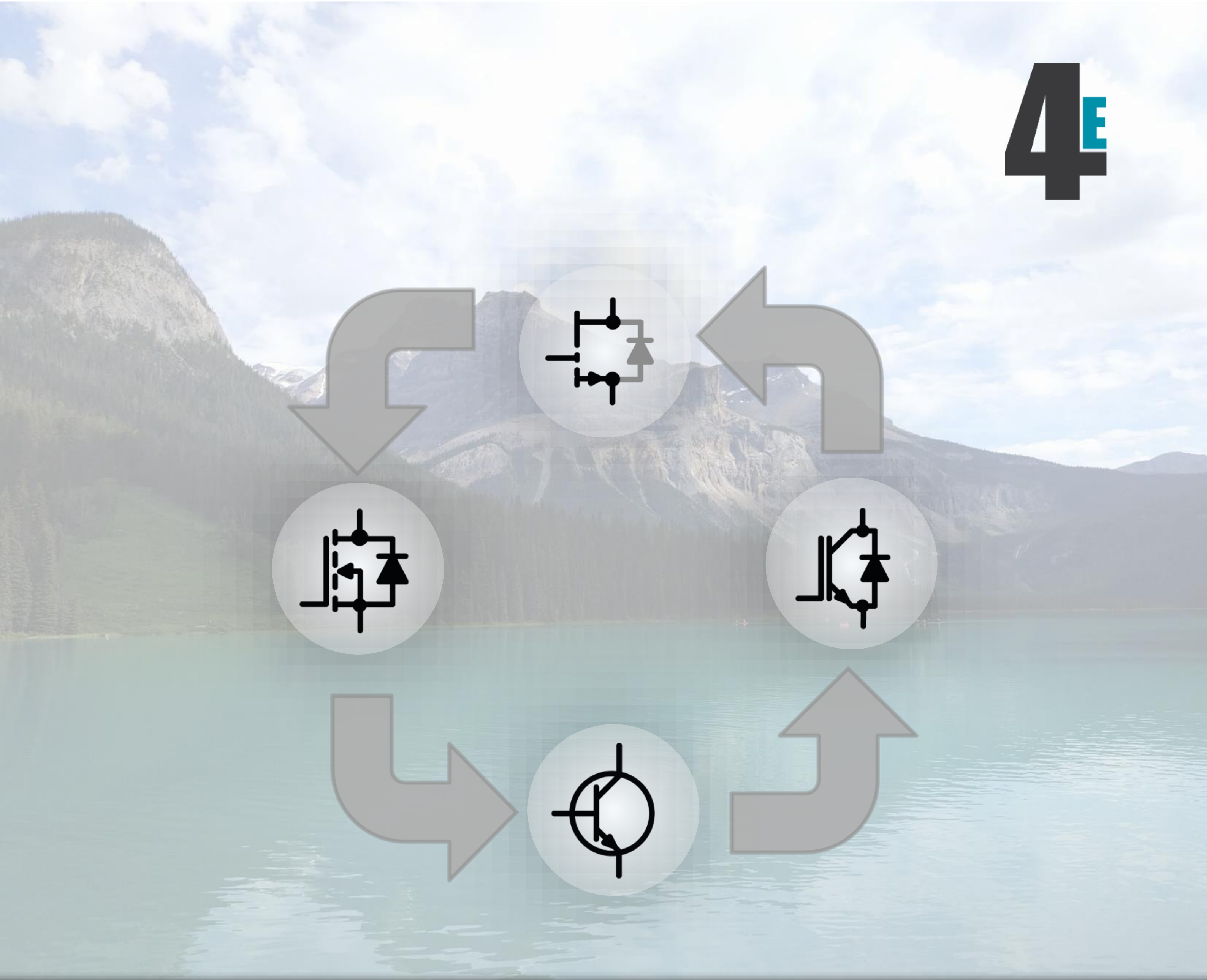

Wide Bandgap Technology:
DC-Wallbox Pre-Scoping Study

4E Power Electronic Conversion Technology Platform (PECTA)

September 2024

Technology Collaboration Programme
by iea

Power Electronic Conversion Technology Platform - 2024
The report was commissioned by the IEA Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E) – Power Electronic Conversion Technology Platform (PECTA).

It was formally approved by the Management Committee of PECTA, consisting of Roland Brueniger, Christian Holm Christiansen and Peter Bennich.

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Abstract:

The 4E PECTA DC-Wallbox pre-scoping study aims to enhance understanding of DC-Wallboxes and provides an overview of the current DC charging market, emphasizing the efficiencies of commercially available chargers across different power levels. The study highlights the increasing demand for DC chargers, particularly the fast chargers, which range from 20 kW to over 350 kW and have achieved efficiencies of around 95%. Efforts to further improve the energy efficiency of DC chargers are essential, as they are at least as efficient as AC chargers when considering all conversion stages. The report underscores the importance of targeting fast charging and higher efficiencies for future DC chargers, noting that the market for low power DC chargers (<11 kW) is still in its early stages but holds significant potential for growth and innovation. Follow-up activities proposed include market analysis and monitoring, deeper investigations into energy efficiency, and development of regulatory frameworks to support high-efficiency DC-Wallboxes. The study concludes that the DC charger market is poised for substantial changes and rapid growth, necessitating close monitoring of trends and technological breakthroughs by energy authorities to develop accommodating policies and standards.

About the IEA 4E Power Electronic Conversion Technology Platform (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 Bandgap 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:
https://pecta.iea-4e.org.

About the IEA Implementing Agreement on Energy Efficient End-Use Equipment (4E):
The Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E TCP), has been supporting governments to co-ordinate effective energy efficiency policies since 2008. Fourteen countries and one region have joined together under the 4E 0TCP platform to exchange technical and policy information focused on increasing the production and trade in efficient end-use equipment. However, the 4E TCP is more than a forum for sharing information: it pools resources and expertise on a wide range of projects designed to meet the policy needs of participating governments. Members of 4E find this an efficient use of scarce funds which results in outcomes that are far more comprehensive and authoritative than can be achieved by individual jurisdictions. The 4E TCP is established under the auspices of the International Energy Agency (IEA) as a functionally and legally autonomous body.
Current members of 4E TCP are Australia, Austria, Canada, China, Denmark, European Commission, France, Japan, Korea, Netherlands, New Zealand, Switzerland, Sweden, UK and USA.

The main collaborative research and development activities under 4E include the

- Electric Motor Systems Platform (EMSA)
- Solid State Lighting (SSL) Platform
- Efficient, Demand Flexible Networked Appliances Platform (EDNA)
- Power Electronic Conversion Technology Platform (PECTA)

Further information on the 4E TCP is available from: www.iea-4e.org

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Executive Summary

The 4E PECTA DC-Wallbox pre-scoping study aims to enhance the understanding of current applications in the field of DC-Wallboxes. This study provides an overview of the DC charging market, with a detailed analysis of the efficiencies of commercially available DC chargers for different power levels. It presents a market study based on different reports and literature. Additionally, it examines the future trajectory of the DC-Wallbox market.

The report emphasizes the increasing demand for DC chargers, particularly due to their role as Level 3 chargers aimed at fast charging. These chargers, which range from 20 kW to over 350 kW, are essential for meeting the high current requirements of rapid battery charging. Current commercially available DC chargers have achieved maximum efficiency figures of around 95 %. Efforts to improve DC charger energy efficiency are essential. In addition, overall grid to battery charging efficiencies show that DC chargers are at least as efficient as AC chargers when considering all conversion stages (such as on-board chargers etc.).

The study highlights the importance of targeting fast charging and higher efficiencies for future DC chargers. While the market for low power DC chargers (<11 kW) is currently in its infancy, with few companies developing solutions, this segment represents a potential significant area for future growth and innovation. However, at the time of the publication of this report, it is still unclear which power levels will be relevant in the future for this specific type of market (3 kW, 5 kW, 7.5 kW, 10 kW etc.). However, voices from industry (questionaires) see low power DC-chargers as interesting alternative to high-power on-board chargers. In addition, it should be noted that it was identified that relatively significant stand-by losses can occur during EV-Wallbox idle mode operation. To further investigate the development and adoption of energy-efficient low-power DC-Wallboxes, the report proposes several **follow-up activities:**

- **Market analysis and monitoring:**
  - Conducting regular reviews of the energy efficiency of low-power DC-Wallboxes in the market to identify a change of trends or technological breakthroughs.
  - Whenever it becomes obvious that the market is moving into a specific direction: Endorsing measurements and investigations of commercially DC-Wallboxes to better understand the semiconductor utilization and relevant dedicated parameters such as energy efficiency under charging conditions (different power and voltage levels).
  - Advocating deeper analysis into AC vs DC chargers in terms of cost, efficiency, circular economy, life cycle analysis etc.
  - Investigation of EV-Wallbox stand-by losses.
- **Regulatory Framework:**
  - Supporting the development of more complete guidelines DC-charger datasheets dedicated to energy efficiency.
  - Supporting policy formulations for incentivizing DC-Wallbox with highest efficiency levels.
  - Focusing on emerging trends, technological breakthroughs, and shifts in consumer demand. Adjust policies to support the most efficient technologies.

