EU efficiency for home storage systems – a new and simple procedure

Dr.-Ing Andreas Piepenbrink,
E3/DC GmbH, Osnabrück, Germany

Abstract – in this paper battery and solar inverter topologies combined with lithium ion home batteries are investigated and compared. 5 products of the german market are measured against eachother. The paper derives a **compact measurement procedure to propose an EU efficiency coefficient** for charge/discharge efficiency between solar input and private customer grid (input/output), which allows to judge different types of systems in different operating conditions and load levels. System efficiency of complete home storage system including battery system can be easily determined in the laboratory, neglecting complex simulation based models and omitting physical effects of battery system. The load profile and solar annual distribution is reduced to simple and constant operating points by means of using fixed power level at system input and fixed load level at system output.

A calculation model based on few, but available inverter and battery data, shows excellent agreement between calculation and laboratory procedure. In this paper the architectural advantages of DC powered systems are shown and large differences between different home products are shown and proven.

Introduction to the problem – 30000 home battery systems in Germany have been build by 31th December 2015. These systems are using solar panels as energy source on the roof of private homes and lithium batteries are used to store solar energy targeting maximum usage of solar energy inside the household. The systems are sold to private customer mainly via the sales channels of regional electrical installators, claiming annual level of

- up to 30% solar direct self consumption
- up to 30-40% battery based self consumption and
- up to 30-40% remaining grid consumption

The efficiency of solar inverter without battery usage is high and well known from the so called EU efficiency of solar inverters, showing typical losses in solar yield versus relative power level of nominal inverter power. The efficiency of solar inverters is computed according the following formula:

$$\eta_{Euro} = 0{,}03 \times \eta_{5\%Pn} + 0{,}06 \times \eta_{10\%Pn} + 0{,}13 \times \eta_{20\%Pn} + 0{,}1 \times \eta_{30\%Pn} + 0{,}48 \times \eta_{50\%Pn} + 0{,}2 \times \eta_{100\%Pn}$$

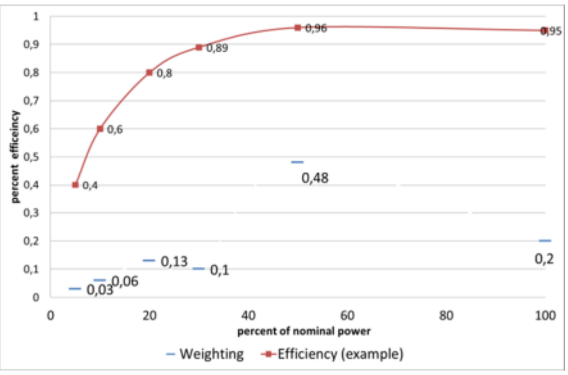


Figure 2: EU efficiency of solar inverters – 32% low power; 48% half power; only 20% full power

The efficiency of the grid power (from customers point of view) is 100%, because the losses are outside his house.

Contrary to known and established solar EU efficiency procedure the whole market of home battery business is missing a value for the battery part. Why the market is missing the efficiency of stored energy at home charged by solar inverters? The excuses, why this number cannot be given, starts from spending research money in academic procedures combined with simulation models without any practical results for manufacturers up to now, continued in the fear of manufacturers, that their system could have weak efficiency and ending in excuses, that different batteries and different inverter types need different investigations and cannot be measured in standardized procedure. As of now, no simulation can model the nonlinear battery physics accurately, therefore simulation based models will also be insufficient to model battery system efficiency.

The technical data sheet offers data, which are often valid and not correct for real life component efficiency. These numbers are mainly irrelevant to derive the EU efficiency for storage process of solar energy (example: standby consumption is given, but power on loss is not given).

