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MICROINVERTER PV SYSTEMS: NEW EFFICIENCY RANKINGS AND FORMULA FOR ENERGY YIELD ASSESSMENT FOR ANY PV PANEL SIZE AT DIFFERENT MICROINVERTER TYPES

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ABSTRACT: The market for microinverters is growing, especially in Europe. Driven by rising electricity prices, many small photovoltaic energy systems are being installed. Since 2014, microinverters have been studied indoors and outdoors at Paderborn University. In the indoor lab, conversion efficiencies as a function of load have been measured with high accuracy and ranked according to Euro- & CEC weightings: The latest rankings of 2022 are included in this paper. In the outdoor lab, energy yields have been measured using identical and calibrated crystalline silicon PV modules. Until 2020, measurements were carried out initially with 215W_p modules. Because of increasing module power nowadays, 360 W_p modules are now being used. These extremes have been investigated: An older module with 215 W_p and a new module offering 360 W_p (both with 60 cells). Appling the low-power modules, the challenge for the microinverters was during weak-light conditions, for high-power modules, some inverters temporarily reached their power limits, so output was reduced. A method to determine actual energy yield has been developed, using a linear equation and a reference configuration: So yield for any module & inverter configuration can be determined by just two coefficients.
Keywords: Microinverter, System Performance, Energy Rating, Yield

1 INTRODUCTION

Microinverters are inverters that are connected mostly to a single PV module (occasionally to two modules, as indicated in the tables; few are available for four modules, but these are not considered here), so each module–inverter combination acts as an independent power plant. The microinverter consists of a maximum power point tracker (MPPT), the DC-AC inverter, and an islanding protection unit (see e.g., [1]). For higher power requirements, several module-inverter combinations are interconnected in parallel on the AC output side. This configuration offers various advantages: Easier planning and installation, easy up- and downscaling of a plant, including extensions or repair that could be carried out even during power plant operation. Logistics is simplified. Effect of shadowing is very limited, and due to low system voltages, potential induced degradation (PID) does not occur. An excellent overview of the development and the advantages of microinverters has been compiled by H. Oldenkamp [2]. However, costs of power plants based on micro inverters are about 10–20% higher. Some of the inverters cannot be operated by themselves and require a control unit (often combined with a remote shutdown option and a monitoring system), or a protective device for grid interfacing (depending on national regulations), thus adding extra costs. Also, conversion efficiency may not be as high as for central inverters. Due to smart master–slave concepts centralized solutions with multiple but relatively large inverters may offer higher yields under weak light conditions. [3] is giving a performance comparison of a microinverter, a power-optimizer, and a central inverter.

2 MEASUREMENTS

2.1 Indoor tests for conversion efficiency measurements

Due to the reproducible test conditions in the indoor lab, the inverters have been examined individually with predefined and controlled input data. Input has been a PV module simulator with data being set corresponding to the modules used in the outdoor test. The main output data being recorded is the delivered AC power of the inverters, all measured by a Zimmer LMG 670. Besides input power, output is also a function of input voltage. If input voltage is getting too low, the inverters even stop operating. The following examinations are based on the possible range of input data (including voltage) given the specific PV module also used for the outdoor investigation

Peak efficiency is often reached close to the maximum load of the inverter. Peak efficiency (often promoted in data sheets) is not a helpful value since most of the time the inverters operate in the range of 20% to 40% of their rated power – at least under non-arid conditions. Consequently, an adequately weighted efficiency is a more adequate value to rate conversion devices. One type of weighted efficiency is the so-called "European Efficiency" η_{Euro} which it is calculated according to:

$$\eta_{Euro} = 0.03 \cdot \eta_{5\%} + 0.06 \cdot \eta_{10\%} + 0.13 \cdot \eta_{20\%} + 0.1 \cdot \eta_{30\%} + 0.48 \cdot \eta_{50\%} + 0.2 \cdot \eta_{100\%} \quad (1)$$

The other is the "CEC efficiency" by the California Energy Commission (CEC). CEC efficiency is computed as an average value of DC–AC conversion efficiencies at six pre-defined relative output values between 10% and 100% of its rated power (with an emphasis on higher irradiance levels) is determined by:

$$\eta_{CEC} = 0.04 \cdot \eta_{10\%} + 0.05 \cdot \eta_{20\%} + 0.12 \cdot \eta_{30\%} + 0.21 \cdot \eta_{50\%} + 0.53 \cdot \eta_{75\%} + 0.05 \cdot \eta_{100\%} \quad (2)$$

For the "European Efficiency", weighting factors for high relative power values are lower.

