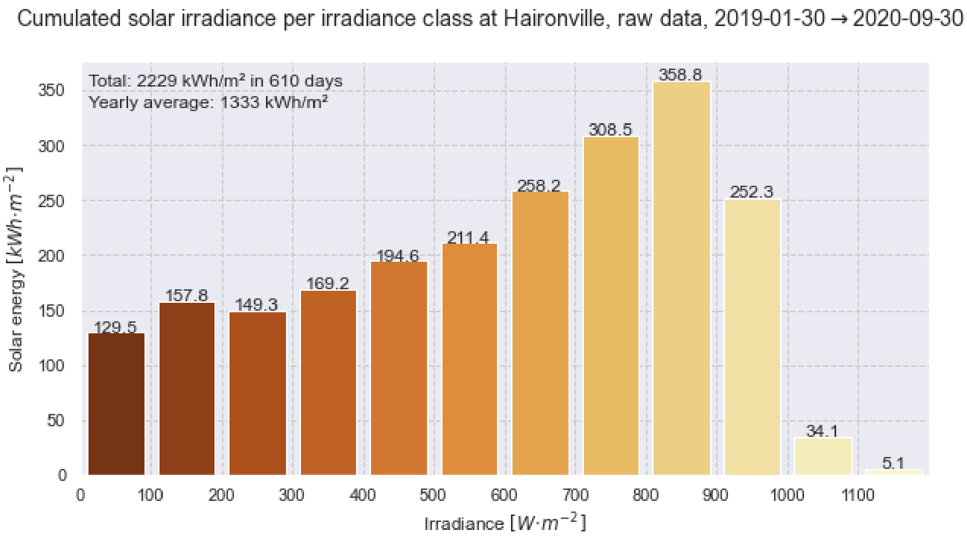

FIGURE 7 : CUMULATED SOLAR IRRADIANCE AT HAIRONVILLE.

Most of the solar energy is received at high irradiance, totaling at 2229 kWh/m² for the studied timeframe (610 days, two springs and summers, one full winter). Cumulated irradiance from a full year (2019-01-30 to 2020-01-29) totals at 1149 kWh/m². PVsyst software gives us 1134 kWh/m²·y for the closest available city, Nancy, which is rather close to our experimental data considering the relatively short sample we compare it with.

One could be interested in how the measured irradiance is spread, as shown in Figure 8. While most of the solar energy is received at high irradiance, a large part of the data points is beneath 100 W/m². 70% of data points are below 400 W/m².

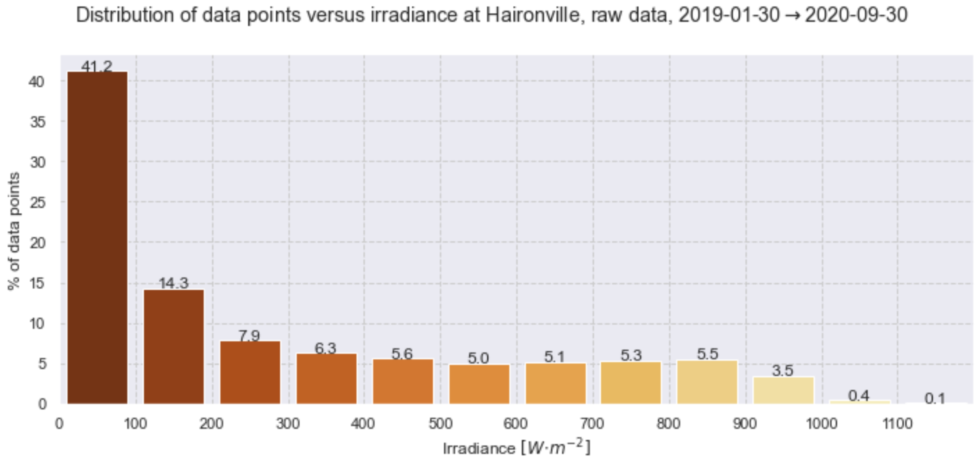

FIGURE 8 : DISTRIBUTION OF DATA POINTS VERSUS IRRADIANCE AT HAIRONVILLE.