The study concludes that the DC charger market is poised for substantial changes driven by technological innovation, increased charging power demand, and reduced charging times. With the market expected to more than double in the next five years, significant advancements in DC charger technology will be necessary to support the growing number of electric vehicles. Consequently, it is advised that energy authorities closely monitor market trends and technological breakthroughs and develop policies and standards that can accommodate these rapid advancements, particularly as lower power DC chargers gain market penetration.

Contents

1. Introduction

The aim of the 4E Power Electronic Conversion Technology Platform (PECTA) DC-Wallbox study is to create a better understanding of the state-of-the-art applications in the field of DC-Wallboxes at the time of its preparation. In general, this IEA 4E study presents a brief overview of the DC charging market as it stands in the present day, and covers, among other things, the detailed analysis of efficiencies of a DC charger commercially available in the market. It also discusses different potential power converter technologies suitable for DC chargers, a market study presented by a survey from an industrial partner and includes a summary of available reports and literature review. The secondary objective of the report is to present a bigger picture of the DC-Wallbox story, to understand where the market is heading to in the near future.

This study also examines other intriguing aspects that focus on the future perspective of renowned companies that operate or have the potential to operate in the future, in the field of EVSE. This report reveals valuable insights into the possibilities, expectations, and tendencies that could be foreseen regarding the available performance classes of the DC- Charger section. Does this technology only deliver market gratification up to certain power classes? In future, shall the focus be on Business to Business (B2B), Business to Consumer (B2C) or even both groups at the same time? These are some questions that need to be addressed through case studies and surveys.

The overall goal of PECTA includes collecting and analyzing information about new Wide Band Gap (WBG) based power electronic devices, coordinating internationally acceptable approaches that promote WBG-based power electronics, and developing greater understanding and action amongst governments and policymakers.

1.1. The DC chargers classification:

In the European Union, recharging points are classified into two main categories, based on their power output and speed. Category 1 is recharging via AC, while Category 2 is recharging via DC. The European Alternative Fuels Observatory [1] presents a classification of the EV chargers in Tab. 1, based on the reports [2], and [3] :

Category	Sub-Category	Maximum Power Output	Definition pursuant to Article 2 of AFIR
Category 1 (AC)	Slow AC recharging point, single-phase	$P < 7.4$ kW	Normal-power recharging point
	Medium-speed AC recharging point, triple-phase	$7.4 \text{ kW} \leq P \leq 22$ kW	
	Fast AC recharging point, triple-phase	$P > 22$ kW	
Category 2 (DC)	Slow DC recharging point	$P < 50$ kW	High power recharging point
	Fast DC recharging point	$50 \text{ kW} \leq P < 150$ kW	
	Level 1-Ultra-Fast DC recharging point	$150 \text{ kW} \leq P < 350$ kW	
	Level 2- Ultra-fast DC recharging point	$P > 350$ kW	

Tab. 1. Categories of EV chargers

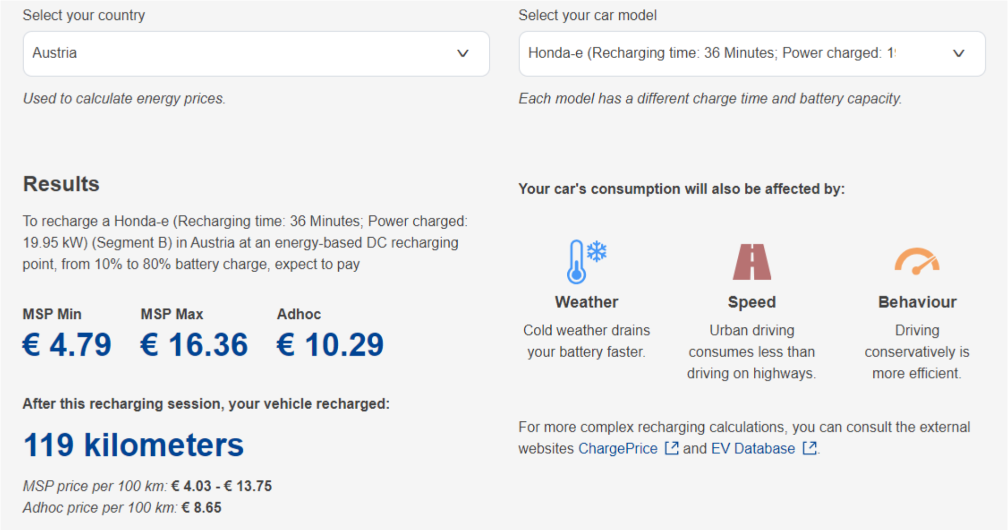
In [4], the EV chargers are categorized as:

1. ‘Normal Power Recharging Point’: recharging points that allow a transfer of 22 kW or less, to an electric Vehicle. It excludes devices with a power less than or equal to 3.7 kW, which are installed in private households or for purposes that are not for mobility.

2. ‘High Power Recharging Point’ refers to recharging points that allow for electrical power transfer of more than 22 kW.

In a few other articles on EV charging [5] and [6], the EV chargers are categorized in a different format. However, for the sake of homogeneity and simplicity, we will stick to the EU classification of chargers.

As a study of the distance covered for the charging power consumed, the price calculator from the Alternative Fuels Observatory, European Commission [7] can be used.



Select your country

Austria

Used to calculate energy prices.

Select your car model

Honda-e (Recharging time: 36 Minutes; Power charged: 1

Each model has a different charge time and battery capacity.

Results

To recharge a Honda-e (Recharging time: 36 Minutes; Power charged: 19.95 kW) (Segment B) in Austria at an energy-based DC recharging point, from 10% to 80% battery charge, expect to pay

MSP Min	MSP Max	Adhoc
€ 4.79	€ 16.36	€ 10.29

After this recharging session, your vehicle recharged:

119 kilometers

MSP price per 100 km: **€ 4.03 - € 13.75**
Adhoc price per 100 km: **€ 8.65**

Your car's consumption will also be affected by:

Weather
Cold weather drains your battery faster.

Speed
Urban driving consumes less than driving on highways.

Behaviour
Driving conservatively is more efficient.

For more complex recharging calculations, you can consult the external websites ChargePrice and EV Database.

Fig. 1. Calculation of KM driven on a 20kW DC charging cycle

The Fig. 1 shows that for a charging cycle of 20 kW, the Honda-e electric vehicle can cover a distance of 119 km or 75 miles. The same can be obtained for other vehicles to investigate the distance that can be covered with one cycle of DC recharge.

The recent report from the European Commission in 2024, titled “Preparatory Study for Ecodesign of Electric Vehicles Chargers” serves as a very important document for this study and therefore, the next section will aim to present a brief summary of it.

1.2. The European Commission Report of April 2024

Very recently, the European Commission published report in April, 2024, titled “Preparatory Study for Ecodesign of Electric Vehicles Chargers”, and presents a detailed overview of the Electric vehicle charger market [8]. Fig. 2 below shows the total number of recharging points from 2020 to 2024, installed in the EU. Although the AC chargers still dominate the market in terms of number of units installed, there is a higher rise in percentage for DC chargers.

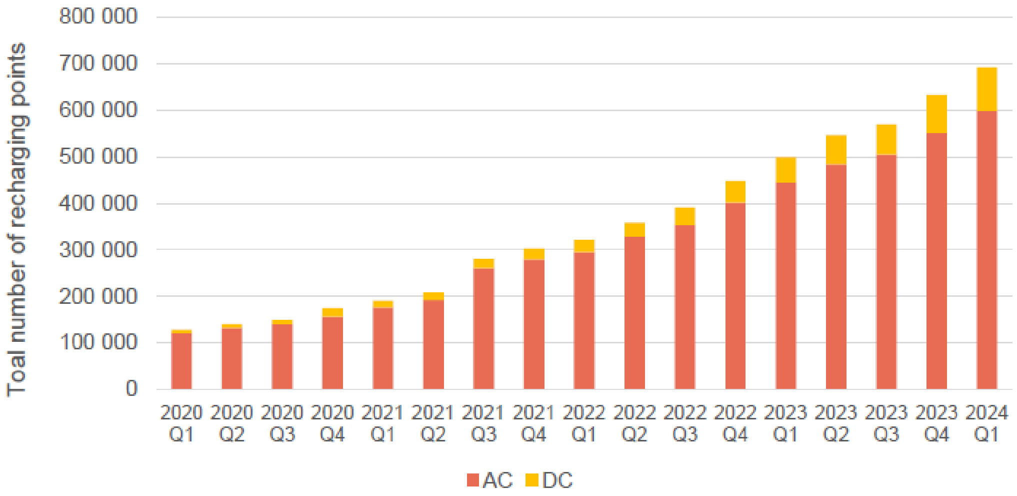


Fig. 2. Current development of total number of recharging points since 2019 in the EU region [8]

The below Fig. 3 shows the most recent map of the spread of EV chargers in the EU region. It can be observed that the around 60% of the installed capacity is distributed across only three countries (Netherlands, France and Germany).

