Effects of Feed-In Power Limitations of Photovoltaic Systems

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Limiting the feed-in power of residential photovoltaic systems is an important tool for electric grid operators to maintain a reliable energy supply. PV curtailment is effectively loss of green energy, therefore, this article aims to raise awareness that the PV potential lost through curtailment is far less than it is widely believed.

Keywords: photovoltaic; curtailment; feed-in limitation; inverter oversizing; grid management

The basic principle of a power system is that the produced electric power must be equal to the current consumption. Due to the falling costs in production, the solar photovoltaic (PV) capacity is projected to more than double by 2030 and overtake coal in the mid-2030s to become the second-largest installed global capacity [1]. The growing number of photovoltaic systems, however, which are mainly connected to low-voltage electric grids, lead to new challenges for grid operators in terms of maintaining a safe and reliable grid operation. On days with high solar radiation grid operators are faced with periods of overproduction of electricity and the high simultaneity of solar energy generation, especially in poorly developed grids, can lead to overloading of the grid. An alternative to cost-intensive grid reinforcement is the so-called feed-in management of photovoltaic systems. The simplest form is to limit or curtail the AC feed-in power of the generator to a constant value below the rated DC power of the photovoltaic array. PV curtailment can be done at two points in the grid - directly at the inverter or at the feed-in point. Curtailment at the inverter can occur by oversizing the inverter. Oversizing of inverters describes the situation when a PV array is assembled with a higher capacity than the rated size of the inverter. This is quite possible, as PV systems often produce less than their rated power. In times of optimal performance, the inverter limits the AC output by controlling the voltage and current. This means that the PV power is curtailed by the inverter [2]. Curtailment of PV power at the feed-in point may be necessary to match supply and demand within the grid. One of the key issues is to maintain sufficient flexibility and balancing capability within the grid to balance demand and supply with controllable energy generators [3]. A prescribed feed-in curtailment may hinder reaching the full potential of the maximum available renewable energy generation at a specific location, because PV arrays may tend to be designed smaller to avoid running into the curtailment. Hence, this article discusses the effects on the annual electricity yield of a small-scale residential photovoltaic system under multiple curtailment scenarios. The effects of self-consumption and/or an optional battery storage are not taken into account. These assumptions ensure that only the PV electricity generated is taken into account in the evaluation and that the results are independent of individual boundary conditions. As a result, the outcome of this report has a higher informative value and applies both to a curtailment by the inverter and to a feed-in limitation by the local grid operator.

Methodology

In order to investigate the effects of feed-in power limitations on the annual yield, an Example Plant was defined. The representative plant has a rated power of 10 kilowatt-peak (kWp) and is composed of twenty "FuturaSun FU 500 SILK Premium"-modules and a "Fronius Symo 10.0-3-M"-inverter and was situated in five European capitals. In order to obtain representative results, the locations for the calculations have been chosen in such a way that they are evenly distributed over the longitudes of Europe. Not only was the location of the Example Plant varied, but also the orientation and inclination. The fictitious PV system was aligned in six different orientations and for each of these orientations, the modules were set up with an inclination of 30°, 60°, and 90°. Since the orientation does not matter for an inclination of 0°, this setup was simulated only once for each site. The selected locations and some additional information are listed in **Table 1 a), b)** and **c)**, from the northernmost location to the southernmost. A list of the parameter variation performed at each simulation site is given in this table as well. For the elaboration of the results in this article, a total of 95 simulations were performed. All data featured in this paper was simulated with PV*SOL premium 2022 [4]. The output of the simulations is the course of the grid feed-in in kWh over an entire year in a one-minute resolution. This value is used to calculate the electrical grid feed-in power of the PV system in kW. To keep the time required for the simulations low, they were carried out without curtailment. The PV curtailment was implemented in post-processing with MATLAB. The approach of introducing a feed-in limit in post-processing makes it possible to apply a power limitation to any value over the entire range of the rated power. Thus, a statement can be made not only about a certain curtailment value. For the purpose of this paper, the ratio of the maximum permitted feed-in power to the nominal power of the PV generator is referred to as the feed-in limit.

After curtailing the simulation data, the corresponding curtailed annual electrical yield can be calculated for each feed-in limit. The ratio between the yield under curtailment and the yield of a PV system without curtailment is referred to as yield-ratio in this paper and provides information on how a curtailed system performs compared to a system in unimpaired operation. This yield-ratio can take any value between 0 and 1 and the actual relative yield loss due to curtailment is defined as the difference between 1 and the yield-ratio.