Such distribution, skewed towards low irradiance points, hints that our raw data needs to be processed and filtered.

B. Distribution of the production, without shading

Each rack supporting our modules has different shading conditions. In Haironville, the closest objects casting shadows are rows of trees located on the east and west of the modules.

Take note that only direct shading is removed from the study. Diffuse irradiance (from sky or ground albedo) is not accounted for. Comparison between modules is seriously hindered by the various shading conditions. The following graphs and calculations only take into account those unshaded points.

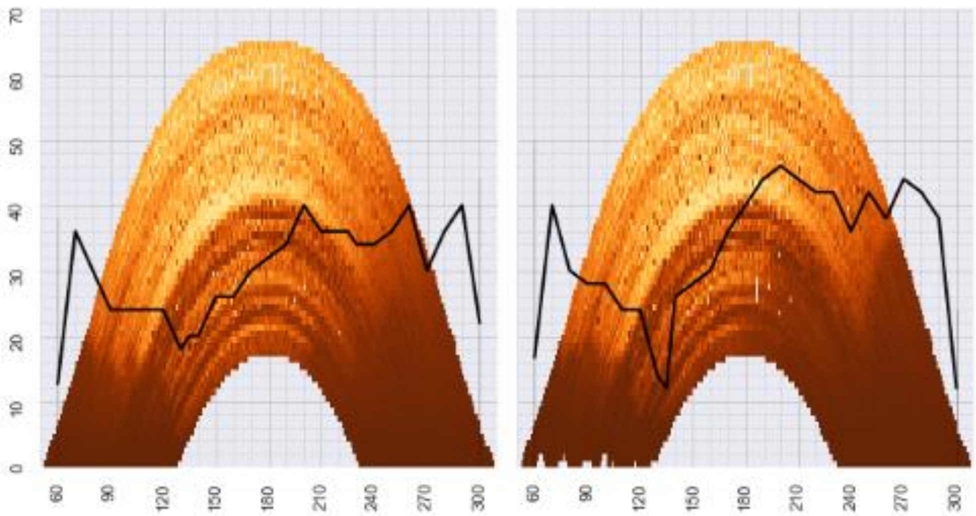

FIGURE 9 : NORMALIZED DC POWER VS SUN POSITION IN THE SKY, AND ON-SITE NEAR SHADING.
(LEFT) CRYSTALLINE SILICON REFERENCE MODULES, (RIGHT) PHOSTER MODULES
ANY POINT BENEATH THE BLACK LINE IS TO BE CONSIDERED SHADED.

By filtering out the shaded data, unshaded solar energy totals now at 1565 kWh/m² for the studied timeframe (610 days) as shown in Figure 10. The low irradiance points are now noticeably fewer, as per Figure 11. By ensuring our data is comparable between modules, we have reduced the total energy of this study by 30%.

Applying the shading mask enables us to remove plenty of low irradiance data points that contribute little to the global production.