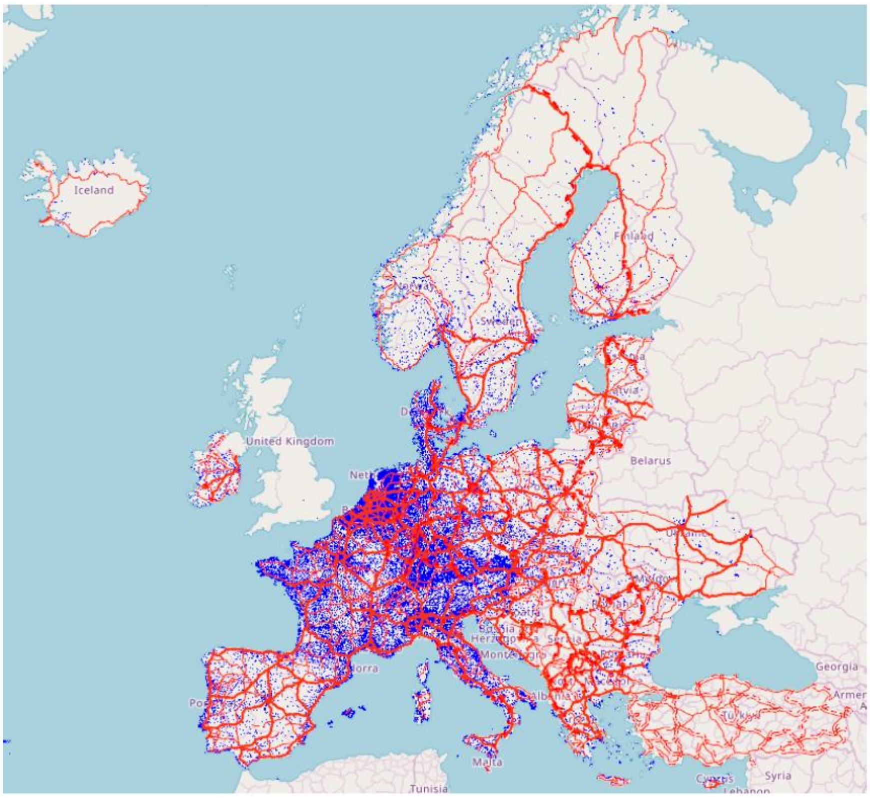


Fig. 3. Distribution of public recharging points in Europe [8]

Another very important dataset is shown in Fig. 4, which shows the total installed capacity of EV chargers in all the EU countries till 2019. There are charging infrastructure targets set by the EU and all EU nations are trying to meet the targets. In this regard, the present and future status of these targets (year 2024, 2025, 2026) for each EU country is shown in Fig. 5. Although in terms of number of installed charger points, the figures look good and at the present time (2024), most countries meet the targets set by the EU, it will get difficult for most nations to reach the EU targets in the next couple of years.

This means that even though a lot of work has been done, much more is needed to be done in the near future.

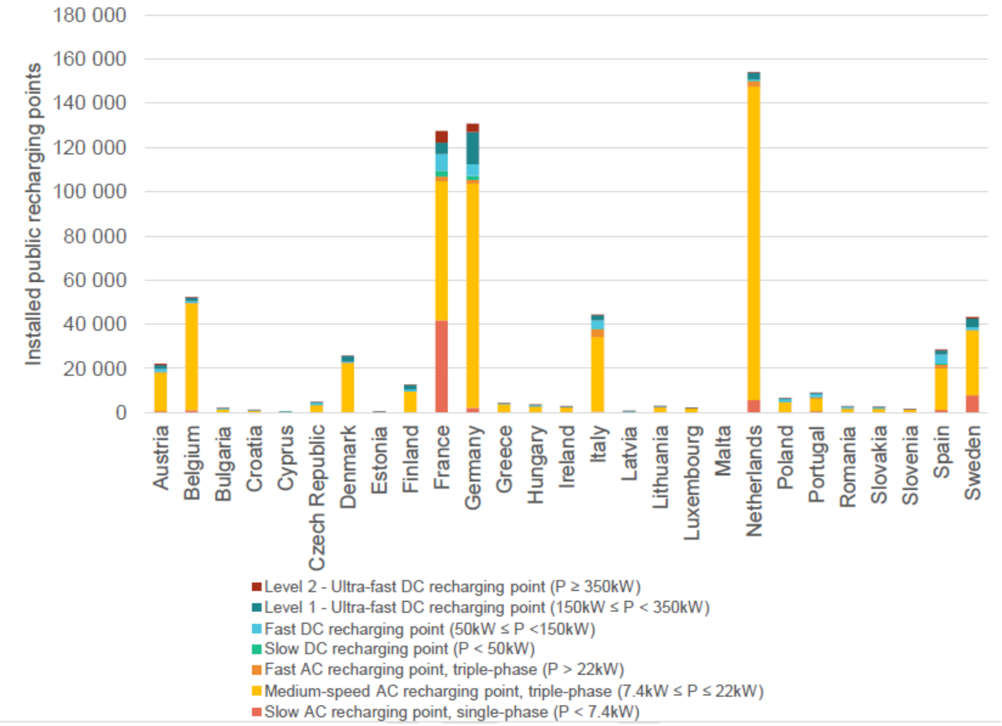


Fig. 4. Country wise list of total charger points installed till 2022 [8]

One important factor is the calculation of number of recharging points needed, and it depends on the level of power. While the Support study for the Impact Assessment (IA) of the AFIR ((European regulation on deployment of alternative fuels infrastructure (EU) 2023/1804 (2023)) predicted 1 kW per BEV and 0.66 kW per Plug-In Hybrid Electric Vehicle (PHEV), the values were reassessed at 1.3 kW per BEV, and 0.8 kW per PHEV. These are the figures that the considered the minimum level of infrastructure that needs to be put in place in the EU. The ratios can be even higher, depending to the future penetration of the EVs into the automobile market. For the minimum number of charges to be installed figures, different opinions have been observed among the different stakeholders, since there are various factors that affect this number. A balance between the availability of chargers and their utilization, the average energy consumption of the vehicles, proportion of private charging and charging power, all affect the total number of required chargers. There is an expectation that a threshold of 5 million public recharging points will be exceeded between 2030 and 2035. However, it is important to note that the average power output of the charging points was 14 kW at the time of the published report, and this number has now gone up to 40 kW at the present time. So different assumptions like AFIR, AFIR IA, and the European Automobile Manufacturers Association (ACEA) have different predictions for the number of charging points to be installed in the EU region.

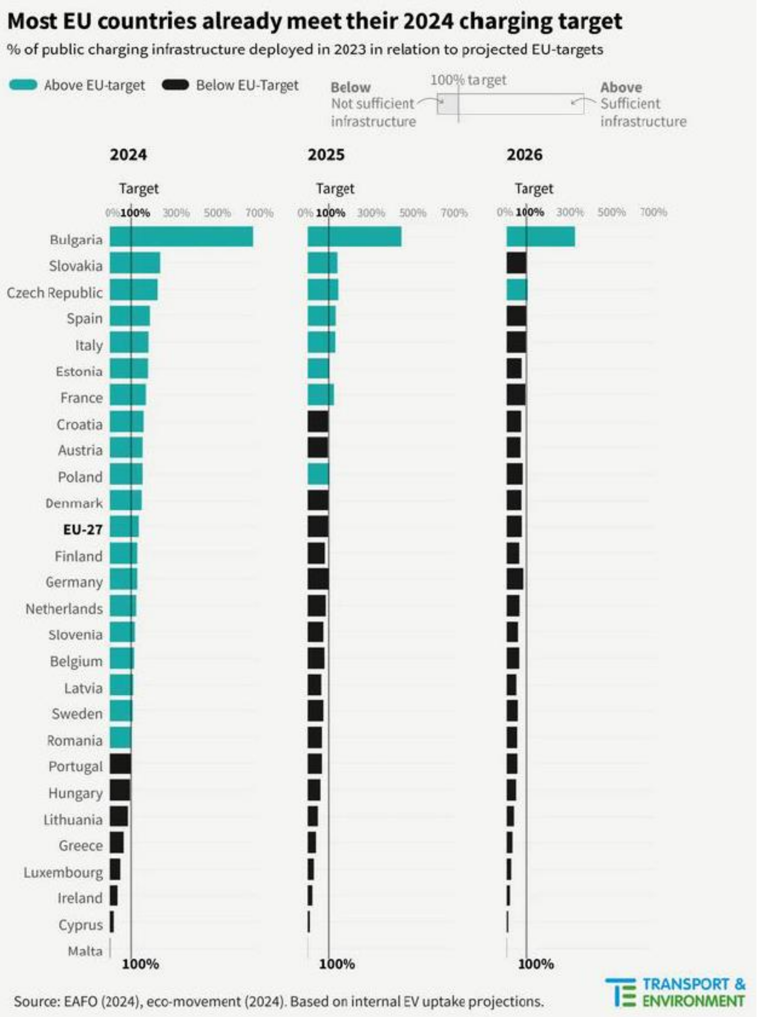


Fig. 5. NIR charging infrastructure targets for 2030 and current progress [8]

In terms of the usage, it is important to understand the contribution of Light and Heavy Duty Vehicles towards the use of chargers. The estimations presented in Fig. 6 show that most recharging points result from the demand from private passenger cars. The requirement of charging points for Heavy duty vehicles is still not significant. POx in the figure below denotes different policy options analyzed in the AFIR IA.

