Performance Analyses of a 454 kWp Grid-Connected Rooftop Photovoltaic System in Southern Norway

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***Abstract*— This paper analyzes and compares the actual measured and simulated performance of a 454 kWp grid-connected photovoltaic system installed on the rooftop of the university building. The data presented in this study were measured from June 2018 till June 2020. The annual production in 2019 was 375MWh. The performance of the system was simulated using PVsyst software. Surprisingly, simulation results somehow predicts the yield similar to the actual field performance in 2019, despite the unpredicted Nordic climatic conditions and other systematic errors from inverters and shadows. The PV panel orientation have positive impact on the performance enhancement during long sun hours.**

Keywords—Silicon PV, Rooftop, SMA, Grid connected

I. INTRODUCTION

The global warming and environment protection is one the key motivating factors that had pushed the world toward renewable energy research. Among them Photovoltaics (PV) have gained attention due to conversion into electrical energy without CO_2 emissions [1]. According to a report from NVE, the tendency in Norway is that the use of electricity will replace the use of fossil fuels, and this is expected to continue about the future electricity usage from now to 2030 [2]. The Norway's cumulative installed PV capacity reached approximately 68 MW at the end of December 2018 which was 27 MW in 2016 [3].

With a growing PV industry, the ability to give accurate predictions on power production over a systems lifetime, becomes of vital importance. PV system size and performance strongly depend on metrological variables such as solar energy, wind speed, snowfall and ambient temperature and, therefore, to optimize a PV system performance, extensive studies related to the metrological variables have to be done [4].

This is the first time that we are reporting the performance of approximately 0.5 Megawatt peak system from Norway. In fact, a limited number of rooftop grid connected systems performance have been reported from Norway. Current study on these aspects will be of great importance to the Norwegian PV industry.

The outline of this paper is as follows: firstly, on the PV system components. Then the simulation of energy yield and finally the comparison of actual yield with simulation and limiting factors effecting the yield.

II. PV SYSTEM INSTALLATION

A grid connected PV system is installed at the rooftop of Vestfold campus of University of Southeastern Norway (USN). It is located in Borre having Longitude: 10.456° Latitude: 59.382° and Elevation at 14 m. Total cost of the PV plant is 8 million Norwegian kroner (8.8k USD). Three thousand square meters of solar panel are responsible for producing a quarter of the annual electricity demand of the university campus. Figure 1 shows an arial photo of PV system. PV system is designed so that daily operations, data logging and procedures for periodic maintenance and control can be easily performed.

Fig. 1. PV system consisting of 1682 panels installed on USN rooftop.

The solar cells are supplied from Canadian Solar, which is the third largest solar cell manufacturer in the world. The name of the panel is CS6k-270p having nominal maximum power of 270W with voltage and current at maximum power is 30.8V and 8.75A respectively under standard test conditions (STC). The module conversion efficiency is 16.50% and temperature coefficient of P_{max} is -0.40%/°C at STC. Such temperature coefficient results in better yield in colder climate where the panel temperature is lower than 50°C even during summer session [5]. Such 1682 Canadian solar panels are installed to cover the whole roof of the building in 102 strings with total 454140 Wp covering whole surface area of the flat roof.

Thanks to the Statsbygg for funding this PV system

SMA Sunny Tripower 25000 TL-30 dual channel string inverters have been installed to work at maximum power tracking to collect and convert maximum power up to 25000W DC. Such 18 SMA string inverters are installed in six different ventilation rooms at the roof. Each string inverter has its own gateway and a cluster controller is set up so that the solution lies on grid access and data logging. The whole energy produced is feed to three-phase grid in WYE configuration. Table I summarizes the PV plant key components.

