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Performance Comparison of Photovoltaic Modules under Low Sunlight

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Abstract: The DC energy produced by photovoltaic (PV) modules can change depending on the cell type, module components and module technology. The cell efficiency, sensitivity of the cell to light, recombination losses and how much the light reflects within the cell will affect the amount of produced energy. In addition, the energy produced will change depending on what wavelength light and how much can be transmitted through the front glass and encapsulant and how much light is reflected from back encapsulant and back cover. The front glass transmissivity, patterned surface and existence of ARC (anti-reflective coating) are all very important. In this research project, 14 modules were tested: 4 modules Glass/Glass (Perc Mono Cell), 4 modules Glass/Ceramic (Perc Mono Cell), 2 modules Glass/Glass bifacial (HIT Cell), 1 module Standard (Framed, Mono-n type Cell), 2 modules Standard (Framed, Poly Cell), 1 module Standard (Framed, Perc Mono Cell). This paper compares the normalized Wh/Wp ratios of the different modules under low irradiance (morning and afternoon light) and analyzes and investigates the obtained results as per the cell type used, module components and module technology.

Key words: Bifacial solar panels, heterojunction with HIT (intrinsic thin layer), mono, poly, glass/glass photovoltaic module, glass/ceramic photovoltaic module.

1. Introduction

The produced energy by PV module depends on cell type, module components and module technology. There are currently many types of solar cells: multijunction, polycrystalline, mono crystalline, heterojunction, thin film, and emerging types (dye, perovskite, organic, inorganic etc.). The highest efficiencies reached at lab conditions are given in Table 1. Within the Crystalline category, the developments in the polysilicon purification, the crytallization and wafer slicing processes and technologies, have reduced crystal impurity and inefficiencies thereby reducing recombination and optical losses. Furthermore, improvements in AG pastes, better engineering of metallization and backside treatments have all resulted in both higher efficiencies and lower prices. Outside of the crystalline category, much more refined coating techniques along with purer and also some new materials have resulted in higher efficiencies.

Aside from the cells, the different components used in the modules such as front cover and encapsulants with higher light transmissivity and anti-reflection at more extended wavelengths, all components with higher thermal dissipation and emissivity, back cover and encapsulants with higher light reflectivity, better conducting metallization all have contributed to higher module efficiencies. All the developments aforementioned can lead to different absorptions of light both in intensity and wavelength, hence different production portfolios of electricity of solar modules under low light conditions. In this study, we have included 13 different types of photovoltaic modules and compared their performances under low light. As each came with a different DC power, all output has been normalized by dividing by their respective power Wh/Wp.

2. Materials and Methods

The PV modules having different label power can

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produce energy at different rates in the same time range. So it is proper to compare their energy produced per Wpeak. In this study 13 different type modules were tested: 4 modules Glass/Glass (Perc Mono Cell), 4 modules Glass/Ceramic (Perc Mono Cell), 2 modules Glass/Glass bifacial (HCT Cell), 1 module Standard (Framed, Mono-n type Cell), 2 modules Standard (Framed, Poly Cell), 1 module Standard (Framed, Perc Mono Cell). Their properties are given in Table 2. All the modules were installed at same orientation facing South at tilt angle of 30°, and all were connected to single optimizers. Due to the limited availability of optimizers, some modules were not measured for certain periods.

3. Results

Because the tested PV modules have different properties and location on the rack, the start time of energy production for each module was different. The monthly average start time for each module is given in Table 3.

The monthly average end time is given in Table 4, the monthly total operation time in Table 5 below. Also the monthly normalized Wh/Wp are calculated for morning and afternoon time (Figs. 2-10). There is also a comparative graph of daily start times as well as daily end times. Variations in start and end times abound. While the module Standard-Perc Mono started the energy production firstly from January to March and again in November, the module Mono-N type started early in May, the module GG-HIT in June, the module GG-Perc Mono 3S in October, as per Table 3. For July and August, there is no difference in between the modules as to start time. This is due to strong sun and insensitivity of the optimizer for variations less than 5 minutes as recording is every 5 minutes.

Table 1 Efficiency for different cell types [1].

Cell type	Efficiency (%)
Multijunction	46
Mono	25
Poly	21.3
HIT	25.6
CIGS	22.3
CdTe	22.1
a-Si:H	13.6
Perovskite	22.1

