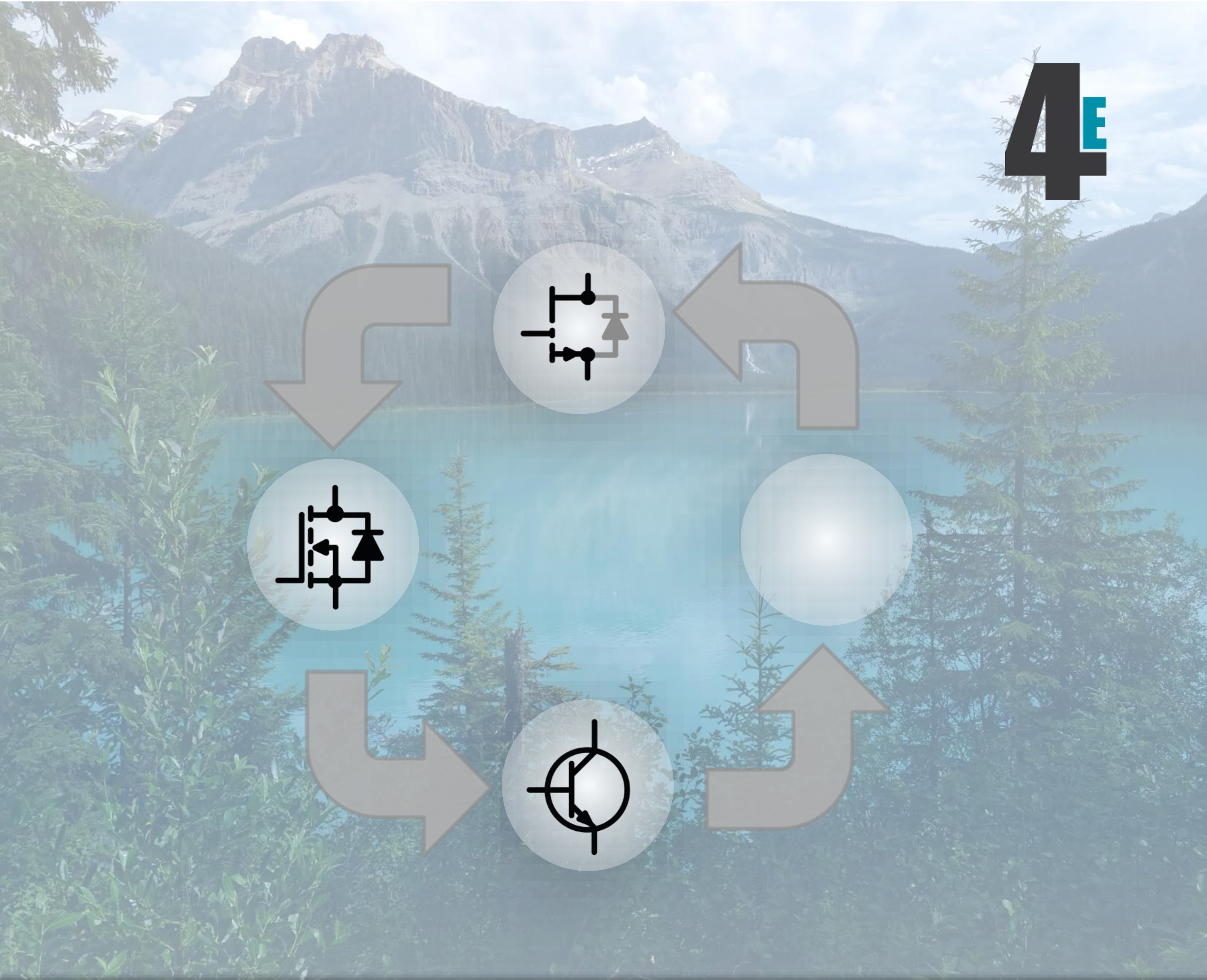

Energy Efficiency Measurement of Wide Bandgap-Based Power Supplies

4E Power Electronic Conversion Technology Annex (PECTA)

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Abstract:
This report discusses different measurement methods to evaluate the efficiency of WBG-based power supply solutions, including electrical and calorimetric methods, and compares the performance of Si-based and GaN-based chargers. The efficiency of chargers was measured at different load conditions, and it was observed that the maximum efficiency occurred generally at higher powers. GaN-based solutions outperformed Si-based chargers at higher power levels, leading to significant energy savings. The report suggests that regulations for efficiency can be tightened and different voltage modes shall be included to ensure further energy savings. The benefits of using WBG devices are more evident in terms of power density, which could lead to their wider adoption in other power electronic applications and to savings of resources.

About the 4E Power Electronic Conversion Technology Annex (PECTA):
Power electronic devices incorporating Wide Band Gap (WBG) technologies are maturing rapidly and offer enormous opportunities for improved energy efficiency. 4E´s PECTA assesses the efficiency benefit of utilizing the emerging WBG technology, keeps participating countries informed as markets for Wide Band Gap technologies devices develop, and engages with research, government and industry stakeholders worldwide to lay the base for suitable policies in this area.

Further information on PECTA is available at:
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Executive Summary

Measurement of small losses and high efficiencies are prone to large errors, especially in the case of high-frequency power electronics components and converters. This report discusses different measurement setup to evaluate the efficiency performance of WBG-based power supply solutions, including electrical measurement methods and their verification with calorimetric methods. A selection of Si-based and GaN-based chargers in the market was investigated to showcase the measurement process, and to compare and better understand their performance. The report summarizes the measurement results of PECTA´s Task F within the first phase 2019 – 2024 and made corresponding conclusions.

The consistency and accuracy of the different measurement methods were determined by comparing different samples of identical charger models. This also showed the error range at different output powers. Additionally, the efficiency and THDi levels of all the investigated chargers were measured at different load conditions, with a communication board to access different output voltage modes. The maximum efficiency occurred generally at higher powers, while it was observed that the chargers were designed to optimize efficiency at lower voltage mode, if several voltage modes are able to attain the nominal maximum power.

The comparison of the efficiency between Si-based and GaN-based chargers of the same power level shows that the investigated chargers present a similar performance at rated power levels up to 30 W. For example, for two chargers with a nominal maximum power of 30 W (Si-based 30 W and GaN-based 30 W), the efficiency at the rated power of four load conditions (25%, 50%, 75% and 100%) was similar, of around 90%.

In the higher power range, GaN-based solutions outperform their Si counterparts for which the average efficiency was 92% for GaN-based 60 W and 90% for Si-based 60 W. Although these numbers are very close, the difference becomes much more considerable in terms of saved energy losses, especially at higher output powers. Calculation showed that considering the daily loading of all worldwide smartphones (6,26 Billion smartphones in 2021), the charging of those devices with GaN-based chargers instead of Si-based chargers would lead to savings of 2.2 TWh.

According to the actual EU commission regulation 2019/1782 for external power supplies, the average efficiency for output powers higher than 49 W must be at least 88%, which was met by mostly all chargers that have been tested. The GaN-based charges showed in general substantial better performance. Therefore, the electrical efficiency regulation requirements could be increased to promote the adoption of GaN-based technologies, aiming for higher efficiencies.

However, it should be noted, that todays 20 V/65 W chargers come with several different features (e.g., single output PD charging: 5 V (15 W) – 20 V (65 W); Dual output: first output: PD charging e.g., (5 V (15 W) – 20 V (65 W)) and second output: either PD charging (5 V (15 W) – 20 V (65 W)) or QC (quick charging: 5 V, 15 W); more than 2 outputs: combination of the defined above). So one output addresses several different voltage and dedicated maximum power ratings per voltage level (limited by the output current of in this specific case 3 A). The EU commission regulation 2019/1782 for external power supplies is however, not precisely addressing how to handle a single charger that provides different voltage and power levels and multiple outputs.

The benefits of using WBG devices are more evident in terms of power density, with a reduction of about two-fold, both in volume and weight. Power density is currently a strong motivation for using GaN devices among manufacturers. As the power charger market was the first to experience the penetration of WBG devices, and the associated advantages have emerged, it can be foreseen that other power electronic applications will also benefit from their wider adoption, not only in terms of more material saved from high power density, but also from higher efficiencies.

Contents

1. Measurement Setup

1.1. Scope

This report describes a generic measurement setup to assess voltage and current waveforms of an AC/DC power stage, to determine the electrical efficiency of wide bandgap (WBG) based power electronic solutions. It summarizes the results of PECTA´s Task F of the first phase 2019 – 2024, but can be updated according to new insights or relevant inputs from PECTA experts during the foreseen 2nd phase of PECTA (2024 – 2029).

The current document is primarily based on the following standards and European regulation documents:

- EN 50530 (Overall efficiency of grid connected photovoltaic inverters) and IEC 62891 (Maximum power point tracking efficiency of grid connected photovoltaic inverters)
- IEC 61683 (Photovoltaic systems – Power conditioners – Procedure for measuring efficiency)
- IEC 62301 – Household electrical appliances - Measurement of standby power
- IEA 4E EDNA Guidance Note on Measurement and Data Collection
- Code of Conduct on Energy Efficiency of External Power Supplies v5, European commission, Ispra, 29 October 2013
- EU Commission Regulation 2019/1782 of October 2019 laying down Ecodesign requirements for external power supplies pursuant to Directive 2009/125/EC and repealing Commission Regulation EC No 278/2009

1.2. Definitions

AC: Alternating current.

DC: Direct current.

Device under test (DUT): The device under test is a circuit supplied by an AC or DC source, operating under specific load (full, partial or no load) conditions.

Apparent power: The apparent power is the total power (active and reactive power) drawn by the DUT. Unit: VA.

Active power: The active power is the resistive amount of power drawn by the load, which has to be transferred by the DUT including losses of the DUT. Unit: W.

Reactive power: The reactive power is the power which flows back and forth between Source and DUT. Unit: Var.

Source: The source is required to power the DUT and provides the amount of energy drawn by the DUT and the equipped load (if available). The source can be either the power grid itself, an AC or a DC simulator or any other kind of conventional power supply. The type of source depends on the DUT and its specifications (AC/DC, DC/DC, DC/AC circuit, input voltage, input frequency, power rating).

Load: The load is an additional device or component which consumes electric power and is directly attached or including additional cables or wiring to connect it to the DUT's electrical output terminals.

Rated input voltage: Supply voltage specified by the manufacturer of the DUT.

Rated input frequency: Supply frequency specified by the manufacturer of the DUT, can be zero in the case of DC.

Rated output voltage: Nominal output voltage specified by the manufacturer of the DUT.

Rated output frequency: Nominal output frequency specified by the manufacturer of the DUT, can be zero in the case of DC.

Rated power: Nominal power specified by the manufacturer of the DUT.

Electrical efficiency: The electrical efficiency is the ratio between the total active output power and the total active input power, measured at the input and output terminals of a DUT.

Condition/Mode: Condition or mode is a state or function that specifies the performance of the load connected to the DUT. In principle there are several types of conditions or modes that can be relevant for the DUT. This includes for example off mode, standby mode (or no-load condition), nominal condition, etc.

Rated efficiency: The rated efficiency is the electrical efficiency of the DUT under rated (nominal) conditions.

Partial efficiency: The partial efficiency is the electrical efficiency of the DUT under partial load conditions.

Power factor: The power factor is the ratio between the active input power and the apparent power related to the DUT.

Silicon (Si): Material which is currently used in most available power semiconductors.

Wide Bandgap (WBG): Material, which is similar to silicon, but coming with a larger bandgap and further beneficial material characteristics supporting improved intrinsic physical characteristics, such as gallium nitride (GaN) and silicon carbide (SiC).

1.3. General Measurement Conditions

The following chapter describes a general setup, and relevant aspects to consider prior to establishing a test setup for measuring the energy efficiency of AC/DC chargers.

Temperature: All tests are carried out in a room or test cabinet with an air conditioner controlling the local room temperature. The ambient temperature shall be maintained at 23 °C (±3 °C) during both summer and winter season.

Test cabinet: The DUT is placed in a test cabinet for safety and security purposes.

Measurement equipment: All input and output voltage and current waveforms are monitored via digital multimeters, current and differential voltage probes including an oscilloscope, and a power analyzer to monitor input and output current and voltage waveforms.

Input voltage and frequency: If the test voltage and frequency are not determined by a standard or guideline, both input voltage and frequency shall be equal to the rated input voltage and frequency of the country or a set of countries for which the measurements are conducted. The deviation between the rated characteristics and real voltage and frequency values should be within a maximum limit of ±1 %. For European grids the following specification can be considered:

- Input voltage single phase: 230 V_{rms}
- Mains frequency: 50 Hz

In other regions or countries such as United States or Japan different regulations may apply. The United States and Canada for example utilize 120 V (±6 %) and 60 Hz nominal frequency. Japan´s low voltage grid operates at 100 V_{rms} and 50 Hz in eastern regions, and at 60 Hz in western parts. It has to be noted, that a lower input mains voltage results in higher nominal currents for the same nameplate power.

Example: 100 W (Nameplate output power) external Laptop charger for 230 V_{rms} and 120 V_{rms} 50/60 Hz operation. Nominal current for European low voltage grids results in approximately 0.43 A, and for US requirements in 0.83 A. Unity power factor is assumed for this specific example.

Input voltage waveform: The input voltage supplied by the source is in general not of purely 50 Hz sinusoidal nature but contains additional harmonic content. The harmonic content of the input voltage should not exceed a total of 2 % up to the 13th harmonic under nominal load operation of the DUT. Thus, this includes harmonic content up to and including 650 Hz for 50 Hz and 780 Hz for 60 Hz mains, respectively. The harmonic content is defined by:

$$\text{THD (\%)} = 100\frac{\sqrt{V_2^2+V_3^2+V_4^2+\cdots}}{V_1},$$

where V_1 is the fundamental signal of the respective waveform and V_2, V_3, V_4 etc. are the harmonics of higher orders. The harmonic content of the voltage supply shall be recorded during all conducted test scenarios.

Ideally, the ratio between Sinusoidal peak voltage and rms voltage is defined by:

$$\frac{V_{pk}}{V_{rms}} = \sqrt{2} = 1.414.$$

According to IEC62301 for the supplied non-ideal source voltage this ratio shall be between the designated limits of

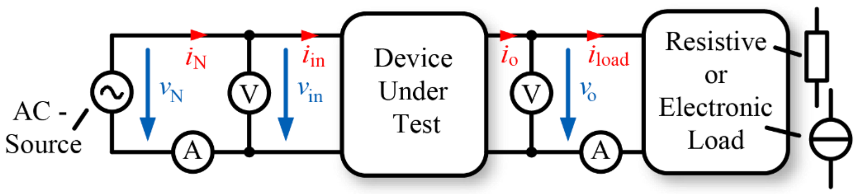
$$1.34 < \frac{V_{pk}}{V_{rms}} < 1.49.$$

1.4. General Measurement Setup

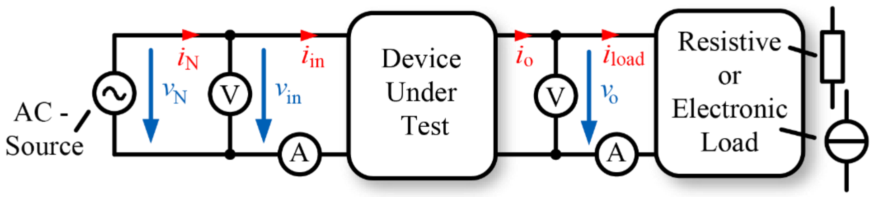
In order to measure the electrical efficiency, both the input and the output power of the DUT shall be determined. Therefore, input voltage, input current, output voltage and output current must be measured as accurately as possible. The respective DC power then calculates to

$$P = VI.$$

For the active AC power, fundamental and harmonics with resistive content must be considered. The nature of measuring voltage and current simultaneously requires positioning one of both measurements closer to the DUT compared to the residual one. For both, input and output power evaluation, two different options are feasible – either voltage or current probe directly attached to the input/output terminals. Thus, four different solutions exist. The two most common versions will be discussed in the following, and are illustrated in Figure 1 (a) and (b).



(a)



(b)

Figure 1(a) Measurement setup 1: voltage and current probe arrangement for a DUT (AC/DC converter) supplied from an AC-source for high power loads. (b) Measurement setup 2: Voltage and current probe arrangement for a DUT (AC/DC converter) supplied from an AC-source for low power loads.

The setup for the DUT electrical efficiency measurement should be chosen according to the respective power rating and internal resistive values of the current and voltage sensor.

- For **high power** measurements setup 1 (as shown in Figure 1 (a)) is recommended.
- For **low power** measurements setup 2 (as shown in Figure 1 (b)) is recommended.

The different setups are required to maintain sufficient accuracy (should be less than 1 % per calculated power value) of the power measurement and thus the electrical efficiency of the DUT. Usually, voltage probes are modelled as ideal open circuit, whereas current sensors are in general considered as short circuit. However, depending on the chosen current sensor technology, in most power analyzers a simple shunt measurement with dedicated electrical components (e.g. voltage amplifier) to shape the measured output voltage across the shunt resistor, is considered. This resistor however, results in an additional voltage drop and extra losses which are not associated with the DUT. Assuming an external 200 W AC/DC converter for 230 V_{rms}/50 Hz input, 12 V_{DC} output and a shunt resistor of 0.5 Ω to measure the input current, the voltage drop of the shunt resistor calculates to:

$$V_{shunt,rms} = R_{shunt} I_{N,rms} = 0.48\ V$$

and the dedicate losses result in:

$$P_{shunt} = R_{shunt} I_{N,rms}^2 = 0.47\ W.$$

Also, the input resistance of the voltage probe is not infinite and can be expected to be typically around 1 MΩ or higher (exact value depends on probe type and is specified in voltage probe datasheet). Therefore, the additional current drawn from the source can be estimated to

$$I_{V,rms} = \frac{V_{N,rms}}{R_V} = 230\ \mu A$$

and dedicated losses are:

$$P_V = \frac{V_{N,rms}^2}{R_V} = 0.053\ W.$$

A smaller value for the DC-side shunt resistor is required to reduce resistive losses due to a distinctly higher output current under nominal load operation. As can be seen from the previous equations, and also illustrated in Figure 2, it is obvious that the measurement accuracy is higher in this specific case with the chosen parameters at hand, if the current sensor is connected to the supply side and the voltage meter directly to the DUT.

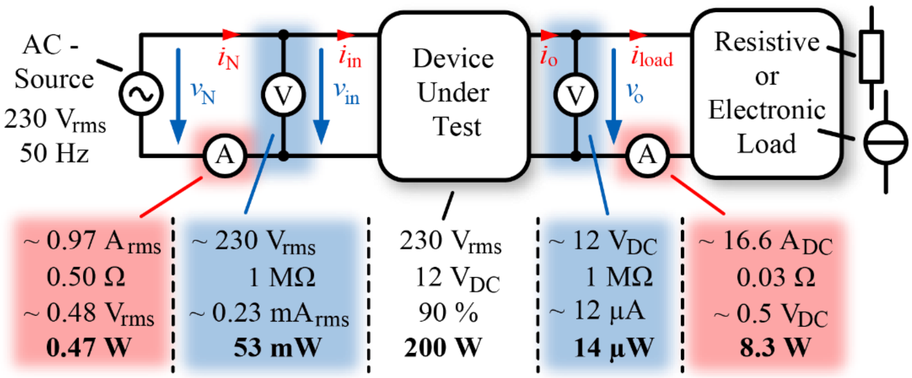


Figure 2 Measurement setup 1 considering real values for internal resistance of voltage and current sensors. DUT nameplate output power is 200 W with an electrical efficiency of 90%. The DUT is an AC to DC converter with a nominal input voltage 230 V and a DC output voltage of 12 V. Parasitics of internal components are neglected.

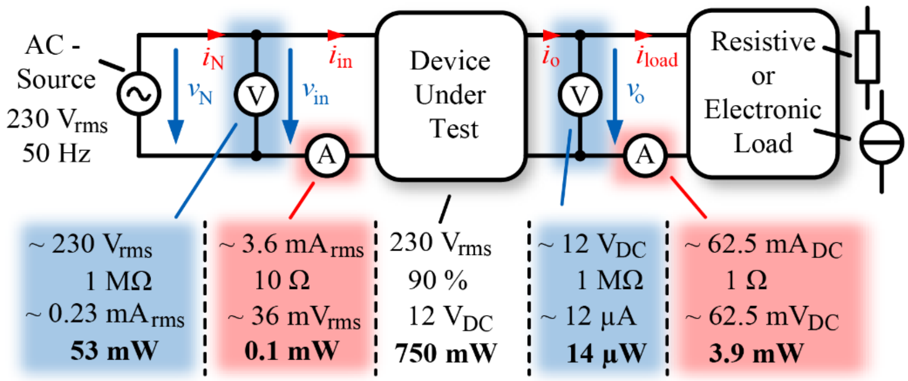


Figure 3 Measurement setup 2 considering real values for internal resistance of voltage and current sensors. DUT nameplate output power is 750 mW with an electrical efficiency of 90%. The DUT is an AC to DC converter with a nominal input voltage 230 V and a DC output voltage of 12 V. Parasitics of internal components are neglected.

A second example for low power measurements is demonstrated in Figure 3. Here the internal high ohmic resistance and its dedicated power consumption will highly inflict the power measurement. Therefore, the voltmeter shall be connected to the supply side for this type of DUT instead of connecting it to the DUT input terminal. Both examples for Figure 2 and Figure 3 assume that the DUT comes with an efficiency of 90 %. Furthermore, it can be seen that for setup 1 it is of major importance to connect the ampere meter to the load, whereas the voltage probe should be connected to the DUT side, due to the high losses of the shunt, considered for high resolution. For setup two both output probes come with rather low losses compared to the nameplate power. However, as the voltage sensor still has significant lower losses due to the low voltage, it should be preferred to be connected directly to the DUT output terminals.

The difference in accuracy of both test setups related to the input power measurement shall be highlighted for a low power measurement in the following. DUT specifications and both, current and voltage probe is specified in the following:

$$P_{\mathrm{o}} = 750\ \mathrm{m}W, V_{\mathrm{in}} = 230\ V, \eta_{\mathrm{DUT}} = 90\ \%, R_{\mathrm{shunt}} = 10\ \Omega, R_{\mathrm{V}} = 1\ \mathrm{M}\Omega$$

For **setup 1**, the input power can be calculated to

$$P_{\mathrm{in,meas}} = V_{\mathrm{in,rms,meas}} I_{\mathrm{shunt,rms}} = V_{\mathrm{in,rms}}\left(I_{\mathrm{in,rms}} + I_{\mathrm{V,rms}}\right) =$$

$$= V_{\mathrm{in,rms}}\left(\frac{P_{\mathrm{o}}}{\eta_{\mathrm{DUT}} V_{\mathrm{in,rms}}} + \frac{V_{\mathrm{in,rms}}}{R_{\mathrm{V}}}\right) = 886.2\ \mathrm{m}W$$

For setup 1, $V_{\mathrm{in,rms,meas}}$ equals $V_{\mathrm{in,rms}}$. The current measured by the shunt connected to the source adds up due to the current drawn by the voltage probe and the DUT.

For **setup 2**, the input power results in

$$P_{\mathrm{in}} = 833.3\ \mathrm{m}W, I_{\mathrm{in}} = 3.62\ \mathrm{m}A$$

$$P_{\mathrm{in,meas}} = V_{\mathrm{in,rms,meas}} I_{\mathrm{shunt,rms}} = \left(R_{\mathrm{shunt}} I_{\mathrm{in,rms}} + V_{\mathrm{in,rms}}\right) I_{\mathrm{in,rms}} =$$

$$= \left(R_{\mathrm{shunt}} \frac{P_{\mathrm{o}}}{\eta_{\mathrm{DUT}} V_{\mathrm{in,rms}}} + V_{\mathrm{in,rms}}\right) \frac{P_{\mathrm{o}}}{\eta_{\mathrm{DUT}} V_{\mathrm{in,rms}}} = 833.5\ \mathrm{m}W$$

As can be seen, the **measurement error** related to **setup 1** is approximately **6.35 %**, whereas for **setup 2** an error due to loading of voltage and current probes of around **0.02 %** exists. Therefore, for the chosen parameters at hand, regarding input voltage, current sensor, voltage probe and DUT output power, test setup 2 should be preferred over measurement setup 1.

According to IEC 62301, the break-even current for supply side voltage measurement is given by:

$$I_{\mathrm{in,rms,boundary}} = V_{\mathrm{in,rms}} \sqrt{\frac{1}{R_{\mathrm{shunt}} R_{\mathrm{V}}}} = 73\ mA$$

or the break-even power computes to:

$$P_{\text{in,boundary}} = V_{\text{in,rms}}^2 \sqrt{\frac{1}{R_{\text{shunt}} R_{\text{V}}}} = 16.7\ W.$$

1.5. Load Conditions

The load conditions for electrical efficiency measurements for power electronic converters as specified in commission regulation (EU) 2019/1782 for external power supplies are defined as follows:

- Load condition 1: 100 % · P_o ± 2 % (referred to as full-load or nominal load mode)
- Load condition 2: 75 % · P_o ± 2 % (referred to as partial load mode)
- Load condition 3: 50 % · P_o ± 2 % (referred to as partial load mode)
- Load condition 4: 25 % · P_o ± 2 % (referred to as partial load mode)
- Load condition 5: 10 % · P_o ± 1 % (referred to as partial load mode)
- Load condition 6: 0 % · P_o - (referred to as no-load mode)

The average efficiency η_{avg} can then be calculated via: $\eta_{avg} = (\eta_{25\%} + \eta_{50\%} + \eta_{75\%} + \eta_{100\%})/4$, which is different compared e.g. to the European efficiency of PV inverters which include additional weighting factors ($K_{5\%} = 0.03$, $K_{50\%} = 0.48$, etc.).