TABLE I. PV SYSTEM PROFILE

Modules	1,682 x Canadian Solar CS6K-270M
Total gross area	2,942.2 m²
Angle of inclination	15°
Communication	SMA Cluster Controller
Inverter	18x Sunny Tripower 25000 TL-30
Electric Grid	Three-phase (230V/400V, 50 Hz, WYE)

The solar panels are installed at lower inclination angle i.e. 15° to optimize the capture of solar energy with minimum shading on the neighboring PV arrays and efficiently unitizations of the rooftop surface area. All PV panels are installed in two orientations: southeast +45^{o} (E=90^{o}, S=0^{o}, W=-90^{o}) and southwest -45^{o} (E=90^{o}, S=0^{o}, W=-90^{o}). Out of total, 1056 panels (total nominal power 285.12kW) are installed in the southwest (SW) and remaining 738 panels (total nominal power 199.26kW) are installed facing southeast (SE) c.f. table II.

TABLE II. PANALS ON BOTH TRACKER OF INVERTERS WITH ORIENTATION IN SOUTH EAST (SE) AND SOUTH WEST (SW)

Inverter ID	**Panals on tracker A**	**Orientation**	**Panals on tracker B**	**Orientation**	**Panals on inverter**
110	0	SW	51	SW	51
120	54	SW	63	SW	117
130	60	SW	60	SW	120
310	40	SW	52	SE	92
320	54	SE	47	SE	101
410	57	SE	69	SE	126
420	13	SW	13	SW	26
430	24	SW	32	SW	56
510	57	SW	57	SW	114
520	54	SW	51	SW	105
530	46	SW	40	SE	86
540	45	SE	45	SE	90
550	40	SE	40	SE	80
610	60	SE	50	SE	110
620	50	SE	60	SE	110
810	54	SW	55	SW	109
820	60	SW	28	SW	88
830	69	SW	32	SW	101

III. PV SYSTEM SIMULATION

Before installation, the whole design of the PV system was modeled and possible performance was simulated using PVSyst photovoltaic simulation software. The average out door temperature at site is 7.6°C and global and diffuse irradiation annual sum are 954kWh/m^2 and 475kWh/m^2 respectively. Table III shows the simulated energy production. For 454kW installed capacity the 405MWh DC energy production is predicted. After deducting cable and inverter losses around 375MWh will be available to feed to 3-phase grid. This green energy production will reduce the carbon footprint by saving 201tons of CO_2 production per year. PV performance data is tabulated in table III and detailed losses from DC production to the final AC energy feeding to the grid is presented in an energy flow diagram in figure 2.

TABLE III. OVERVIEW PHOTOVOLTAICS (ANNUAL VALUES)

Energy production DC [Qpvf]	405,148.5kWh
Energy production AC [Qinv]	375,812.7 kWh
Total nominal power generator field	454.14 kW
Performance ratio	79.9 %
Specific annual yield	776kWh
Phase imbalance	0 kvarh
Reactive energy [Qinvr]	0 kvarh
Apparent energy [Qinva]	375,812.7 kVAh
CO_2 savings	201,586 kg

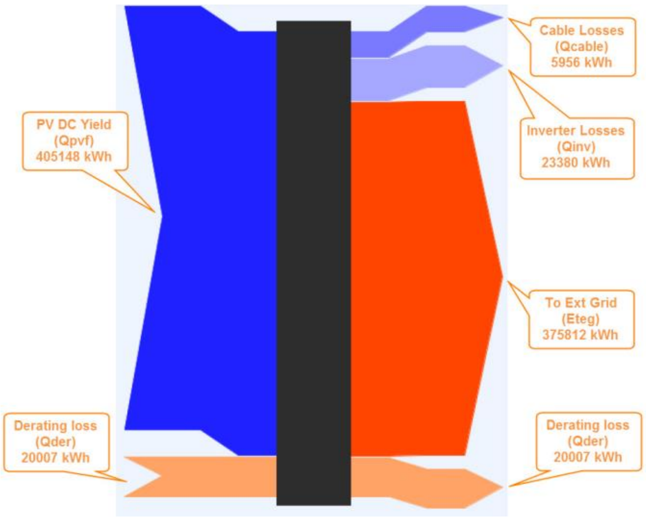

Fig. 2. Energy flow diagram (annual balance).