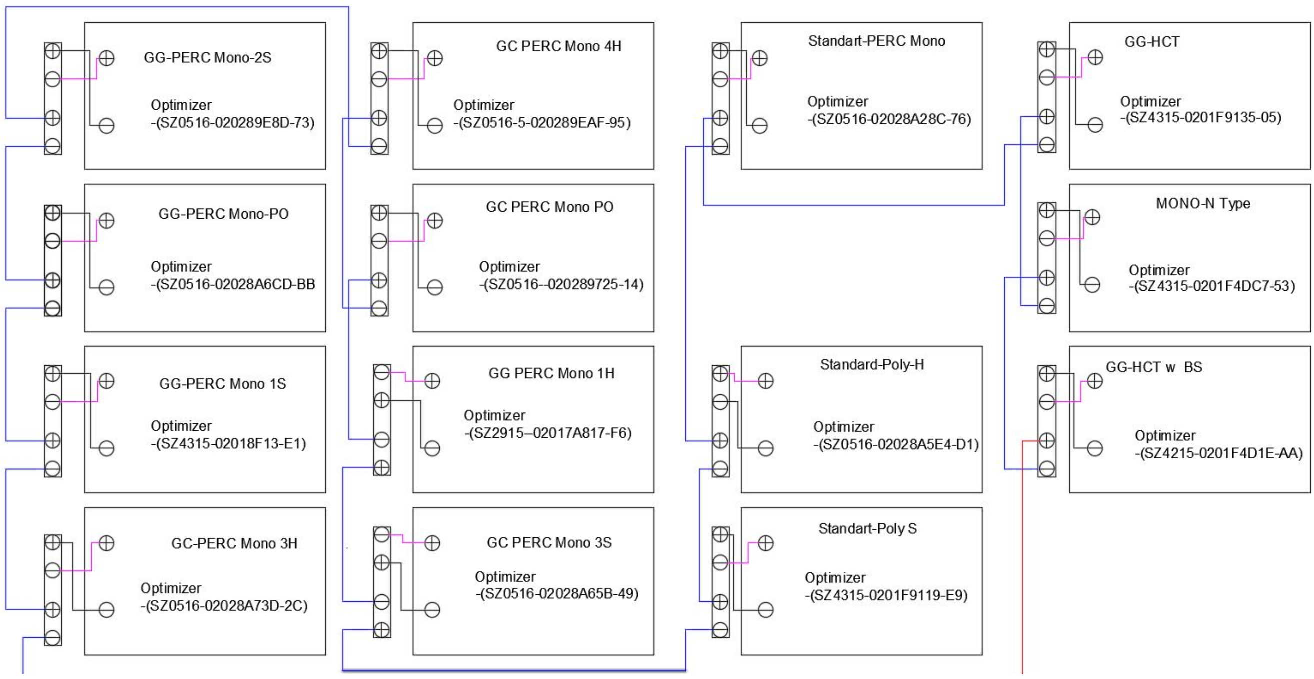

Fig. 1 The diagram of site setup and connections for modules under study.

Table 2 The properties of the modules used in our study.

Module ID	Label power (W)	Cell type	Backcover	Back encapsulant	Encapsulant ID	Framed
GG-HCT	300	HIT-Bifacial	Glass	Transparent	-	-
GC-Perc Mono-3S	228.8	Perc Mono	Ceramic	Transparent	3	-
Mono-N type	310	N type	Backsheet	Transparent	-	Yes
GG-Perc Mono-1S	280.2	Perc Mono	Glass	White	1	-
Standard-Perc Mono	290	Perc Mono	Backsheet	Transparent		Yes
GG-Perc Mono-PO	250	Perc Mono	Glass	Transparent	PO	-
GC-Perc Mono-4H	271.3	Perc Mono	Ceramic	Transparent	4	-
GG-Perc Mono-1H	282	Perc Mono	Glass	White	1	-
GC-Perc Mono-3H	259.5	Perc Mono	Ceramic	Transparent	3	-
Standard-Poly-S	240	Poly	Backsheet	Transparent		Yes
Standard-Poly-H	250	Poly	Backsheet	Transparent		Yes
GC-Perc Mono-PO	271.6	Perc Mono	Ceramic	Transparent	PO	-
GG-HCT w BS	300	HIT-Bifacial	Glass (covered black sheet)	Transparent	-	-
GG-Perc Mono-2S	274.1	Perc Mono	Glass	Transparent	2	

Table 3 The monthly average start time (hh:mm:ss) for energy production of tested modules.

Module ID	January	February	March	May	June	July	August	October	November
GG-HCT	06:43:25	06:39:50	06:21:35	06:03:21	05:45:30	05:00:00	05:00:00	06:46:21	06:17:04
GC-Perc Mono-3S	-	-	-	06:04:11	05:48:03	05:00:00	05:00:00	06:40:48	06:16:36
Mono-N type	06:42:38	06:39:19	06:20:33	06:02:35	05:45:57	05:00:00	05:00:00	06:44:18	06:12:48
GG-Perc Mono-1S	06:44:13	06:39:50	06:22:16	06:04:04	05:46:51	05:00:00	05:00:00	06:45:06	06:14:56
Standard-Perc Mono	06:38:41	06:34:39	06:19:03	06:03:56	05:46:09	05:00:00	05:00:00	06:45:21	06:12:32
GG-Perc Mono-PO	06:48:57	06:43:58	06:31:41	-	-	-	05:00:00	-	-
GC-Perc Mono-4H	06:45:00	06:40:21	06:21:35	-	-	-	05:00:00	06:45:48	06:16:44
GG-Perc Mono-1H	06:46:35	06:44:29	06:24:05	-	-	05:00:00	05:00:00	06:42:45	06:12:56
GC-Perc Mono-3H	-	-	-	-	-	-	05:00:00	06:45:57	06:15:24
Standard-Poly-S	-	-	-	06:02:53	05:46:06	05:00:00	05:00:00	07:00:51	06:25:32
Standard-Poly-H	-	-	-	06:07:11	05:49:15	05:00:00	05:00:00	-	-
GC-Perc Mono-PO	06:51:19	06:42:56	06:22:27	-	-	-	05:00:00	-	-
GG-HCT w BS	06:41:51	06:39:50	06:21:00	06:51:42	05:45:51	05:00:00	05:00:00	07:01:42	06:25:16
GG-Perc Mono-2S	06:49:44	06:41:23	06:30:16	06:04:00	05:46:33	05:00:00	05:00:00	-	-

Table 4 The monthly average end time (hh:mm:ss) for energy production of tested modules.