Before the curtailment results are presented, the next section shows the different results from the parameter study. For the following illustrations, the values of the y-axis are in relation to the nominal power of the PV generator. **Figure 1** shows the summed monthly yield for a south-facing plant with a 30° inclination at all locations. It can be seen that the southernmost plant has the highest yield on average and the northernmost the lowest. **Figure 1** also shows for a representative week how the subsequent curtailment of the simulation results was carried out, using the example of a 25%, 50%, and 75% feed-in limit. A fictitious feed-in limit was applied over the entire simulation horizon, the values above this limit are considered as curtailment loss, and the values below the limit as curtailed PV power. Due to the higher global radiation and the higher proportion of direct radiation, it can be seen that the power limit is exceeded more often for the PV system in Rome than for the system in Oslo.

Table 1 a). *List of Locations, used for the study.*

Location; Latitude; Longitude; Database; Time Period; annual sum of global radiation (% diffuse)
Oslo; 59.95°; 10.72°; Meteonorm 7.2c3; 1991-2010; 900 kWh/m^2 (51.1%)
Berlin; 52.52°; 13.41°; DWD; 1995-2012; 1042 kWh/m^2 (52.1%)
Vienna; 48.23°; 16.50°; Meteonorm 6.1; 1991-2010; 1188 kWh/m^2 (47.5%)
Ljubljana; 46.07°; 14.52°; Meteonorm 8.1; 1996-2015; 1229 kWh/m^2 (47.9%)
Rome; 41.88°; 12.46°; UNI 10349; 1986-2005; 1611 kWh/m^2 (38.1%)

Table 1 b). *List of Orientations (Azimuth) used for the study.*

Orientation (Azimuth)
east/west(-)
east (90°)
south/east (135°)
south (180°)
south/west (225°)
west (270°)

Table 1 c). *List of Inclinations used for the study.*

Inclination
0°(south)
30°
60°
90°

Results

The figures in this section show the most important findings from the calculations. To illustrate the results, the ratio of curtailed yield to maximum yield is plotted over the feed-in limit. In **Figure 2**, the AC power values after the inverter are plotted according to their frequency over the entire simulation year. The area under the curve thus represents the electrical yield in kWh. As can already be seen in **Figure 1**, a higher PV output is achieved in Rome and thus also a higher yield. The yield above the feed-in limit is considered a loss due to the curtailment. **Figure 2** also shows the difference between the individual sites with a southern orientation and 30° inclination. It can be seen that in the southern locations the curtailment in the lower area has a greater effect on the yield losses. This is due to the fact that global irradiation is higher in these areas, resulting in more frequent and higher peaks in PV generation. Above a feed-in limit of 75%, no major differences can be observed between the individual locations.

Similar behavior can also be observed with a change in orientation and inclination, as shown in **Figure 3** - more direct irradiation of the modules by the sun leads to greater losses in yield due to the increased PV generation. A further comparison between the locations Oslo and Rome is carried out in **Figure 3**. "Rome - South - 30°" represents the PV system with the highest curtailment loss.

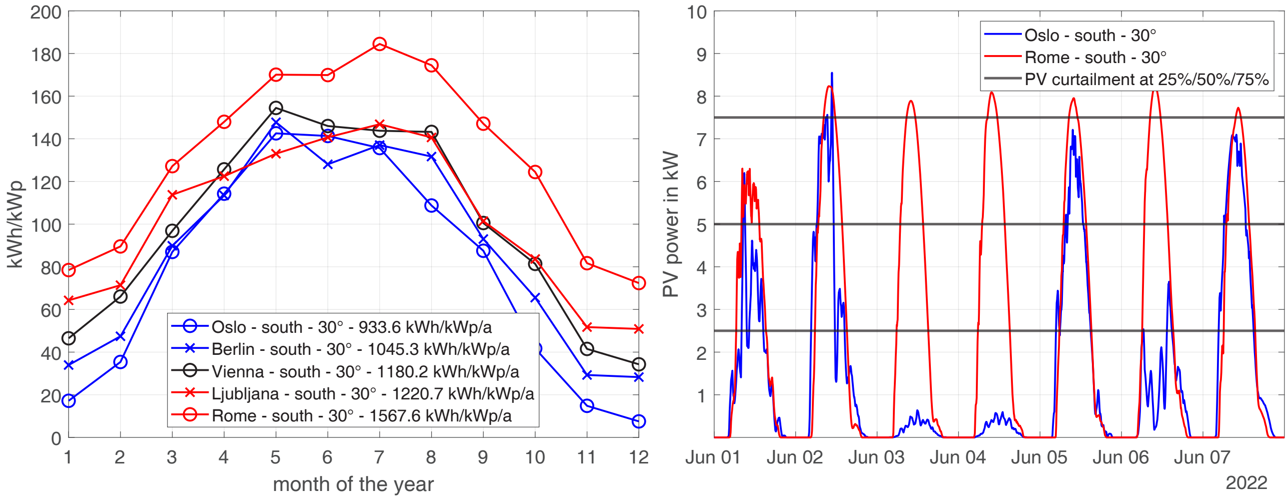

Figure 1. Comparing the monthly yield over all locations (left) and Example of curtailing the simulated PV power in MATLAB (right).