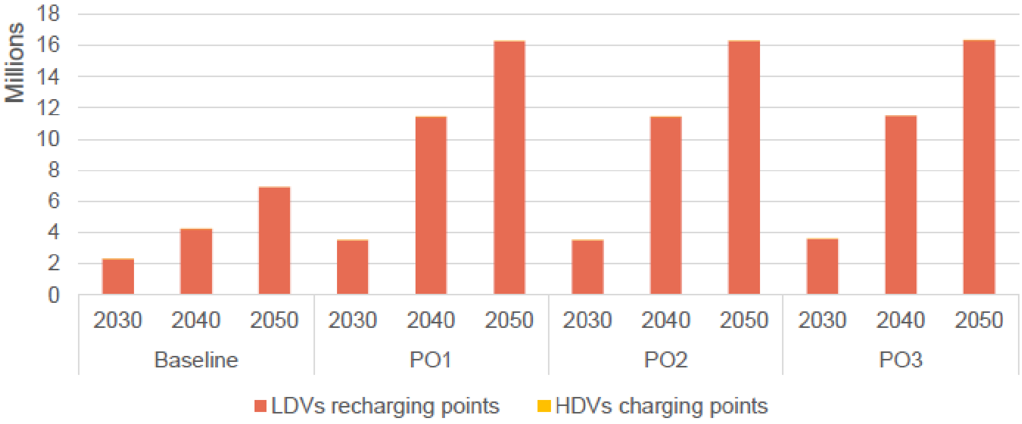


Fig. 6. Estimated stock of recharging points [8]

The public chargers have a lesser contribution to the total number of required chargers than the private chargers. The data for the breakup of the number of public chargers vs private chargers needed for the EU is shown in Fig. 7

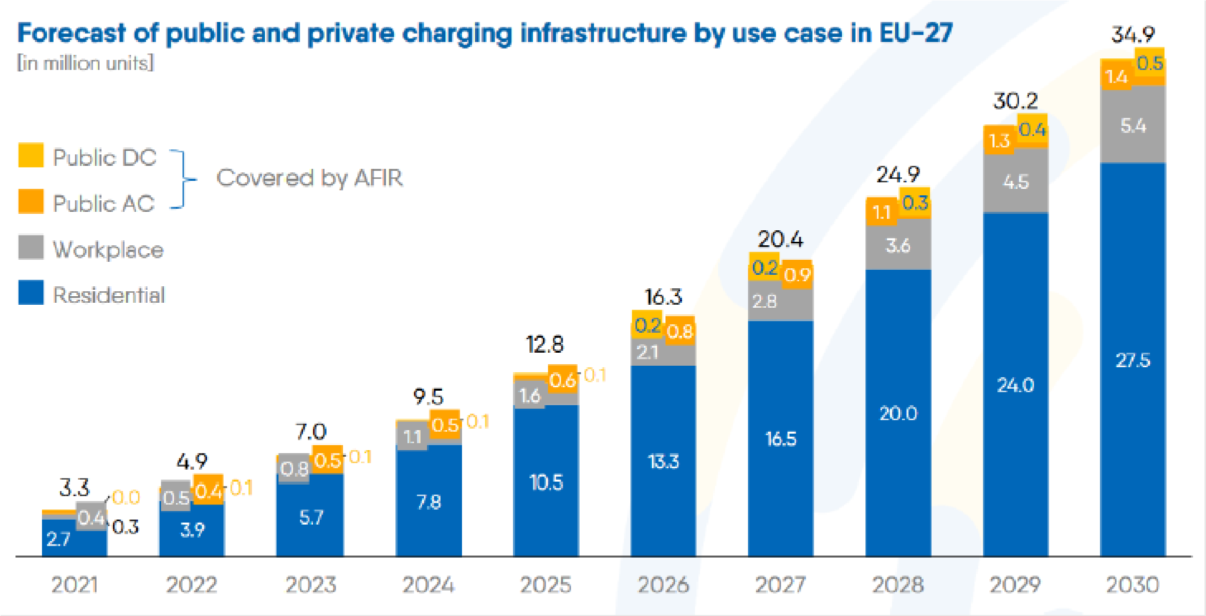


Fig. 7. Public and Private charging infrastructure [8]

In terms of the private charging infrastructure, the Transport and Environment (2024) suggests that there is an average of 0.8 private recharging points per EV at the present time. An assumption that 80% of EV owners have a recharging point at their home would lead to a figure of 6.16 million recharging points in Europe in 2023. One critical assumption to be noted is that the role of residential charging will steadily decline in the future such that it is around 50% by 2050. Therefore, the share of public charging points is expected to increase significantly in the future.

In addition to the road transport, the scenario of maritime and aviation energy requirements is also set to change drastically in the future. Fig. 8 shows that the energy demand in 2030 can be estimated at 1000 to 4000 MWh. PO1, PO2 and PO3 are different policy options analyzed in the AFIR IA.

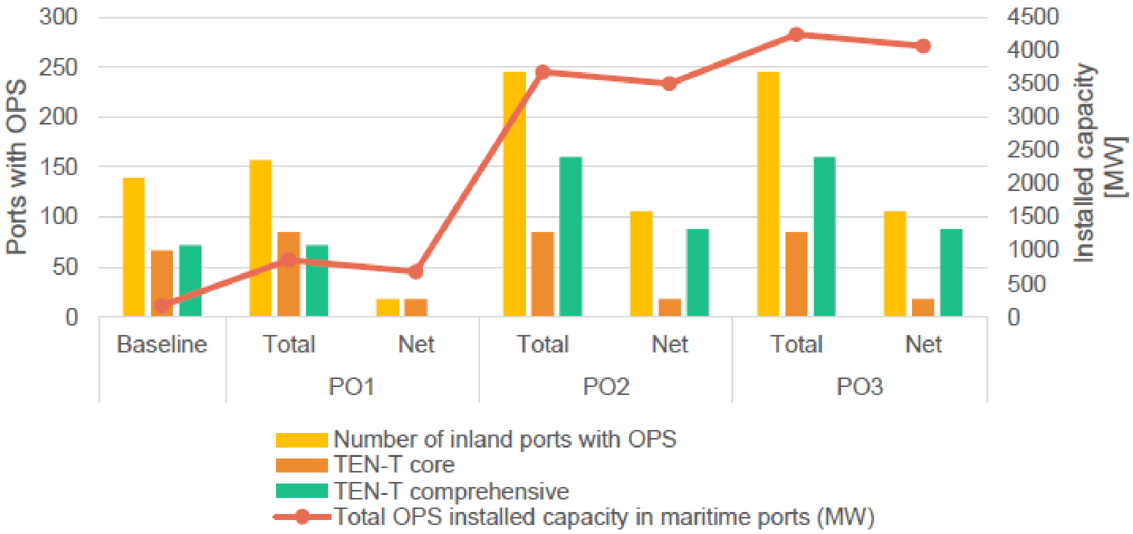


Fig. 8. Expected On-Shore Power supply deployment in 2030 in maritime ports [8]

For the aviation industry, the number of charging points required in 2030 can be estimated at 4 to 5 thousand at the airport, and 6,000 to 10,000 recharging points at the outfield (Fig. 9).

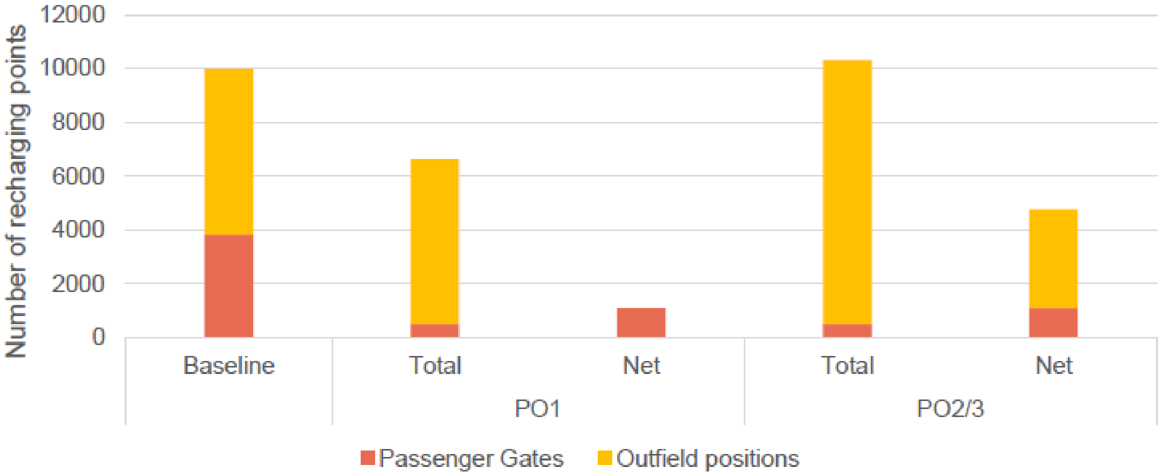


Fig. 9. Expected recharging points deployed at airports [8]

One important takeaway from the European Commission report [8] is the outlook of the general market trends. It is established that the development for DC charging power has been showing steady rise in the recent years. As a breakup of the DC chargers, in terms of range of power, the Fig. 10 below shows the share of chargers from different categories of power, towards the total number of developed DC chargers. A clear uptrend may be observed in the development of fast chargers in recent times.