Due to shorter days of winter with snowfall, the energy generation will be significantly reduced during winter months. Figure 3 shows a plot of PV yield both DC and AC from whole PV plant in respective months.

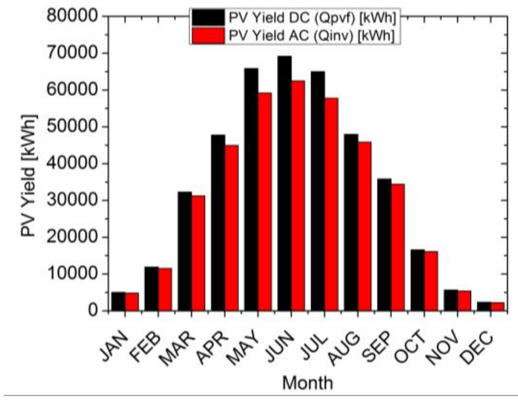

Fig. 3. Simulated annual energy yeild on PV system.

IV. RESULTS AND DISCUSSION

The plant was partially operational from March 2018 while connecting only few strings to grid and got fully operational from June 2018. Year 2018 summer was unexpectedly very dry and sunny which has significantly enhanced the energy production compared to the simulation results. While comparison with simulated energy the AC energy production from August until December is relatively lower in both years that are mainly driven by the climate. First three month of year 2019 have shown less production due to unpredicted weather and the amount of snow. We do not have any mechanism to remove the snow from panels other than relying on air temperate and direct sunrays who melt the snow from PV panels. Therefore, conversion efficiency on many sunny days is lost or minimized due to the shading effect of the snow from previous days. Additionally, the favorable power temperature coefficient (-0.40%/°C) effect will not be fully utilized during colder months. Hence, simulation results can only provide a guess to the energy production as weather conditions in Norway is continuously changing over the whole year. Similarly, January 2020 is surprisingly snow free and sunnier ever observed in past years so energy yield over the month was 3595kWh. This energy is almost 3.5 times higher than yield from Jan 2019.

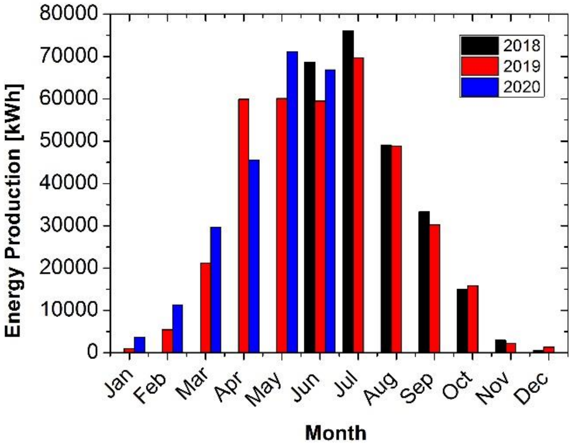

Fig. 4. Annual DC energy yeild year 2018 to 2020.

Surprisingly, three month (April until June) of year 2019 have produced almost similar energy yield. While looking at the global irradiance, the average peak solar energy have increased over three-month period. AC power from a number of inverters leveled out during the middle of the summer sunny days for few hours c.f. Fig.5. Figure 7 indicates two of the southwest inverters (120 &130) and one of the southeast inverter (410) have reached the AC conversion limit at noon for up to 3 hours. The other inverters have responded typically to the increase of solar intensity around noontime. While comparing with the data sheet of the inverter, the input DC current and voltage from strings to inverter are within the maximum input limitation. It is speculated that any of the inverter setting is preventing the output yield beyond 23kWh. Whereas the inverter have the capability of 25kWh. So we are working on this problem so that inverter process maximum power from the PV strings and feed to the grid as maximum output yield get lost due to inverter issue.