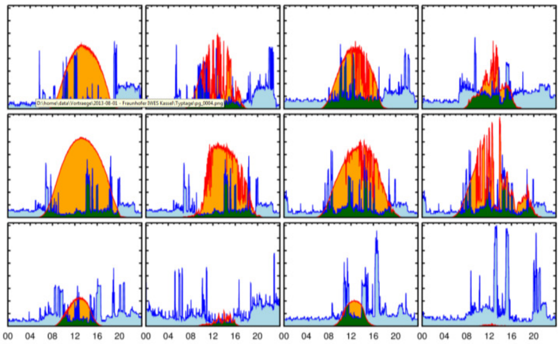


Figure 1: annual solar and customer load profile distribution (24h, 12 typical days) – source: Next Energy Oldenburg

More negative than missing the number for efficiency of the battery system is the fact, that in grid coupled systems (AC) the solar inverter influence is regularly ignored and the data sheet often contains numbers for isolated battery inverter based unit, omitting the fact, that these systems **have to use the grid twice to store and are therefore victims of solar inverter AC efficiency**, especially in low power operation points (cf. 3). Figure 3 shows the typical load profile for battery charge and discharge based on many households in germany, installed since between 2012 and 2016.

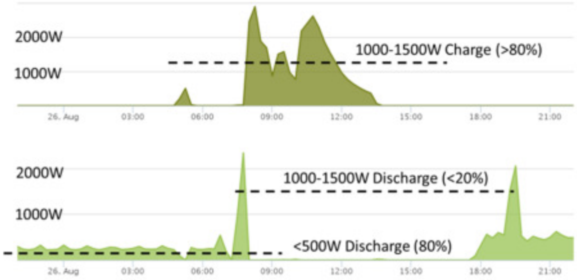


Figure 3: typical charge and discharge (home battery) profile for german household – strong deviation from standard load profile – very low discharge power (average)

This paper derives **a very simple "black box" approach (cf. 4)** to measure the EU efficiency for **battery systems by**

- Taking into account the load profiles from customers to **find constant and to simply represent input and output loads** (instead of taking complete profiles and simulation models)
- **Using an 8 channel standard power measurement unit to black box measure complete system without any constraint for system type (e.g. DC, AC, string storage, cf. 2)**
- **making the capacity of battery system irrelevant and independent for measurement process**
- enabling quick and simple charging and discharging according data sheet of system to reduce procedure **to one! battery cycle**
- **avoiding opening system**
- starting and ending charge and discharge based on system messages (empty and full charge signals)

Measurement procedure

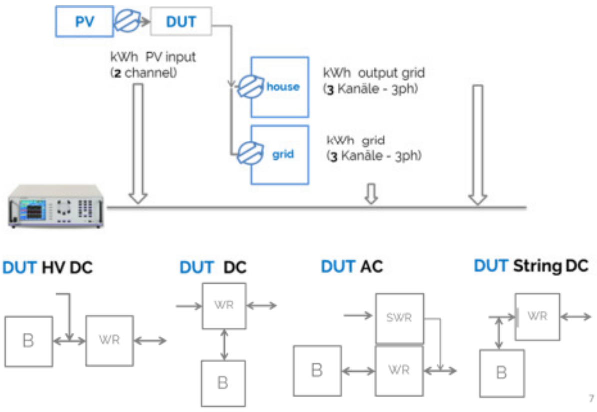


Figure 4: AIO 8 (All In One 8 Channel) measurement setup for all types of storage systems including power source (solar inverter)

Figure 4 shows the setup, which is as follows:

- **DC Input of system is a constant load at fixed input voltage and fixed input power** (e.g. 1000W) – 2 channels for 2 PV strings are measured both, when necessary
- **Charging of battery:** DC Input at constant power (e.g. 1000W) is applied and **battery is automatically fully charged from empty level to full battery level**
- Discharge: 2 System **load's (resistance) at constant power (e.g. 250W or 1000W)** are applied and battery is automatically **fully discharged from full to empty battery level**
- **3ph AC grid of customer household is measured** and **3ph AC output of system is measured** (in total 6 channels of output of the system) – feedin and grid consumption are minimized (ideally zero) or subtracted to isolate system efficiency down best possible level, when charging or discharging battery

Deriving EU efficiency

Load profile curves of private customer (cf. 3) allow to reduce them into 2 **levels** (**250W consumption** with **70% coverage**, **1000W** consumption covering typical efficiency of system by **30% of load profile**).