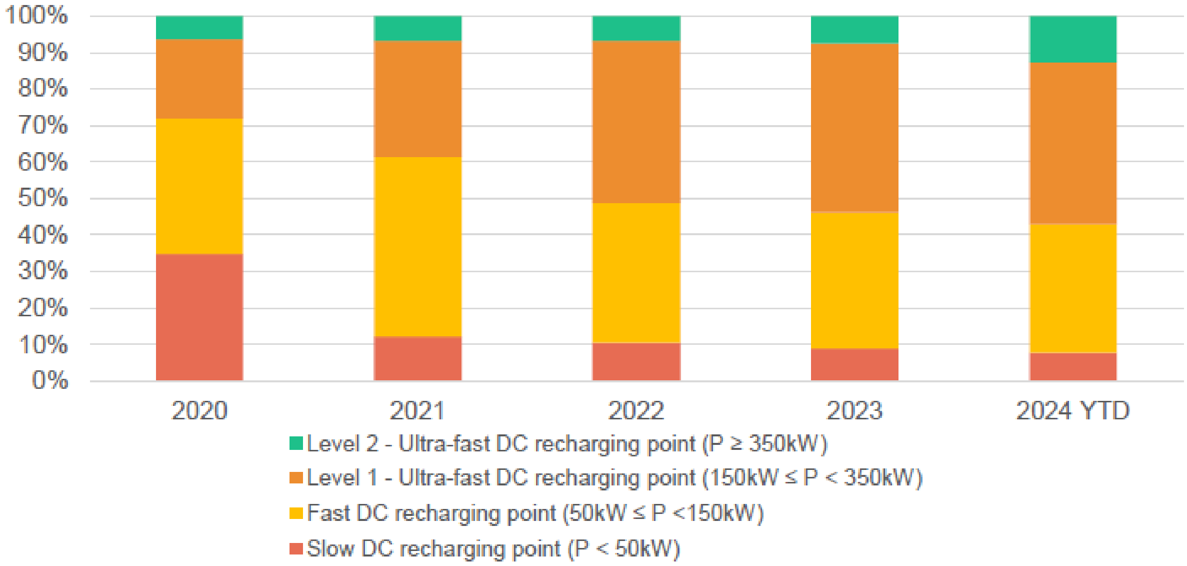


Fig. 10. Share of DC recharging points [8]

For the case of Heavy Duty trucks and buses, the driving and rest periods for truck and bus drivers are defined in Regulation (EC) No. 561/2006. For long-haul traffic conditions, the maximum allowed driving time of 4.5 hours is frequently fully used. Vehicles must then be recharged within the mandatory break of 45 minutes. This requires charging power that is not covered by today's Combined Charging System (CCS) standard. Therefore, the Megawatt Charging System (MCS), which has up to 3.75 MW, is currently under development. ACEA estimates that a total number of 35000 MCS will be needed in 2030.

However, AFIR estimates that a total of 2800 chargers will be needed by 2030, amounting to total charging power of 7.5 GW, along the almost 110,000 km of the TEN-T corridors.

Additionally, the report also talks about future technology upgrades required for the charging infrastructure. The sale of Vehicle-to-Everything (V2X) ready vehicles will increase by 70% between 2025 and 2030, such that the V2G capabilities of chargers will also need to develop in a similar pace. Discussing about the wireless chargers, it is understood that the wireless charging technology is not yet on the market, and therefore, all predictions will need to be proven in time.

In terms of the price of the chargers, Fig. 11 presents an overview of the cost of AC chargers. A wide range of prices can be observed in the figure. The graph also shows the correlation between the prices and the available maximum charging power.

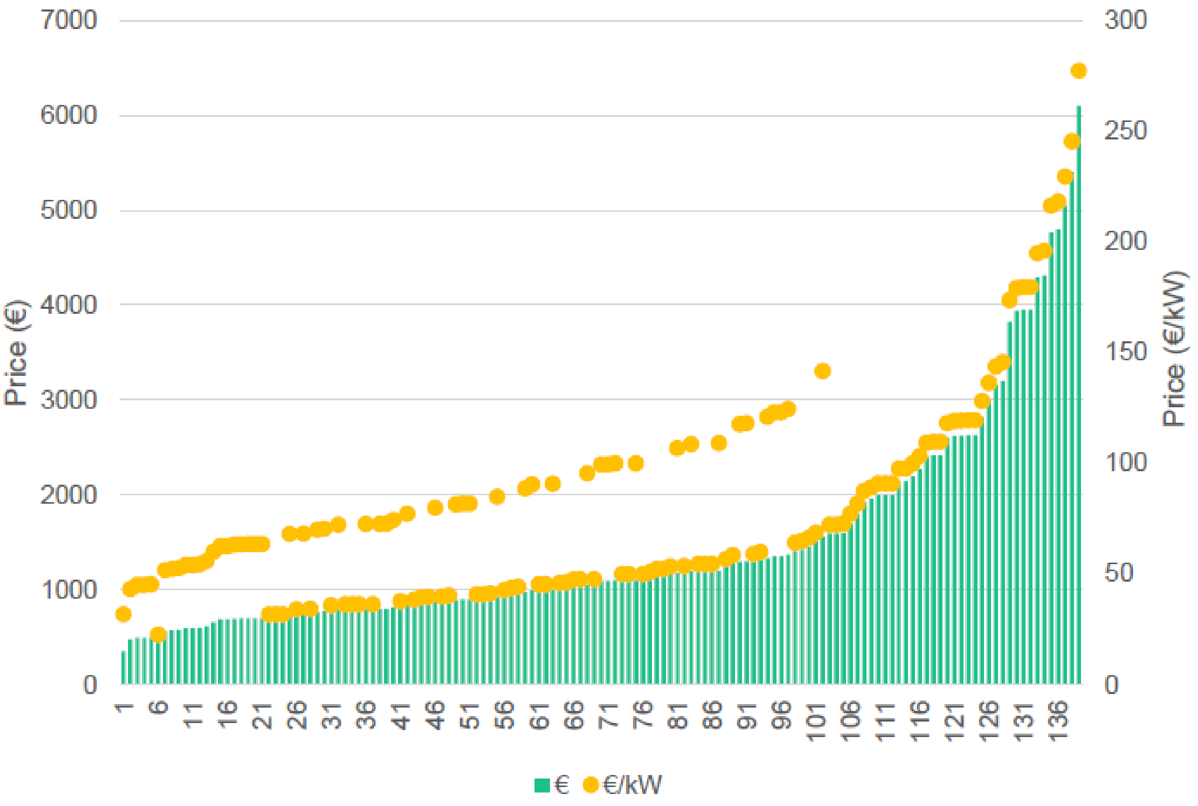


Fig. 11. Price and power of different AC recharging points [8]

For DC charger cost overview, Fig. 12 shows that the costs are significantly higher than the AC chargers. It can also be observed that the number of DC chargers available in the market are much less in comparison to the AC chargers and therefore, the sample size for DC charger study is smaller.

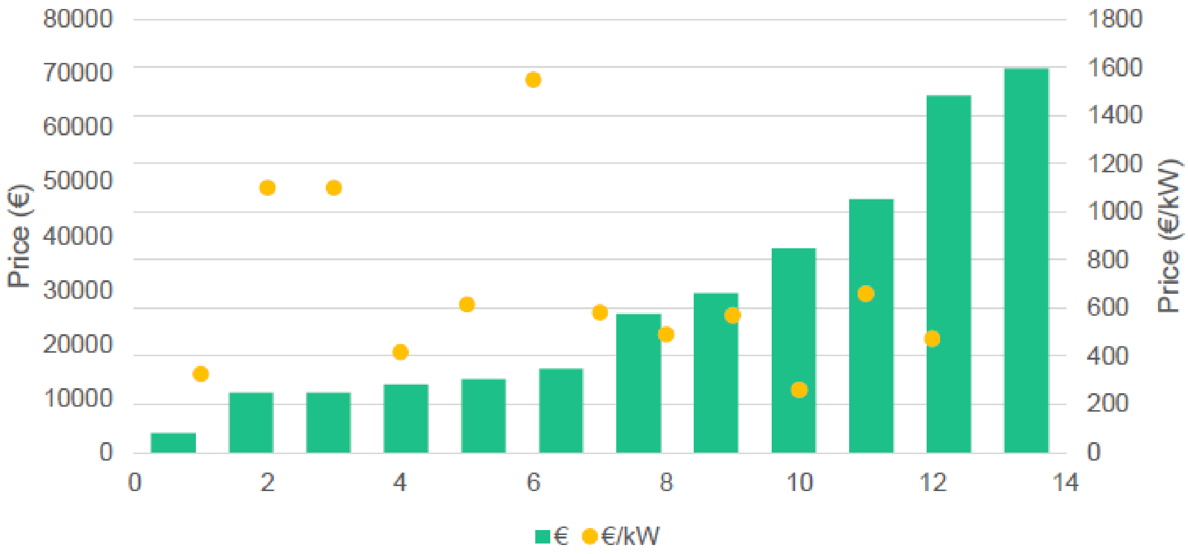


Fig. 12. Price Vs. Power for different DC recharging points [8]

In conclusion, the report emphasizes on the rise in demand for the chargers for the future. The market is in its early days and is expected to see significant changes in the future. So, the dominance of AC chargers and private charging stations is expected to shift towards more DC chargers and public charging stations, respectively in the future. Similarly newer technologies like Wireless charging are yet to unfold in the future markets. The report also reveals that although present demand of charging power is not majorly contributed by HEVs, but the demand from trucks and buses will increase in the coming days and hence, MW level superchargers will become necessary.