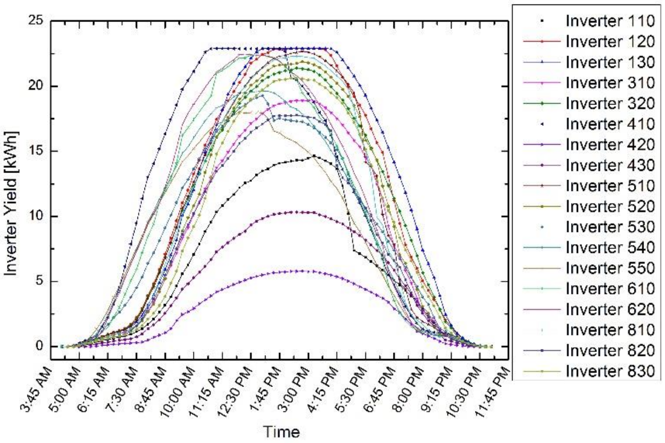

Fig. 5. Energy generation from all inverters on a sunny day in summer (12 July 2019).

Figure 6 shows the solar path of summer and winter day [6]. It clearly shows the position of sunrise and sunset from northeast and northwest respectively. Therefore, installation of PV modules in southeast and southwest is one of the optimized way to harvest sun energy during longer summer hours. While comparing output of all strings, the performance of PV modules facing southeast are largely enhanced during early hours after sunrise c.f. Fig. 7 (b&d). Similarly, southwest modules enhance the energy production in the afternoon until the sunset as direct sun rays are falling on the modules with lesser reflection loses c.f. Fig. 7 (a&c). Some of the modules have shown a sudden drop in the yield in the afternoon resulting of the shading from the ventilation room installed at the same roof. These rooms partially shade some of PV modules resulting in bypassing of least producing modules in the string.

Fig. 6. Solar path on a summer day (top) 12th july and winter day (bottom) 4th January at PV system location [6].

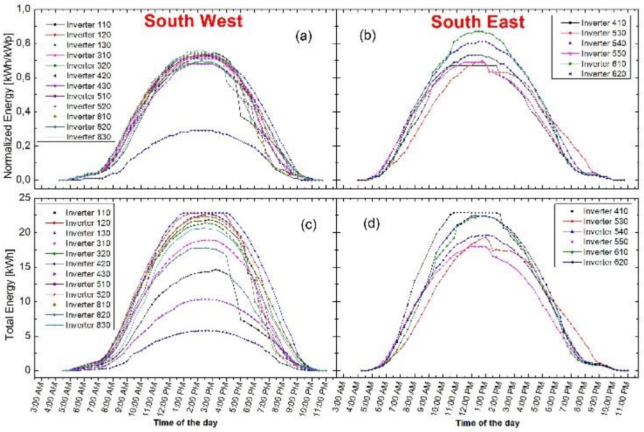

Fig. 7. Inverter yields from South west (a & c) and south east (b & d) invertes on 12th July 2019. Top graphs represent normalized energy (kWh/kWp) while bottom shows total yield (kWh).

The winter days are very short and solar elevation angle even at noon is very small. Hence, solar rays falling on the PV modules at low angle reflect at larger extent. Moreover, the peak sun intensity is around hundred watts per meter square. Both of these factors govern the low energy yield in winter months if modules are not covered with snow. Since the sun-hours are limited to six hours in January, so the modules facing to southeast or southwest behave in the same way c.f. Fig. 8.

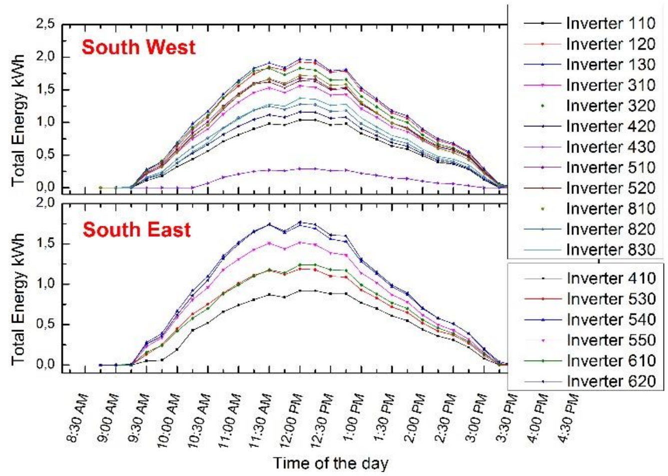

Fig. 8. Energy production on a winter day (4th Jan 2019) from both directional group of PV modules.