The output power values used for the inverters (adjusted by controlling the DC input current) are continuously increased in 1024 steps from 0 to maximum. Each step takes eight seconds while the measurement duration is 500 ms. Figure 1 shows an example for the measuring procedure.

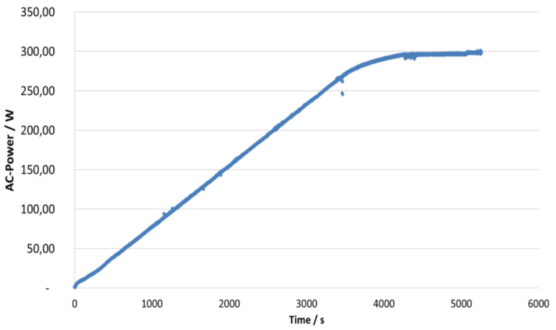

Figure 1: Example for measured AC power output (in Watt) as a function of measurement duration (in seconds) for linear increasing DC input current.

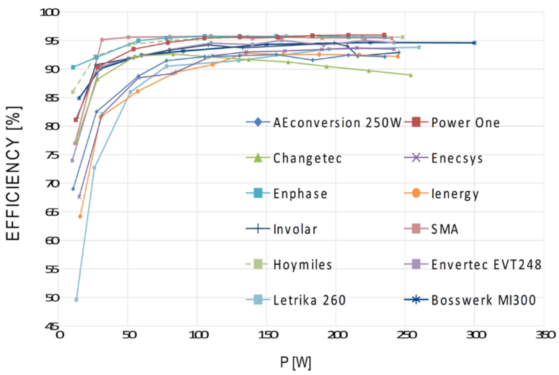

Figure 2: Measured DC-AC conversion efficiencies as a function of power output, for twelve microinverters with single PV module inputs (updated for 2022).

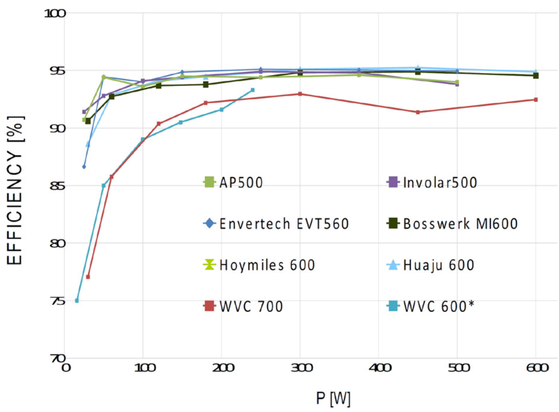

Figure 3: Measured DC-AC conversion efficiencies as a function of power output, for eight microinverters with two PV module inputs, including the latest models of Hoymiles, Huaju, Bosswerk.

The measured DC-AC conversion efficiencies of all inverters are shown in Fig. 2 and Fig. 3. Based on those measurements, the European (EU) efficiencies and the CEC efficiencies for the micro inverters have been calculated according to (1) and (2), eleven micro-inverters are designed for single modules, eight inverters have inputs for two PV modules: Involar MAC 500, APS YC 500, Envertech EVT-560, WVC 600, WVC 700, Hoymiles MI 600, Huaju HY 600, and Bosswerk Mi600.

Comment: WVC 600* stopped operating at a measured power of 250 W. After a test run at higher temperatures, the inverter failed constantly. Since the documentation of WVC 600 and WVC 700 inverter has been extremely poor, its rated power has been assumed. For this reason, WVC 700 is shown first with the assumed rated power of 600 W, then with 700 W. The maximum measured power of the WVC 700 inverter was 600 W only.

The ranking considering the European (EU) conversion efficiency is shown in Table I.

Comments: Envertech EVT 560 and PowerOne/ABB Micro-0.25-i have the same conversion efficiency, thus sharing rank number 5, so do Involar MAC 500 and Bosswerk Mi600, thus sharing rank 8 as well as Aptronic INV 250-45 and Enecsys SMI-S-240W, thus sharing rank 16.

Table I: Ranking of all tested microinverters by “European Conversion Efficiency”, according to (1).