1.6. Uncertainty

In general, every measurement comes with uncertainties, as voltage and current probes as well as connectors, cable, and wiring are not ideal components. Thus, uncertainties characterize the dispersion of a measurement. However, also inconsistent behavior of the product can lead to uncertainties of measured results as they are dedicated to a specific state of the DUT.

IEC 62301 determines the following relevant parameters contributing to the uncertainty of a measurement:

- Power measuring instrument (voltage probe, current sensor, temperature sensor etc.);
- Wiring (additional parasitic resistors, capacitors occur etc.);
- Voltage and THD of the converter;
- Ambient temperature of the DUT (example: junction temperature of the semiconductor is relevant in terms of switching and conduction losses. The higher the ambient temperature, the higher the junction temperature for a given power loss performance. Thus, the ambient temperature can influence the performance of the converter.).

IEC 62301 identifies several types of uncertainties that can but do not need to be considered (depending on their significance):

1. Uncertainty of the measuring instrument ($P_{u,1}$):
   a. Measured value (the reading);
   b. The power range;
   c. The power factor;
   d. The temperature of the power meter and shunt.
2. Uncertainty due to measurement method ($P_{u,2}$) and wiring (mostly measurement method can bring in significant uncertainty);
3. Uncertainty due to source ($P_{u,3}$) e.g. grid, converter etc. – voltage tolerance (1 % change of input voltage results in 2 % change of power for resistive load):
   a. $P_{\text{R}} = \frac{V_N^2}{R_{\text{load}}} = \frac{(V_{\text{N}}+1\%\,V_{\text{N}})^2}{R_{\text{load}}} = \frac{V_N^2}{R_{\text{load}}}(1.01)^2 = 1.02\frac{V_N^2}{R_{\text{load}}} = \frac{V_N^2}{R_{\text{load}}} + P_{\text{u,3}}$
   b. $P_{\text{u,3}} = 0.02\frac{V_N^2}{R_{\text{load}}}$
4. Uncertainty due to temperature ($P_{u,4}$) of the DUT (as aforementioned);
5. Other not defined uncertainties ($P_{u,5}$).

All uncertainties are defined in watt. The total uncertainty ($P_{u,tot}$) eventually can be calculated including uncertainty factors of all aforementioned uncertainties (1-5) by:

$$P_{\mathrm{u,tot}}(W) = \sqrt{P_{\mathrm{u},1}^2 + P_{\mathrm{u},2}^2 + \cdots + P_{\mathrm{u},5}^2}.$$

Uncertainties should be included as far as defined in datasheets or relevant/significant in terms of measurement failure or error.

1.7. Electrical Measurement Test Setup

Modern low-wattage cell phone or laptop power supplies can change their output voltage from 5 V to 20 V, which is depending on the target device to be charged. A laptop for example normally requires a charging voltage of 20 V, whereas a cell-phone is demanding a charging voltage in the 5 V range. Product specifications of a 60 W DC-charger, which allows 5 different voltage configurations at the output (5 V, 9 V, 12 V, 15 V, 20 V) are given in Table 1. By inspecting Table 1 it is obvious that the output current of the device is limited to 3 A. Therefore, the full output power of 60 W can only be delivered during a 20 V loading scenario. Hence, the charger requires a communication interface between the charger itself and the device to be charged, in order to set the correct output voltage before the charging process is going to be initiated. In order to verify the electrical efficiency for all different operating points (5 V – 20 V; 0 W – 60 W), the test setup requires an additional communication board which allows to set the different voltage and loading scenarios manually. Examples of such communication boards are the Infineon/Cypress CY4533 EZ-PD or the TI TIDA-050012.

Table 1 Proposed table to record WBG converter measurements.

60 W Output			
	DC output voltage	**Max. DC output current**	**Maximum output power**
	5 V	3 A	15 W
	9 V	3 A	27 W
	12 V	3 A	36 W
	15 V	3 A	45 W
	20 V	3 A	60 W

An example of a test setup including current and voltage sensors, a power analyzer, a communication board, and an electrical load is shown in Figure 4.

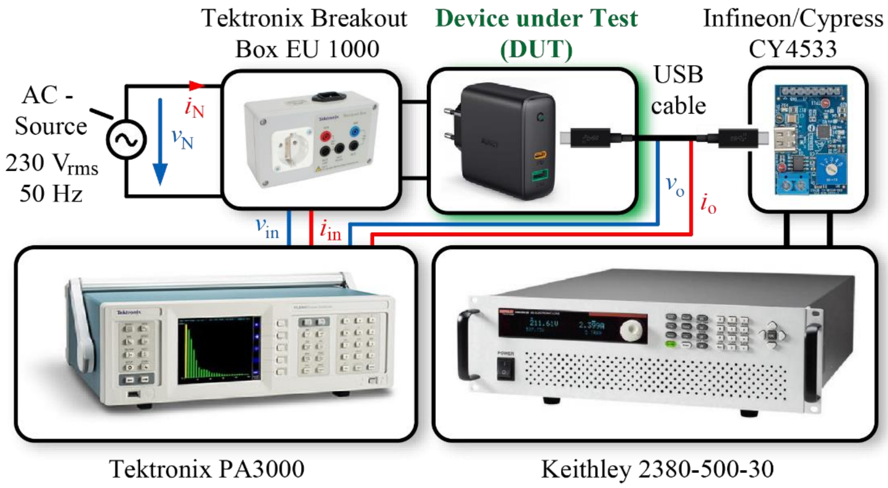


Figure 4:Test setup including measurement devices, source, load and power analyzer.

The test equipment consists of the following products and devices:

- Power analyzer: Tektronix PA3000
    - Integrated 1 A shunt: for input current measurements
    - Integrated 30 A shunt: for output current measurements
- Tektronix break-out box: BB1000-EU (240 V)
- PD Communication Kit (Eval board): Infineon/Cypress CY4533 EZ-PD
- Current Sink: Keithley 2380-500-30

1.8. Measurement Procedure

The following parameters should be recorded during the measurement:

- I_{in} … input current RMS
- V_{in} … input voltage RMS
- P_{in} … active input power
- V_o … DC- and RMS output voltage. For multistage systems – DC-link voltage of DC-bus
- I_o … DC- and RMS output current
- P_o … active output power as average over instantaneous active power
- η … system efficiency
- THD_v … harmonic distortion of input voltage
- THD_i … harmonic distortion of input current
- T_{amb} … ambient temperature
- S_{in} … apparent input power (can be computed afterward)
- λ … power factor (can be computed afterward)

The initial heat up time of the system for each load condition (from 0% - 100%) should be at least 10 minutes. This is also proposed in IEC 62891. It is important that measuring times are not too short, as also additional temperature effects on the system efficiency dedicated to wide bandgap and Si (e.g., change of internal on-resistance due to higher junction temperature, etc.) and other materials such as copper or aluminum, must be reflected in the measurement.

Only measurements after the initial 10 minutes of heat up time are accepted. Initial measurements from 0 to the 10 minutes mark are only relevant for general monitoring and shall not be recorded. If a stabilization cannot be observed a stabilization time of at least 5 minutes must be considered. If the power level is changed from one condition to the next one (e.g. 25% to 50%), a general stabilization period of at least 3 minutes should be considered. Again, data recorded or calculated efficiency values during the stabilization period must not be recorded but can be used to determine whether thermal equilibrium is reached.

A table such as Table 2 that can be used as a template is shown on the following page.

It should be noted that for power supplies < 75 W a low power factor is expected, as according to 61000-3-2 no active power factor correction is required for these types of devices.

Table 2 Proposed table to record WBG converter measurements.

Converter Name and Type:

____

Nameplate Power Rating and Voltage class:

____

Load Conditions	$V_{in,rms}$ (V)	$I_{in,rms}$ (A)	P_{in} (W)	S_{in} (VA)	λ (1)	V_o (V)	I_o (A)	P_o (W)	η (%)	THDv (%)	THDi (%)	T_{amb} (°C)	Comment
0 %													
25 %													
50 %													
75 %													
100 %													

1.9. Further Information for Validation of the Efficiency of Converters

In order to get an indication on effects of WBG devices on the system efficiency it is in general not sufficient to just identify the system efficiency of the DUT. There are several additional parameters that can impact the performance of WBG devices.

It might be assumed that the manufacturers of AC/DC converters in general do not replace silicon with WBG components for the sole purpose of improving their energy efficiency. Other drivers might be the demand of customers for more compact and smaller AC/DC converters, allowing easier handling. Thus, efficiency would play a secondary role. Manufacturers tend to stay on the limit of compliance for efficiency regulations as a way to optimize cost of the products. Therefore, the interest of manufacturers leans towards reduced volume, weight, input/output filter volumes, etc.

4E PECTA is mainly focused on efficiency improvement due to the integration of WBG semiconductors in products. Thus, if Silicon and WBG products are compared, ideally additional information (data) should be recorded, to quantify the energy efficiency improvements due to WBG, but also the power density, and additional relevant parameters.

Additional information about the product is:

- Switching frequency — absolutely relevant
- Topology — absolutely relevant
- Total volume/weight — absolutely relevant
- Internal voltages (if applicable, e.g. device drain-source voltage) — absolutely relevant
- Packages (thermal impedance) — beneficial if available
- Commutation loop related to par. Inductance (Power loop) — beneficial if available
- Transformer core size and type — beneficial if available
- Volume of the EMI-Filter part — beneficial if available

If one of these parameters cannot be addressed, it must be stated in the measurement report, that one or more of these parameters were not accessible. It should be noted, that there is no standardized process to identify these additional parameters as this may require destructive opening and dedicated measurements, nor is it intended by product manufacturers to share this data with any externals.

Eventually, two examples should highlight the relevance of reporting the aforementioned additional information that should be provided for a fair comparison of Si and WBG. The figures in these examples are fictitious, and not based on real measurements of available products.

Example 1:

First product:

- 10 kW Si MOSFET-based charger
- *30 kHz switching frequency*
- 95 % measured efficiency
- *5 kW/dm^3 power density*

Second product:

- 10 kW WBG-based charger
- *70 kHz switching frequency*
- 95 % measured efficiency
- *7.5 kW/dm^3 power density*

The **goal of using WBG in this example is to achieve a higher power density while maintaining the (overall) system efficiency.**

If only the system efficiency of both products would have been used as reference to compare each other, without considering other parameters such as switching frequency and volume, it would be misleadingly concluded that the integration of WBG instead of silicon would have no effect on the energy efficiency of the DUT. This statement would be incorrect, as due to the integration of WBG and its lower switching losses, the switching frequency of the semiconductors could be increased, leading to the same energy efficiency and higher power density.

Example 2:

First product:

- 1 kW Si based on-board charger
- 30 kHz switching frequency
- 5 kW/dm^3 power density
- *93% measured efficiency*

Second product:

- 1 kW WBG based on-board charger
- 30 kHz switching frequency
- 5 kW/dm^3 power density
- *95.5% efficiency*

WBG has been chosen in this example to merely optimize the system efficiency. Measurement results clearly show that there is an increased system efficiency due to the integration of WBG devices. However, the power loop in this example was assumed to be unfavorable and also suboptimal packages such as TO220 packages have been utilized. The efficiency potential for WBG in this example is expected to be even more significant than the observed results from the field test, as high parasitic inductance values due to package dominate. Leads and bad wiring can limit WBG performance. Such information and analysis would be beneficial and facilitate a more comprehensive comparison.

Additionally, it must be mentioned that validating different products will be even more complex especially if one or more technologies are hybridized.

1.10. Considerations of Electrical Measurements without a Power Analyzer

The simplest way to measure input and output power is by using an existing power analyzer, for example those power analyzers from Tektronix, Dewesoft or Rohde & Schwarz. If a power analyzer is not available, the active input and output power must be derived by using current sensors and voltage probes. Results should be double checked via an oscilloscope. To obtain the correct active input and output power the following rules must be followed.

Only current and voltage waveforms with same frequency and phase angle contribute to the active power of a system. For AC/DC products it is hence not sufficient to use digital multimeters, as at least a Fast Fourier Transform (FFT) feature is required to separate harmonics, and to obtain the phase angle between voltage and current waveforms of the same frequency.

Generic formulas are given to obtain fundamental apparent, active and reactive power of a system:

$$S_{\text{fund}} = \frac{1}{T}\sqrt{\int_{t_x}^{t_x+T} v_{\text{fund}}^2(t)\,dt \cdot \int_{t_x}^{t_x+T} i_{\text{fund}}^2(t)\,dt} = V_{\text{fund,rms}} \cdot I_{\text{fund,rms}}$$

$$P_{\text{fund}} = \frac{1}{T}\int_{t_x}^{t_x+T} v_{\text{fund}}(t) i_{\text{fund}}(t)\, dt \cdot = V_{\text{fund,rms}} \cdot I_{\text{fund,rms}} \cdot \cos(\varphi_{\text{fund}})$$

$$Q_{\text{fund}} = \sqrt{S_{\text{fund}}^2 - P_{\text{fund}}^2} = V_{\text{fund,rms}} \cdot I_{\text{fund,rms}} \cdot \sin(\varphi_{\text{fund}})$$

$$\varphi_{\text{fund}} = \varphi_{\text{V,fund}} - \varphi_{\text{I,fund}}$$

where $V_{\text{fund,rms}}$ and $I_{\text{fund,rms}}$ are the RMS value of the fundamental component of the voltage and current waveform, φ_{fund} is the phase difference between them, Q the reactive power and T the respective time of the periodic signal.

Thus, the following formula should be considered for deriving the active power of a generic waveform with several harmonics involved and based on results of an FFT:

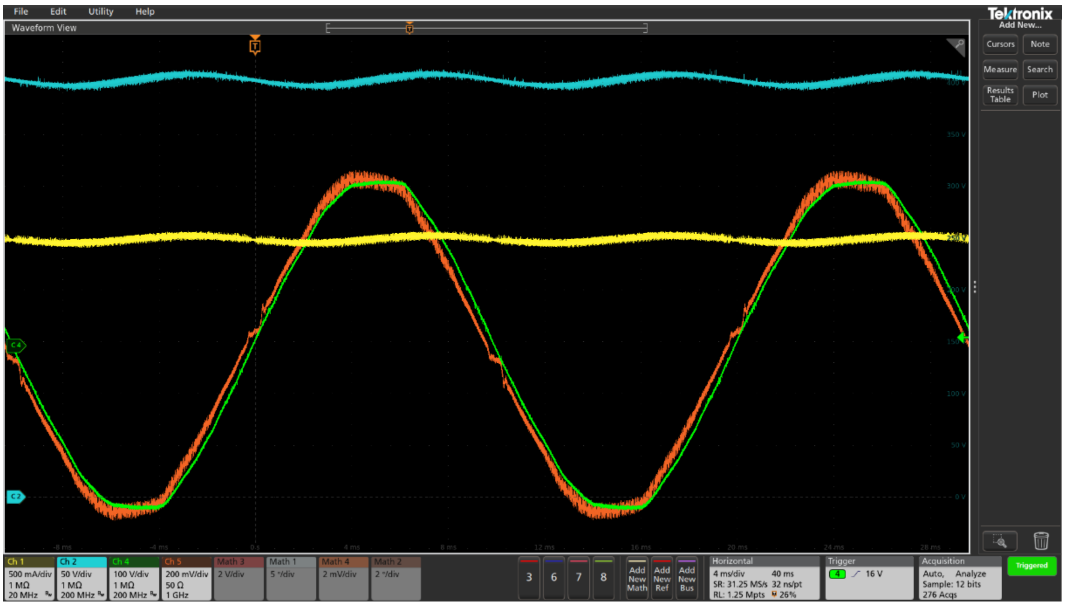
$$P = \sum_k V_{\text{k,rms}} \cdot I_{\text{k,rms}} \cdot \cos(\varphi_{\text{k}})$$

An example highlights the correct approach and address inaccuracy, if limited (insufficient) information is recorded:

The following voltage and current waveforms (green: grid voltage, orange: grid current) are obtained from an on-board charger at 1 kW charging power.

Two things can be initially observed:

- Whereas the grid voltage seems to show mostly sinusoidal behavior, the grid current comes with additional distortions and higher harmonics.
- Grid voltage appears to be lagging slightly (approx. 6°). This effect originates according to X- and Y-capacitors (differential mode and common mode mitigation) of the grid connected filter of the charger.



The following parameters were recorded at 1kW loading:

$V_{in,pk}$ (V)	$V_{in,1,pk}$ (V)	$I_{in,pk}$ (A)	$I_{in,1,pk}$ (A)	φ_1 (°)	P_{in} (W)
322.26	321.14	6.56843	6.43227	5.6	**1027.9**

Assuming that there is no active power in the harmonics, the correct input power results in:

$$P_{in} = 1027.9\text{ W}$$

If phase angles of V and I would not be considered, the recorded input power would result in:

$$P_{in} = V_{in,1,pk} * I_{in,1,pk} / 2 = 1032.83\text{ W}$$

And when results from a general multimeter would be taken into account, the derived input power would lead to:

$$P_{in} = V_{in,pk} * I_{in,pk} / 2 = 1058.37\text{ W}$$

An input power derivation (even without considering any measurement errors due to range etc.) would thus result in deviations of:

Reference value	Derived input power	Error
1027.9 W	1027.9 W	0 %
1027.9 W	1032.83 W	0.5 %
1027.9 W	1058.37 W	2.97 %

So, even if the differences in results of the input power seemed to be minor in terms of absolute values, the efficiency can be still heavily affected due to an incorrect measurement process when measuring efficiency values in the 96 % to 99 % efficiency range. It has to be noted that active power transported via harmonics will further increase these errors, if not considered.

2. Measurements with Power Analyzer Setup

2.1. Measurement Setup

The following test equipment has been used for input and output power measurements:

- Power analyzer: Tektronix PA3000
    - Integrated 1 A shunt: for input current measurements
    - Integrated 30 A shunt: for output current measurements
- Tektronix breakout box: BB1000-EU (240 V)
- PD Communication Kit (Eval board): Infineon/Cypress CY4533 EZ-PD
- Current Sink: Keithley 2380-500-30

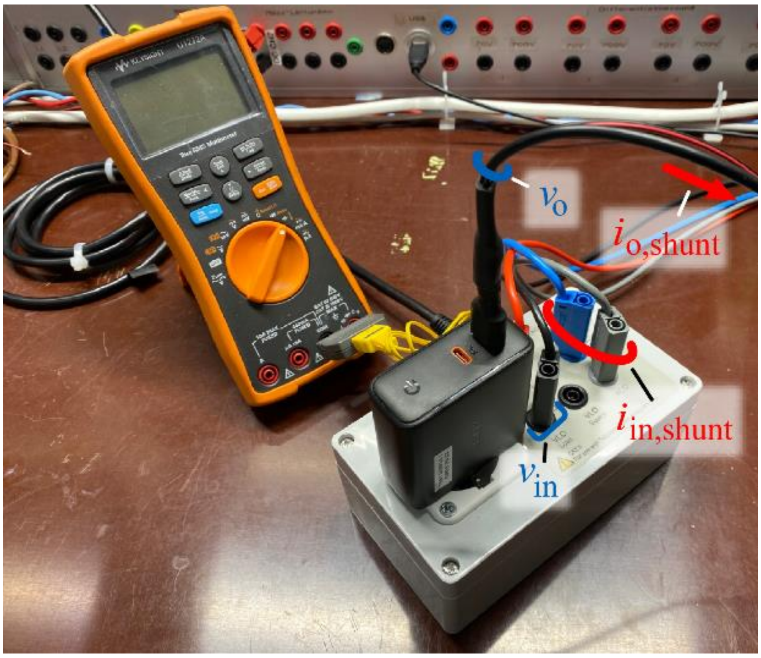


Figure 5: Power supply test stand including Tektronix breakout box, power supply, voltage and current measurements and a Keysight U1272A for ambient temperature measurement. This figure does not include, power analyzer, current source and communication board.

2.2. Accuracy of PA3000 Power Analyzer

2.2.1. Current Sensor Characteristics

Table 3 Tektronix PA3000 1 A and 30 A shunt resistor AC characteristics (45 Hz – 850 Hz).

PA3000 current sensors (45 Hz – 850 Hz)		
	reading (%)	range (%)
1 A shunt	0.04	0.04
30 A shunt	0.04	0.04

Table 4 Tektronix PA3000 1 A and 30 A shunt resistor DC characteristics.

PA3000 current sensors (DC)			
	reading (%)	Range (%)	Offset (A)
1 A shunt	0.05	0.1	0.0001
30 A shunt	0.05	0.1	0.01

Table 5 Tektronix PA3000 1 A and 30 A shunt resistor range.

PA 3000 current sensor range (A_{peak})									
1 A shunt	0.0125	0.025	0.05	0.125	0.25	0.5	1.25	2.5	5
30 A shunt	0.5	1	2	5	10	20	50	100	200

2.2.2. Voltage Sensor Characteristics

Table 6 Tektronix PA3000 voltage sensing AC characteristics (45 Hz – 850 Hz).

PA 3000 voltage sensor (45 Hz - 850 Hz)		
	reading (%)	range (%)
V_{rms}	0.04	0.04

Table 7 Tektronix PA3000 voltage sensor DC characteristics.

PA 3000 voltage sensor (DC)			
	reading (%)	Range (%)	Offset (V)
V_{dc}	0.05	0.1	0.05

Table 8 Tektronix PA3000 voltage sensor range.

PA 3000 voltage sensor range (V_{peak})									
V_{peak}	5	10	20	50	100	200	500	1000	2000

2.2.3. Accuracy of Documented Input and Output Power

Table 9 Tektronix PA3000 input power accuracy for different load and range settings for 20 V charging operation.

Accuracy of Input power (V_o = 20 V) for different load conditions			
	60W	**30W**	**15W**
$V_{rms,acc}$ (V)	0.233	0.233	0.233
$I_{rms,acc}$ (A)	0.000458	0.000194	0.000097
W_{acc} (W)	0.166	0.075	0.0375

Table 10 Tektronix PA3000 output power accuracy for different load and range settings for 20 V charging operation.

Accuracy of output power (V_o = 20 V) for different load conditions			
	60W	**30W**	**15W**
$V_{DC,acc}$ (V)	0.08	0.08	0.08
$I_{DC,acc}$ (A)	0.0066	0.00335	0.001725
W_{acc} (W)	0.372	0.187	0.0945

2.3. Measurement Results

2.3.1. GaN A power supply

2.3.1.1. Device Overview

Figure 6: The GaN A power supply.

The GaN A is a power supply that comes with 2 different charging outputs:

PD (power delivery) 3.0 – USB type - C: 60 W, 5 V/3 A, 9 V/3 A, 12 V/3 A, 15 V/3 A, 20 V/3 A

QC (quick charging) – USB type - A: standard 5 V/2.4 A

The maximum charging power for the different available output voltage modes are depicted in Table 11.

Table 11 Output power ratings for different output voltage modes.

GaN A PD Output			
	DC output voltage	**Max. DC output current**	**Maximum output power**
	5 V	3 A	15 W
	9 V	3 A	27 W
	12 V	3 A	36 W
	15 V	3 A	45 W
	20 V	3 A	60 W
GaN A QC Output			
	DC output voltage	**Max. DC output current**	**Maximum output power**
	5 V	2.4 A	12 W

Input specifications are defined as follows:

- AC input voltage: 100 V_{rms} - 240 V_{rms}
- AC input frequency: 50/60 Hz

Note: All tests have been performed for 230 V_{rms}/50 Hz

2.3.1.2. Power Density

According to datasheet specifications and illustrated in Figure 7, as well as verified in the laboratory the overall **dimensions** (**excluding AC socket**) of the power supply are given by:

- Length: 64 mm / 2.5 in
- Width: 67 mm / 2.6 in
- Height: 29 mm / 1.1 in

Figure 7: Basic dimensions of GaN A 60 W power supply.

The total **weight** of the device (**including socket**) results in **150 g**.

This leads to a maximum **power density** of:

- **0.483 kW/dm³ or 8.39 W/in³** – excluding socket
- **0.4 kW/kg** – including socket

2.3.1.3. Topology

The GaN based power supply is based on a standard rectifier bridge, followed by a QR flyback converter operating in discontinuous mode. The flyback primary side semiconductor is based on GaN technology, whereas both the paralleled rectifier input stages and the synchronous rectifying MOSFET on the secondary side is based on silicon MOSFET and diodes. Furthermore, an additional Si-based DC/DC Buck converter with CC/CV control, directly connected after the PD output capacitors to generate the 5V QC port. Therefore, it can be concluded that the GaN A power supply is not solely based on GaN power semiconductor devices but incorporating both Si and GaN transistor technology.