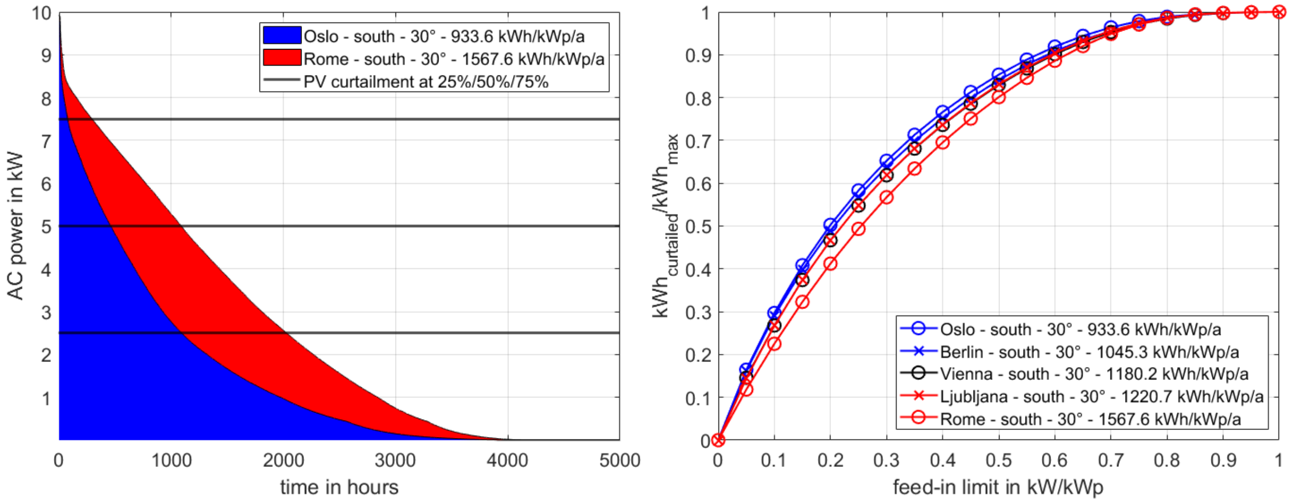

Figure 2. AC load distribution after inverter for Oslo and Rome (left) and Comparing the yield-ratio over all locations (right).

Table 2. *Yearly yield-loss at different levels of curtailment for the majority of the simulations.*

Yearly yield-loss at feed-in limit in %		**30°**			**60°**			**90°**		
		25%	**50%**	**75%**	**25%**	**50%**	**75%**	**25%**	**50%**	**75%**
Oslo	east/west	23.9	2.5	0.0	19.4	0.2	0.0	14.0	0.1	0.0
	east	34.8	9.2	0.8	37.3	13.0	1.7	33.3	10.2	0.8
	south/east	40.2	13.5	1.8	43.1	16.7	2.9	37.6	11.3	0.9
	south	41.7	14.7	2.1	44.6	17.3	2.9	38.0	10.7	0.9
	south/west	39.9	13.1	1.6	43.1	16.4	2.6	37.8	11.4	0.9
	west	33.7	8.5	0.6	36.2	12.0	1.3	32..4	9.4	0.5
Berlin	east/west	28.1	4.4	0.1	21.1	0.2	0.0	13.0	0.1	0.0
	east	37.0	11.6	1.1	36.9	13.4	1.8	30.6	9.3	0.5
	south/east	42.4	15.6	2.6	44.0	17.9	3.2	37.3	11.4	0.8
	south	43.1	15.9	2.8	44.1	17.1	2.8	35.5	9.7	0.9
	south/west	40.8	14.0	2.1	41.6	15.5	2.5	34.5	9.6	0.7
	west	34.7	9.6	0.8	34.3	11.3	1.2	28.4	8.0	0.4
Vienna	east/west	30.6	5.6	0.1	22.8	0.3	0.0	13.7	0.1	0.0
	east	39.4	12.6	1.3	38.7	14.1	1.8	31.9	9.7	0.6
	south/east	44.2	16.2	2.6	44.4	17.3	2.7	36.0	9.8	0.7
	south	45.2	17.0	2.9	45.1	17.0	2.6	34.9	8.9	0.9
	south/west	43.9	15.7	2.4	43.8	16.7	2.4	36.5	10.5	0.8
	west	38.4	11.4	1.0	37.9	12.7	1.4	31.1	8.5	0.4
Ljubljana	east/west	30.9	5.8	0.2	22.5	0.3	0.0	13.4	0.1	0.0
	east	39.0	12.0	1.2	38.5	13.5	1.7	31.7	9.4	0.6
	south/east	44.1	16.0	2.4	44.7	17.4	2.7	36.7	10.6	0.9
	south	45.2	16.9	2.7	45.4	17.2	2.9	35.7	10.1	1.1
	south/west	43.8	15.5	2.2	44.3	17.0	2.5	36.4	10.4	1.0
	west	38.1	11.1	0.9	37.4	12.3	1.2	30.6	8.2	0.4
Rome	east/west	37.2	8.2	0.2	26.0	0.3	0.0	14.4	0.1	0.0
	east	45.5	15.2	1.5	44.2	15.9	1.8	35.5	10.1	0.6
	south/east	50.1	19.3	2.7	49.5	19.4	2.6	39.4	10.4	0.8
	south	50.7	19.9	2.9	49.1	18.2	2.5	36.1	9.1	0.7
	south/west	49.4	18.6	2.5	48.6	18.2	2.1	38.0	9.2	0.6
	west	44.4	14.1	1.2	42.7	14.0	1.1	33.6	8.0	0.3