Rank No.	Manufacturer Model, Type	European Efficiency	Relative eff. of #1
1	SMA Sunnyboy 240	95.4%	100.0%
2	Enphase M 215	95.2%	99.8%
3	Hoymiles MI 500	95.0%	99.5%
4	Hoymiles MI 600	94.7%	99.3%
5	Envertech EVT-560	94.6%	99.2%
5	PowerOne/ABB Micro-0.25-i	94.6%	99.2%
7	Huaju HY 600*	94.5%	99.0%
8	Involar MAC 500	94.3%	98.8%
8	Bosswerk Mi600*	94.3%	98.8%
10	APSystems YC 500	94.1%	98.6%
11	Bosswerk MI300*	93.5%	98.0%
12	Envertech EVT-248	93.2%	97.7%
13	Involar MAC 250	92.7%	97.2%
14	WVC 700 (at 600W)	91.6%	96.0%
15	Changetech ELV 300-25	90.9%	95.3%
16	Aptronic INV 250-45	90.4%	94.7%
16	Enecsys SMI-S-240W	90.4%	94.7%
18	Ienergy GT 260	89.9%	94.3%
19	Letrika 260	88.7%	93.0%
20	WVC 700 (at 700W)	73.3%	76.8%
21	WVC 600 (failed)	0.0%	0.0%

* new in 2022

Table II shows the same, but with the CEC-efficiency formula (2) applied. Comment: Envertech EVT-560, Involar MAC 500, and Bosswerk Mi600 have the same conversion efficiency, thus sharing rank 7.

Table II: Ranking of all microinverters by “CEC Efficiency”, calculated according to (2).

Rank No.	Manufacturer Model, Type	CEC-Efficiency	Relative eff. of #1
1	Enphase M 215	95.6%	100.0%
2	PowerOne/ABB 0.25-i	95.5%	99.9%
3	Hoymiles MI 500	95.4%	99.8%

4	SMA Sunnyboy 240	95.1%	99.5%
5	Hoymiles MI 600	95.0%	99.4%
6	Huaju HY 600*	94.9%	99.3%
7	Envertech ENV-560	94.6%	99.0%
7	Involar MAC 500	94.6%	99.0%
7	Bosswerk Mi600*	94.6%	99.0%
10	APSystems YC 500	94.5%	98.9%
11	Bosswerk Mi300*	94.1%	98.5%
12	Envertech EVT-248	94.1%	98.4%
13	Involar MAC 250	93.9%	98.2%
14	Enecsys SMI-S-240W	92.0%	96.3%
15	WVC 700 (at 600 W)	91.6%	95.9%
16	Letrika 260	91.5%	95.8%
17	Ienergy GT 260	91.5%	95.7%
18	AEconversion 250	91.2%	95.5%
19	Changetech ELV 300-25	90.9%	95.1%
20	WVC 700 (at 700W)	87.5%	91.6%
21	WVC 600 (failed)	0.0%	0.0%

* new in 2022

2.2 Thermal issues

In 2021/22, we started also to investigate thermal behavior of newer inverters: Some of the inverters failed when operated close to their nominal power (WVC 600, 700), independent of temperature (see Table I and II). Others (e.g., the Huaju HY 600) reduce their power output at 60°C, but operate normally at 25°C (see Fig. 4), but after cooling down, the inverters operated normally, without any damage. Possibly, that overheating issue was due a relatively compact inverter size.

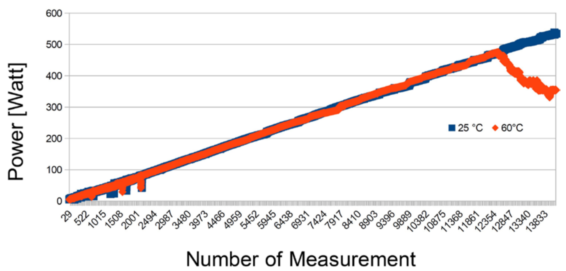

Figure 4: AC power output of the Huaju HY 600 inverter at 25°C (blue line) and at 60°C (red line) ambient temperature (heat chamber in the laboratory).

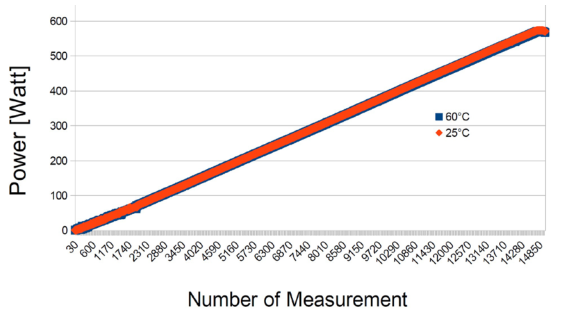

Figure 5: AC power output of inverters at 25°C (blue line) and at 60°C (red line) ambient temperature of Bosswerk Mi600 and Hoymiles HM 600.