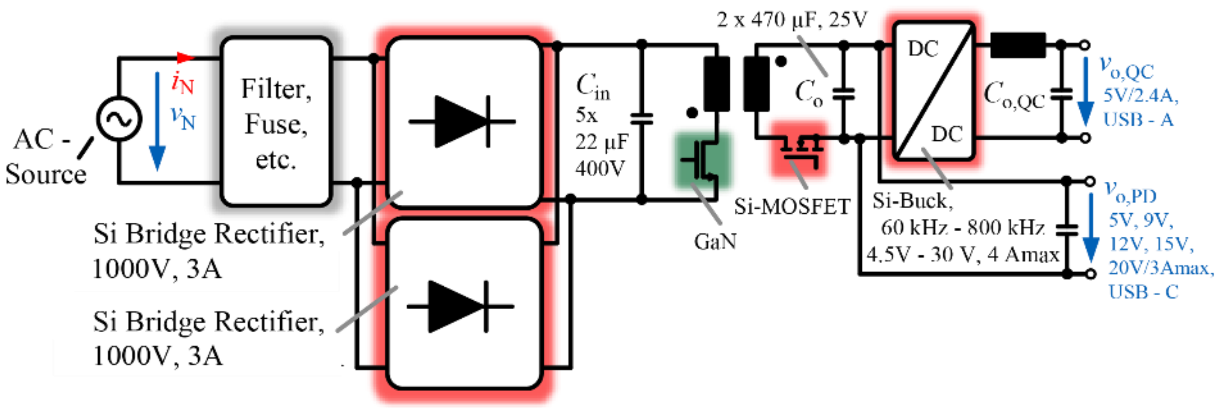


Figure 8: Basic schematic of the GaN A power supply with PD and QC port.

2.3.1.4. Switching Frequency

The switching frequency of the flyback converter is changing for different out power values. While operating in 20 V charging mode the switching frequency shows its maximum at around 55 kHz, it is non-linearly decreasing for smaller loads and even reaches values of approximately 0.6 kHz during 5 V PD no-load operation.

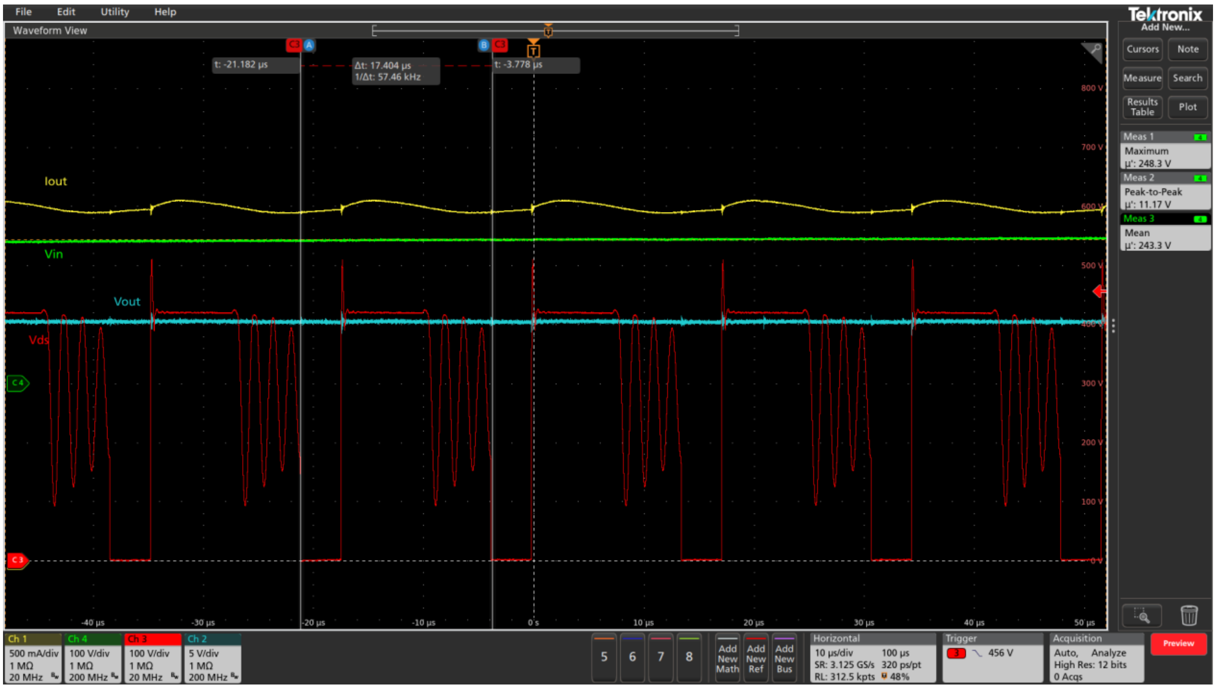


Figure 9: Switching frequency measurement for the GaN A power supply for output voltage 20 V and output current 3 A.

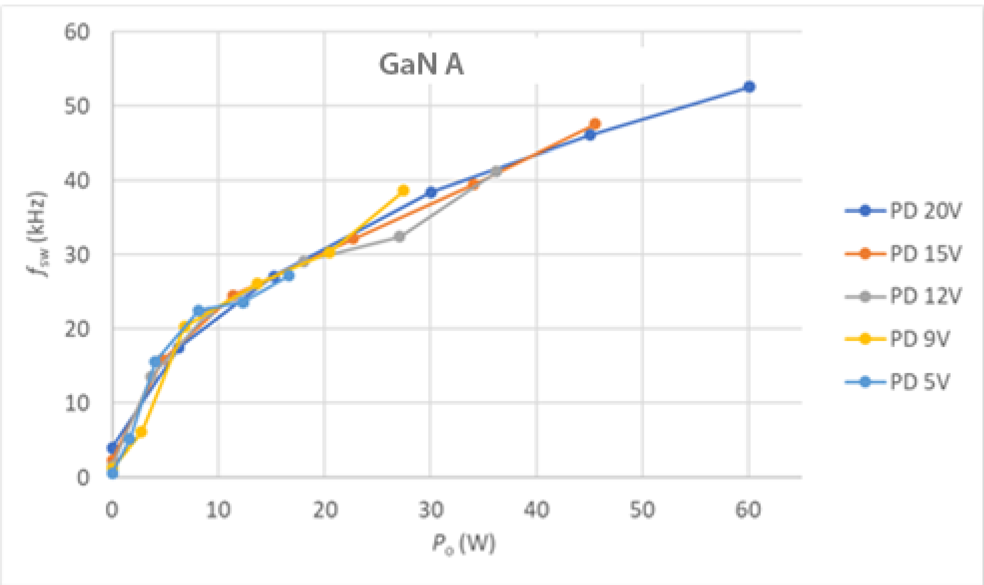


Figure 10: DC/DC flyback converter GaN transistor switching frequency for different load conditions (0 W – 60 W) and charging voltage levels (5 V – 20 V).

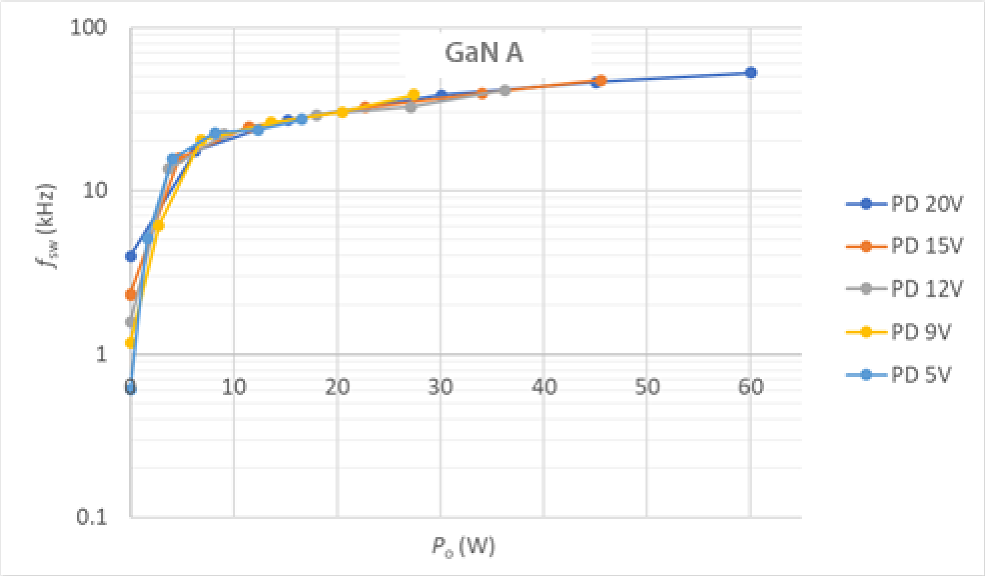


Figure 11: DC/DC flyback converter GaN transistor switching frequency for different load conditions (0 W – 60 W) and charging voltage levels (5 V – 20 V).

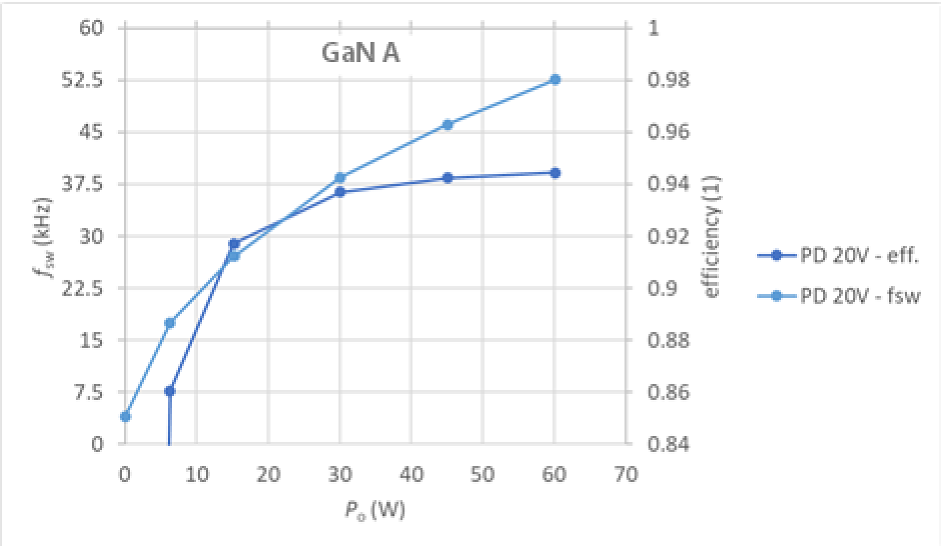


Figure 12: GaN A port electrical efficiency and DC/DC flyback converter switching frequency of dedicated primary-side GaN transistor for different load conditions (0 W – 60 W) and a charging voltage of 20 V.

2.3.1.5. Blocking Voltage

As the flyback topology consists of an input rectifier stage with 5 x 22 µF, the DC-link voltage of the primary side (C_{in}) results in 300 V. The flyback converter operates in discontinuous mode. Thus, the blocking voltage of the GaN transistor is constituted by

$$v_{DS,GaN} = V_{in} + \frac{N_p}{N_s}(V_o + V_F) \sim 430\ V\ (@20V_o, i_L > 0)$$

as long as enough energy is stored in the flyback transformer ($i_L > 0$) and

$$v_{DS,GaN} = V_{in} = 300\ V\ (@20V_o, i_L = 0)$$

if the flyback transformer current is 0 A.

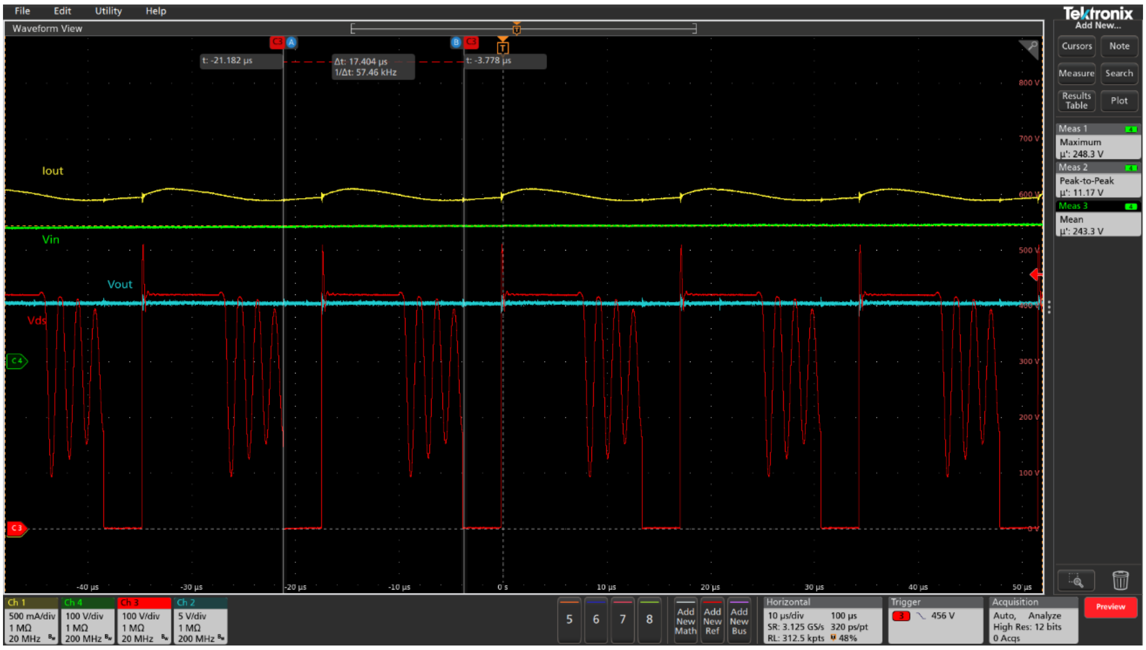


Figure 13: Relevant voltage and current waveforms of the GaN A power supply. Green: input voltage, yellow: output current, cyan: output voltage, red: GaN-transistor drain source voltage.

2.3.1.6. Efficiency - Overview

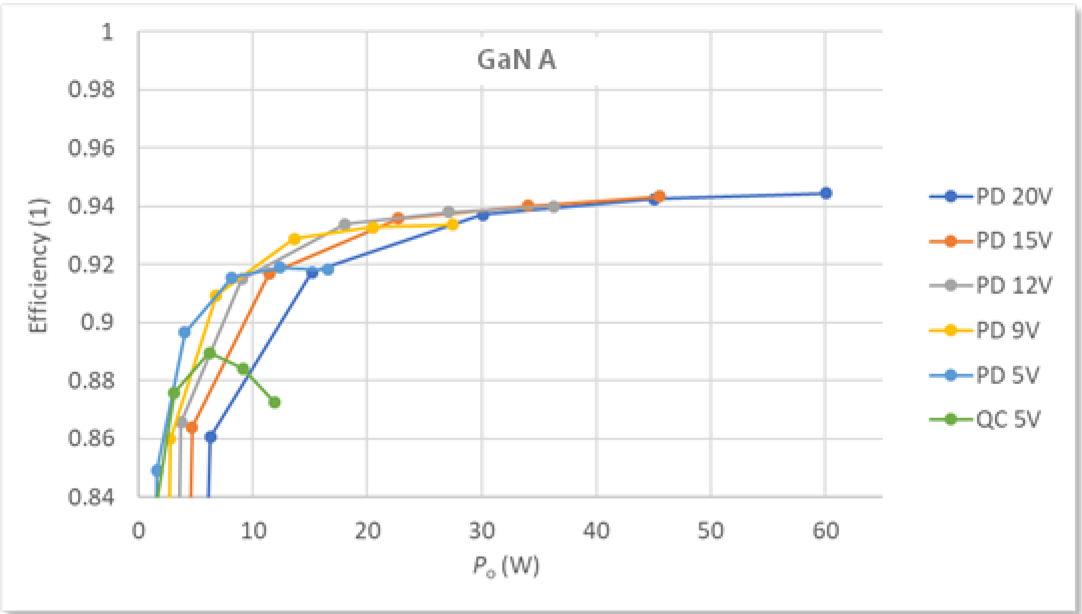


Figure 14: Efficiency over output power curves of GaN A charger output, for charging voltages 5 V, 9 V, 12 V, 15 V, 20 V.

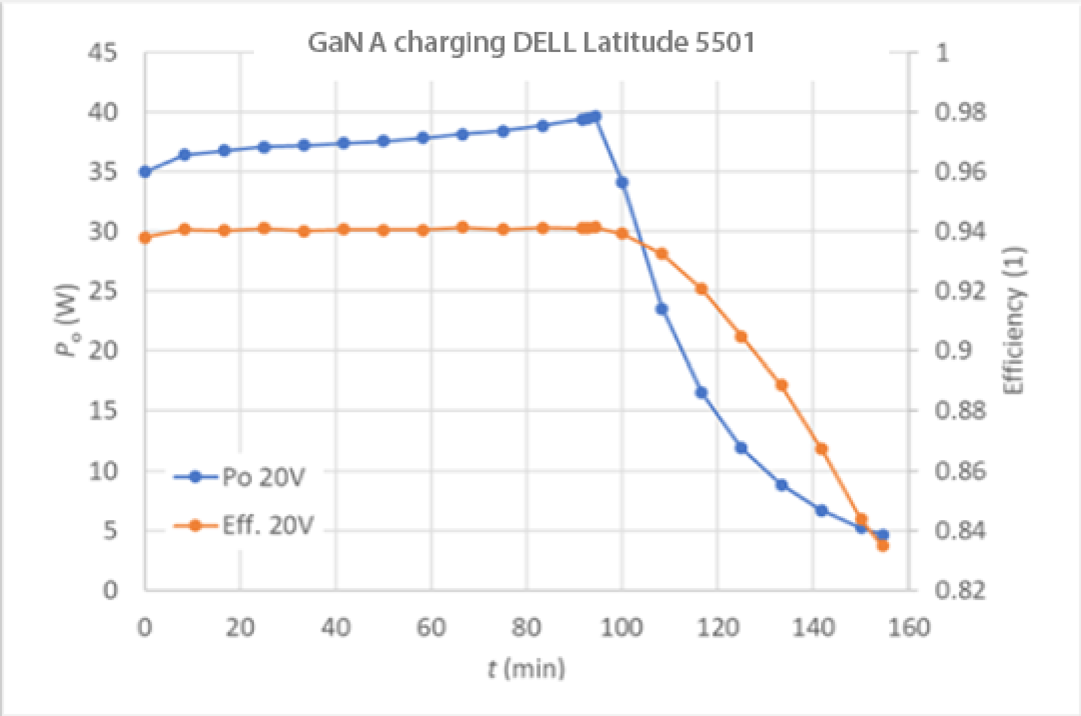


Figure 15: Output power and efficiency over time of a GaN A charging an inactive DELL Latitude 5501 laptop. GaN A output voltage during charging mode: 20 V.

2.3.2. GaN B power supply

2.3.2.1. Device Overview

Figure 16: The GaN B power supply.

The GaN B is a power supply that comes with different output voltage modes of 5 V, 9 V, 15 V, and 20 V. The maximum charging power for the different available output voltage modes are depicted in Table 12.

Table 12 Output power ratings for different output voltage modes.

GaN B PD Output		
DC output voltage	**Max. DC output current**	**Maximum output power**
5 V	3 A	15 W
9 V	3 A	27 W
15 V	3 A	45 W
20 V	3.25 A	65 W

Input specifications are defined as follows:

- AC input voltage: 100 V_{rms} - 240 V_{rms}
- AC input frequency: 50/60 Hz

Note: All tests have been performed for 230 V_{rms}/50 Hz

2.3.2.2. Test Setup

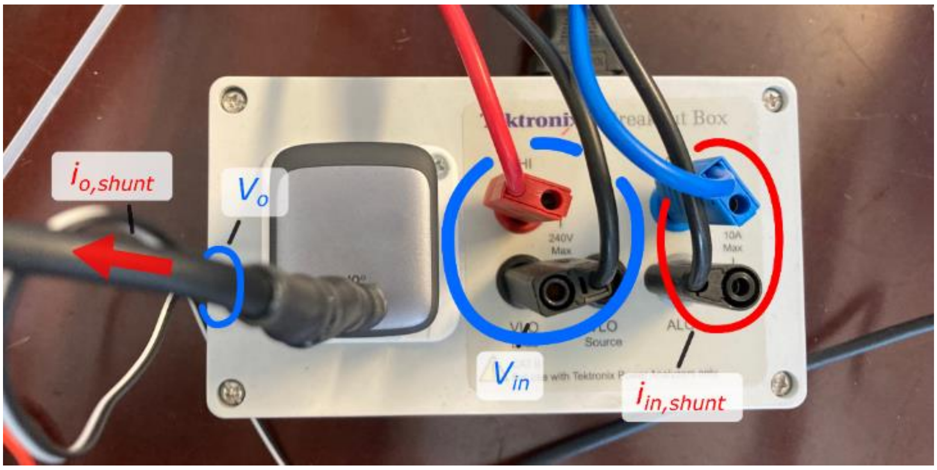


Figure 17: Power supply test stand including Tektronix breakout box, power supply, voltage and current measurements. This figure does not include power analyzer, current source and communication board.

2.3.2.3. Power Density

As verified in the laboratory and illustrated in Figure 18 the overall **dimensions** (**excluding AC socket**) of the GaN B are given by:

- Length: 44 mm / 1.7 in
- Width: 42 mm / 1.6 in
- Height: 36 mm / 1.4 in

Figure 18: Basic dimensions of the GaN B power supply.

The total **weight** of the device (**including socket**) results in **119 g**.

This leads to a maximum **power density** of:

- **0.977 kW/dm³ or 17.07 W/in³** – excluding socket
- **0.556 kW/kg** – including socket

2.3.2.4. Topology

The GaN B power supply is based on a standard B4 rectifier bridge with DC-link capacitor. The DC-DC converter (a Flyback converter) consists of an active clamp IC and CV/CC ZVS flyback IC (primary side), an air gapped transformer and a MOSFET including output capacitors at the secondary side. Both primary-side ICs are based on GaN technology.

Furthermore, an USB PD IC is directly connected to the PD output. The GaN charger is not solely based on GaN power semiconductors but incorporating both Si and GaN technology, i.e., the diode bridge rectifier and the secondary-side MOSFET are based on Si semiconductors.

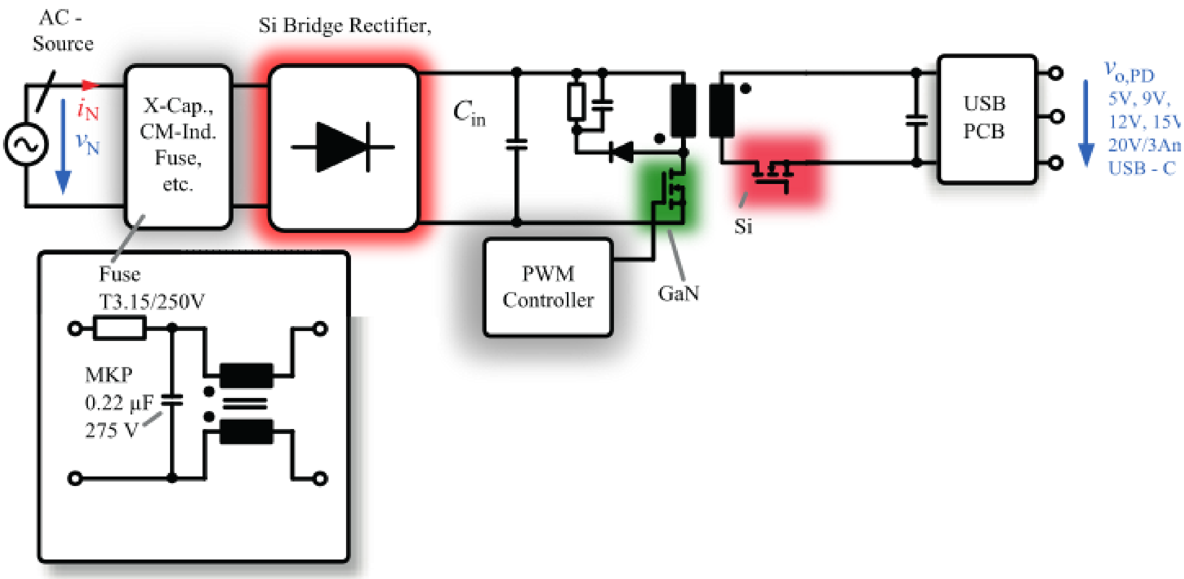


Figure 19: Basic schematic of the GaN B power supply.

2.3.2.5. Efficiency - Overview

In this section, results of several different electrical efficiency measurements are illustrated. This includes also a different power supply samples of the same product type to identify possible deviations between different samples. Eventually, one full charging cycle of a fully discharged shut-down power laptop battery (20 V charging mode) is recorded.

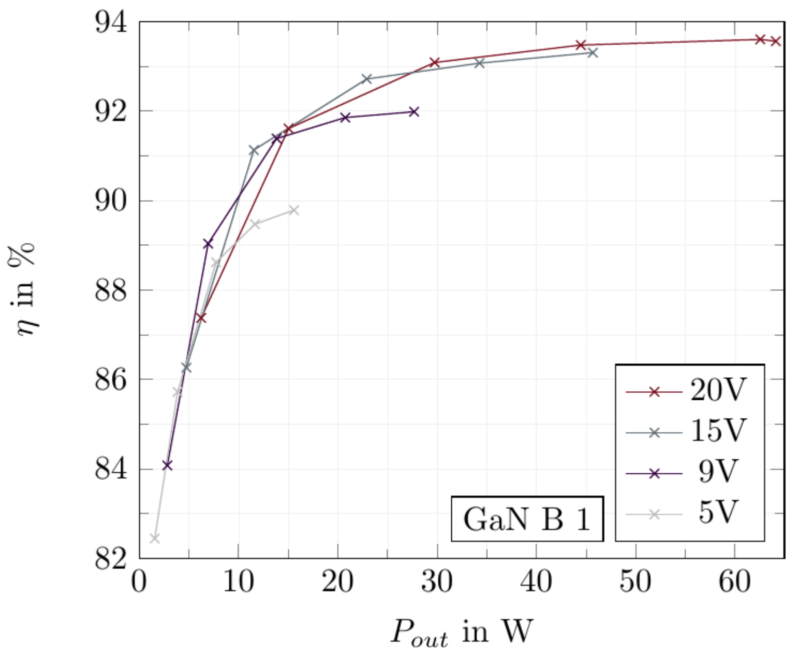


Figure 20: Efficiency over output power curves of GaN B 1, for charging voltages 5 V, 9 V, 15 V, 20 V.