Module ID	January	February	March	May	June	July	August	October	November
GG-HCT	15:32:22	16:54:19	17:32:08	19:05:28	18:44:55	17:30:00	17:30:00	17:31:21	16:07:28
GC-Perc Mono-3S	-	-	-	19:03:18	19:11:03	17:30:00	17:30:00	17:28:54	16:06:24
Mono-N type	15:33:57	16:55:52	17:33:30	19:02:32	19:13:36	17:30:00	17:30:00	17:33:06	16:10:20
GG-Perc Mono-1S	15:33:55	16:56:23	17:32:33	19:05:14	19:12:24	17:30:00	17:30:00	17:00:21	15:26:56
Standard-Perc Mono	15:37:06	16:59:29	17:33:00	19:04:56	19:12:57	17:30:00	17:30:00	17:34:18	16:10:16
GG-Perc Mono-PO	15:33:57	16:55:52	17:32:38	-	-	-	17:30:00	-	-
GC-Perc Mono-4H	15:34:44	16:57:25	17:32:30	-	-	-	17:30:00	17:31:21	16:09:52
GG-Perc Mono-1H	15:33:57	16:55:52	17:32:38	-	-	17:30:00	17:30:00	17:32:06	16:10:56
GC-Perc Mono-3H	-	-	-	-	-	-	17:30:00	17:32:06	16:10:55
Standard-Poly-S	-	-	-	19:04:04	19:12:42	17:30:00	17:30:00	17:30:51	16:05:12
Standard-Poly-H	-	-	-	19:03:25	19:09:27	17:30:00	17:30:00	-	-
GC-Perc Mono-PO	15:32:22	16:53:48	17:31:03	-	-	-	17:30:00	-	-
GG-HCT w BS	15:32:22	16:53:48	17:31:35	19:04:35	19:11:48	17:30:00	17:30:00	17:29:48	16:05:00
GG-Perc Mono-2S	15:31:35	16:55:21	17:31:52	19:03:42	19:12:48	17:30:00	17:30:00	-	-

Table 5 The monthly average morning operation time (h) of tested modules.

Module ID	January	February	March	May	June	July	August	October	November
GG-HCT	3.2763	3.3362	3.6402	3.9441	4.2417	5	5	3.2275	3.7156
GC-Perc Mono-3S	-	-	-	3.9304	4.1992	5	5	3.1342	3.7233
Mono-N type	3.2895	3.3448	3.6576	3.9569	4.2342	5	5	3.2617	3.7867
GG-Perc Mono-1S	3.2632	3.3362	3.6288	3.9324	4.2192	5	5	3.2483	3.7511
Standard-Perc Mono	3.3553	3.4224	3.6826	3.9343	4.2308	5	5	3.2442	3.7911
GG-Perc Mono-PO	3.1842	3.2845	3.4720	-	-	-	5	-	-
GC-Perc Mono-4H	3.2500	3.3276	3.6402	-	-	-	5	3.2367	3.7211
GG-Perc Mono-1H	3.2237	3.2586	3.5985	-	-	5	5	3.2875	3.7844
GC-Perc Mono-3H	-	-	-	-	-	-	5	3.2342	3.7433
Standard-Poly-S	-	-	-	3.9520	4.2317	5	5	2.9858	3.5744
Standard-Poly-H	-	-	-	3.8804	4.1792	5	5	-	-
GC-Perc Mono-PO	3.1447	3.2672	3.6258	-	-	-	5	-	-
GG-HCT w BS	3.3026	3.3362	3.6500	3.1382	4.2358	5	5	2.9717	3.5789
GG-Perc Mono-2S	3.1711	3.3103	3.4955	3.9333	4.2242	5	5	-	-

Table 6 The monthly average normalized Wh/Wp in morning.

Module ID	January	February	March	May	June	July	August	October	November
GG-HCT	13.68	28.24	28.15	24.21	27.22	21.90	20.71	19.19	25.55
GC-Perc Mono-3S	-	-	-	22.71	25.18	18.14	17.9	18.26	25.19
Mono-N type	13.57	28.45	27.95	23.6	25.95	18.95	18.47	18.44	25.2
GG-Perc Mono-1S	13.92	28.21	27.76	23.21	25.16	17.98	17.9	18.13	25.04
Standard-PercMono	13.85	28.16	27.91	22.75	25.11	18.34	17.91	18.07	25.41
GG-Perc Mono-PO	11.64	26.81	26.62	-	-	-	18.18	-	-
GC-Perc Mono-4H	13.25	27.32	26.91	-	-	-	17.28	18.67	25.08
GG-Perc Mono-1H	13.51	28.05	27.61	-	-	17.73	17.54	18.51	25.06
GC-Perc Mono-3H	-	-	-	-	-	-	17.66	18.63	25.19
Standard-Poly-S	-	-	-	22.54	24.65	17.81	17.26	17.73	23.85
Standard-Poly-H	-	-	-	22.09	24.63	17.58	17.27	-	-
GC-Perc Mono-PO	12.86	26.94	26.62	-	-	-	17.26	-	-
GG-HCT w BS	12.12	24.92	24.60	21.07	23.48	17.36	16.76	16.86	22.7
GG-Perc Mono-2S	13.19	27.78	27.35	23.38	25.74	16.79	13.45	-	-