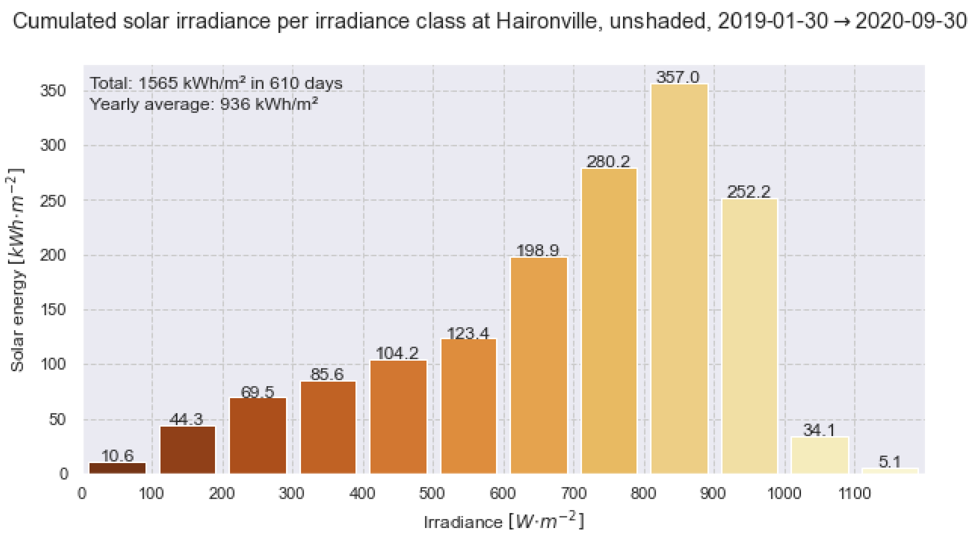

FIGURE 10 : SOLAR IRRADIANCE AT HAIRONVILLE, UNSHADED.

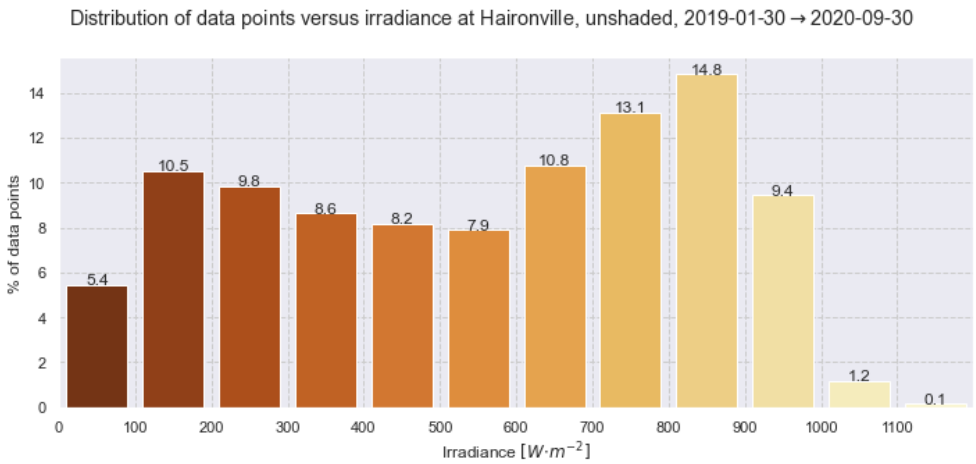

FIGURE 11 : DISTRIBUTION OF UNSHADED DATA POINTS VERSUS IRRADIANCE AT HAIRONVILLE

C. Solar production analysis

Now that raw data has been filtered to allow comprehensive comparison between our modules, we can actually process produced electricity data. Note that, considering the measurement uncertainties, any reported difference less than 5% can be considered negligible.

To ensure comparable results and avoid scaling effects, power production (P) can be normalized with installed power of each module: $P_{\mathrm{norm}} = \frac{P}{P_{\mathrm{peak}}}\,[\mathrm{kW/kW_p}]$

Such normalized production can also be derived from the produced energy (E), called specific yield (y). Energy is extrapolated from the time delta (Δt) between two data points, which is currently 5 min: $E = P \times \Delta t$ $[\mathrm{kWh}]$.

$$y = \frac{\sum E}{P_{\mathrm{peak}}} = \frac{5}{60} \times \frac{\sum P}{P_{peak}}\ [\mathrm{kWh/kW_p}]$$

The specific yield is calculated for each module across any wanted timeframe, and can be analyzed through various conditions. Here will be reported specific yields summed from 2019-01-30 and 2020-09-30, and split per irradiance class (above 0 to 100W/m², 100–200 W/m², and so on). Data is shown in Table 2 and

Figure 12.