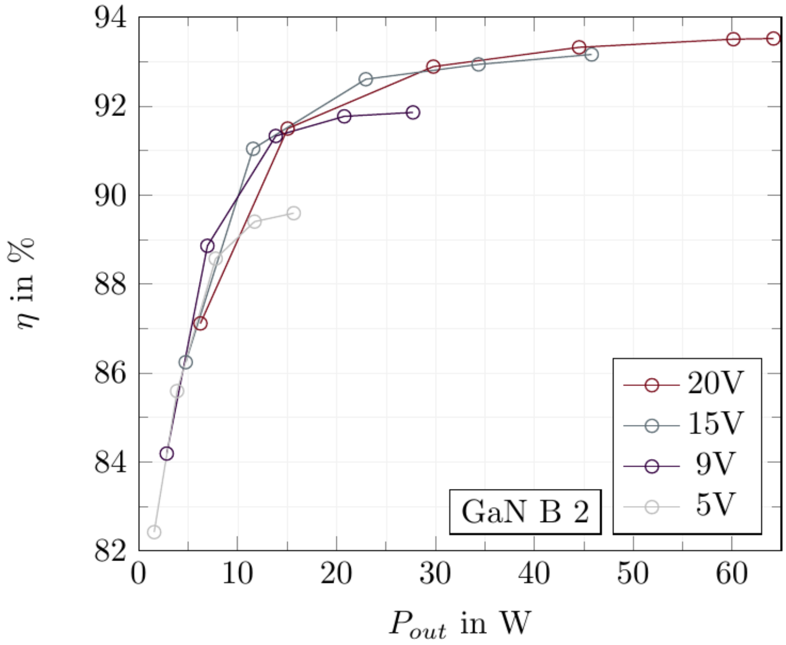


Figure 21: Efficiency over output power curves of GaN B 2, for charging voltages 5 V, 9 V, 15 V, 20 V.

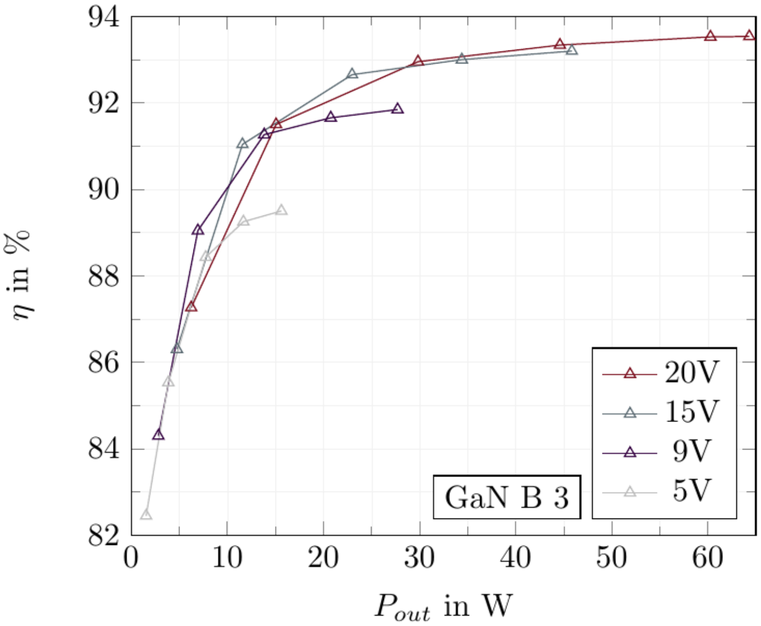


Figure 22: Efficiency over output power curves of GaN B 3, for charging voltages 5 V, 9 V, 15 V, 20 V.

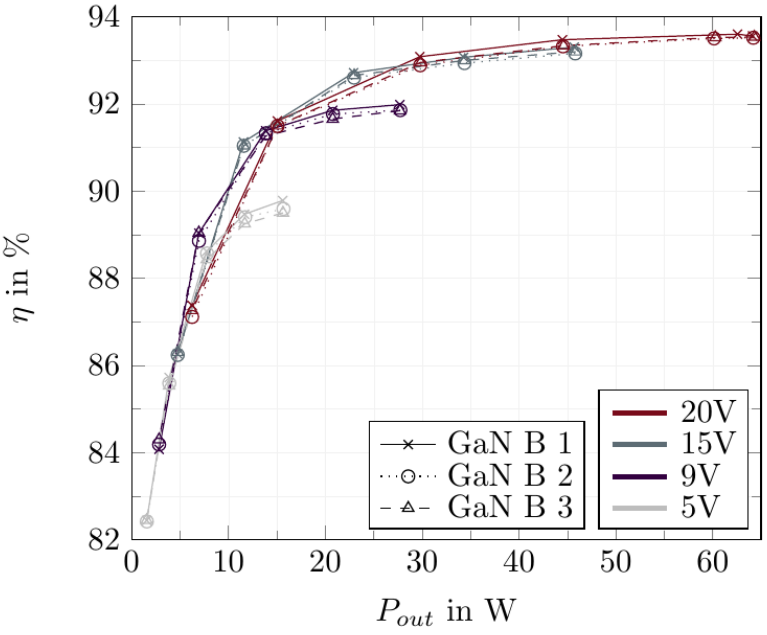


Figure 23: Efficiency over output power curves of GaN B 1, 2 and 3, for charging voltages 5 V, 9 V, 15 V, 20 V.

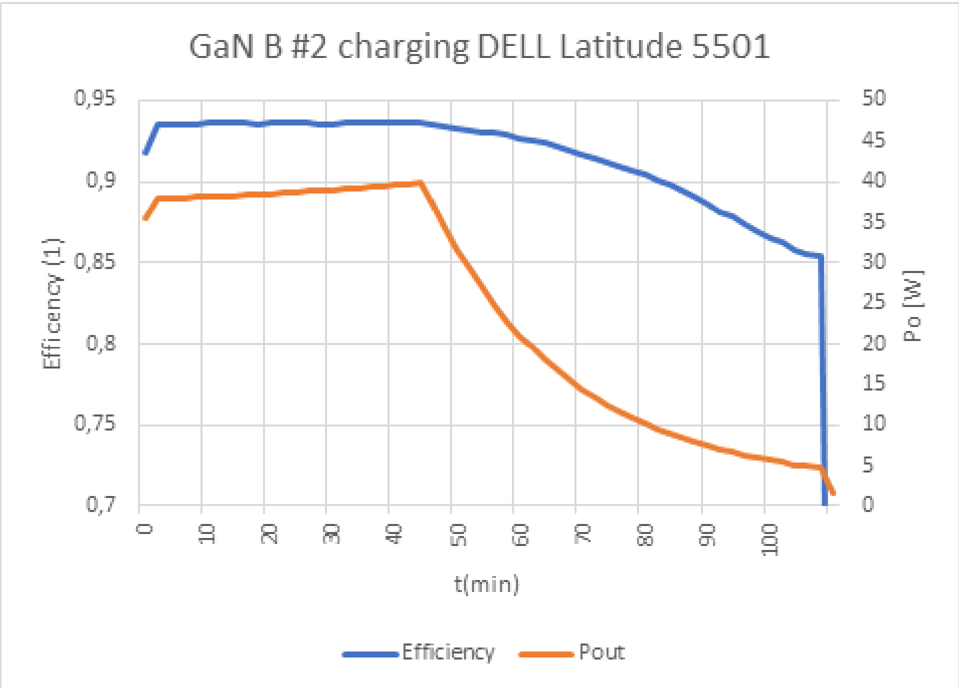


Figure 24: Output power and efficiency over time of the GaN B #2 charging an inactive DELL Latitude 5501 laptop. GaN B output voltage during charging mode: 20 V.

2.3.2.6. Switching Frequency

Due to the compact design of the GaN B, it was not possible to measure the switching frequency with the charger open.

2.3.3. Si A power supply

2.3.3.1. Device Overview

Figure 25: Si A 65 W power supply.

The Si A is a power supply that comes with different output voltage modes of 5 V, 9 V, 12 V, 15 V, and 20 V. The maximum charging power for the different available output voltage modes are depicted in Table 13.

Table 13 Output power ratings for different output voltage modes.

Si A PD Output		
DC output voltage	**Max. DC output current**	**Maximum output power**
5 V	3 A	15 W
9 V	3 A	27 W
12 V	3A	36 W
15 V	3 A	45 W
20 V	3.25 A	65 W

Input specifications are defined as follows:

- AC input voltage: 100 V_{rms} - 240 V_{rms}
- AC input frequency: 50/60 Hz

Note: All tests have been performed for 230 V_{rms}/50 Hz

2.3.3.2. Test Setup

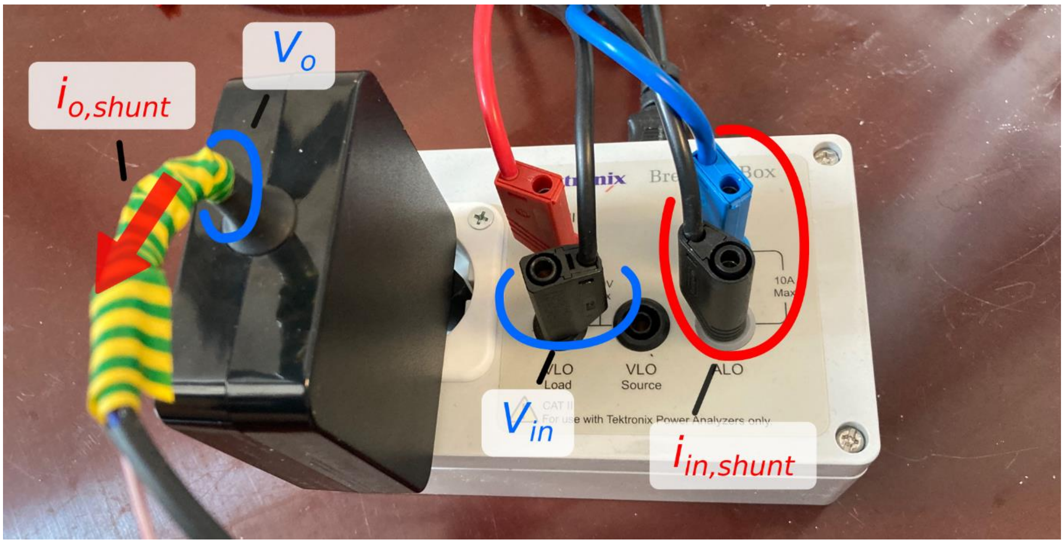


Figure 26: Power supply test stand including Tektronix breakout box, power supply, voltage and current measurements. This figure does not include power analyzer, current source and communication board.

2.3.3.3. Power Density

According to datasheet specifications and illustrated in Figure 27, as well as verified in the laboratory the overall **dimensions** (**excluding AC socket**) of the Si A are given by:

- Length: 7.5 cm / 2.95 in
- Width: 7.5 cm / 2.95 in
- Height: 2.8 cm/ 1.10 in

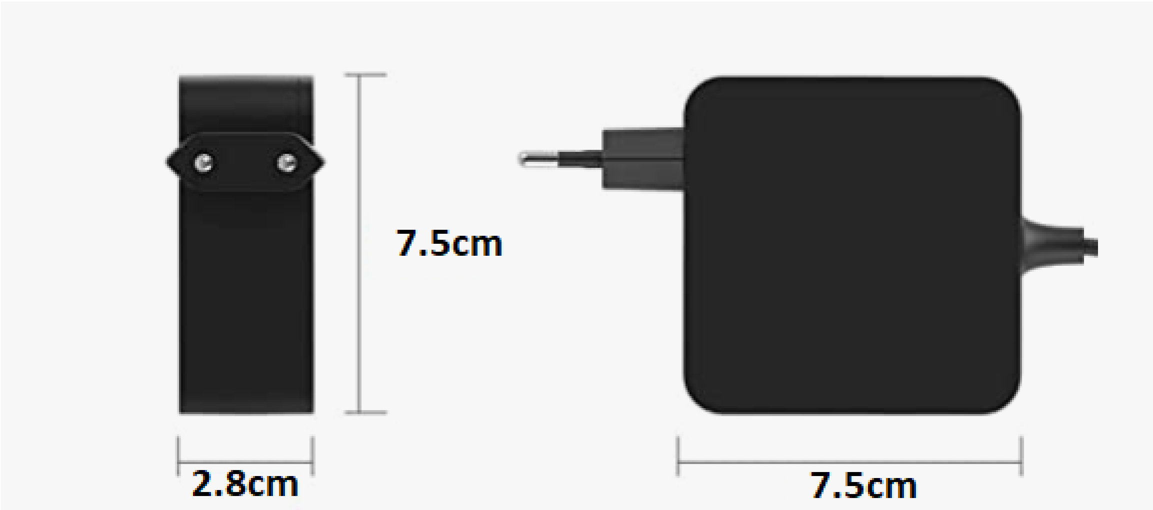


Figure 27: Basic dimensions of Si A power supply.

The total **weight** of the device (**including socket**) results in **181 g**.

This leads to a maximum **power density** of:

- **0.385 kW/dm³ or 6.33 W/in³** – excluding socket
- **0.359 kW/kg** – including socket and cable

2.3.3.4. Topology

Similar to the already discussed low wattage chargers, the Si A power supply is based on a standard rectifier bridge, followed by a flyback converter as well. To ensure PD output, a USB Type-C and PD Source Controller is used to provide the PD output. All semiconductors utilized in this power supply are based in silicon technology.

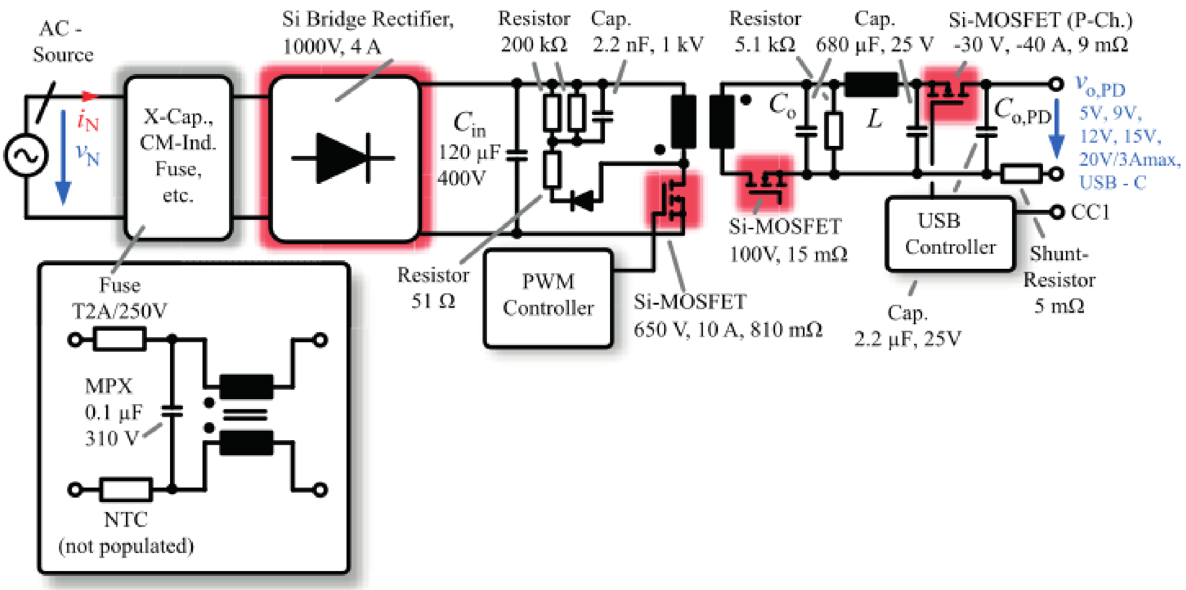


Figure 28: Basic schematic of the Si A.

2.3.3.5. Switching Frequency

The switching frequency of the flyback converter is changing for different output power values. While operating in 20 V charging mode the switching frequency shows its maximum at around 65 kHz, it is non-linearly decreasing for smaller loads and even reaches values of approximately 22 kHz during 5 V PD no-load operation. It can also be seen from Figure 29 that no valley switching is incorporated in the control here, which directly deteriorates the efficiency.

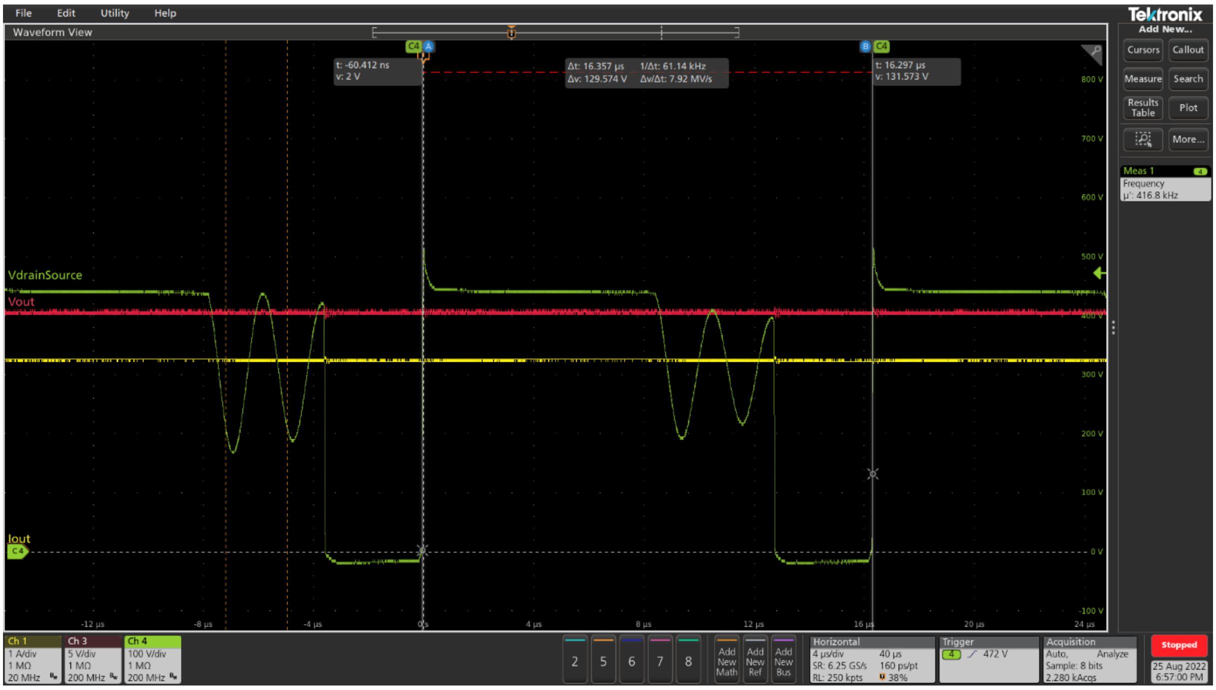


Figure 29: Switching frequency measurement for Si A for an output voltage 20 V and output current 3.25 A

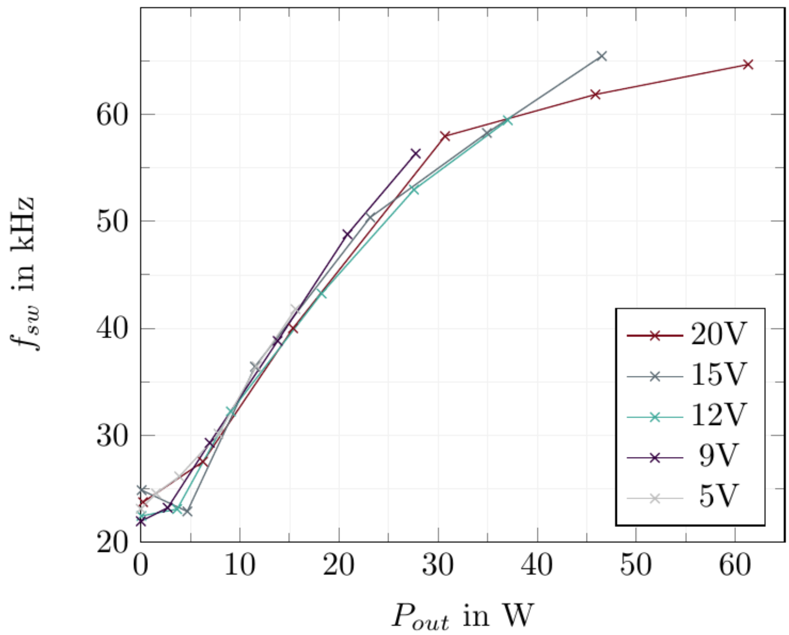


Figure 30: DC/DC flyback converter transistor switching frequency for different load conditions (0 W – 60 W) and charging voltage levels (5 V – 20 V).

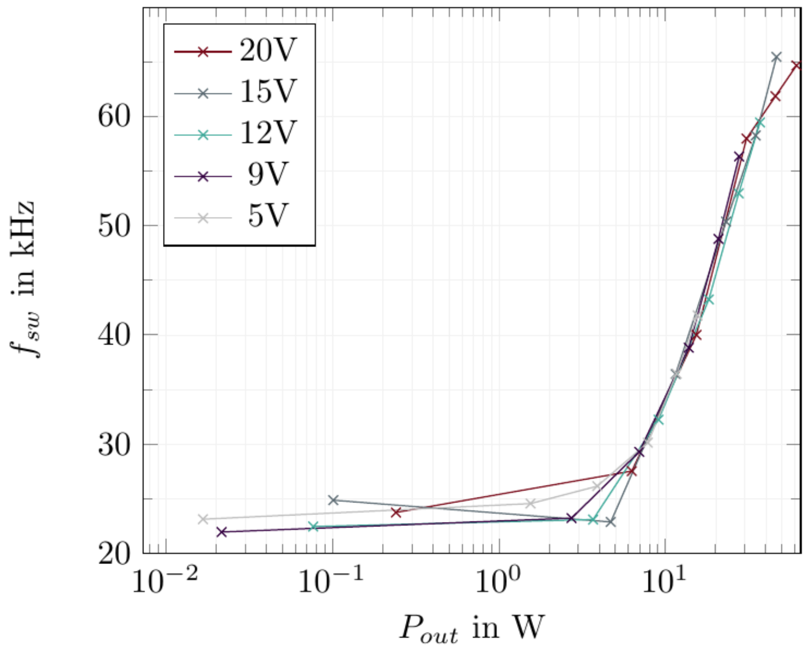


Figure 31: DC/DC flyback converter transistor switching frequency for different load conditions (0 W – 60 W) and charging voltage levels (5 V – 20 V).

2.3.3.6. Efficiency - Overview

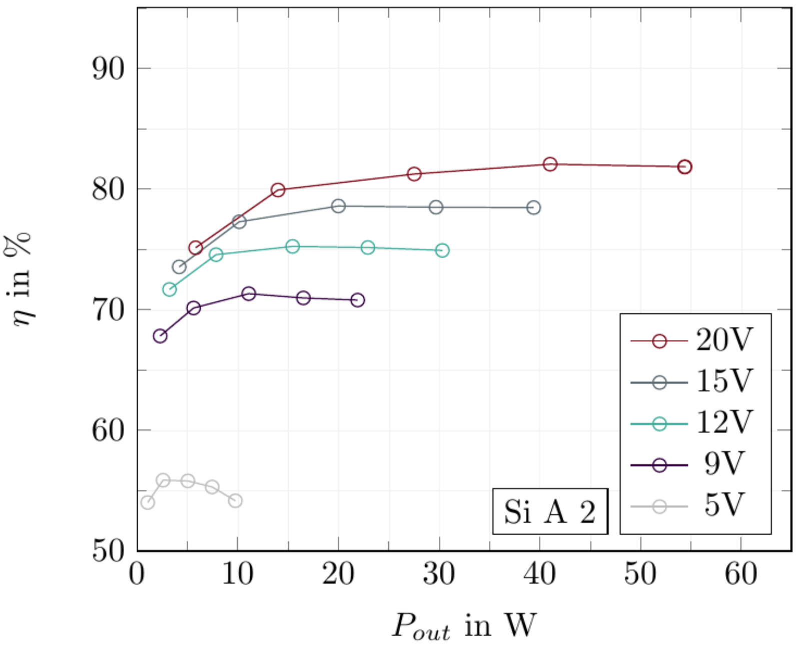


Figure 32: Efficiency over output power curves of Si A 2 charger output, for charging voltages 5 V, 9 V, 12 V, 15 V, 20 V.