Table 7 The monthly average normalized Wh/Wp in afternoon.

Module ID	January	February	March	May	June	July	August	October	November
GG-HCT	3.84	10.84	13.63	25.67	27.15	25.75	23.79	16.69	3.06
GC-Perc Mono-3S	-	-	-	24.73	26.41	24.28	23.18	15.77	2.78
Mono-N type	3.75	10.59	13.57	25.35	27.19	24.67	23.03	16.35	2.83
GG-Perc Mono-1S	3.79	10.43	13.61	25.23	26.12	23.52	22.67	15.9	2.77
Standard-PercMono	3.8	10.62	13.43	25.18	26.69	24.74	22.74	16.4	2.93
GG-Perc Mono-PO	3.13	9.66	12.65	-	-	-	22.83	-	-
GC-Perc Mono-4H	3.53	10.17	13.14	-	-	-	22.8	16.23	2.98
GG-Perc Mono-1H	3.46	10.07	13.21	-	-	23.71	22.65	16.10	3.05
GC-Perc Mono-3H	-	-	-	-	-	-	22.51	15.76	2.53
Standard-Poly-S	-	-	-	24.49	25.74	23.52	22.27	15.54	2.79
Standard-Poly-H	-	-	-	24.2	25.89	23.37	22.14	-	-
GC-Perc Mono-PO	3.39	9.9	12.78	-	-	-	22.03	-	-
GG-HCT w BS	3.26	9.08	11.81	23.05	24.49	22.37	21.45	14.97	2.55
GG-Perc Mono-2S	3.5	10.0	13.23	25.51	27.36	21.94	15.03	-	-