Solar input is drastically reduced to **one level** (**1000W).** The solar power for charging the battery is normally higher, but the self consumption is subtracted before the battery can be charged. As a fact, battery chargers for homes have typically max. 1000-2000W as nominal power level.

Calculation model for EU efficiency of battery system

According Figure 4 the inverter components are modeled by using

- **efficiency number for DC charge** (from **solar module to battery** plus **battery charge loss**) – typically 10% or more, because battery charge is typically 5% and inverter loss is also typically 5%; in AC systems this number is higher, because 2 AC grid conversions are included, necessary to store solar energy into the battery
- **efficiency number for AC discharge** (**from battery to grid**) – typically 5-10% or more due to inverter losses
- **power on loss as one number for system** (system is fully switched on, all inverters on at 0W output power)

The formulas to compute charging / discharging losses and efficiency are derived by:

Charging_loss (Wh) = t_charge (h) * power_on_loss (W) + (1-eta_DC (%)) * t_charge (h) * charging_power (W)

including

t_charge (h) ~ capacity (Wh) * DOD(%) / charging_power (W)

Therefore the charging losses can be derived by

Charging_loss (Wh) = capacity (Wh) * DOD(%) *
[power_on_loss (W) / charging_power (W) + (1 - eta_DC (%))]

The charging power reduces the losses and the capacity increases the losses. Eta_DC (%) is the efficiency from solar module into the battery plus battery charge loss due to internal battery chemistry process. The discharging losses can be derived in analogy using the formula

Discharging_loss (Wh) = capacity (Wh) * DOD(%) *
[power_on_loss (W) / discharging_power (W) + (1 - eta_AC (%))]

Adding both losses the total loss is

Total_loss (Wh) = capacity (Wh) * DOD(%)*power_on_loss(W)*
[1 / charging_power (W) + (1 - eta_DC(%)) +
1 / discharging_power (W) + (1 - eta_AC (%))]

So the total daily losses in customers 24h profile are

- **proportional to capacity**
- **reverse proportional to charge and discharge power**
- **proportional to power_on_loss**
- proportional to **efficiency losses**

As design parameters therefore only the efficiency losses of inverters as well as power_on_loss remain. Contrary to the public discussion in germany of standby consumption (when no charge or discharge happens, the power_on_losses are very decisive, when charging and discharging, which covers ideally up to 24h of 230-260 days.

The efficiency for a charge / discharge profile is dervived by:

Efficiency (%) = 1 - Total_loss (Wh) / (capacity (Wh) * DOD(%))

resulting in the final formula for system efficiency

Efficiency (%) = 1 –
[**power_on_loss** (W) / charging_power (W) + (1 - **eta_DC** (%)) +
power_on_loss (W) / discharging_power (W) + (1 - **eta_AC** (%))]

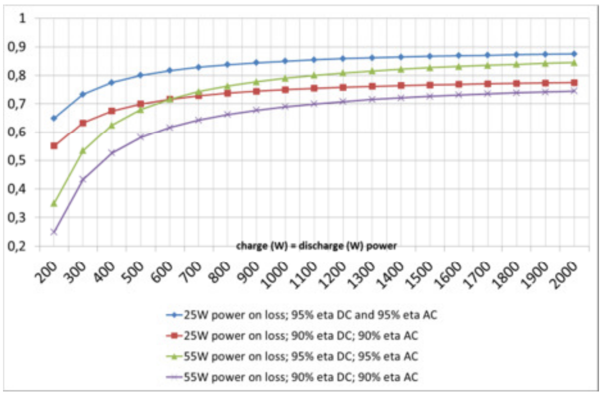


Figure 5: efficiency curves versus power_on_losses and eta_DC (%) / eta AC (%) examples

As already stated, the efficiency is independent from capacity. However, the **3 parameters** (eta_DC, eta_AC and power_on_losses) can be easily found and adjusted in order to validate the measurements and they correlate very good to the consumption and losses known from the system design considerations.