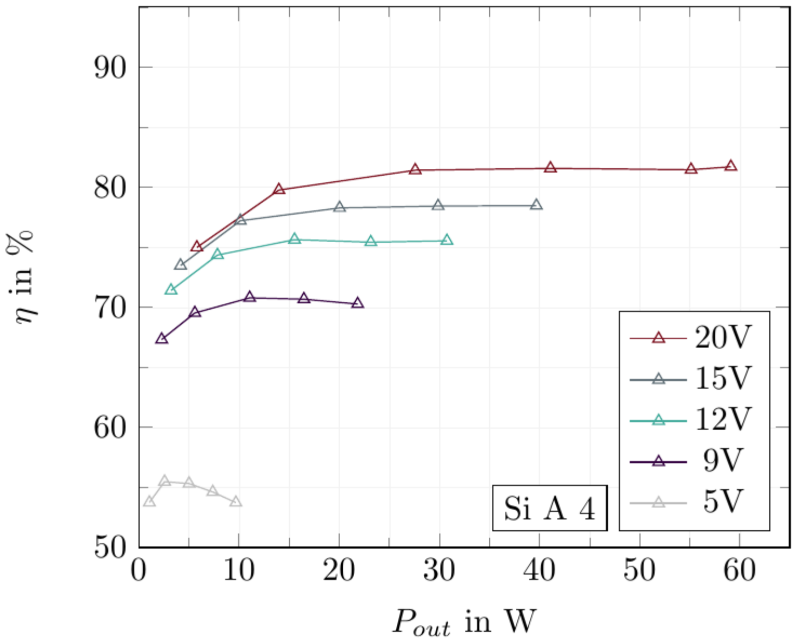


Figure 33: Efficiency over output power curves of Si A 4 charger output, for charging voltages 5 V, 9 V, 12 V, 15 V, 20 V.

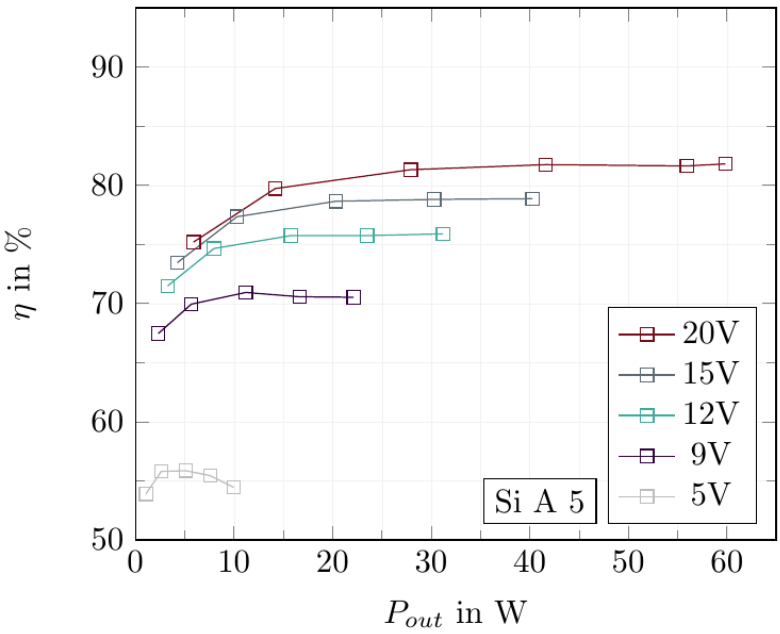


Figure 34: Efficiency over output power curves of Si A 5 charger output, for charging voltages 5 V, 9 V, 12 V, 15 V, 20 V.

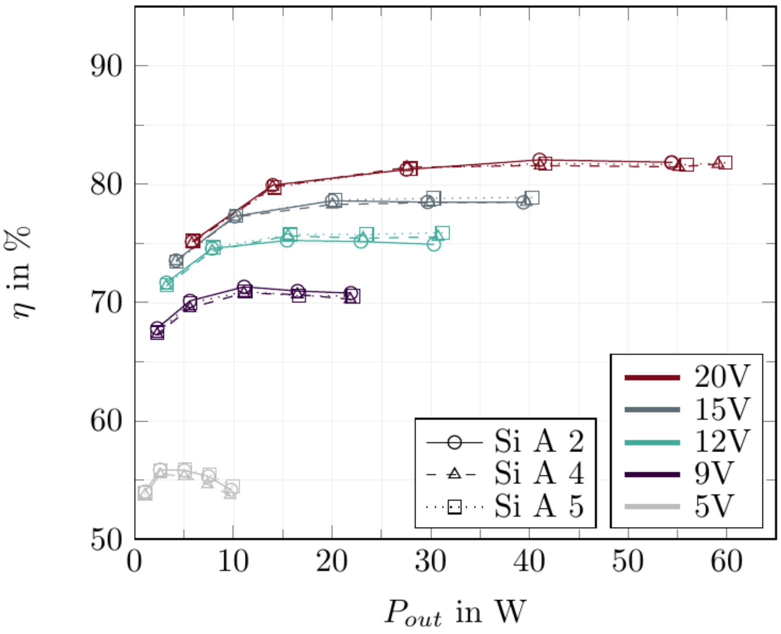


Figure 35: Efficiency over output power curves of Si A 2, 4 and 5 charger output, for charging voltages 5 V, 9 V, 12 V, 15 V, 20 V.

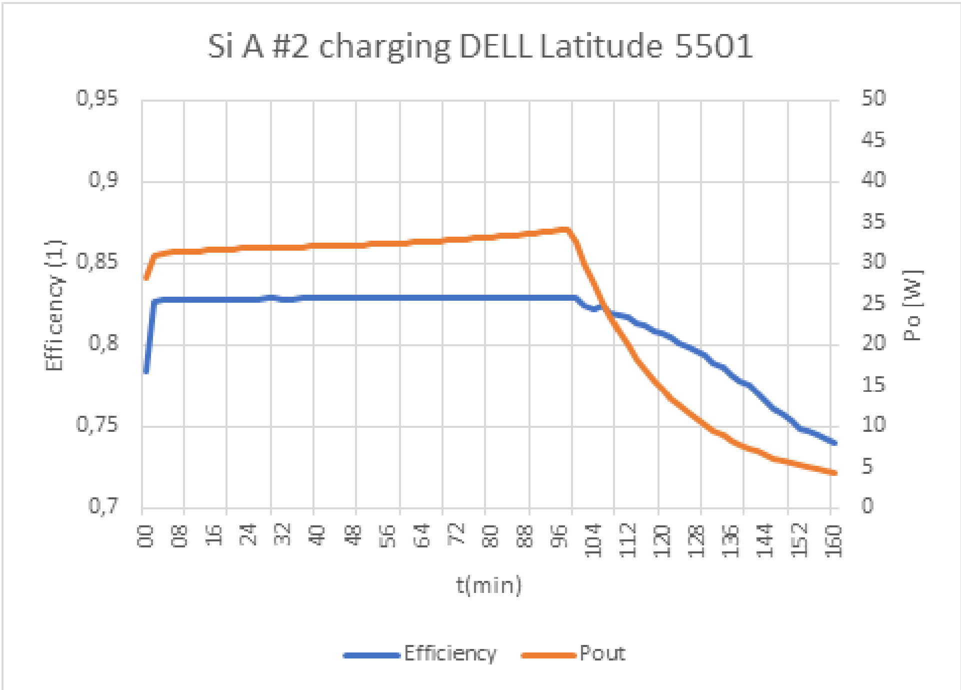


Figure 36: Output power and efficiency over time of a SI A 2 charging an inactive DELL Latitude 5501 laptop. Si A output voltage during charging mode: 20 V.

2.3.4. Si B power supply

2.3.4.1. Device Overview

Figure 37: Si B power supply.

The Si B 65W is a power supply which comes with different different output voltage modes of 5 V, 9 V, 12 V, 15 V and 20 V. The maximum charging power for the different available output voltage modes are depicted in Table 14.

Table 14 Output power ratings for different output voltage modes.

Si B PD Output		
DC output voltage	**Max. DC output current**	**Maximum output power**
5 V	3 A	15 W
9 V	3 A	27 W
12 V	3A	36 W
15 V	3 A	45 W
20 V	3.25 A	65 W

Input specifications are defined as follows:

- AC input voltage: 100 V_{rms} - 240 V_{rms}
- AC input frequency: 50/60 Hz

Note: All tests have been performed for 230 V_{rms}/50 Hz

2.3.4.2. Power Density

According to datasheet specifications and illustrated in Figure 27, as well as verified in the laboratory the overall **dimensions** (**excluding AC socket**) of the Si B are given by:

- Length: 7.5 cm / 2.95 in
- Width: 7.5 cm / 2.95 in
- Height: 3 cm/ 1.18 in

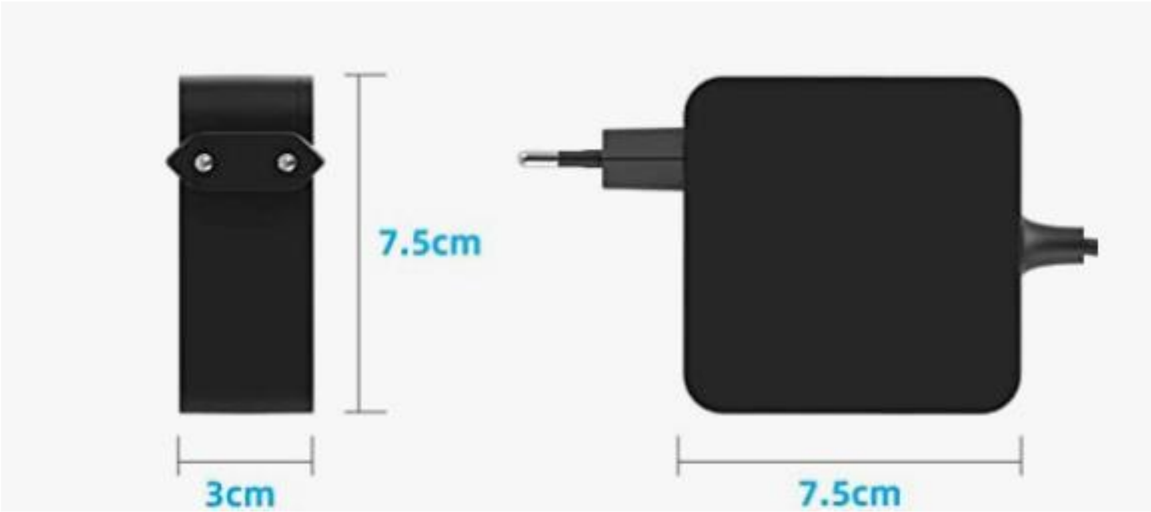


Figure 38: Basic dimensions of Si B power supply.

The total **weight** of the device (**including socket**) results in **174 g**.

This leads to a maximum **power density** of:

- **0.385 kW/dm^3 or 6.33 W/in^3** – excluding socket
- **0.374 kW/kg** – including socket

2.3.4.3. Topology

The Si B power supply is based on a standard rectifier bridge, followed by a flyback converter. To generate the PD output a USB PCB is utilized. All semiconductors utilized in this power supply are based on silicon technology.

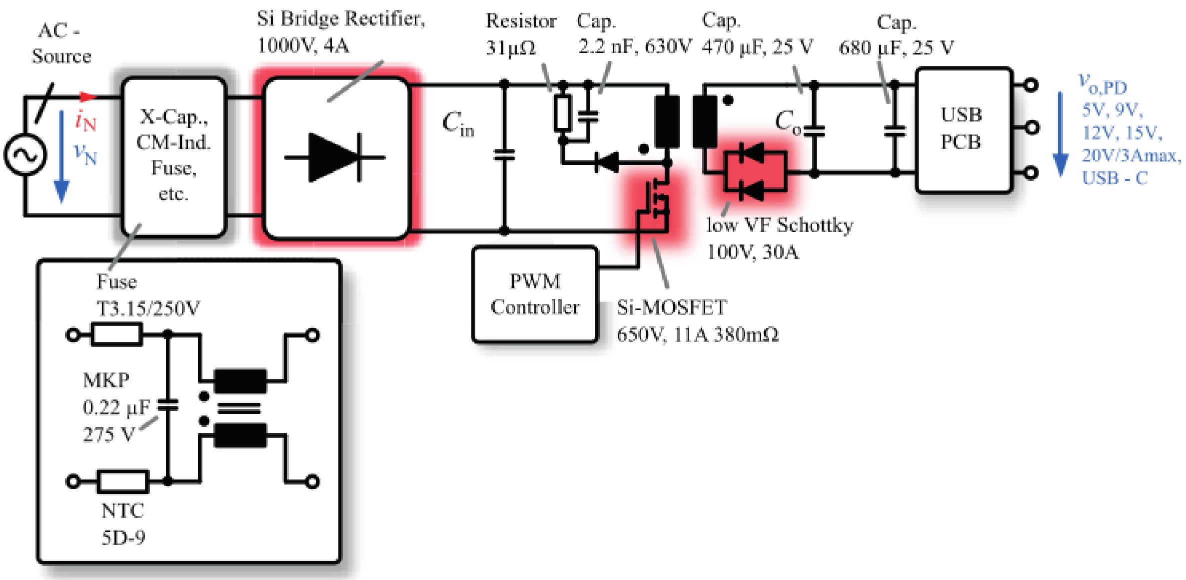


Figure 39: Basic schematic of the Si B power supply.

2.3.4.4. Switching Frequency

The switching frequency of the flyback converter is changing for different outpower values. While operating in 20 V charging mode the switching frequency shows its maximum at around 65 kHz, it is non-linearly decreasing for smaller loads and even reaches values of approximately 22 kHz during 5 V PD no-load operation.

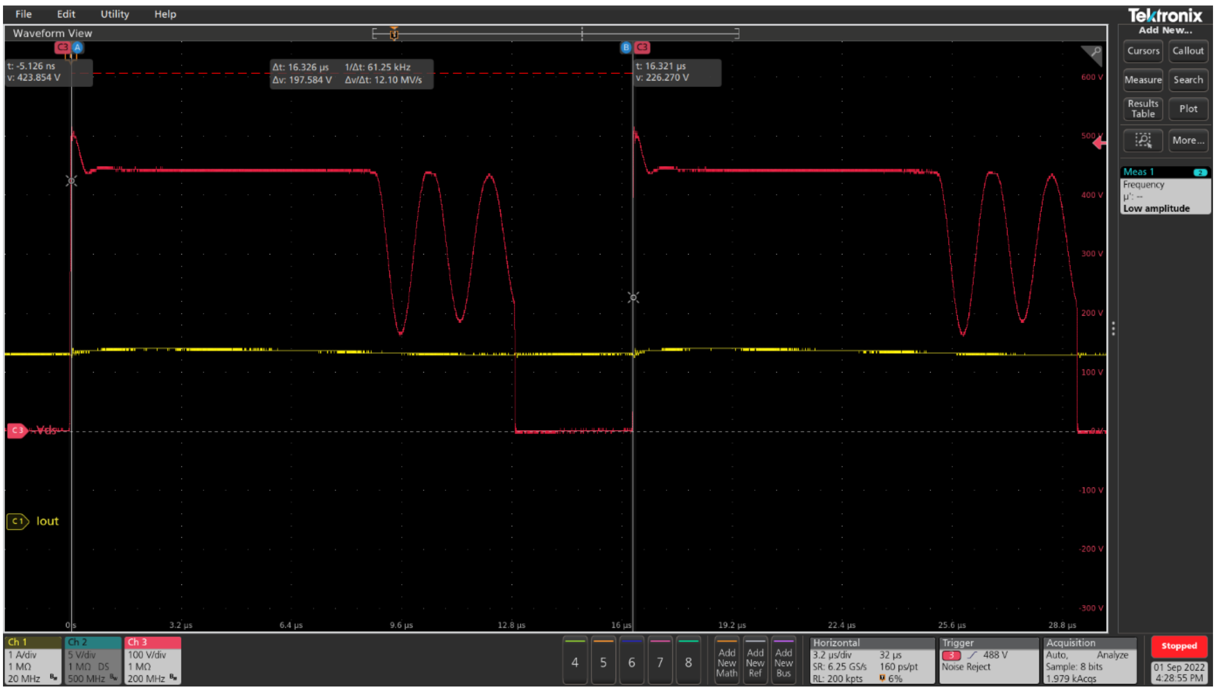


Figure 40: Switching frequency measurement for Si B for an output voltage 20 V and output current 3.25 A

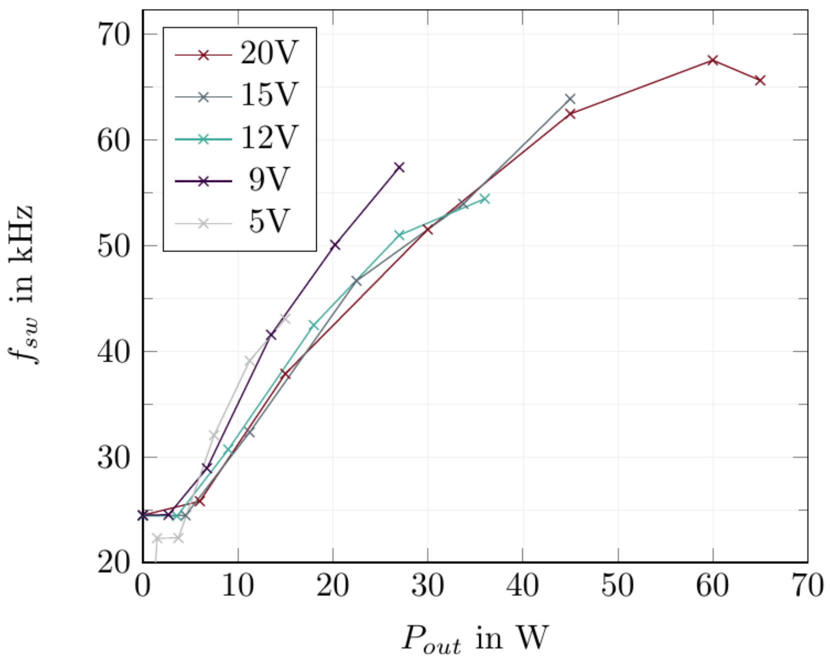


Figure 41: DC/DC flyback converter transistor switching frequency for different load conditions (0 W – 60 W) and charging voltage levels (5 V – 20 V).

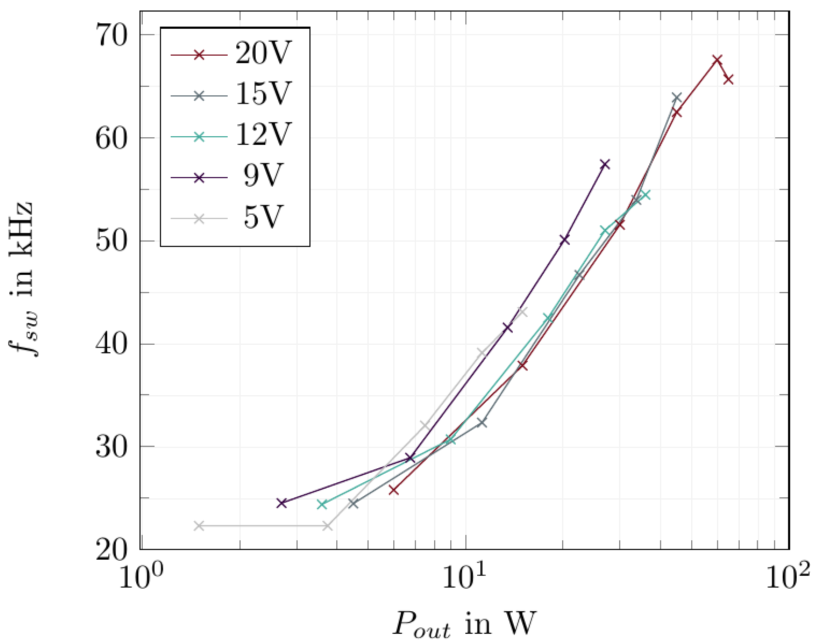


Figure 42: DC/DC flyback converter transistor switching frequency for different load conditions (0 W – 60 W) and charging voltage levels (5 V – 20 V).

2.3.4.5. Efficiency - Overview

The efficiency measurement was done on two Si B power supplies: Si B 2 and Si B 3.

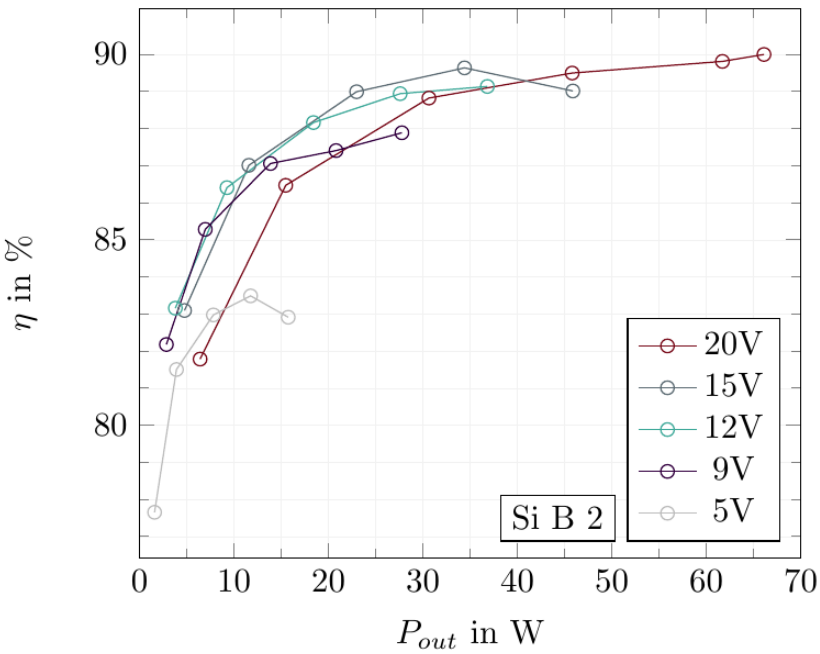


Figure 43: Efficiency over output power curves of Si B 2 charger output, for charging voltages 5 V, 9 V, 12 V, 15 V, 20 V.

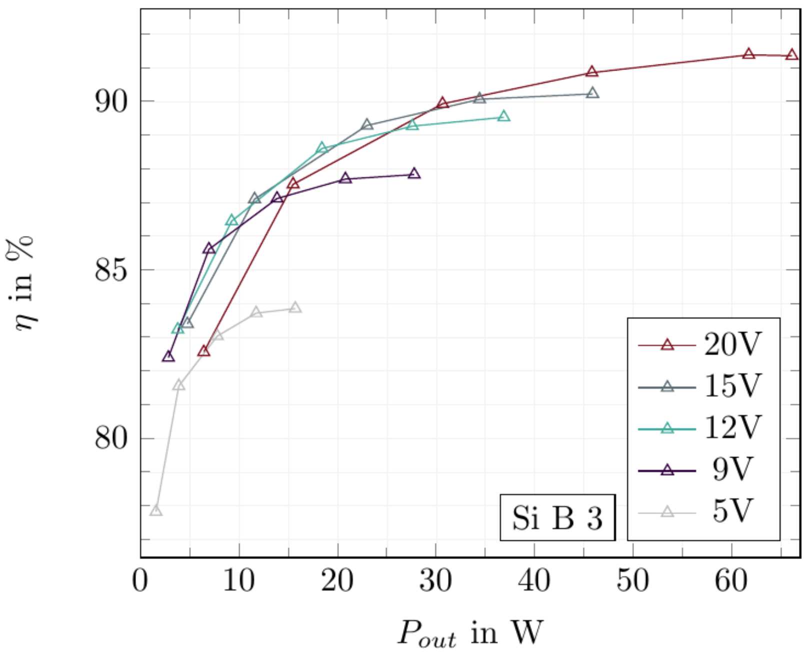


Figure 44: Efficiency over output power curves of Si B 3 charger output, for charging voltages 5 V, 9 V, 12 V, 15 V, 20 V.

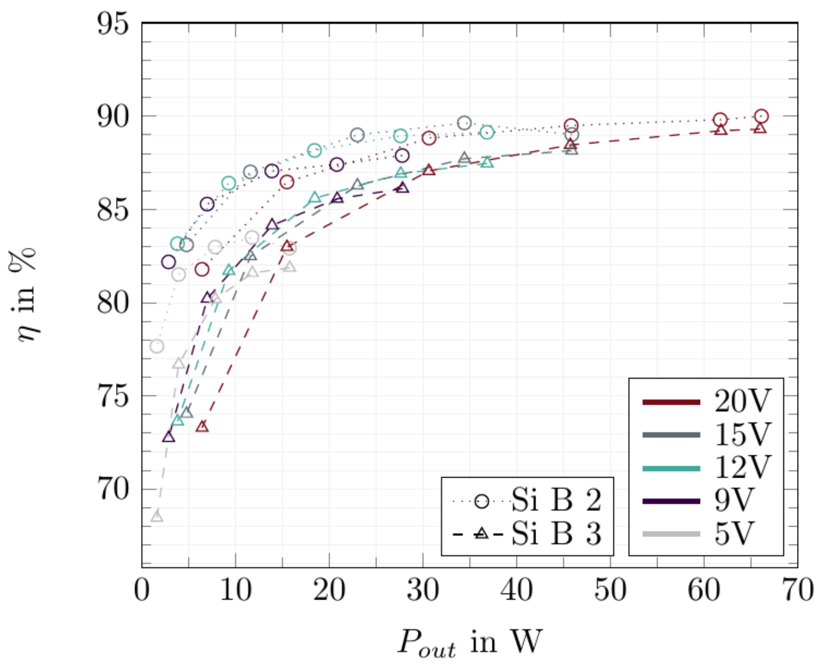


Figure 45: Efficiency over output power curves of Si B 2, and 3 charger output, for charging voltages 5 V, 9 V, 12 V, 15 V, 20 V.