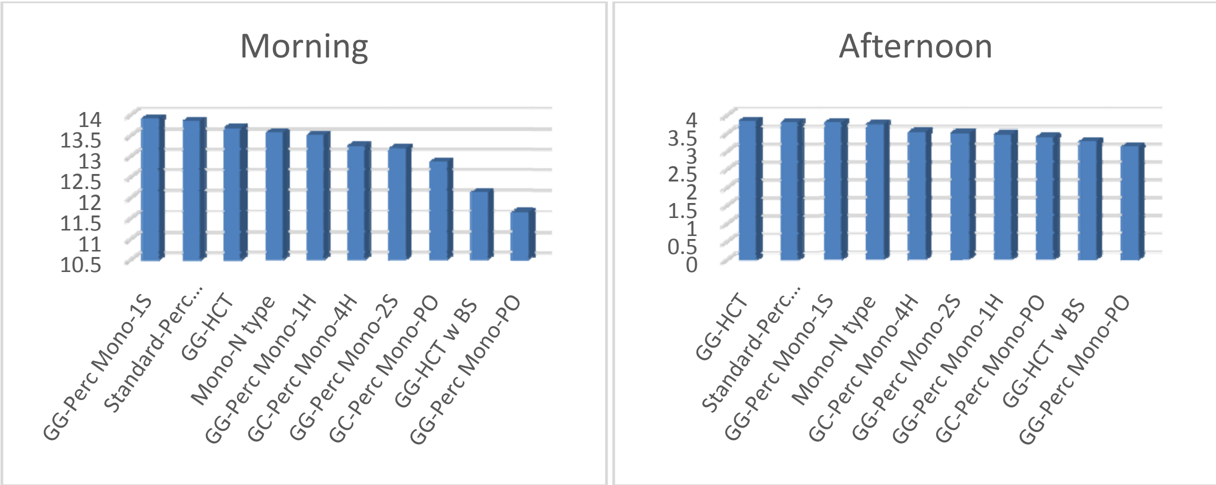

Fig. 2 **Normalized average Wh/Wp for January.**

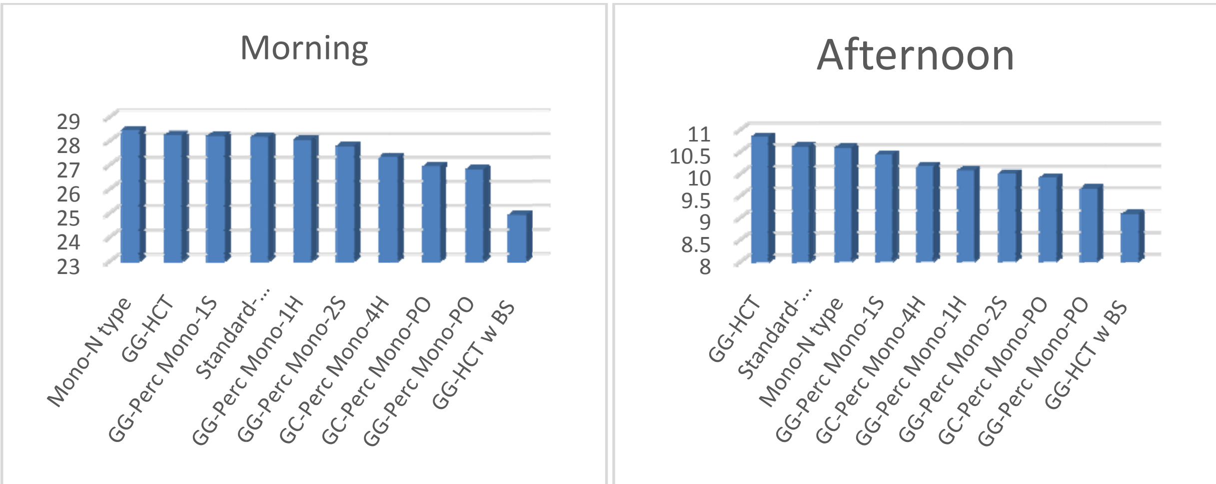

Fig. 3 **Normalized average Wh/Wp for February.**

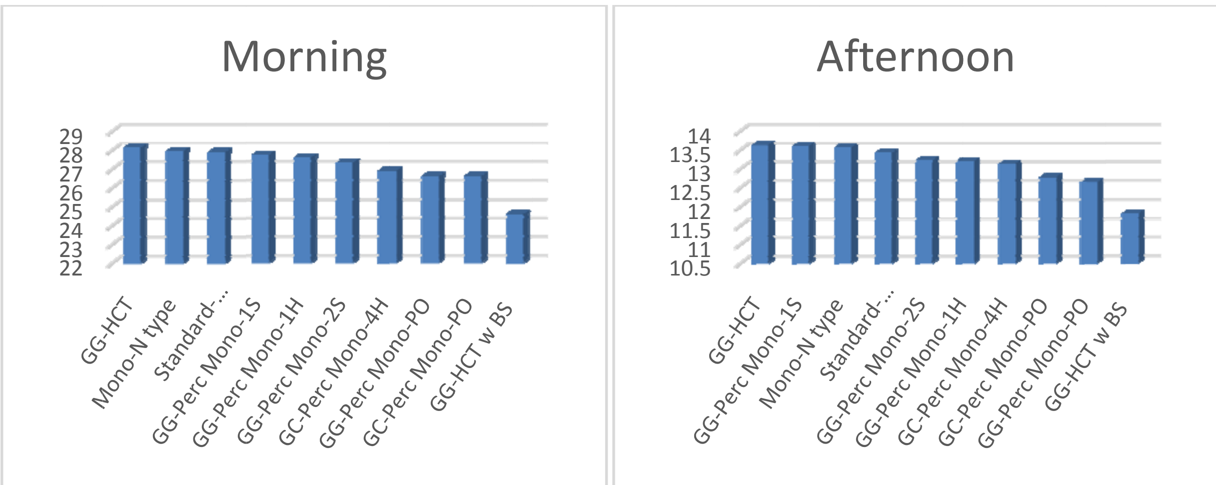

Fig. 4 **Normalized average Wh/Wp for March.**

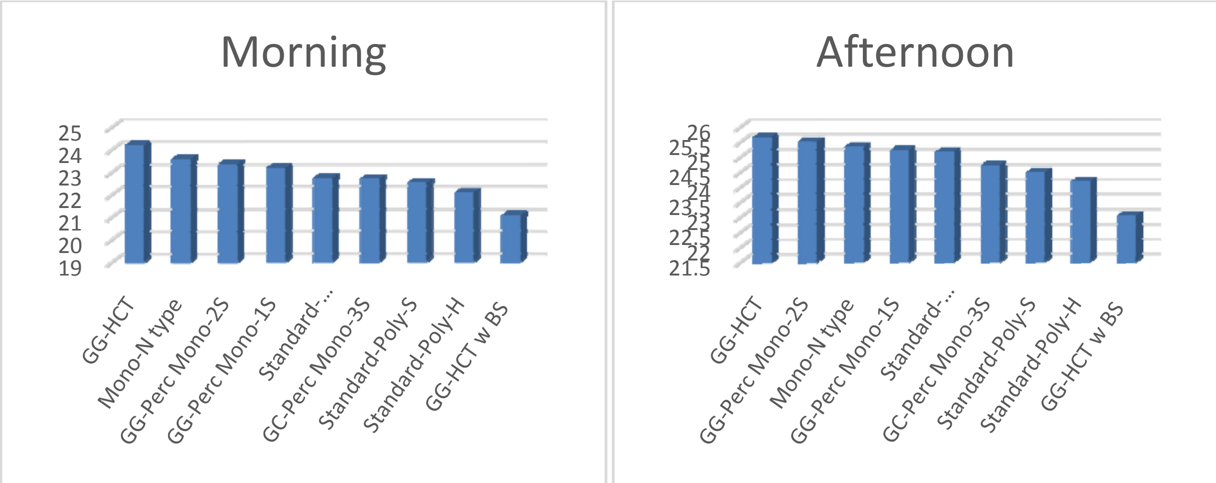

Fig. 5 **Normalized average Wh/Wp for May.**

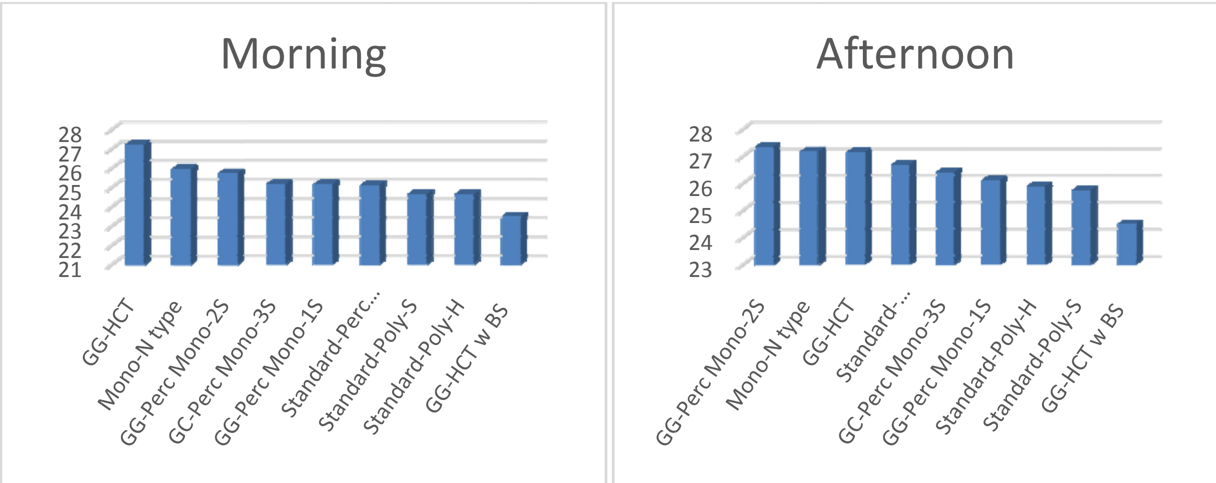

Fig. 6 **Normalized average Wh/Wp for June.**

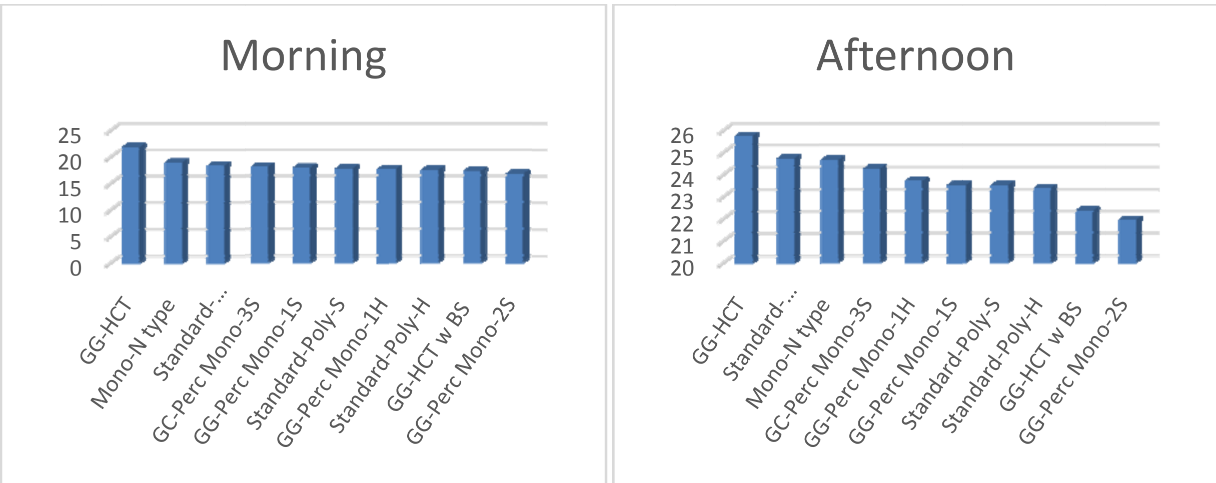

Fig. 7 **Normalized average Wh/Wp for July.**

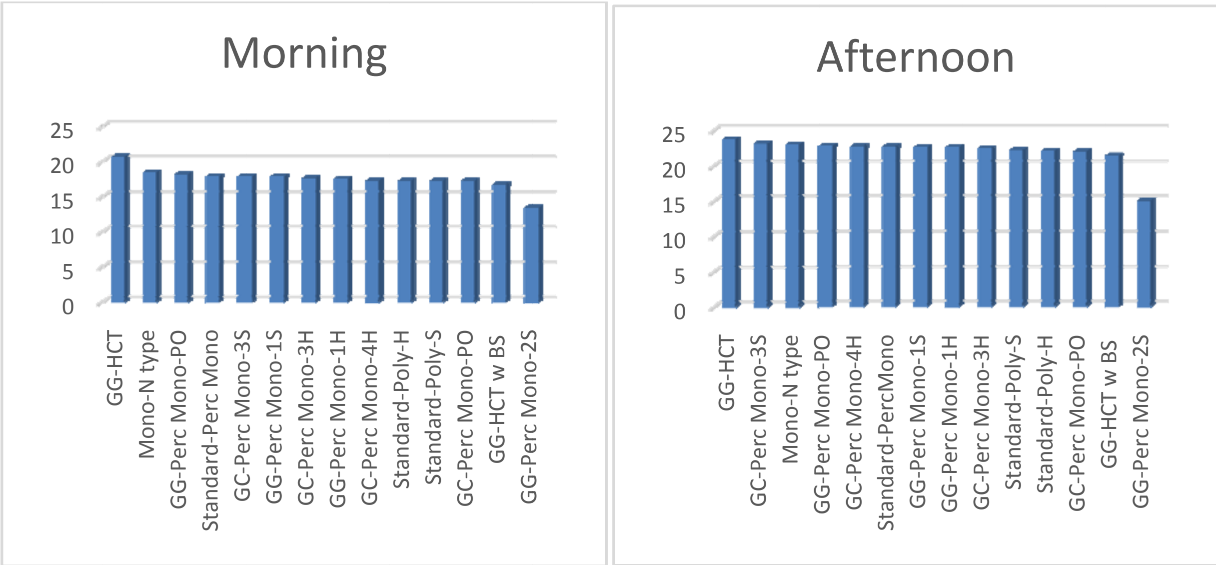