While comparison of the energy production during the spring and summer months of year 2019 with year 2020 the difference is significant. The reason behind such difference is revealed in figures 9-12 with detailed energy production from each string inverters in the duration of March until June. March 2019 have relatively higher amount of snowfall, which resulted in the loss of energy nearly half month while modules surface was covered with snow for many days. Whereas during March 2020 such period was limited to lesser snowy days resulting in nearly 40% more energy production compared to same month of 2019. While setting side by side the energy production from April 2019 with April 2020 the former month have produced 24% more energy. The production in April 2020 to large extent is lowered by the production loss from five string inverters (610, 620, 810, 820, 830). Due to COVID-19 the unmanned operation was unable to reset the inverter errors. Therefor the production loss is limited by the system errors. Inverters 610 and 620 were turned off for 25 days while 810, 820 and 830 were off for 2 weeks. Hence, total monthly energy is contributed mostly from 13 inverters.

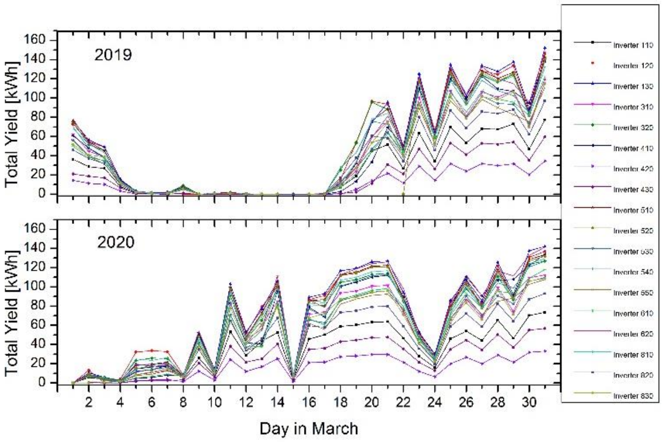

Fig. 9. Energy yeild in March 2019 and 2020 from all grid inverteres.

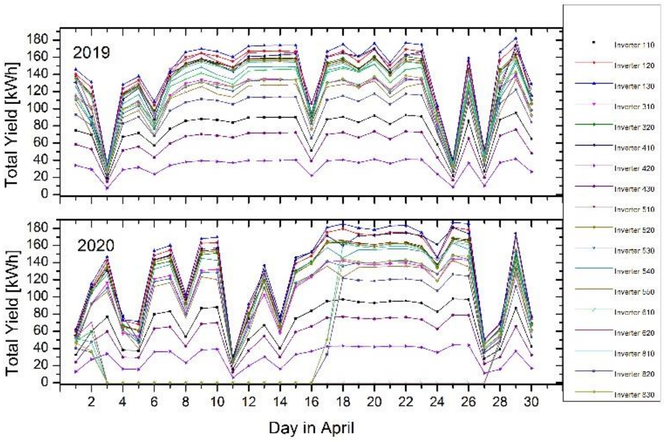

Fig. 10. Energy yeild in April 2019 and 2020 from all grid inverteres.

May 2020 have more sunny days compared to May 2019 so despite the energy loss for a week from three inverters the total monthly output is higher due to the less cloudy days c.f. fig. 11. However, during comparison of June 2020 with June 2019 all grid inverters have normal operation over the whole June in both years so weather is the major governing factor for the total yield. Hence, comparatively more sunny weather had allowed the PV system to produce more energy in June 2020. Figure 13 shows the horizontal solar irradiance data of four months from a metrological station situated 27 km away from the PV plant.