Modules	0	100	200	300	400	500	600	700	800	900	>1000	Total
mc-Si reference	10	45	70	84	99	116	185	255	318	218	34	1435
PHOSTER	7	36	61	78	97	114	183	254	320	222	35	1407
Difference [%]	-35	-21	-12	-6.9	-1.9	-1.7	-1.3	-0.4	0.6	+1.5	+1.8	-2
Difference [%]	-13%				-0.13%			+0.6%				-2%

TABLE 2: DC SPECIFIC YIELD PER IRRADIANCE CLASS, AND PERCENTAGE OF DIFFERENCE WITH REFERENCE, BETWEEN 2018-11-12 AND 2020-09-30.

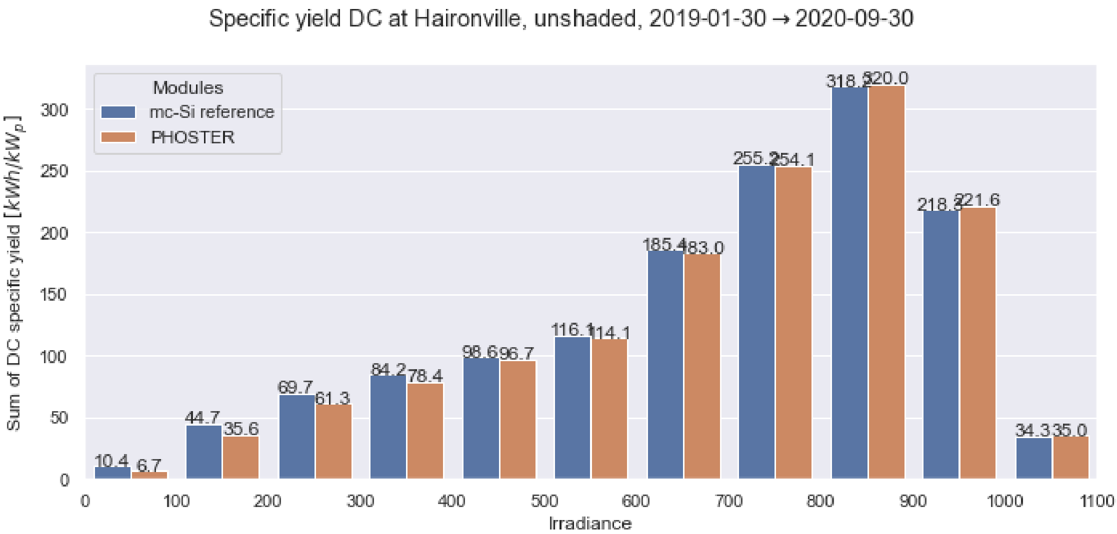

FIGURE 12 : DC SPECIFIC YIELD PER IRRADIANCE CLASS, BETWEEN 2018-11-12 AND 2020-09-30.

Overall, silicon references and PHOSTER modules perform in a similar manner, with only 2% difference, which is within our margin of error for this analysis. These similar performances cover all irradiance classes above 400 W/m².

It is only below 400 W/m² that there is a sensible difference, in favor for the silicon reference. It could be explained by higher-than-expected series resistance in the PHOSTER modules, affecting their fill factor and their response at low irradiance. However, this difference only affects 13% of the total energy.

With this broad scope on the production, we can first say that PHOSTER modules perform overall similarly to the silicon reference modules.

Definitions

Bin	Interval into which data is grouped. In this report averages, sums, etc. are calculated for each irradiance range (0—100, 100—200, … 900—1000, >1000 W/m²).
Class	See *bin*.
Specific yield	Produced energy normalized to installed power. Symbol y, Unit kWh/kW$_p$.
Unshaded data	Data filtered to leave out moments where any module is shaded by surrounding objects.