Fig. 8 Normalized average Wh/Wp for August.

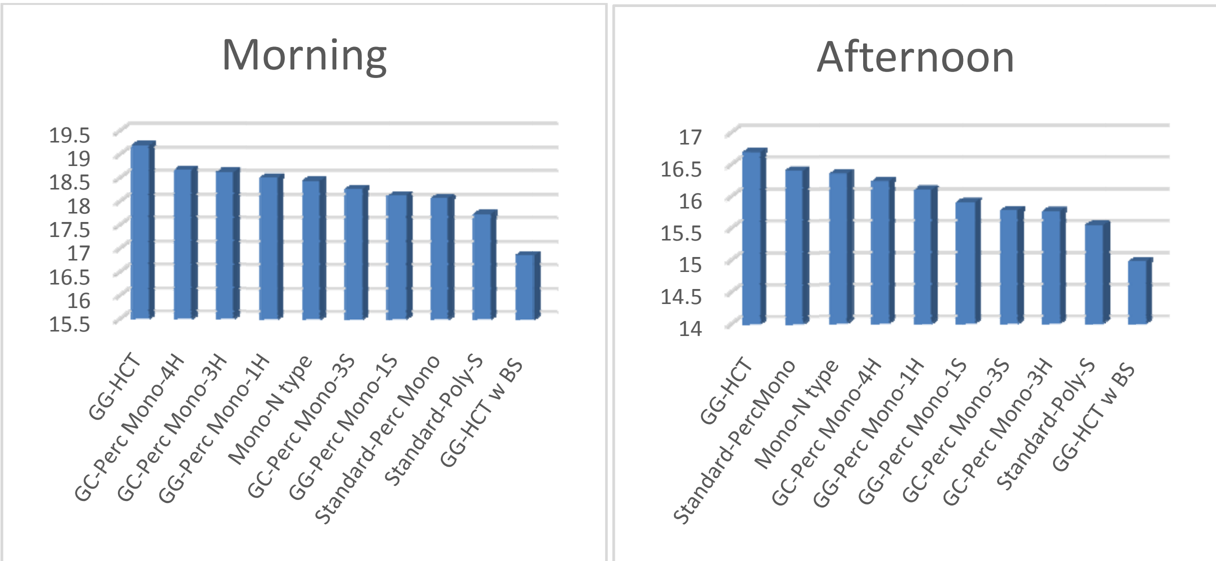

Fig. 9 Normalized average Wh/Wp for October.

It should be noted that all modules with Perc Mono cells have the SAME cells but do behave quite differently from each other. The reason may be the difference between standard single glass plus backsheet versus glass-glass and glass-ceramic construction as well as the very different encapsulants used in each one of them.

When we compare the time of operation versus the energy produced, it is clear that more time does not mean more output. In January for instance perc mono GG1S has lower operation time but higher output than the n-type, HCT and standard perc mono. It has also outperformed the other white GG 1H. As all the perc monos with White back including the standard perc mono module have outperformed all transparent perc mono in January, February and March it's safe to say White back encapsulant or cover helps with very low light. It should be mentioned that this changes under higher light as transparent GG4H gets better performance going into August, September and October.