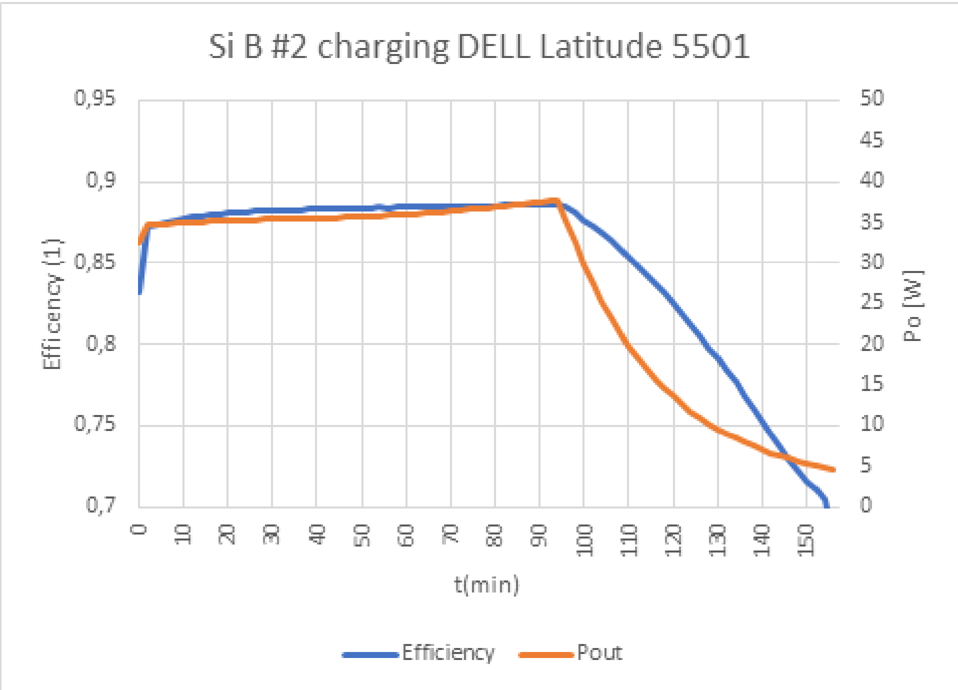


Figure 46: Output power and efficiency over time of a Si B 2 charging an inactive DELL Latitude 5501 laptop.

3. Measurements with Oscilloscope Setup

3.1. Measurement Setup

3.1.1. Calorimetric Verification Methodology

Measurement of small losses and high efficiencies are prone to large errors, especially in the case of high-frequency power electronics components and converters. Particularly when there is a need to electrically measure current waveforms [1]. For this reason, a reference calorimeter is extremely useful to verify the accuracy and sensitivity of any electrical system.

The sources for the inaccuracies can be summarized as [2]:

- Limited probe bandwidth
- Limited accuracy and measurement range
- Phase mismatch between voltage and current measurements
- Probe loading effects (burden)
- Electromagnetic interference (EMI)

Calorimetric systems directly measure the losses thermally and provide a measurement that is independent of the operation frequency of the device under test (DUT). A novel dual-chamber calorimeter is presented in [2], as shown in Figure 47 and Figure 48, for measurement of losses down to 500 mW with an unprecedentedly high accuracy, which is enabled by the following characteristics:

- Reducing the flow rate drastically for achieving a higher sensitivity. The same coolant flows in both chambers; hence, there is no need to measure extremely low flow rates. As a result, the sensitivity is high enough to measure losses as low as 500 mW with significantly lower costs.
- Replacing the time-consuming calibrations, balance tests, and data processing by a real-time calibration for faster loss evaluations.
- Avoiding the need for perfect thermal insulation since low levels of heat leakage, if equal for both chambers (which holds in identical chambers with symmetrical designs), do not introduce measurement inaccuracies.

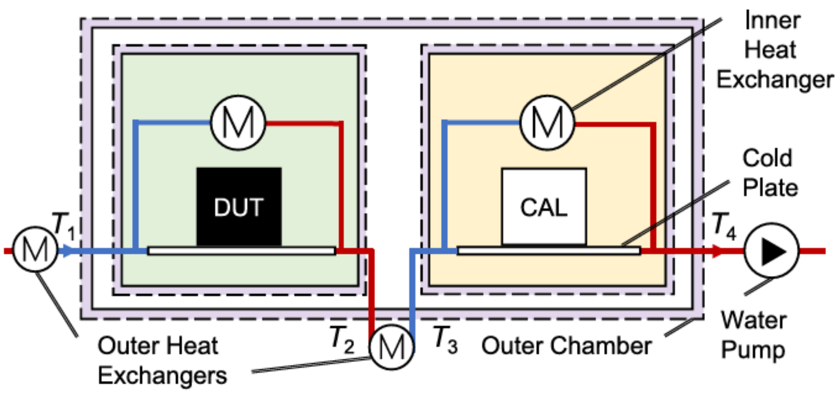


Figure 47: Schematic view of the calorimeter. Water flows in the identical chambers containing DUT and CAL. The water temperature rise is measured across both chambers and compared for the loss evaluation. The blue lines indicate the cold water and red lines represent the hot water after absorbing the energy dissipated in the chambers. The arrows show the flow direction.

The proposed calorimeter enables geometry-independent loss measurements by transferring the heat to the water through heat exchangers (convection) and cold plates (conduction). Two identical heat-insulated chambers are placed inside an outer chamber that isolates the calorimeter from the ambient (see Figure 48b). The water at the ambient temperature flows through the DUT chamber and after absorbing the heat generated by the DUT, gets cooled down to the ambient temperature using an external heat exchanger. The liquid then flows through the calibration (CAL) chamber and heats up with its dissipated power (P_{CAL}). After the calibration chamber, another external heat exchanger cools down the liquid to the ambient temperature. The entire heat-transfer cycle is repeated until the temperatures reach a steady state. Such a closed loop for the coolant ensures a constant flow in both chambers and eliminates the need for precise flow measurements. Temperature gradients $T_4 - T_3$ and $T_2 - T_1$ are measured and compared constantly, and a proportional-integral (PI) regulator adjusts P_{CAL} such that both chambers have equal steady-state temperature gradients. Thus, the DUT losses, P_{DUT}, can be derived at steady state as

$$T_2 - T_1 = T_4 - T_3 \Leftrightarrow P_{DUT} = P_{CAL}.$$

Such a system can be used to evaluate any electrical measurement system for its accuracy and correctness. After an electrical setup is verified with the calorimeter, one can utilize it for other measurements, with the reduced measurement time as calorimeters are typically slow.

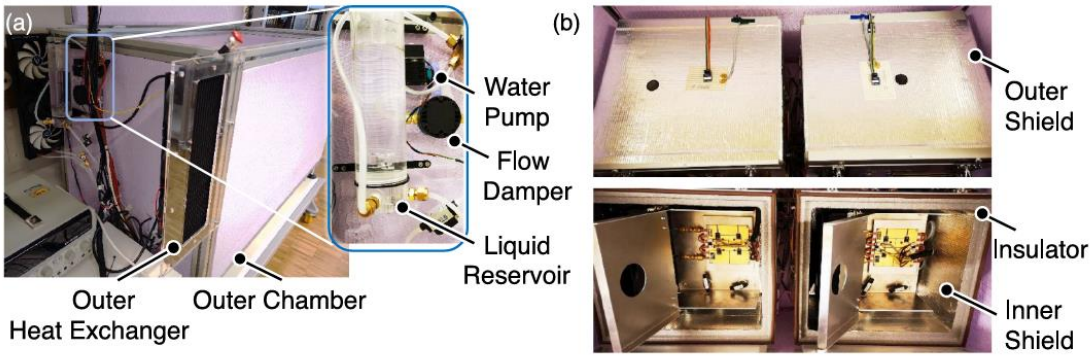
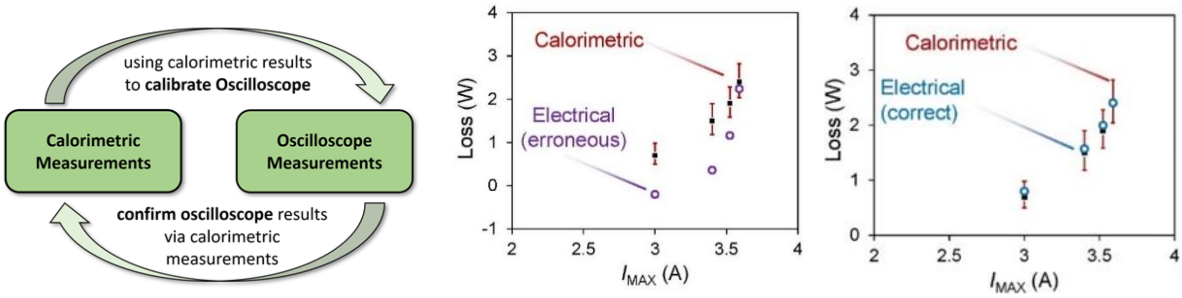


Figure 48: Calorimeter design. (a) Outer chamber and heat exchangers, together with the water circuit. (b) Inner chambers with the aluminum fixtures inside and shielding foils all over the inner and outer walls.

3.1.2. Verification with Electrical Measurements

The calorimeter is employed to verify the electrical loss/efficiency measurements using the MSO68B oscilloscope system, whose description comes in section 3.1.3.

Based on the experiments presented in [3], the oscilloscope system which is going to be employed for this report could measure the losses as low as 1 W accurately.



(a) Calibration approach. (b) Erroneous electrical measurements. (c) Correct electrical measurements using the MSO68B oscilloscope system

Figure 49: Verification of electrical measurement setups with the reference calorimeter. The fundamental harmonic for this measurement was 277 kHz, and MSO68B could provide acceptable accuracy for the measurement of low levels of losses.

To highlight the importance of the verification with the calorimeter, Figure 49b and Figure 49c present the comparison between two electrical setups with the reference calorimeter. In this experiment, the losses of a high-frequency inductor are measured when excited by a 277-kHz source (fundamental). The results from the first electrical setup in Figure 49b fail to match the calorimeter results, especially for low losses. Whereas, the MSO68B setup (Figure 49c) provides accurate results for all the measurements, which are in perfect agreement with the results from the reference calorimeter.

For the continuation of this report, the verified electrical setup are used for the investigation of power supplies.

3.1.3. Equipment Examples

The specifications of the measurement equiment used are listed in the following tables.

Table 15 Specification of the oscilloscope MSO68B.

Part number	MSO68B
Bandwidth	1 GHz – 10 GHz
Input resistance selection	1 MΩ or 50 Ω
DC gain accuracy	±2.0% at >2 mV/div
ADC resolution	12 bits
Sample rate	12.5 GS/s on > channels

Table 16 Specification of the current probe TCP0030A.

Part number	TCP0030A
Bandwidth	DC to > 120 MHz
Current range	5 – 30 A
DC to 60 Hz accuracy, ≤ 5 A	±1%
Sensitivity	1 mA

Table 17 Specification of the voltage probe THDP0200.

Part number	THDP0200
Bandwidth	200 MHz
Differential voltage	±1500 V
Input impedance at the probe tip	10 MΩ || <2 pF

3.1.4. Oscilloscope Setup

Figure 50 shows how the oscilloscope was set up for our measurements. Channel 1 is the input current, Channel 2 is the output current, Channel 3 is the input voltage, and Channel 4 is the output voltage. All four channels were configured with an input impedance of *1 MΩ*. The current channels were configured with a bandwidth of *120 MHz*, while the voltage channels were configured with a bandwidth of *200 MHz*. Plot 1 which is on the left displays the current with the first 40 harmonics. The bars are the harmonics (in *dBµA*) and the white lines are the maximum acceptable values for the harmonics according to the IEC class A standard.

Remarks:

- The advantage of using the Tektronix MSO68B oscilloscope (or other models with similar functions) was that by means of user pre-defined Math functions, the required operating efficiency, the THD values, and much more were visible directly while doing the measurements.

- The High-Res feature of the oscilloscope used for the measurements ensures high-precision measurements of up to 12-bits resolution.
- The efficiency and THD curves plotted in the next section were obtained by calculating the average value of an 8-cycle single acquisition.
- The Tektronix High-Voltage Differential Probes were used at 1500 V_{pk} range and at full *200 MHz* bandwidth.

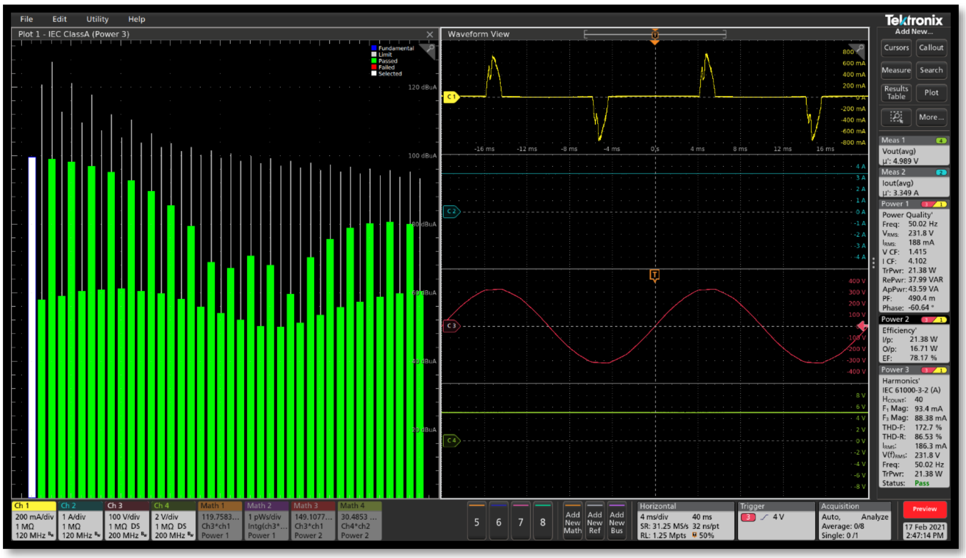


Figure 50: A screenshot of the Oscilloscope for the Baseus GaN Laptop Charger - 65W at full Output Power

3.2. Resistive Load Test Specifications

3.2.1. Measurement Procedure

1. Plug in the charger to a power strip that is switched off and connect the output of the charger to the variable power resistor set to maximum resistance (initially).
2. Connect the two differential probes to measure the voltage at the input of the charger and at the output of the charger. Make sure to AutoZero both probes. It should be noted that output voltage measurement should be made before the communication board to exclude its influence on the measured efficiency.
3. Degauss and AutoZero the current probes, and after switching the power strip on, connect one to measure the input current and the other to measure the output current.
4. Adjust the variable resistor to obtain the wanted power (100%, 75%, 50%, and 25% output power) and measure the Efficiency and THD values of the input current. Decreasing the value of the variable power resistor even more when obtaining 100% output capacity would cause a controller lockdown of the charger's internal AC/DC converter, thus it will not be functional anymore.
5. Switch off the input power and adjust the communication board to access different voltage modes. Repeat the last step for measurements at different load conditions.
6. Degauss the current probes after changing the charger to maintain accurate results. Make sure that the probe jaw is closed when doing so.

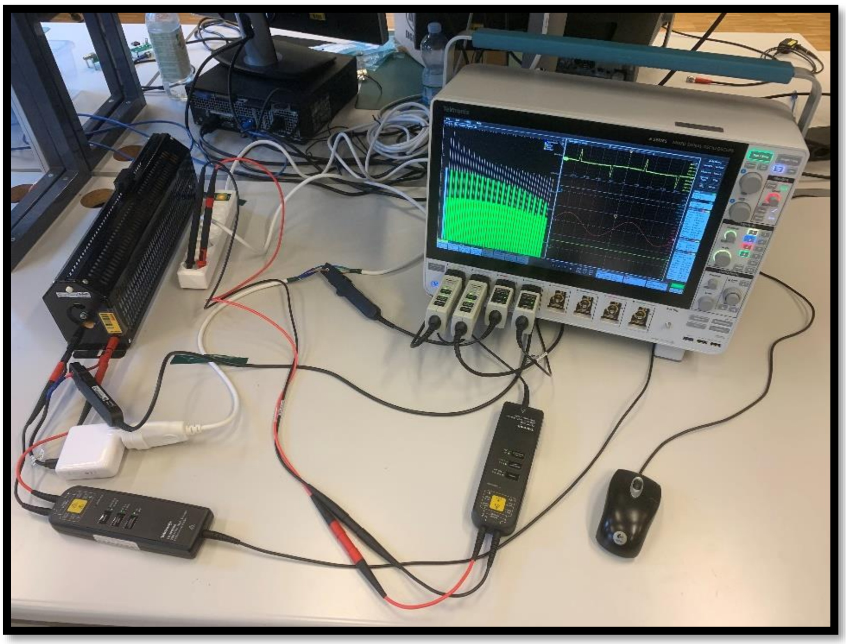


Figure 51: Measurement setup with oscilloscope.

3.2.2. Specifications for the Investigated Chargers

Here the specifications of the investigated Si-based and GaN-based chargers are listed in the following tables.

Table 18 Specification of Si-1 charger (5 W).

Charger index	Si-1
Rated max. power	5 W
Dimension (L × W × H)	4.8 ×3.5 ×1.4 cm
Weight	25 g
Power density	0.2 W/g, or 0.21 W/cm^3
USB ports	1 × USB-A

Table 19 Specification of Si-2 charger (30 W).

Charger index	Si-2
Rated max. power	30 W
Dimension (L × W × H)	5.2 × 2.6 × 5.4 cm
Weight	111 g
Power density	0.27 W/g, or 0.41 W/cm^3
USB ports	1 × USB-C

Table 20 Specification of Si-3 charger (60 W).

Charger index	Si-3
Rated max. power	60 W
Dimension (L × W × H)	6.5 × 2.8 × 6.5 cm
Weight	144 g
Power density	0.42 W/g, or 0.51 W/cm^3
USB ports	1 × USB-C

Table 21 Specification of GaN-1 charger (30 W).

Charger index	GaN-1
Rated max. power	30 W
Dimension (L × W × H)	3.4 × 3.8 × 4 cm
Weight	63 g
Power density	0.48 W/g, or 0.58 W/cm^3
USB ports	1 × USB-C

Table 22 Specification of GaN-2 charger (45 W).

Charger index	GaN-2
Rated max. power	45 W
Dimension (L × W × H)	3.1 × 2.9 × 6.2 cm
Weight	91 g
Power density	0.49 W/g, or 0.81 W/cm^3
USB ports	1 × USB-A, 1 × USB-C

Table 23 Specification of GaN-3 charger (60 W).

Charger index	GaN-3
Rated max. power	60 W
Dimension (L × W × H)	6.7 × 2.9 × 6.4 cm
Weight	153 g
Power density	0.39 W/g, or 0.48 W/cm^3
USB ports	1 × USB-A, 1 × USB-C

Table 24 Specification of GaN-4 charger (65 W).

Charger index	GaN-4
Rated max. power	65 W
Dimension (L × W × H)	2.8 × 5 × 5 cm
Weight	113 g
Power density	0.58 W/g, or 0.93 W/cm^3
USB ports	2 × USB-C

3.3. Measurement Results

3.3.1. Test Results of Different Samples from an Identical Model

In order to benchmark the accuracy and consistency of the measurement method, we performed tests and measured the efficiency curves of different samples for an identical charger model (60W GaN-3 charger). A communication board (CY4533 EZ-PD) was used to access different output voltage modes and the results are shown as below.

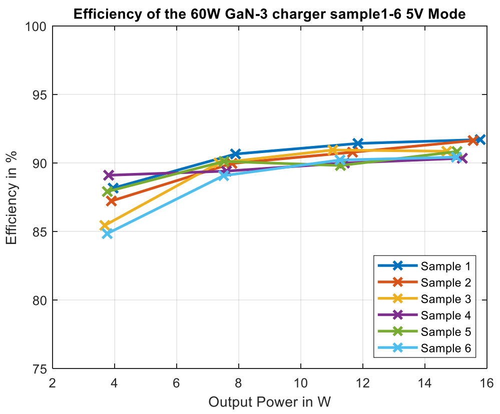


Figure 52: 5V mode.

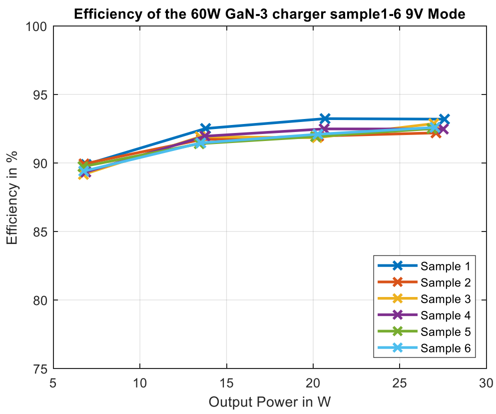


Figure 53: 9V mode.

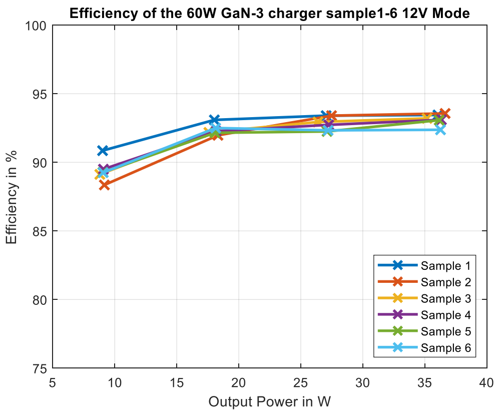


Figure 54: 12V mode.

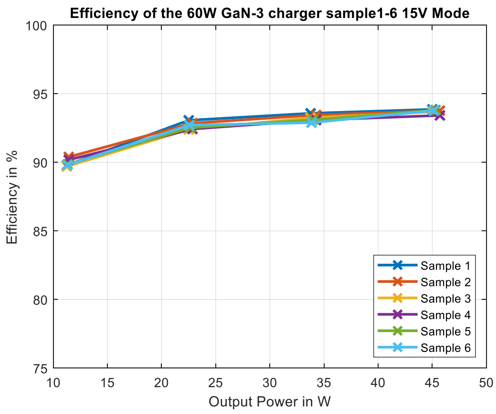


Figure 55: 15V mode.

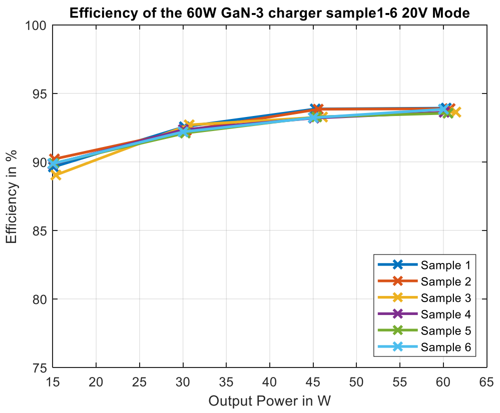


Figure 56: 20V mode.

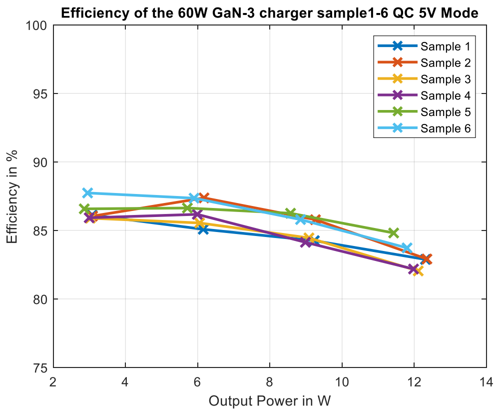


Figure 57: QC 5V mode.

The nominal maximum power can only be obtained at high voltage mode, i.e., 20 V. It can be observed that among the 6 samples under test, the difference in efficiency is less than 2% at the high power range (> 20 W), and between 2% to 4% at lower powers (< 10 W) with lower efficiencies. This demonstrates the consistency and accuracy of the electrical measurement method at the high power range and shows the error range of samples at low powers.

3.3.2. Efficiency and THD Curves with Static Load

The seven chargers (3 Si-based and 4 GaN-based) listed in Section **Fehler! Verweisquelle konnte nicht gefunden werden.** were tested. Output powers are adjusted by varying the load resistance value and different voltage modes are chosen by using a communication board. The efficiency curves and THDi curves of the input current at different output voltage modes are presented as follows.

It should be noted that since there is no THD requirement for <75W consumer products, the measured THDi levels are high for either Si chargers or GaN chargers because a simple diode rectifier bridge is used at the front. However, such measurements for THD and power factor are required for power supplies with higher power levels, which are not investigated in this report.

3.3.2.1. Results of Si-1 charger

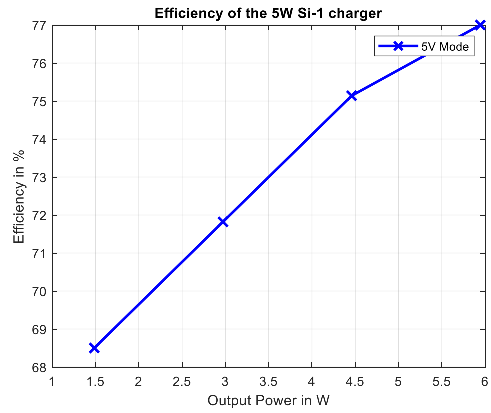


Figure 58: Efficiency versus power of Si-1.

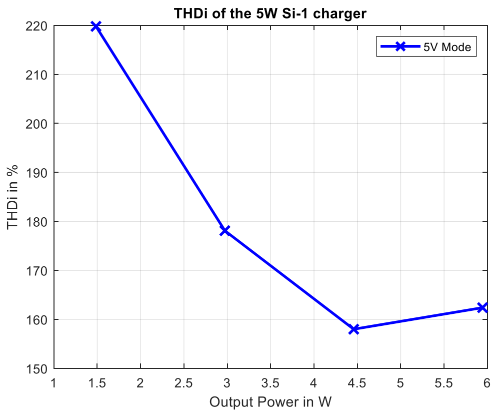


Figure 59: THDi versus power of Si-1.