Other inverters did not show any power reduction (e.g., Bosswerk Mi600, Mi300, and Hoymiles HM600), even at elevated temperatures (see Fig. 5).

2.3 Outdoor measurements for yield assessments

The new configuration for the tests, using ten 360 W_p modules (lower row, from left), is shown in Figure 6. Modules have been manufactured by Solarwatt®, the power output at STC of each module has been measured in the factory in Dresden (Germany). Additionally, one module has been sent for a precision measurement to the testing laboratory ISFH in Hameln (Germany). It turned out that the factory measurements have been very accurate (362 W_p vs. 359.34 W_p ±3% at ISFH in July 2021).

Besides the effects already observed with the 215 W_p modules, such as distinct conversion efficiencies at different irradiance levels, speed of MPPT algorithms, minimum thresholds for initiating operation; additionally, temporal saturation effects are observed at some inverters with the new 360 W_p modules applied.

Figure 6: Configuration of PV modules of PV outdoor laboratory for electrical energy yield comparison of microinverters using eight equal, calibrated PV modules (of 360 W_p each) as inputs.

The resulting electrical energy yields during the course of a day for the different microinverters and module configurations are shown in Figure 7 for a daily course and in Table III (see [4]) over a longer period of time for the 215 W_p modules. To some extent, the above-mentioned effects can be observed.

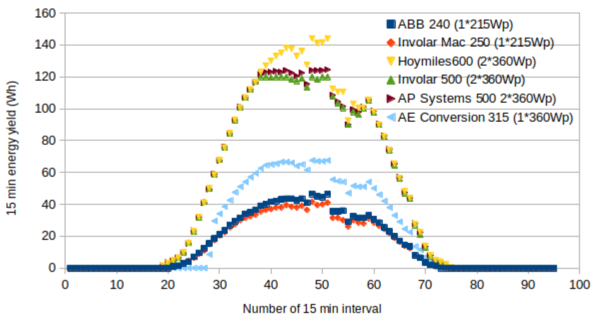

Figure 7: Example of electrical energy yield measurements (during an interval of 15 minutes) of different inverters and 2 different PV module sizes during a mostly clear day (some clouds in the afternoon).

Table III: Former ranking of microinverters by relative energy yield measured, using the 215 W_p modules (1 or 2 of them, as number of inputs), referenced to former #1 (Power One/Aurora/ABB, type Micro-0.25-i) [4].

Rank No.	Manufacturer Model, Type	Relative yield vs. ABB
1	Involar MAC 500	100.7 %
2	Power One/Aurora/ABB Micro-0.25-i	100.0 %
3	APSystems YC 500	99.3 %
4	Hoymiles MI 600	97.4 %
5	SMA Sunnyboy 240	95.2 %
5	Enphase M215	95.2 %
7	Involar MAC 250	94.2 %
8	Envertech EVT 300	94.0 %
9	WVC 700 (at 600 W)	91.7 %
10	AEconversion/Aptronic INV 250-45	92.5 %
11	Envertech EVT 248	92.1 %
12	Ienergy, GT 260	91.5 %
13	Enecsys SMI-S-240W	88.7 %
14	Hoymiles MI 250	78.4 %
15	Changetec ELV 300-25	75.6 %

While the different types of effects make it quite cumbersome to predict an energy yield for a certain configuration at a certain location, a more consumer-friendly yield-predicting method has been elaborated by performing some yield data analysis.

Each microinverter has been directly connected to a calibrated electrical energy meter with a S_0-interface. To secure an accurate yield measurement, the calibrated electrical energy meters are replaced on a regular base with new freshly calibrated ones. All S_0-interfaces have been connected to a server-based data acquisition system.

3 UNIVERSAL YIELD ASSESSMENT

To ease the characterization of a specific combination of PV module & microinverter, a linear equation has been applied to a well investigated reference characteristics of a very good inverter without issues for low irradiance, MPPT, and saturation. The inverter chosen as a reference has been the Enphase M 215, which ranked #1 at the CEC-efficiency rankings, see [4].

Plotting a function of the actual yield (y) over the reference yield (x), that function would be $y = a\,x + b$ with the trivial coefficients $a = 1$ and $b = 0$ for the reference configuration (Enphase M 215 with the Q-cells 215 W_p module). Figure 8 shows the original configuration with the inverters for single modules and the 215 W_p modules attached.