1.3. Summary of reports on AC chargers:

The AC-Wallboxes are more popular for lower ratings and is convenient for household use, thereby facilitating local charging of personal EVs in residential houses. A summary of some of the reports on AC chargers will be presented in this section. As discussed in the previous section, the AC chargers are more suited for private EV charging applications and small public charging outlets. Such chargers are popularly available as Wallboxes which connect to the AC mains socket and supplies AC power to the vehicle onboard charger. The vehicle onboard charger then processes this power to DC, needed for charging the battery.

To determine the current performance trend for AC-Wallboxes in general, information from two impartial institutes were taken into account for an assessment. The first was a test carried out by the "Stiftung Warentest" [9] in 2022, in which 12 AC wall boxes were tested for various key aspects. Within the publicly accessible article from February 23, 2022, the institute's summary contains a table that shows ratings for twelve AC-Wallboxes for electric cars, including those from Mennekes, ABL, Easee and Keba. The Wallboxes cost between 700 and 1,600 euros, excluding additional costs of installation by professionally trained staff or service providers. The institute states which AC-Wallboxes performed well in the test and what makes the test winner stand out. It shows the differences between 11 kW and 22 kW AC-Wallboxes, which charging stations can be controlled via an app, and the electrical safety of the devices. They explain why a specialist company must install the charging station, what it costs, and what tenants need to know if they want to purchase an AC-Wallbox. However, the core information of interest for this study lies in the distribution of different performance classes and their weighted presence.

Tab. 2. Test Specimens considered in the "Stiftung Warentest" 2022 AC-Wallbox test series

	Rated Power	Standby Power	Price @2022
ABB - Terra AC W11-G5-R-0	11 kW	5.0 W	1090.00 €
ABL - Wallbox eMH2 2W2231 Extender	22 kW	1.8 W	1570.00 €
Alfen - Eve Single S-Line 904460587	11 kW	7.0 W	785.00 €
Easee - Home 10103	22 kW	1.5 W	850.00 €
go-eCharger - Homefix 11 kW	11 kW	3.4 W	675.00 €
Heidelberg Wallbox - Energy Control	11 kW	3.8 W	790.00 €
Innogy - eBox smart	22 kW	5.4 W	1200.00 €
Keba - KeContact P30 x-series	22 kW	5.2 W	1330.00 €
LRT - Home Essential+ 11 kW / AC09C	11 kW	0.9 W	900.00 €
Mennekes -Amtron Charge Control 11 C2	11 kW	4.3 W	1290.00 €
PC Electric - Wallbox GLB 353419P	22 kW	4.7 W	1280.00 €
Wallbox Chargers - Commander 2, 11kW	11 kW	5.1 W	1300.00 €

The data in Tab. 2 shows that 7 test specimens are 11 kW Wallboxes, and 5 test specimens are 22 kW Wallboxes. It may be observed from Tab. 2 that some of the 11 kW Wallboxes, most likely due to their user features, easily reach the price of a 22 kW system and thus correspond to a system with half the performance in terms of cost. The fact that this price spread leads to economic success seems to suggest that the average customer is highly attentive to user features offered by the manufacturer.

In terms of charging points, at least specific for Germany by charging capacity, charging points with 3.7 to 15 kW have so far predominated. Unlike the European Union, the German Federal Network Agency only categorizes charging points according to fast and normal charging points and not according to DC or AC charging technology. However, the AC charging points in the EU have an output of less than 22 kW and are therefore quite comparable with the categorization according to normal charging points in Germany.

1.4. Case Study and Market trends for the DC chargers

The AC chargers were discussed briefly in the previous section. However, the AC chargers are considered for slow charging applications, where the output power has a maximum range of 22 kW. For fast charging applications, DC chargers may be used which range from about 15 kW to 350 kW and more. Although a handful of DC chargers are available for a power range of 15-30 kW, the majority of DC chargers are rated for 30 W and more. The handful of the available low-power DC chargers are primarily from Chinese manufacturers like Shenzen Elefine Technology Co. Ltd., whose DC charge stations (Model No.: EF-EVC15KW) are rated for 15 kW DC power. Information from the manufacturer's website reveals that the charger is rated for an input voltage of 380V AC and an output voltage range of 200-750 V DC [10]. DC chargers by Zhejiang Benyi New Energy Co. Ltd. are rated for 20 kW of power and information regarding the same is available on their website at [11].

It is important to note that the DC chargers emerged as a solution for fast charging requirements and hence their availability in higher power range is justified since they belong to the Level 1 and Level 2 chargers (as per Tab. 1) , which are designed for higher power and faster charging times [5]. Since the availability of DC chargers for power ratings less than 30 kW is limited, we will focus our attention majorly to high-power DC chargers, beyond 30 kW power output, in this report.

Presentations and studies by renowned companies and personalities from the field serve as a point of reference here. These include presentations given at the EDNA Conference 2017, starting with Adriana Diaz and Wolfgang Wimmer with the Scoping Study for IEA -4E EDNA, further noteworthy contributions were provided in alphabetical order by:

- Martin Beermann - Joanneum Research
- Marine Gorner - International Energy Agency
- Janosch Marquart - University of Applied Sciences NTB Buchs
- Leonard Mueller - SMARTRICS
- Martin Nöhrer - Austrian Institute of Technology GmbH
- Herbert Pairitsch - Infineon Technologies Austria AG
- Harald W. Scholz - The European Commission's science and knowledge service

As a heavy focus of this study the "EVSE and EV efficiency and OCPP compliance testing report" has been published by the EPE-Centre in collaboration with the University of Canterbury, Christchurch in May 2023 [12].

Originally the New Zealand Report [12] lays the introductory cornerstone of this report. The report states that New Zealand is committed to decarbonization and thus aims to achieve net-zero emissions by 2050. The Government is planning to promote electric vehicle expansion through incentives such as discounts, for example a so-called “Clean Car Discount” or exemptions from road tolls. A fact, that cannot be ignored by an increase in e-vehicles, is that infrastructural impacts are becoming greater. Efforts, focus and a push for power generation, transmission, and distribution networks continue to increase. EV’s represent new loads distributed across industrial, commercial, and residential areas and were initially not foreseen for the original design and dimensioning of the electrical distribution grid. For this reason, it is important to identify new or improved parameters which can help to build efficient relieving mechanisms that can help maintain the grid health. Charging efficiency, for example, becomes important in terms of energy transportation. Reduction of losses in Electric Vehicle Supply Equipment (EVSE’s) lead to reduction of costs for the consumers and results in reduction of the electricity demand and consequently also to relief load on transmission and distribution networks. This chain helps to establish that higher efficiency of the charging infrastructure enables greater distribution of EV’s while helping to reduce the additional burden on the grid.

For further investigations on the efficiencies of DC chargers, it is important to look closely into the different aspects of the EV ecosystem, that directly affect overall energy efficiency of the charging system. The major factors that affect energy efficiency in this context are vehicle charging profiles, the efficiency of the internal On-Board Charger (OBC) of EV‘s and most importantly, the efficiency of the power electronic converters included within the DC charger.

The report examines, amongst others, the efficiency of a range of popular residential and commercial chargers and the efficiency of internal chargers and charging management systems of popular EV’s.

In the DC charger-oriented results listed in the New Zealand Report, it may be observed that the efficiency figures of the DC 'fast' type chargers lie in the 92-95% (depending on the output power of the test) region. Beyond 5 kW, the efficiency became almost constant at around 95%. As a reference, there are reports and articles on converter systems that can achieve much higher efficiencies (>99%) [13]. Back in 2013, an article on the comparative study of Three-Phase Two and Three-Level Unidirectional Hybrid Rectifiers [14] presented efficiency figures of 99%. These data although were designed for research demonstration, may serve as a target basis for DC charger manufacturers.

The New Zealand report discusses another issue of concern for DC chargers, which is the change in efficiency with load. According to the report, the efficiency of the DC charging decreased significantly at less than 25-33% of the rated device power. DC chargers also suffer from the problem of higher standby power. While the standby power varied between 14 - 125 W for DC Chargers, it had a significantly lower range of 4 W to 8 W for AC chargers. Although the AC chargers are not a focus of this study, it becomes necessary to present a comparison between the DC chargers and the AC chargers in terms of standby power consumption. Standby power is the power required to maintain the EVSE in a standby state between charge cycles. Tab. 3 and Tab. 4 present data (obtained from the New Zealand Report) on the standby power consumption of AC chargers and DC chargers, respectively.

Tab. 3. AC Charge Point Standby Power Consumption Summary

	Rated Power	Power Consumption	Power Factor
ABB	7.4 kW	3.98 W	0.27
Etrel	22 kW	7.78 W	0.73
Evnex	7.4 kW	2.97 W	0.28
Siemens	7.4 kW	5.71 W	0.69

Tab. 4. DC Charge Point Standby Power Consumption Summary

	Rated Power	Power Consumption	Power Factor
Delta	25 kW	13.43 W	0.43
Philhong 30 kW	30 kW	71.78 W	0.08
Philhong 60 kW	60 kW	124.6 W	0.07
Tritium	50 kW	57.08 W	0.08

To summarize, the New Zealand report identifies three key points from the above-mentioned topics:

1. The efficiency of DC fast charging is significantly lower than the best possible value.
2. Internal battery management systems do not necessarily prioritize energy efficiency or cost to the consumer over ease of use or product life, which is an unknown inefficiency to the general public.
3. While central monitoring and control appears to be sufficient for the load management of electric vehicles, an understanding of the charging efficiency profiles is required to optimize the benefits.