3.3.2.2. Results of Si-2 charger

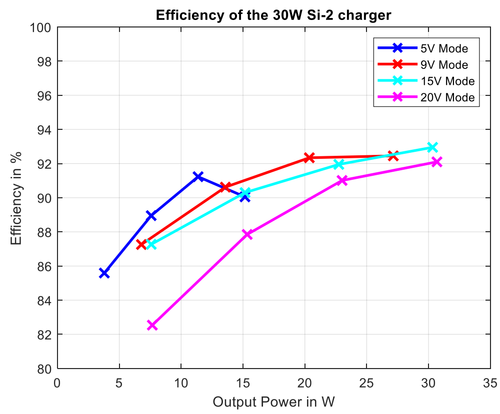


Figure 60: Efficiency versus power of Si-2.

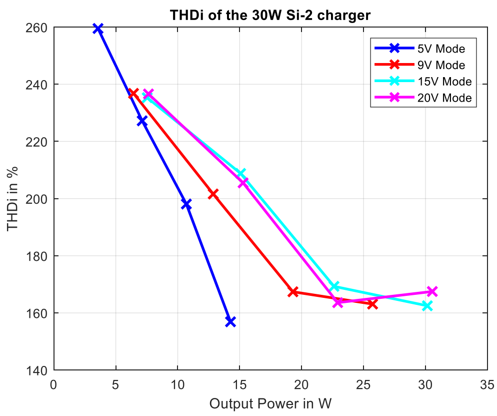


Figure 61: THDi versus power of Si-2.

3.3.2.3. Results of Si-3 charger

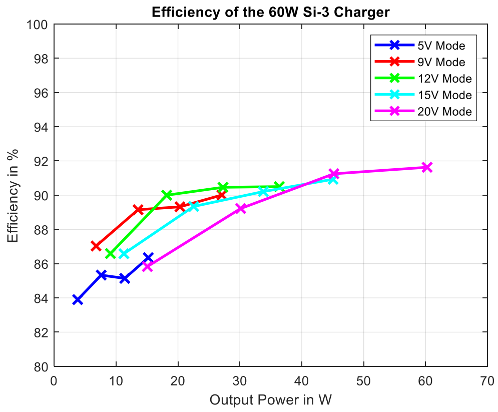


Figure 62: Efficiency versus power of Si-3.

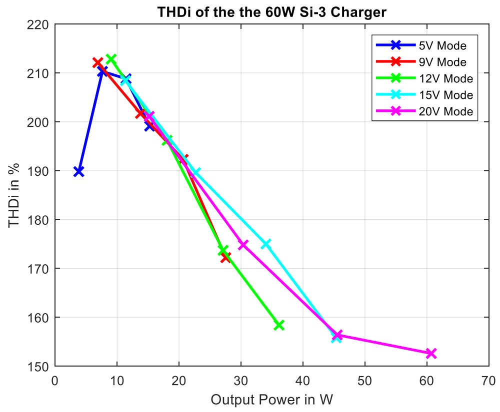


Figure 63: THDi versus power of Si-3.

3.3.2.4. Results of GaN-1 charger

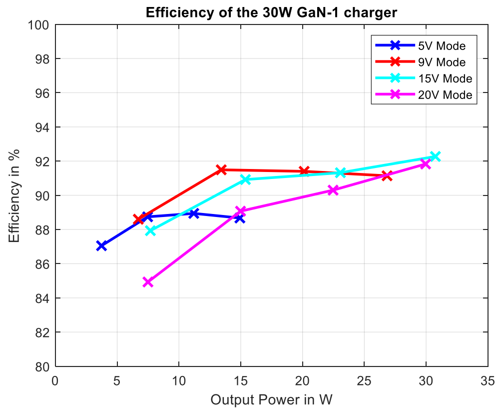


Figure 64: Efficiency versus power of GaN-1.

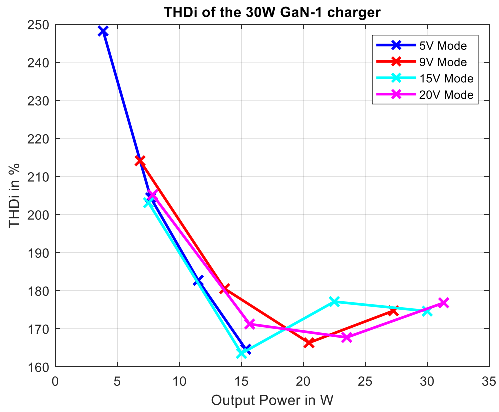


Figure 65: THDi versus power GaN-1.

3.3.2.5. Results of GaN-2 charger

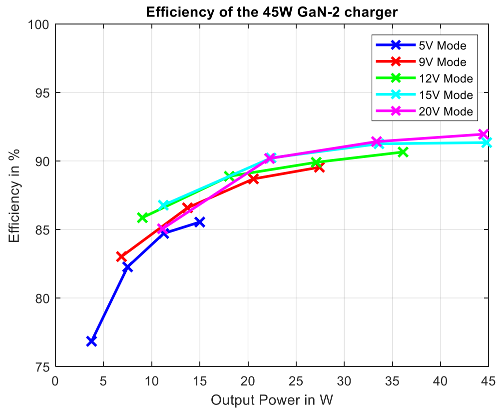


Figure 66: Efficiency versus power of GaN-2.

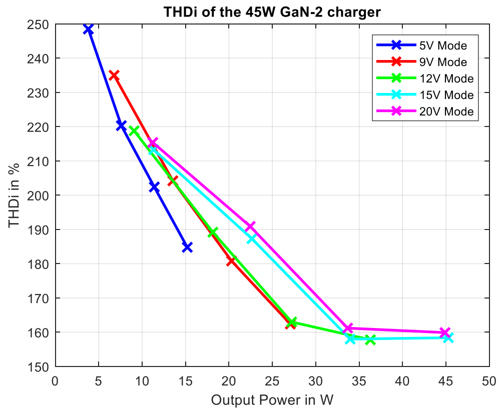


Figure 67: THDi versus power of GaN-2.

3.3.2.6. Results of GaN-3 charger

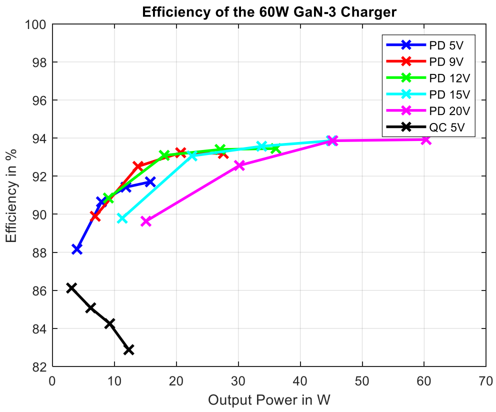


Figure 68: Efficiency versus power of GaN-3.

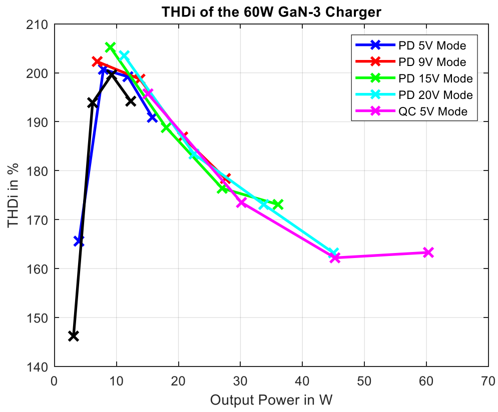


Figure 69: THDi versus power of GaN-3.

3.3.2.7. Results of GaN-4 charger

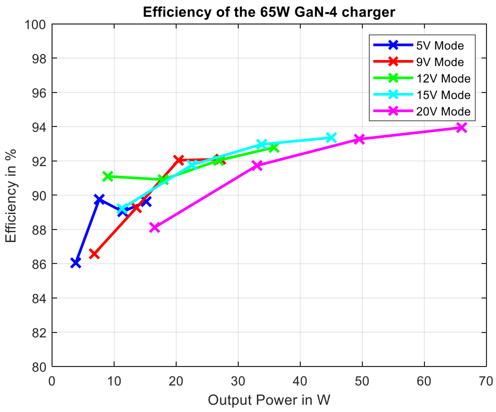


Figure 70: Efficiency versus power of GaN-4.

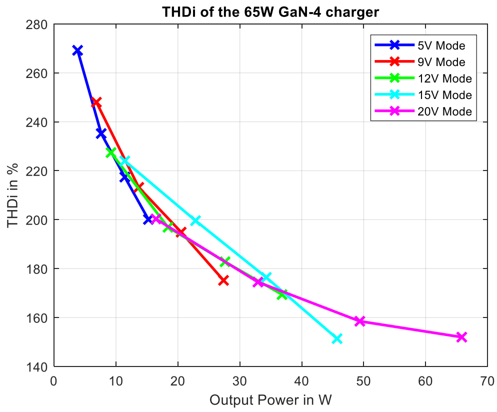


Figure 71: THDi versus power of GaN-4.

Among these chargers, it can be observed that in general, the efficiency increases with the output power, ranging from 80% to 95% across the power range, except for Si-1 charger. The rated maximum power can only be achieved at higher output voltage modes, e.g., 15 V and 20 V. However, it is observed that the lower voltage mode exhibits higher efficiency than the higher voltage mode if both of them are able to achieve the declared maximum power. For example, the efficiency curves at 15 V mode are slightly higher than that at 20 V mode for Si-2 charger and GaN-1 charger.

The THDi level for these chargers, no matter Si-based or GaN-based, is generally high, especially at low output powers, which is expected as there is no requirement at this power level.

4. Electrical Efficiency and Power Density Measurement Results - Summary

4.1.1. Efficiency Comparisons of Si-Based and GaN-Based Chargers

In order to make a fair comparison of the efficiencies of Si-based and GaN-based power solutions, only the chargers with the same power rating and the same output voltage mode are compared. Figure 72 compares the efficiency of two 30 W Si-based and GaN-based chargers at 15 V mode and 20 V mode (the selected chargers are listed in Table 19 and Table 21), both of which are able to reach the rated maximum power.

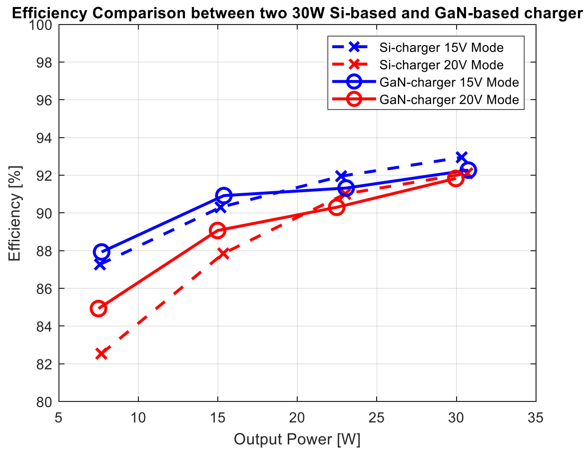


Figure 72: Efficiency Comparison between two 30W Si-based and GaN-based chargers.

These two chargers show similar performance and the difference in efficiency is around 1% at 30 W, which falls into the error range at such power, as analyzed in Section 3.3.1. Therefore, no conclusions can be drawn about whether GaN-based chargers outperform Si-based ones at these powers.

Figure 73 shows the efficiency curve of the 60 W GaN-based charger (GaN-3), which is always higher than the 60 W Si-based one (Si-3) across the whole power range with a difference of more than 2%. This will translate into a difference in losses of about 1.4 W at an output power of 60 W. It is clear that at higher power, the GaN-based solution shows better performance in terms of efficiency and losses saved.

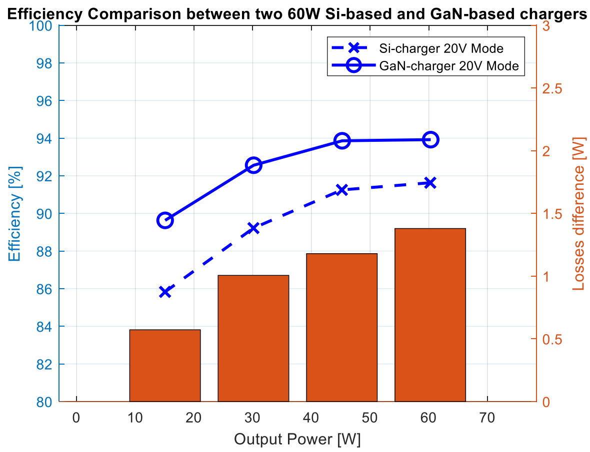


Figure 73: Efficiency Comparison between two 60W Si-based and GaN-based chargers.

To obtain an overall picture of the performance of all the chargers investigated, the efficiency results at the maximum power allowed at different voltage modes are set out in Figure 74, as these chargers are usually used at full power at a certain output voltage. In general, GaN-based chargers outperform Si-based ones in the power range above 30 W, by an increase of about 2-3% in efficiency. In terms of reduced losses, this will become more significant especially when the output power is higher.

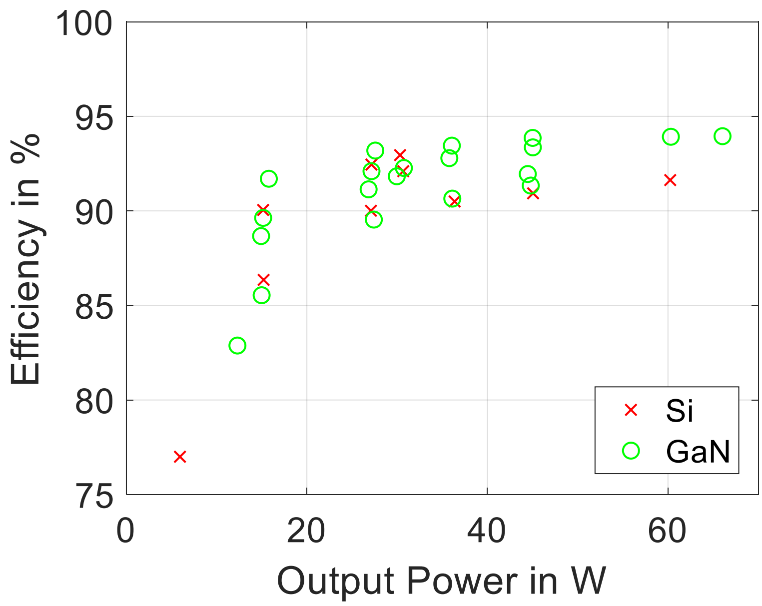


Figure 74: Full power efficiency comparison of all chargers investigated.

Additionally, electrical efficiency measurement results from the power analyzer setup are shown for GaN and Si power supplies for different voltage modes to access different maximum output power (see Figure 75). It can be obtained that the GaN Power supplies have a higher efficiency than the Si power supplies. It should be noted that this may partly result from the fact that the GaN-based systems are developed and designed more recently than the Si-based ones (e.g. utilizing integrated and specialized PWM controllers, taking advantage of valley switching in order to reduce switching losses, etc.).

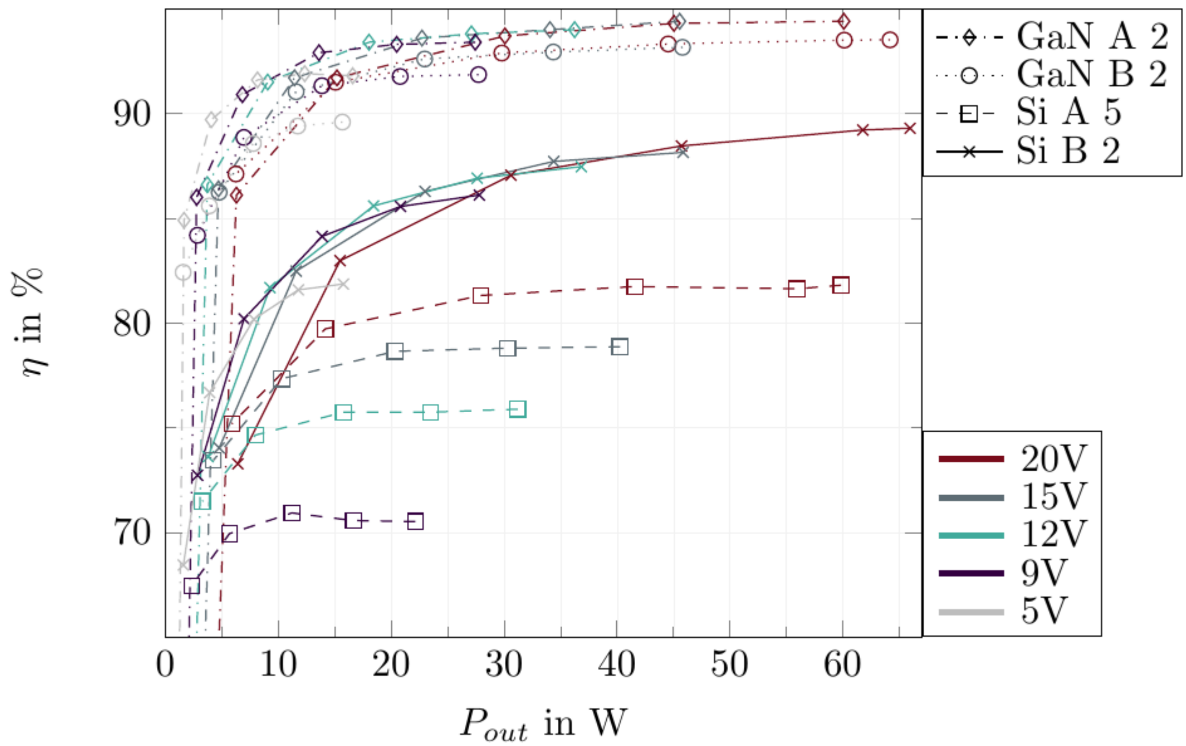


Figure 75: Different charger's efficiencies over output power for different output voltage modes. 12V measurement was not possible with Anker super supply as it does not support 12 V output.

Regarding switching frequency, the GaN Power supply (GaN A) comes with slightly lower switching frequency than the Si power supplies (see Figure 76). Due to the compact design of the GaN B component, it is not possible to measure the switching frequency. It should be noted, that these low wattage power supplies are adapting the switching frequency based on the requested charging power to optimize the electrical efficiency over the full-power range.

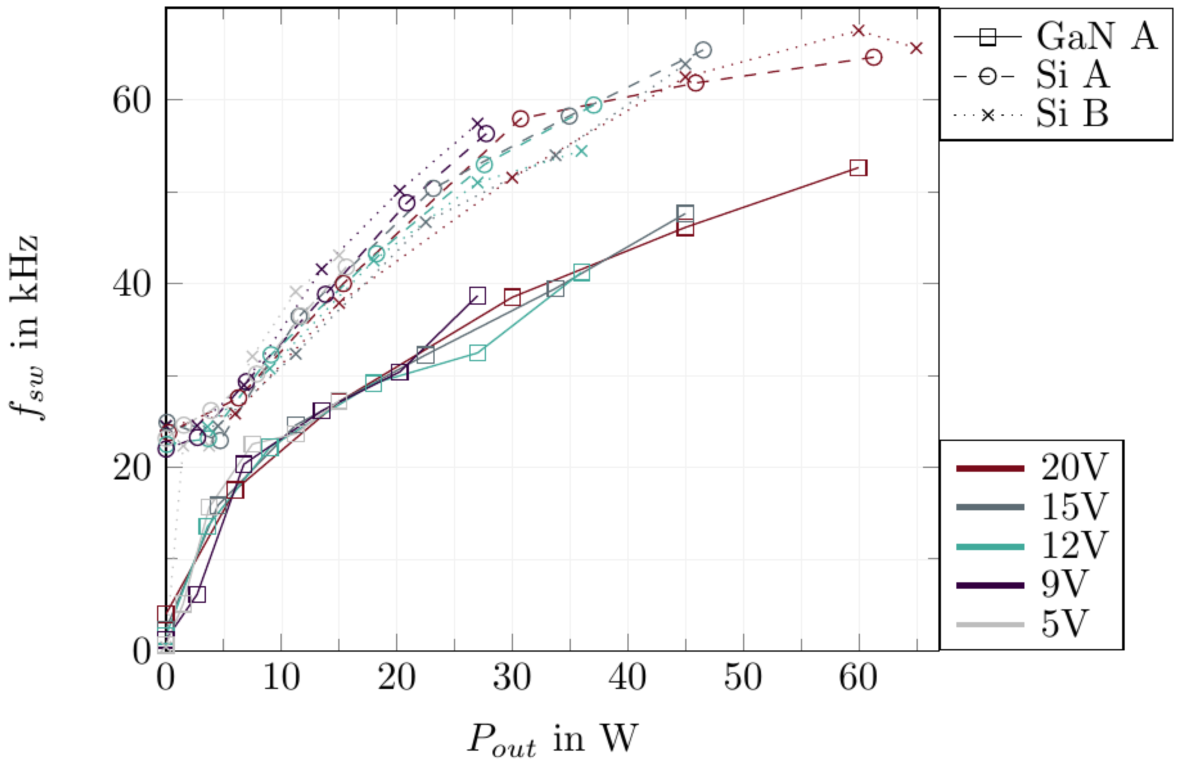


Figure 76: Measured switching frequency of the different chargers.

4.1.1. Power Density Comparisons of Si-Based and GaN-Based Chargers

Another important metric to evaluate the performance of Si-based and GaN-based chargers is the power density since a well-known benefit of using WBG devices is the higher switching frequency to shrink the passive component volumes. The gain is straightforward as shown in Figure 77 and Figure 78.

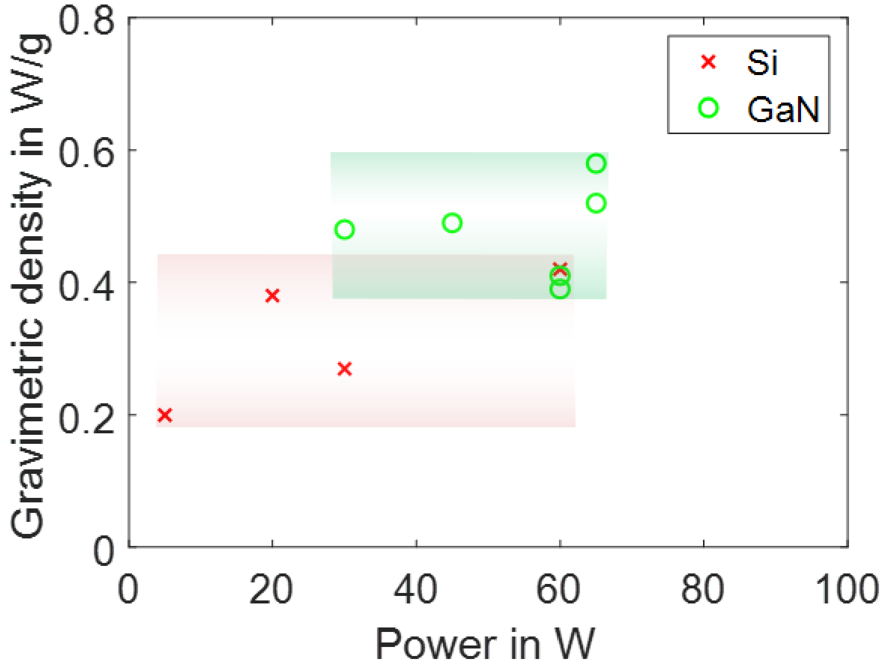


Figure 77: Comparison of gravimetric power densities.

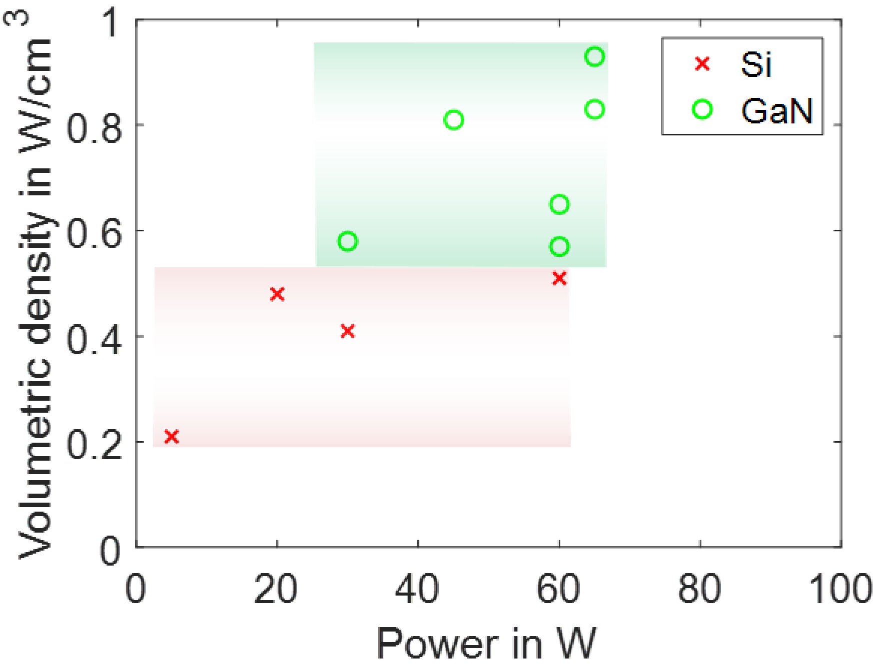


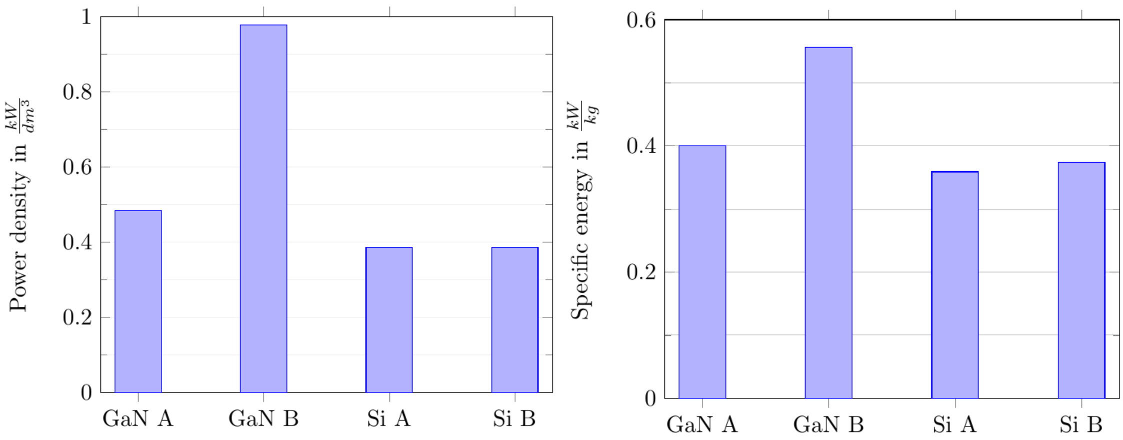
Figure 78: Comparison of volumetric power densities.