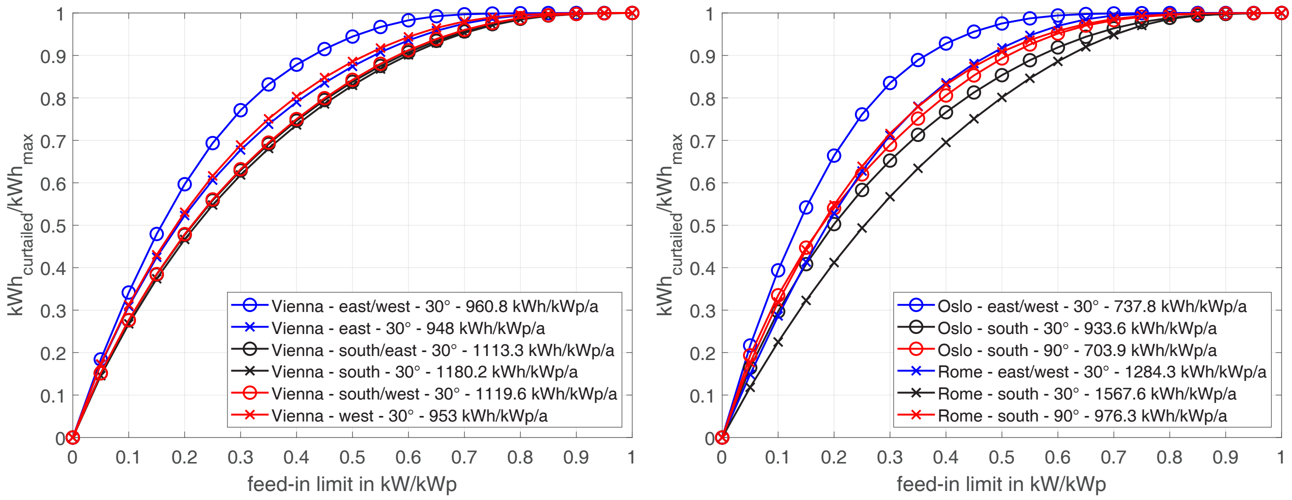

Figure 3. Comparing the yield-ratio for Vienna over all orientations (left) and Comparing the yield-ratio for the extreme scenarios Oslo and Rome (right).

Conclusion

For the future maintenance of grid stability, curtailment of the PV power fed into the electricity grid is of great importance, as the discrepancy between supply and demand is minimized. It is also clear that through this measure, some of the green energy generated is lost. In general, it can be said that due to an optimal placement of the PV modules, power peaks occur more often and the curtailment intervenes more frequently. Due to these circumstances, the curtailment losses also increase. However, by evaluating the 95 simulation results, it can be stated that these losses are less than expected compared to the yield of a PV system with no curtailment. At a feed-in limit of 75% of the nominal power, a maximum loss of only 3.2% can be observed. When the relative losses of all simulations are averaged at this feed-in limit, the average loss is only 1.3%. At lower feed-in limits the overall yield of the PV system decreases. However, a large portion of the yield is still available for use. If the feed-in power is reduced to 50%, there is a 19.9% loss of yield in the worst case. Taking all 95 simulation results into account, the average loss is 11.2% at this feed-in limit. In the worst case, the feed-in power must be reduced to 25% of the nominal power in order to record 50% of the yield as a loss. The resulting yield losses from the majority of the simulations are listed in **Table 2** for defined feed-in limits. One way to further reduce the losses caused by curtailment at the feed-in point is to integrate a battery storage system. On high-yield days, however, the battery storage is often fully charged at the time of maximum PV generation. This can be remedied by forecast-based battery charging. With this method, the charging of the battery storage is postponed to times with high PV power output [5]. ■

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