Allied Market Research have released a report on DC Fast Charging Stations Market- Global Opportunity Analysis and Industry Forecast, 2023-3032 [15]. shows the worldwide market scenario for DC fast chargers. The report states that the European market is found to be the most lucrative segment during the analysis period. It also adds that the Asia-Pacific region is projected to have a dominant share of the market during the analysis period. For example, China has seen a 50% rise to 470,000 Fast Charger installations in the year 2021. This growth has surpassed the 44% growth rate in fast chargers in 2020. The country has a share of more than 40% Fast Chargers and the industry prepares for steady growth in future.

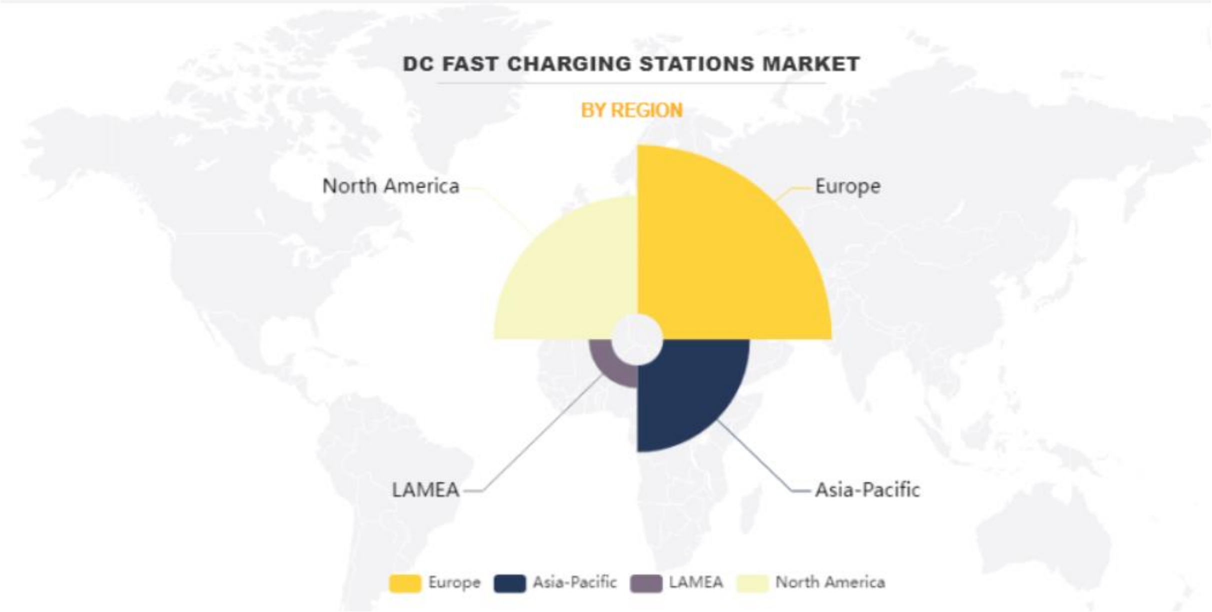


Fig. 13. DC Fast Charging Stations Worldwide Market

Another stochastic source is an article by Statista entitled "Number of direct current (DC) charging points for electric cars in the European Union by power in the years 2020 to 2023" [16] (translated from the German title), which also includes a specified section for charging points with lower output power than 50 kW. In the summary of the introductory text published by Ben Impey on February 14, 2024, the author addressed, among other things that most of the charging points in the EU powered by DC had a capacity of 150 to 350 kilowatts in 2023.

In addition to the number of charging points, the charging power also plays an important role in the charging infrastructure, as the charging time is also reduced with higher power. If the average charging time is reduced, the number of charging points required per EV also decreases, as the individual vehicles obstruct the charging point for a reduced duration.

As an analysis of the data in [16], it should be noted that the number of charging points <50 kW from 2020 to 2021 was just over a third. Beyond 2021, a clear upward trend can be seen. In the first year from 2021 to 2022, the increase in less than 50 kW charging points corresponds to about 58.6 %, while from 2022 to 2023 it increases by 69.6 %. To summarize, it can be observed, that there is a strong increase in the number of DC charging points in the EU for EV applications. The total number of DC chargers installed in the EU region was just under 20.000 Units in 2020. Within the next 3 years, this value increased to well over 80.000 units, exhibiting a more than four-fold increase. Fig. 14 categorizes the DC chargers in terms of capacity and shows the contribution of each category to the total number of DC chargers. It shows that the DC chargers in the range of 150-350 kW have a maximum share (45%) in the total number of DC chargers available in the EU in 2023.

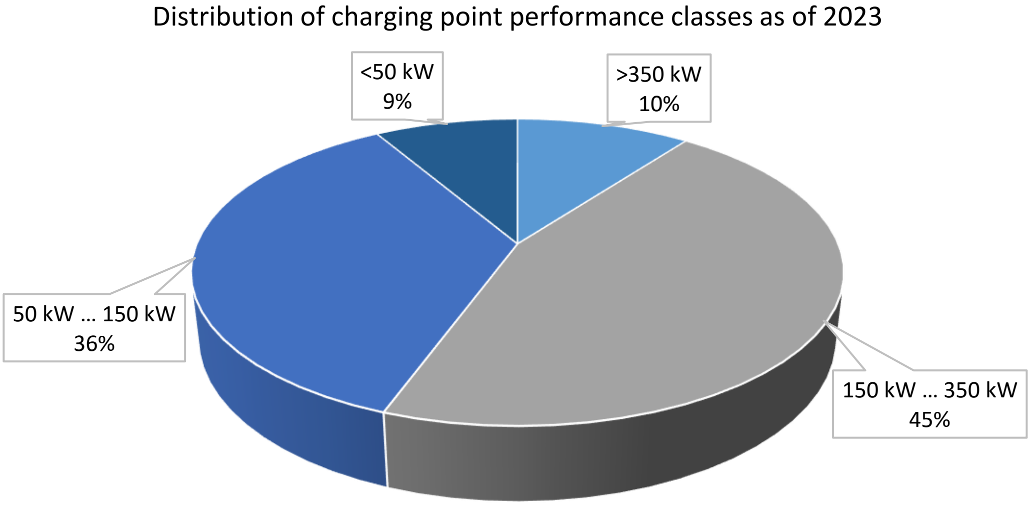


Fig. 14. Total gathered charging point units in 2023 – Amount: 81.872 units

KBV Research, in August 2024, has published a report on ´Global DC Chargers Market Size, Share & Industry Trends Analysis Report by Power Output (10 kW to 100 kW, Less Than 10 kW, and More Than 100 kW), By Application (Industrial, Automotive, and Consumer Electronics), By Regional Outlook and Forecast, 2022 - 2028´ [17]. The report presents a detailed overview of the global DC charger market. In the Fig. 15 shown below (from [17]) a steady rise in the number of DC chargers can be observed till 2028. The report in [17] claims that the global DC charger market is expected to increase to $161.5 Billion by 2028 from a mere $69.3 Billion in 2021, exhibiting a 13.6% CAGR. However, the limiting factor in the expansion of the DC charger market has been identified as the lack of infrastructure for providing fast chargers. EV charging times must aim to match the re-fuelling time of fossil fuel-powered vehicles.

In [18], EVBOX has come up with a report that points out 4 major trends that are shaping the DC fast charging market:

a) Increasing charging speeds: The modern charging market is witnessing the development of fast and super chargers having a power output of 350 kW and above, and this has led to reduction of charging times for EVs.
b) Greater Collaboration: Huge collaborative efforts have been seen over the recent years, where entities with diverse expertise are coming together to foster development in the DC charger technology. Such collaboration can lead to innovative business models where we might see shopping centers or restaurants having DC charging stations, such that all participating entities may reap maximum benefit out of the collaboration effort.
c) Smart Charging: Innovation and inclusion of features such as Load balancing, Vehicle to Grid Technology, Black start and Grid Support have been driving the DC charging ecosystem, such that the future integrated systems have increased reliability.
d) Renewable Energy Integration: The push to move away from fossil fuels is helping the renewable energy sector to penetrate the energy market with an increasing share. The DC chargers, coupled with the possibility of renewable energy integration becomes a vital player in reduction of carbon footprint.