Although different chargers may have different available numbers of output voltage modes and therefore different design concerns, the following graphs are based on the total output power capability at full load as indicated for each charger. It is clear that the GaN-based chargers offer higher power densities both in volume and in weight up to two times on average. Such an increase in power density could come from the improvements in efficiencies, which benefits in the reduction or removal of heat sinks.

This can be also confirmed for a comparison of the other four GaN and Si power supplies investigated. The GaN-based devices come with at least the same or higher power density compared to their Si counter parts. For the GaN B a value of around 0.977$\frac{kW}{dm^3}$ and for GaN A 0.483 $\frac{kW}{dm^3}$ could be achieved. The Si power supplies have both a power density of approximately 0.385 $\frac{kW}{dm^3}$.

Although power density of the GaN B power supply is nearly twice as high compared to the remaining 3 chargers, the difference in terms of power-to-weight ratio is only roughly 40 % higher, but still significantly elevated. The GaN B power supply comes with 0.556 $\frac{kW}{kg}$, followed by GaN A with 0.4 $\frac{kW}{kg}$, Si B with 0.374 $\frac{kW}{kg}$, and Si A with 0.359 $\frac{kW}{kg}$.

It should be noted that GaN A charger consists of two output voltage ports, and thus includes an additional dc-dc converter, which results in a relatively lower power density but still exceeding that of the Si chargers.



(a) (b)

Figure 79: (a) Power density and (b) power-to-weight ratio of the different chargers.

5. Discussion and Conclusions

The consistency and accuracy of the different measurement methods were determined by comparing different samples of identical charger models. This also showed the error range at different output powers. Then, the efficiency and THDi levels of all the investigated chargers were measured at different load conditions, with a communication board to access different output voltage modes. The maximum efficiency occurred generally at higher powers, while it was observed that the chargers were designed to optimize efficiency at lower voltage mode, if several voltage modes are able to attain the nominal maximum power.

The comparison of the efficiency between Si-based and GaN-based chargers of the same power level shows that the investigated chargers present a similar performance at power levels up to 30 W. For example, for two chargers with a nominal maximum power of 30 W (Si-based 30 W and GaN-based 30 W), the efficiency at the rated power of four load conditions (25%, 50%, 75% and 100%) was similar, of around 90%. In the higher power range, GaN-based solutions outperform their Si counterparts for which the average efficiency was 92% for GaN-based 60 W and 90% for Si-based 60 W. Although these numbers are very close, the difference becomes much more considerable in terms of saved energy losses, especially at higher output powers. It should be noted that the difference in efficiency may partly result from the fact that the GaN-based systems are developed and designed more recently than the Si-based ones. More investigations with a broader power range of Si-based and GaN-based chargers are needed to conclude in more detail on the efficiency gain.

Furthermore, the chargers are not optimized in every voltage mode, and in general, the efficiency at lower voltage modes (for lower output power) is lower compared to higher voltage modes (for higher output power). This could result in significant power losses. For example, consider charging a Galaxy S20 battery of 4000 mAh and a battery voltage of 3.86 V with the Si-based 60 W charger and the GaN-based 60 W charger. The efficiency of 5 V mode in the 15 W level could be taken to calculate the energy loss of two different chargers (86.5% for Si solution and 91.5% for GaN power supply). According to Statista, the number of smartphone users reached 6.26 billion in 2021 globally [4]. The total energy lost during the charging process every year can be calculated as 6.26*10^9*(4Ah*3.86V)*(1/0.865-1)*365 = 5.5 TWh. This is equivalent to the total energy consumption of 1.56 million average EU households per year. An increase in efficiency to 91.5% (between Si- and GaN device) would lead to savings of 40% of the energy lost, or 2.2 TWh per year.

According to the EU commission regulation 2019/1782 for external power supplies [5] (see in the appendix), the minimum requirement for the average active efficiency is 88% for output powers higher than 49 W (86% for multiple voltage output), which was met by mostly all chargers that have been tested. The GaN-based solutions in general showed better performance. Although all products come with different switching frequency and control strategy which also impacts efficiency, the electrical efficiency regulation requirements could be increased to promote the adoption of WBG technologies and their implementation strategies aiming for higher efficiencies.

However, it should be noted, that todays 20 V/65 W chargers come with several different features as for example:

- Single output PD charging: 5 V (15 W) – 20 V (65 W)
- Dual output:
  - First output: PD charging as defined above
  - Second output: either PD charging (5 V (15 W) – 20 V (65 W)) or QC (quick charging: 5 V, 15 W)
- More than 2 outputs: combination of the defined above

So one output addresses several different voltage and dedicated maximum power ratings per voltage level (limited by the output current of in this specific case 3 A). The EU commission regulation 2019/1782 for external power supplies is however, not precisely addressing how to handle a single charger that provides different voltage and power levels and multiple outputs.

For example, in the regulation the following is statement is included: "*From 1 April 2020, the average active efficiency shall be not less than the following values: Multiple voltage output external power supplies: P_o > 49,0 W: Average Active Efficiency > 0.86.*" However, it is NOT mentioned if the average efficiency, then applies for all voltage levels or only the voltage level which can provide nominal power > 49 W. The recommendation of IEA 4E PECTA is to give more precise examples that reflect charger configurations as defined above.

In addition, the EU commission regulation 2019/1782 for external power supplies contains the following paragraph: "*From 1 April 2020, instruction manuals for end-users (where applicable), and free access websites of manufacturers, importers or authorized representatives shall include the following information, in the order as set out below: Average active efficiency: Declared by the manufacturer based on the value calculated as arithmetical mean of efficiency at load conditions 1-4. In cases where multiple average active efficiencies are declared for multiple output voltages available at load condition 1, the value published shall be the average active efficiency declared for the lowest output voltage.*"

Here the regulation is addressing the output voltage ("the value published shall be the average active efficiency declared for the lowest output voltage"). However, it is only related to specific "information" that should be included by the manufacturer. It is not addressing the efficiency requirements that must be fulfilled according to the regulation for different voltage levels.

Thus, it is recommended to clarify, in the document which minimum efficiency (or multiple minimum efficiency) applies to a single output PD charger with several voltage and power levels.
Another recommendation is to clarify if different average efficiency levels apply for two different outputs with different ratings (e.g., output 1: PD-charging (5 V - 20V, 15 W - 65 W), output 2: quick charging (5V, 15 W)), as the minimum efficiency for 15W power supplies is lower compared to a 60 or 65 W power supply.

The benefits of using WBG devices are more evident in terms of power density, with a reduction of about two-fold, both in volume and weight, which also has a huge environmental impact in reducing waste. Power density is currently a strong motivation for using GaN devices among manufacturers. As the power charger market was the first to experience the penetration of WBG devices, and the associated advantages have emerged, it can be foreseen that other power electronic applications will also benefit from their wider adoption, not only in terms of more material saved from high power density, but also from higher efficiencies.

To summarize the above-mentioned conclusion, this measurement report of different Silicon and GaN-based power supplies shows that:

- Power density and efficiency are the two main drivers using GaN;
- Industry works primarily towards higher power density, with less focus on exceeding the regulations in terms of efficiency;
- Efficiency does vary substantially among products, GaN-based solutions outperform Si ones for the power range of 60W;
- Below 30W, the efficiency difference between GaN and Si is small.

The industry and policymakers should work closely on standardizations and regulations for both power density and efficiency to fully exploit the advantages of WBG devices and bring forward next-generation efficient power electronic solutions.

Appendices

Appendix 1: Further Definitions

Additional relevant definitions from the legal text of commission regulation EU 2019/1782 of 1 October 2019 related to external power supplies (EU 2019/1782, L 272/97-98, 25.10.2019):

"*External power supply means a device which meets all of the following criteria*

- *It is designed to convert AC power input from the mains power source input into one or more lower voltage DC or AC outputs.*
- *It is used with one or more separate devices that constitute the primary load.*
- *It is contained in a physical enclosure separate from the device or devices that constitute the primary load.*
- *It is connected to the device or devices that constitute the primary load with removable or hard-wired male/female electrical connections, cables, cords or other wirings.*
- *It has nameplate output power not exceeding 250 Watts.*
- *It is used with electrical and electronic household and office equipment included in Annex I.*

Low voltage external power supply *means an external power supply with a nameplate output voltage of less than 6 volts and a nameplate output current greater than or equal to 550 milliamperes (mA).*

Multiple voltage output external power supply *means an external power supply able to convert AC power input from the mains power source into more than one simultaneous output at lower DC or AC voltage.*

Voltage converter *means a device converting the 230 volts mains power source input to 110 volts power output with characteristics similar to mains power source input characteristics.*

Uninterruptible power supply *means a device that automatically provides backup power when the electrical power from the mains power source drops to an unacceptable voltage level.*

Battery charger *means a device that connects directly to a removable battery at its output interface.*

Lighting converter *means an external power supply used with extra low voltage light sources.*

Active power over Ethernet injector *means a device that converts the mains power source input to a lower DC voltage output, has one or more Ethernet input and/or one or more Ethernet output ports, delivers power to one or several devices connected to the Ethernet output port(s), and provides the rated voltage at the output ports(s) only when compatible devices are detected following a standardised process.*

Docking station for autonomous appliances *means a device in which a battery-operated appliance that executes tasks requiring the appliance to move without any user intervention is placed for charging, and that can guide the independent movements of the appliance.*

Mains *means the electricity supply from the grid of 230 (± 10 %) volts of alternating current at 50 Hertz (Hz).*

Information technology equipment *means any equipment which has a primary function of either entry, storage, display, retrieval, transmission, processing, switching, or control, of data or of telecommunication messages or a combination of these functions and may be equipped with one or more terminal ports typically operated for information transfer.*

Domestic environment *means an environment where the use of broadcast radio and television receivers may be expected within a distance of 10 m of the equipment concerned.*

Nameplate output power *(P_O) means the maximum output power as specified by the manufacturer; EN Official Journal of the European Union 25.10.2019 L 272/97.*

No-load condition *means the condition in which the input of an external power supply is connected to the mains power source, but the output is not connected to any primary load.*

Active mode *means a condition in which the input of an external power supply is connected to the mains power source and the output is connected to a primary load.*

Active mode efficiency *means the ratio of the power produced by an external power supply in active mode to the input power required to produce it.*

Average active efficiency *means the average of the active mode efficiencies at 25 %, 50 %, 75 % and 100 % of the nameplate output power.*

Equivalent model *means a model which has the same technical characteristics relevant for the technical information to be provided, but which is placed on the market or put into service by the same manufacturer, importer or authorised representative as another model with a different model identifier.*

Model identifier *means the code, usually alphanumeric, which distinguishes a specific product model from other models with the same trademark or the same manufacturer's, importer's or authorised representative's name.*

Furthermore, in EU 2019/1782, L 272/97-98, 25.10.2019 Annex I, external power supplies meeting the aforementioned specifications are sub divided into different **classes**:

- Household appliances
- Information technology equipment
- Consumer equipment
- Electrical and electronic toys, leisure and sports equipment

According to EU 2019/1782, L 272/100, 25.10.2019 Annex I, the following equipment are considered within these 4 pre-defined subgroups regarding electrical and electronic household and office equipment or home appliances (see Table 25).

Table 25 Equipment considered within the 4 pre-defined subgroups "household appliances", "information technology equipment", "Consumer equipment", Electrical and electronic toys, leisure and sports equipment".

Household appliances	
	Appliances for cooking and other processing of food, preparing beverages, opening or sealing containers or packages, cleaning, and maintenance of clothes.
	Appliances for hair cutting, hair drying, hair treatment, tooth brushing, shaving, massage and other body care appliances
	Electric knives
	Scales
	Clocks, watches and equipment for the purpose of measuring, indicating or registering time
Information technology equipment	
	Including copying and printing equipment and
	Set-Top boxes, intended primarily for use in the domestic environment.
Consumer Equipment	

	Radio sets
	Video cameras
	Video recorders
	Hi-fi recorders
	Audio amplifiers
	Home theatre systems
	Televisions
	Musical instruments
	Other equipment for the purpose of recording or reproducing sound or images, including signals or other technologies for the distribution of sound and image other than by telecommunications
Electrical and electronic toys, leisure and sports equipment	
	Electric trains or car racing sets
	Game consoles, including hand-held game consoles
	Sports equipment with electric or electronic components
	Other toys, leisure and sports equipment

Appendix 2: Energy Efficiency Requirements

The energy efficiency requirements are defined according to EU 2019/1782, L 272/101, 25.10.2019. Regulations according to the EU commission are denoted in the following.

Since April 1st, 2020, according to the EU Commission, the **power consumption** of external power supplies shall not exceed the determined values **under no-load condition**:

for a nameplate output power 0 W < $P_o \leq$ 49 W

1. AC-AC external power supplies (except 3. and 4.): 0.21 W
2. AC-DC external power supplies (except 3. and 4.): 0.10 W
3. Low voltage external power supplies: 0.10 W
4. Multiple voltage output external power supplies: 0.30 W

for a nameplate output power P_o > 49 W and $P_o \leq$ 250 W

1. AC-AC external power supplies (except 3. and 4.): 0.21 W
2. AC-DC external power supplies (except 3. and 4.): 0.21 W
3. Low voltage external power supplies: 0.21 W
4. Multiple voltage output external power supplies: 0.30 W

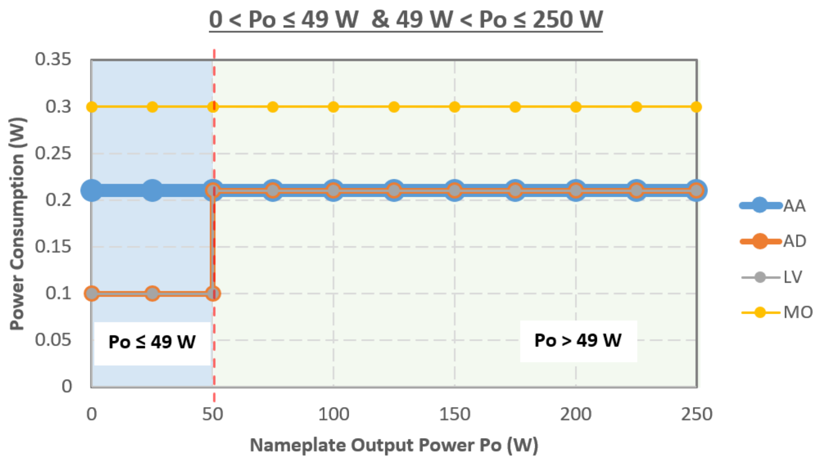


Figure 80: Maximum allowable no-load power consumption for external power supplies for a nameplate output power of 0 W < Po ≤ 250 W. AC-AC external power supplies (AA), AC-DC external power supplies (AD), Low voltage external power supplies (LV), Multiple voltage output external power supplies (MO).

The **average active efficiency** of external power supplies **MUST EXCEED** the determined values:

For a nameplate output power <u>0 W < P_o ≤ 1 W</u>

1. AC-AC external power supplies (except 3. and 4.): $\eta_{avg} = 0.5 \cdot \frac{P_o}{1W} + 0.16$
2. AC-DC external power supplies (except 3. and 4.): $\eta_{avg} = 0.5 \cdot \frac{P_o}{1W} + 0.16$
3. Low voltage external power supplies: $\eta_{avg} = 0.517 \cdot \frac{P_o}{1W} + 0.087$
4. Multiple voltage output external power supplies: $\eta_{avg} = 0.497 \cdot \frac{P_o}{1W} + 0.067$

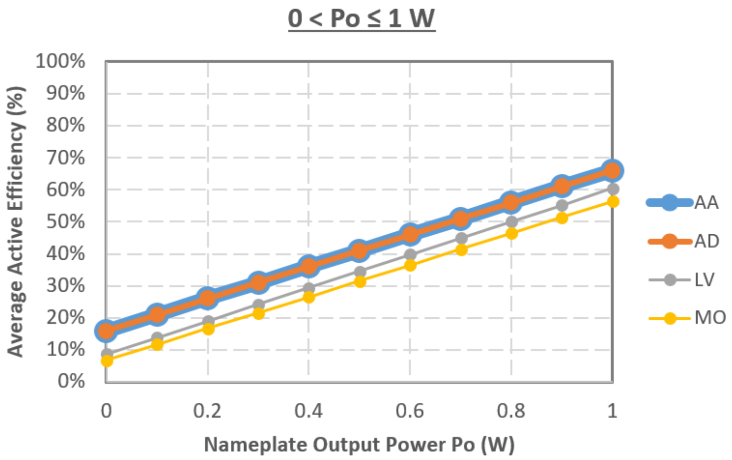


Figure 81: Average active efficiency for external power supplies for a nameplate output power 0 < Po ≤ 1 W. AC-AC external power supplies (AA), AC-DC external power supplies (AD), Low voltage external power supplies (LV), Multiple voltage output external power supplies (MO).

For a nameplate output power <u>P_o > 1 W and P_o ≤ 49 W</u>

1. AC-AC external PS (except 3. and 4.): $\eta_{avg} = 0.071 \cdot \ln\left|\frac{P_o}{1W}\right| - 0.0014 \cdot \frac{P_o}{1W} + 0.67$
2. AC-DC external PS (except 3. and 4.): $\eta_{avg} = 0.071 \cdot \ln\left|\frac{P_o}{1W}\right| - 0.0014 \cdot \frac{P_o}{1W} + 0.67$
3. Low voltage external PS: $\eta_{avg} = 0.0834 \cdot \ln\left|\frac{P_o}{1W}\right| - 0.0014 \cdot \frac{P_o}{1W} + 0.609$
4. Multiple voltage output external PS: $\eta_{avg} = 0.075 \cdot \ln\left|\frac{P_o}{1W}\right| + 0.561$

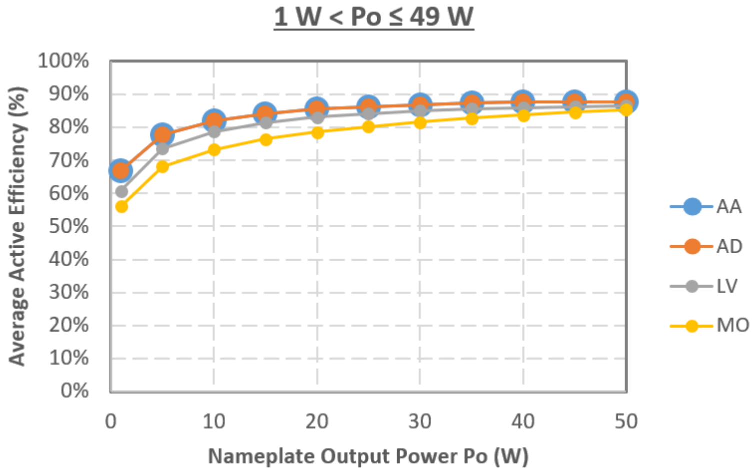


Figure 82: Average active efficiency for external power supplies for a nameplate output power ranging from 1 W < Po ≤ 49 W. AC-AC external power supplies (AA), AC-DC external power supplies (AD), Low voltage external power supplies (LV), Multiple voltage output external power supplies (MO).

For a nameplate output power P_o > 49 W and P_o ≤ 250 W

1. AC-AC external power supplies (except 3. and 4.): $\eta_{avg} = 0.88$
2. AC-DC external power supplies (except 3. and 4.): $\eta_{avg} = 0.88$
3. Low voltage external power supplies: $\eta_{avg} = 0.87$
4. Multiple voltage output external power supplies: $\eta_{avg} = 0.86$

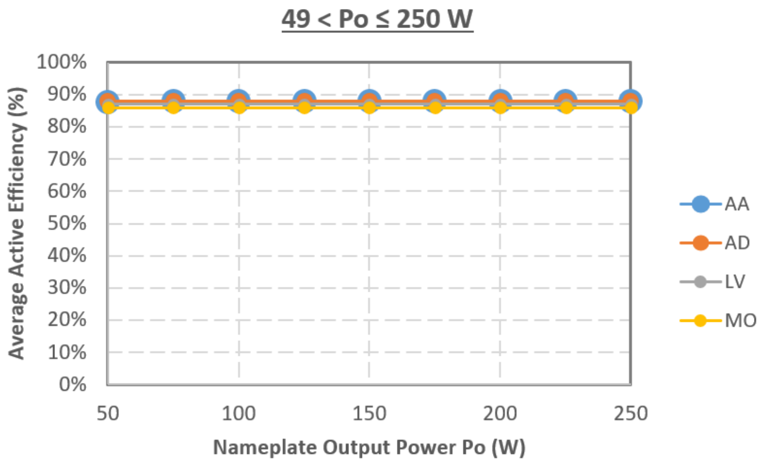


Figure 83: Average active efficiency for external power supplies for a nameplate output power for values 49 W < Po ≤ 250 W. AC-AC external power supplies (AA), AC-DC external power supplies (AD), Low voltage external power supplies (LV), Multiple voltage output external power supplies (MO).

A summary of dedicated average efficiency values for AC-DC external power supplies (AD) ranging from 0 W to 250 W is illustrated in Figure 84.

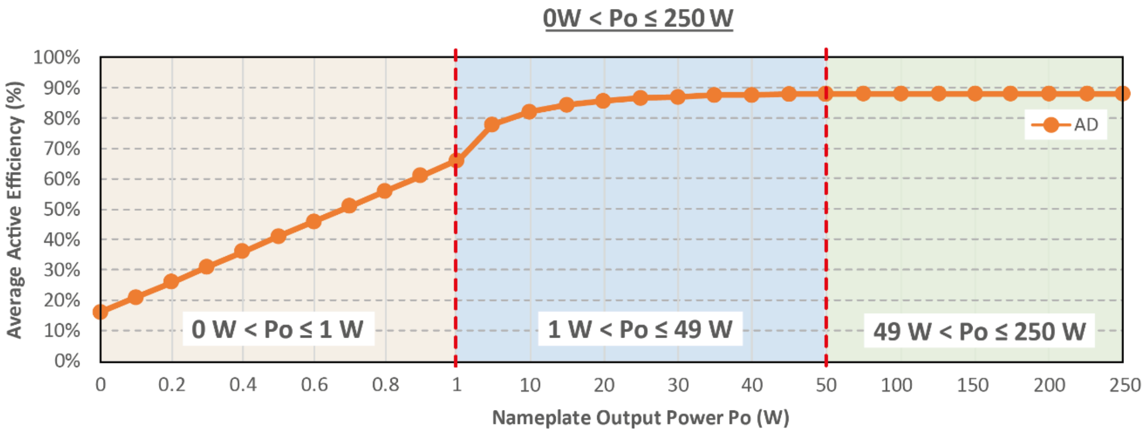


Figure 84: Average active efficiency for external power supplies for a nameplate output power in the range of 0 W < Po ≤ 250 W. AC-DC external power supplies (AD).

References

[1] K. Wang, X. Yang, H. Li, L. Wang and P. Jain, "A High-Bandwidth Integrated Current Measurement for Detecting Switching Current of Fast GaN Devices," in IEEE Transactions on Power Electronics, vol. 33, no. 7, pp. 6199-6210, July 2018, doi: 10.1109/TPEL.2017.2749249.

[2] A. Jafari et al., "High-Accuracy Calibration-Free Calorimeter for the Measurement of Low Power Losses," in IEEE Transactions on Power Electronics, vol. 36, no. 1, pp. 23-28, Jan. 2021, doi: 10.1109/TPEL.2020.3001001.

[3] A. Jafari et al., "Calibration-Free Calorimeter for Sensitive Loss Measurements: Case of High-Frequency Inductors," 2020 IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL), Aalborg, Denmark, 2020, pp. 1-8, doi: 10.1109/COMPEL49091.2020.9265756.

[4] Number of smartphone subscriptions worldwide from 2016 to 2021, with forecasts from 2022 to 2027, Statista. Available at: https://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide/.

[5] Commission Regulation (EU) 2019/1782 of 1 October 2019 Laying Down Ecodesign Requirements for External Power Supplies Pursuant to Directive 2009/125/EC of the European Parliament and of the Council and Repealing Commission Regulation (EC) No 278/2009, European Commission, Brussels, Belgium, 2019.