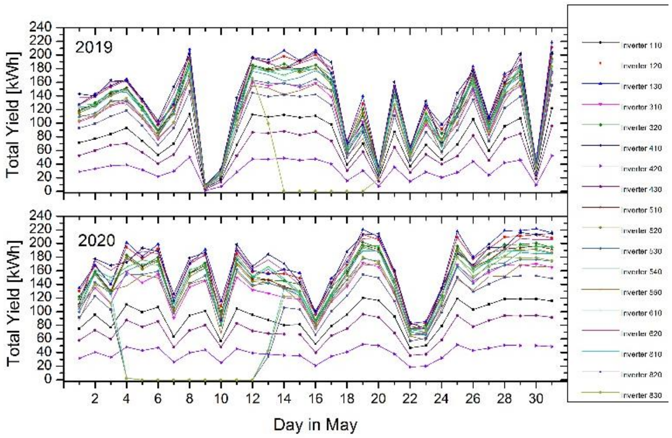

Fig. 11. Energy yeild in May 2019 and 2020 from all grid inverteres.

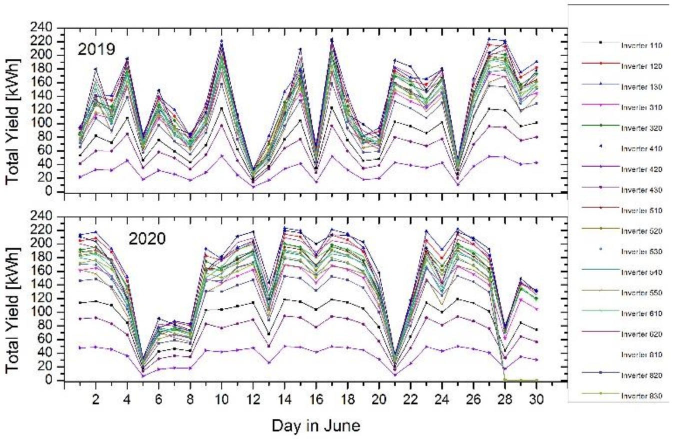

Fig. 12. Energy yeild in June 2019 and 2020 from all grid inverteres.

While comparing the energy yield from March to June in 2019 with global irradiance data, from a metrological station, a clear coordination can be recognized. For simplicity, the irradiance data only from year 2019 is plotted in fig. 13.

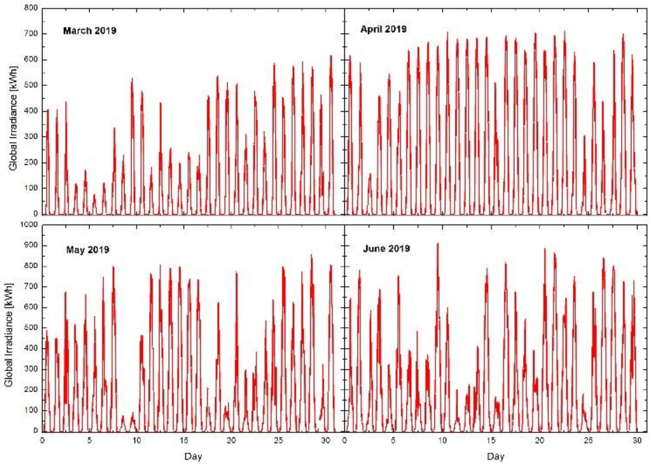

Fig. 13. Global irradiance data from a metrological station for selected months of year 2019.

V. CONCLUSION

A grid connected PV system have been installed and monitored for two years. The specific energy yield per year was 781.60 kWh/kWp during year 2019. The simulation results overestimate the energy yield during winter and autumn months. While the same yield is underrated for summer session. Despite the differences between simulation and actual monthly yields, the overall annual energy feed to the grid during year 2019 was same as simulated. The maximum energy for 117kWp and higher power strings leveled out near noon hours during the sunny summer days and got lost due to inverter technical issues. After redesigning the string or solving the inverter issue, the maximum power could reach up to 400Mwh annually, even higher than the simulated yield. The summer months indicate the clear advantage of PV modules installation direction in SE and SW while the similar advantage in winter month is absent due to limited sun hours. Additionally, the weather have the greatest impact on the yield as the same month have different climatic conditions from year to year resulting in a bigger impact on the annual yield.

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