Applying one charge level and 2 dicharge levels in order to keep the measurement effort low the EU efficiency can be derived by (e.g. assuming 70% discharge <250W; 30% discharge <1000W)

EU efficiency home storage system (low power profile) =
(0,3 * eta (1000W Charge, 1000W Discharge) + 0,7 *eta (1000W Charge, 250W Discharge))

Lab Results from systems used

Figure 6 shows the systems investigated (1ph AC from german company, 1ph DC from E3/DC, 2 types of 3ph

DC, E3/DC and Korean battery All In One system). Due to confidentiality, the 2 competitors brands cannot be named here. Their systems have the following data:

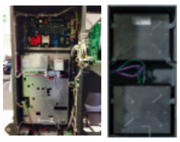
	**Integrated 1ph solar** inverter 2 tracker (4,6kW)	Example: **1ph DC** (60V battery **5,5kWh**) -- **Korean supplier**
	**Integrated** 3ph **solar** inverter 2 tracker (8kW type)	Example: **3ph DC** (120V battery **8,0kWh**) -- **Korean supplier**
	**Example: External** solar inverter 8kW 	Example: **1ph AC** (48V battery **4,8kWh**) -- **german start up**
	**Integrated** 1ph **solar** inverter 2 tracker (4,6kW)	Example: **1ph DC** (48V battery **4,6kWh**) – E3/DC S10 MINI
	**Integrated** 3ph **solar** inverter 2 tracker (12kW)	Example: **3ph DC** (48V battery **6,9kWh**) -- E3/DC S10E12

Table 1: 5 system types investigated for efficiency

The results are as follows:

	1ph AC	**1ph** DC Korea	**1ph** DC E3/DC	**3ph** DC Korea	**3ph** DC E3/DC
1000W/ 1000W	67%	75%	79%	70%	73%
1000W/ 250W	59%	65%	71%	48%	62%
EU value (proposal)	**61,4%**	**68,0%**	**73,4%**	**54,6%**	**65,3%**

Table 2: results from measurements of 5 storage systems (30% @1000W/1000W and 70% @1000W/250W weighting)

Conclusions and facts

Main results are as follows:

- the power on losses affect the losses seriously, because the battery discharge power is relatively low compared to nominal power
- the inverter topology of AC coupled systems allows not to store without grid, therefore additional losses are given due to grid output loss of solar inverter and input loss of battery AC grid store process – AC loss is therefore generally higher and seriously depending on solar inverter low power performance (cf2 1).
- the larger the system power, the better the low power efficiency is, because power on losses of larger inverters are higher – 3ph systems generally are more powerful, therefore losses are slightly higher than identical 1ph storage systems

Some systems (E3/DC 12kW 3ph system versus Korean 3ph system 8kW) have superior efficiency due to TriLINK® Technology, which allows E3/DC to adjust the efficiency to desired level by using phase switch off and by using modern Semikron® state of the art semiconductor types.

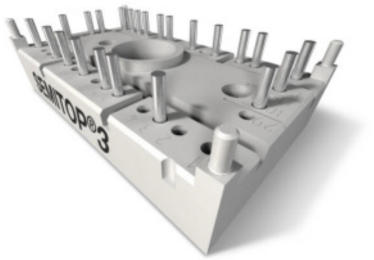


Figure 6: Semikron® semiconductor technology used by E3/DC TriLINK® Technology

Summary

The **loss of 25-30% in annual operation must be taken into account, in many systems >50%,** especially using lead acid batteries, having more than 20% losses in real life. As a result the following efficiency table is valid.

	Solar self consumption	battery self consumption	Grid consumption
Weighting	30%	30-40%	30-40%
Efficiency	<90% real life	<75% real life	100%

Table 3: final results of efficiency spectrum at home

As a consequence approx. **10% additional PV yield must be installed on the roof or 10% less yield from solar yield must be considered.** In normal designs of private household PV the 10% oversizing is no problem and up to 30% is standard procedure. DC Systems (cf. 6) have architectural advantage in efficiency and AC systems have the advantage, that their output power level can be better adjusted to the load profile.

In this paper a simple procedure was found to enable manufacturers and test staff to get quick and reliable measurement for EU efficiency for battery storages and to compare systems of any type and any capacity.

The architecture of the **system type causes** differences of **up to 20% of EU efficiency of the battery**.