The coefficients of the different inverters for the relative yield equation $y = ax + b$ have been elaborated in Table IV: It can be observed that for low daily yields Involar MAC 250 is performing a little bit better than the reference, so b is above 0, for high yields its performance is decreasing (relative to the reference), so a is above 1. For the Envertech EVT 300 the characteristics is vice versa: Performance at low yields is worse than the reference, so b is negative; relative performance is increasing towards high reference yields, so steepness of curve is higher, resulting in an $a > 1$.

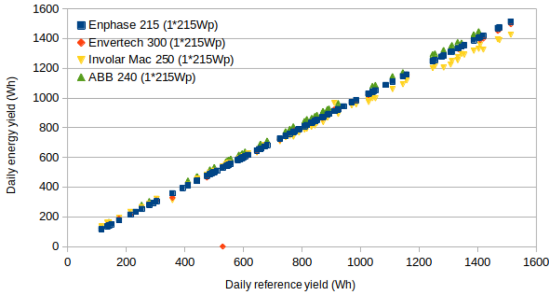

Figure 8: Electrical energy yields of different inverters for single modules with a 215 W_p module attached. Daily reference yield (x-axis) is the energy yield (AC) achieved by an Enphase M215 inverter with a single 215 W_p module applied.

Table IV: Coefficients for relative daily yield $y = a\,x + b$ (referenced to Enphase M 215, all with <u>single</u> 215 W_p modules), yield is given in AC electrical energy

Manufacturer	Type	a	b (Wh)
Involar	MAC 500	0.923	+43.35
Power One /Aurora/ABB	Micro-0.25-i	1.011	+25.90
Envertech	EVT 300	1.020	-33.45
Enphase	M 215	1.000	±0.00
Bosswerk*	Mi 300	0.969	+4.58

*new in 2022

Figure 9 shows the characteristics of different microinverters that can serve two modules, either with two 215 W_p (older measurements) or two 360 W_p modules (latest measurements). Table V shows the corresponding coefficients a (for "steepness") and b (for "offset") of the relative daily yield curve.

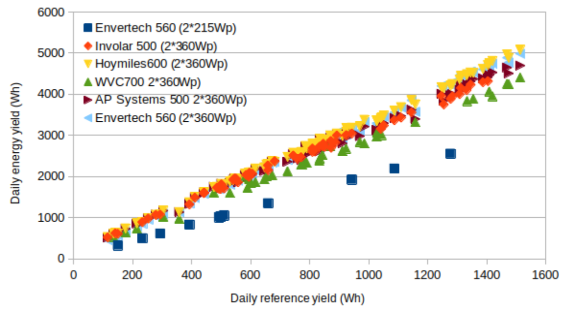

Figure 9: Daily energy yields (AC) of different inverters for two modules with two 215 W_p or 360 W_p modules attached. Reference yield (x-axis) is the yield achieved by an Enphase M215 with a single 215 W_p module applied.

The coefficients of determination R^2 for all regressions of the measurement values to determine the coefficients a and b have been in the vicinity of 0.99 or above.

Table V: Coefficients for relative daily yield $y = a\,x + b$ for microinverters serving two modules, either 215 W_p or 360 W_p types (referred to Enphase M215 with a 215 W_p module), yield is given in AC electrical energy

Manu-facturer	Type (module power)	*a*	*b* (Wh)
Envertech	EVT 560 (2 x 215 W_p)	1.983	+37.80
Envertech	EVT 560 (2 x 360 W_p)	3.227	+109.97
Hoymiles*	MI 600 (2 x 360 W_p)	3.189	+168.32
Involar	MAC 500 (2 x 360 W_p)	2.889	+180.70
AP Systems	YC 500 (2 x 360 W_p)	2.953	+254.77
WVC	WVC 700 (2 x 360 W_p)	2.750	+172.39
Bosswerk*	Mi 600 (2 x 360 W_p)	3.122	+112.17
Huaju*	HY 600 (2 x 360 W_p)	3.141	+153.90

* new or updated (Hoymiles MI 600) in 2022

4 CONCLUSION AND OUTLOOK

The use of a reference configuration together with the two coefficients of a linear equation enables a simple method to describe quite accurately the daily yield performance of any microinverter in combination with any PV module, even with under- or oversized ones. While prices of PV modules are decreasing at a higher pace than prices for microinverters, we will see more configurations with oversized modules and more saturated microinverters more often in the future. This underlines the necessity of a method (e.g., as described) to extrapolate energy yield.

5 REFERENCES

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