The significance of White back encapsulant or cover is also evident as in each month, lowest performance of

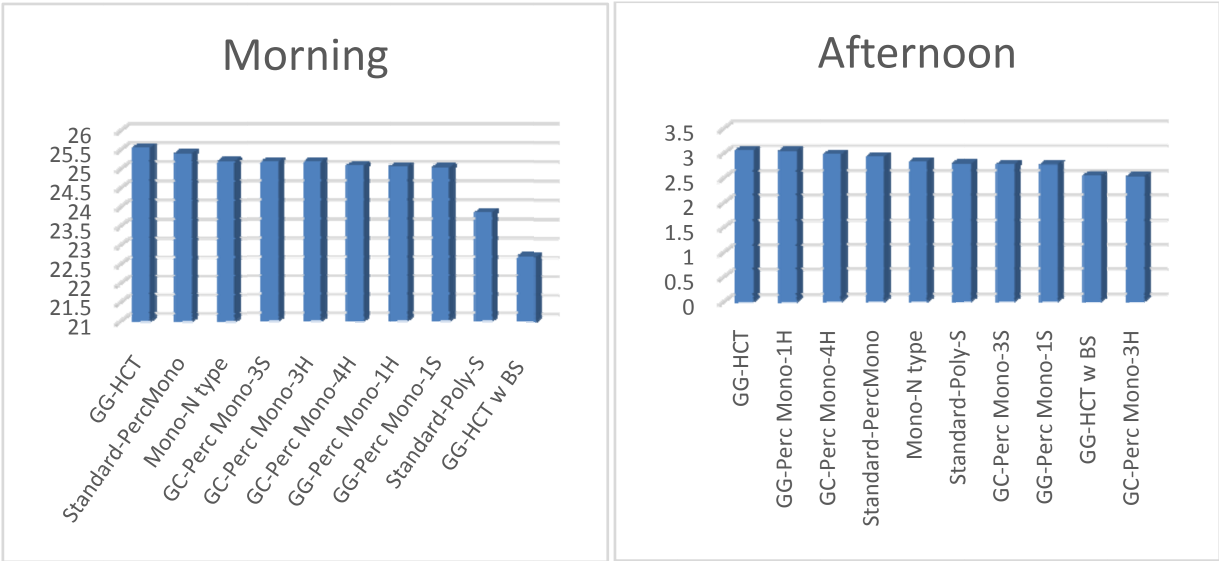

Fig. 10 Normalized average Wh/Wp for November.

the whole bunch goes to the black back covered HCT module.

February is the month when mono n cell beats the bi-facial HCT cell.

March morning light brings forth the power of bi-faciality. Even though the bifacial HCT worked less time than the mono n type and perc monos, it did provide higher output. Again White backed perc monos performed better than transparent backed perc monos.

In May, the polycrystalline panels wake up earlier but still produce less than perc monos.

As light gets stronger into summer, all modules wake up at same time hence work at same hours 4.2 in the morning. Here the bi-faciality goes galore as we also placed the bi-facial module at higher rack to allow for a bigger cone of diffuse and reflected light from back. Again the worst performer is the black covered HCT module.

As summer comes with stronger light, both the polycrystalline and the polyolefin encapsulant modules start catching up with the rest.

October put forth the perc mono in the morning but bi-facial HCT is still the clear winner both morning and afternoon with transparent back perc mono 4H beating the White back perc monos. October has been the only month when transparent GG2S performed even worse than black back covered HCT. This shows even across transparent how important the type of encapsulant is. Clearly #4 encapsulant is superior to #2 at low light both morning and afternoon.

November with lower light, polycrystalline and polyolefin encapsulant modules go to lower output.

4. Discussion

First, the difference between black back sheet and bi-faciality ranges from 10% to 28%.

Second, polycrystalline cells produce lower electricity under low light than the mono n type and perc mono cells.

Third, White encapsulant or White back cover clearly helps in all cases for better performance under low light.

Fourth, polyolefin encapsulant is a poorer performer under low light compared to other encapsulant types.

Fifth, even within eva, different types/compositions of eva contribute to different low light performance.

Sixth, from a cell point of view HCT is a clear winner. This is due to the extended range of wavelength the a-Si adds to the n wafer after HCT the Perc mono is better which is expected as its back treatment does work well to augment the light within the cell.

5. Conclusion

Unlike, the general public opinion in Turkey that module makers are barely assembly plants putting together what has already been produced, our small experiment shows very clearly that the choice of the components that go into a module as well as the technical recipes used during its manufacturing i.e. the differences in performance between GG1H and GG1S modules contribute very significantly to quantity of electricity produced by the modules.

Same cells can behave and produce electricity quite differently given the different module technologies and design.

While it is not the topic of this paper, but same argument can also be extended for the durability of these modules as well if we continue monitoring same test site for many years to come.

Relevance of module technology in terms of materials chosen and the design and engineering of the module is as important as with the cell technology used. The target is to choose and use out-performing cell technology with the better performing module technology. For instance, even if we had included HCT modules which are single-sided with back White covers, we may still have seen bi-facial HCT performing better. This should be an addition for this test as a step forward.

Our results are not yet complete; we need to test further and also analyze further our results to date, going into more detail as to angle of incidence of light at different times in the morning and afternoon and also we need to correlate all data with temperature to neutralize its effects from the performance.

We need to compare the wavelengths contributing most in morning and afternoon with the wavelength receptance of the encapsulants we use in order to fully explain the variations in performance.

References

[1] https://www.nrel.gov/pv/assets/images/efficiency-chart.png.