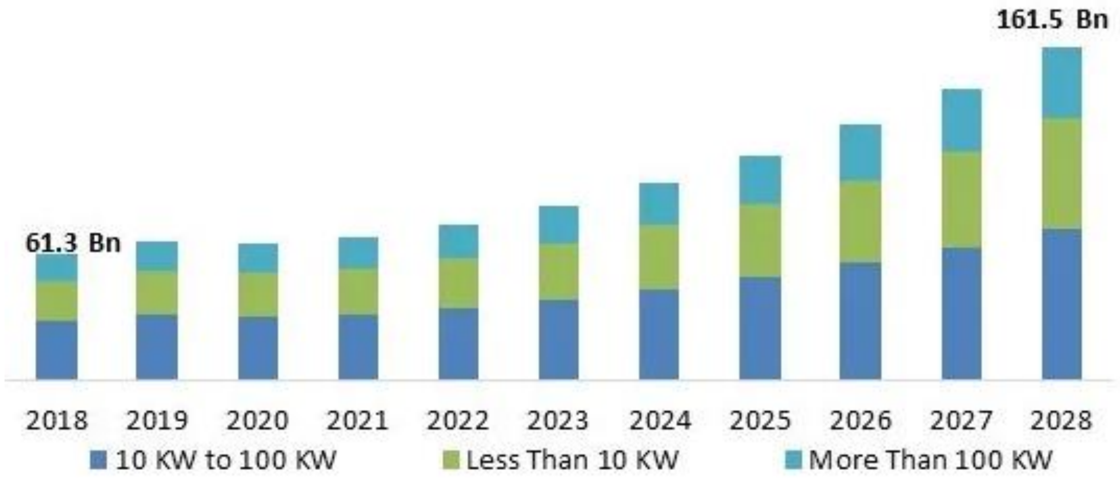


Fig. 15. DC Chargers market size, by Power Output, 2018-2028

In the field of scientific research, a lot of work is being done on DC charging systems. A recent article [19] presents a detailed review of the DC fast charging stations for electric vehicles. Apart from other observations, the article discusses the charging time and cost of charging for chargers. Even with a 50 kW Level 3 Fast charging system, an EV takes an hour to charge from empty to 80% of battery capacity. The article presents a new scheme of categorizing the DC Chargers into Level I, Level II, and Level III, which is different from the EU commission classification. In this case, Level 1 DC chargers have a $V_{DC} = 200-450V, P_{out} = 50kW, I_{out} = 80A$. Level 2 DC chargers are having $V_{DC} = 200-400V, P_{out} = 90kW, I_{out} = 200A$, and Level 3 DC chargers have $V_{DC} = 200-600V, P_{out} = 240kW, I_{out} = 400A$ The Level I category in this article corresponds to slow chargers. Level II and Level III chargers correspond to fast charging systems. Regarding the impact of DC on the charging infrastructure, the article lists the following important points:

1. Supply of DC power: The design efficiency and effectiveness of charging stations for DC supply needs to be studied in greater detail.
2. Power Electronics: The feasibility of power electronic components for high-power fast chargers should be evaluated and more efficient systems must be designed and developed.
3. Impact on battery: the effect of DC Fast charging on the battery health, longevity and degradation rate needs to be further analyzed.
4. Heat management: Further research and investigation is needed for the development of more efficient thermal management systems that can cater to high power DC fast chargers operating under peak charging conditions.
5. Safety measures: DC chargers need to be safe, and Safety protocols, Standard compliances and different protection features form an integral part of DC charger technology.

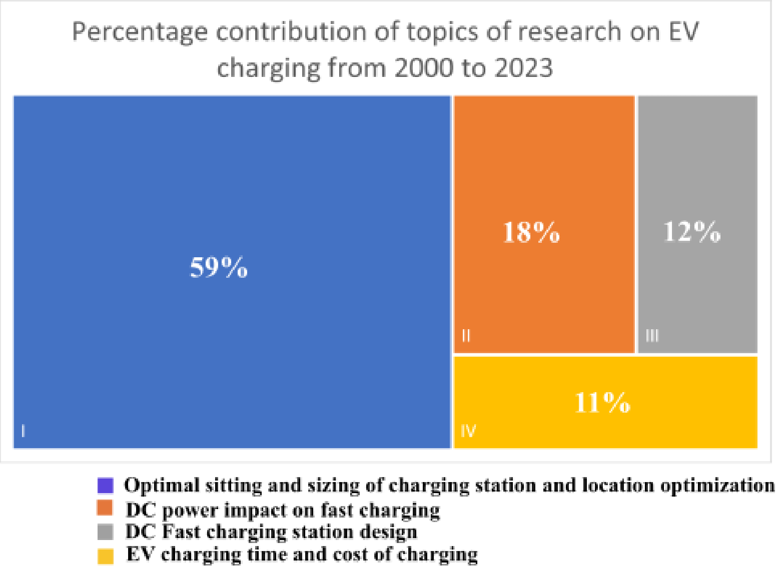


Fig. 16. Contribution of different topics of Research articles on EV chargers from 2003 to 2023

Fig. 16 categorizes all available literature of research articles on EV chargers till 2023 into 4 major categories, based on the focus area. The percentage contribution of each category to the overall literature is shown. It is important to see that not a great deal of research has been conducted on the reduction of charging time and cost of charging. It may be stated that greater research efforts are needed to provide charging power at highest efficiencies at the best possible cost, such that the EVs become more economical.

In the next section, results from the New Zealand Report will be discussed, which can then become a basis of further analysis from our lab experiments.

1.5. Efficiency Analysis from New Zealand Report

The experiment results and their analysis presented in the New Zealand report serves as an important basis to understand, analyze and comment on the efficiency of DC chargers.

1.5.1. DC chargers selected for the study

The DC chargers selected for the study are shown in Tab. 5

Tab. 5. DC chargers used in the study in New Zealand Report

	Charger	Notation In report
1.	**Delta DC Wallbox 25 kW CCS2+CHAdeMO DC charger**	hereafter referred to as ‘Delta’
2.	**Phihong DW 30 kW CCS2+CHAdeMO DC charger**	hereafter referred to as ‘Phihong 30’
3.	**Phihong DS 60 kW CCS2+CCS2 DC charger**	hereafter referred to as ‘Phihong 60’
4.	**Tritium Veefil-RT50 50 kW CCS2+CHAdeMO DC charger**	hereafter referred to as ‘Tritium’

Other than the DC chargers used for the study, several car models were used which are given in Tab. 6 The Tesla, BMW, Hyundai and Nissan cars were chosen for this study.

Tab. 6. Car models used in the study in New Zealand Report

	Vehicle	Notation in the report
1.	**2021 Tesla Model 3 Standard Range Plus**	hereafter referred to as ‘Tesla’
2.	**2017 BMW i3**	hereafter referred to as ‘BMW’
3.	**2017 Hyundai Ioniq**	hereafter referred to as ‘Ioniq’
4.	**2013 Nissan Leaf**	hereafter referred to as ‘Leaf’

1.5.2. Test Methodology

The testing starts with a fully discharged battery at ambient conditions and at the end of the charging cycle, the data is stored for analysis. The charge cycle efficiency is then measured through direct relationship between AC input and DC output power. The outcomes of the Tests are as below:

1. Efficiency of the DC charger calculated during charging cycle.
2. Charge efficiency curves developed for each vehicle/charger combination, from 0 to 100% charging (depending on BMS limitations of the individual Car battery).
3. Knowledge of charger power factor.
4. Knowledge about standby power of each DC charger.

DC output is measured using two methods:

1. In-line for CHAdeMO charging used for Nissan Leaf vehicle
2. Within the charger for CCS2 charging

Before deep diving into the test results, it is important to understand a few terms related to EV charging [20].

OCPP: Open charge Point Protocol. The OCPP was an outcome of the idea proposed by the Dutch Foundation ElaadNL which laid down the requirement for an open protocol to support communication between charging points and the back-end systems.

OCA: Open Charge Alliance. The OCA is an alliance of more than 220 member companies who are active in the electric mobility space.

CHAdeMO: CHAdeMO" is an abbreviation of "CHArge de MOve,"and is a bidirectional flow standardized connector for the connection of the EV to the charger interface of a charging station. It is an outcome of the research from Nissan and a Japanese entity Nichicon. CHAdeMO is quite popular as it supports OCPP-based Charger to EV communication.

CCS2: Combined Charging System Type 2. CCS 2 is the European standard plug and socket type used for connecting electric or plug-in hybrid cars to a DC rapid charger.

Tab. 7. DC charger input and output conductor resistance between the measurement point and charger terminal

Charger	Input resistance ($m\Omega$)	CCS output resistance ($m\Omega$)	CHAdeMO output resistance ($m\Omega$)
Phihong 60	7.4	0	-
Phihong 30	7.8	0	7.6
Delta	8.5	0	4.8
Tritium	1.5	0	1.2

For the case of the CCS 2 in the above Tab. 7 the voltage and current measurement points were located within the charger itself. Therefore, the effective resistance between the measurement point and the charger terminal is assumed to be zero.

1.5.3. DC Charger Test Results

The DC charger test setup has a single cable between AC mains input test point and the charger. For the test of Nissan, a CHAdeMO extension cable has been used, resulting in an additional cable resistance between the charger and the connection to the extension cable. For other tests, measurement probes are directly connected to the Charger, and thus output resistance is neglected.

Power calculations can be calculated from the following equations:

1. $P_{IN\ actual} = P_{IN\ measured} - R_{Input\ cable}(I^2_{IN\ measured\ P1} + I^2_{IN\ measured\ P2} + I^2_{IN\ measured\ P3})$
2. $P_{OUT\ actual} = P_{OUT\ measured} + (I^2_{OUT\ measured} * 2 * R_{Output\ cable})$ (only for Nissan Leaf)

The test results are presented in the following figures. Fig. 17 presents the losses in DC charger test environment cables relative to load across cables. The graphs show the cable losses for each experiment with the different chargers, for the input and output cables. The cable losses of all four chargers chosen for the study (mentioned in Tab. 5) are presented in the figure below.

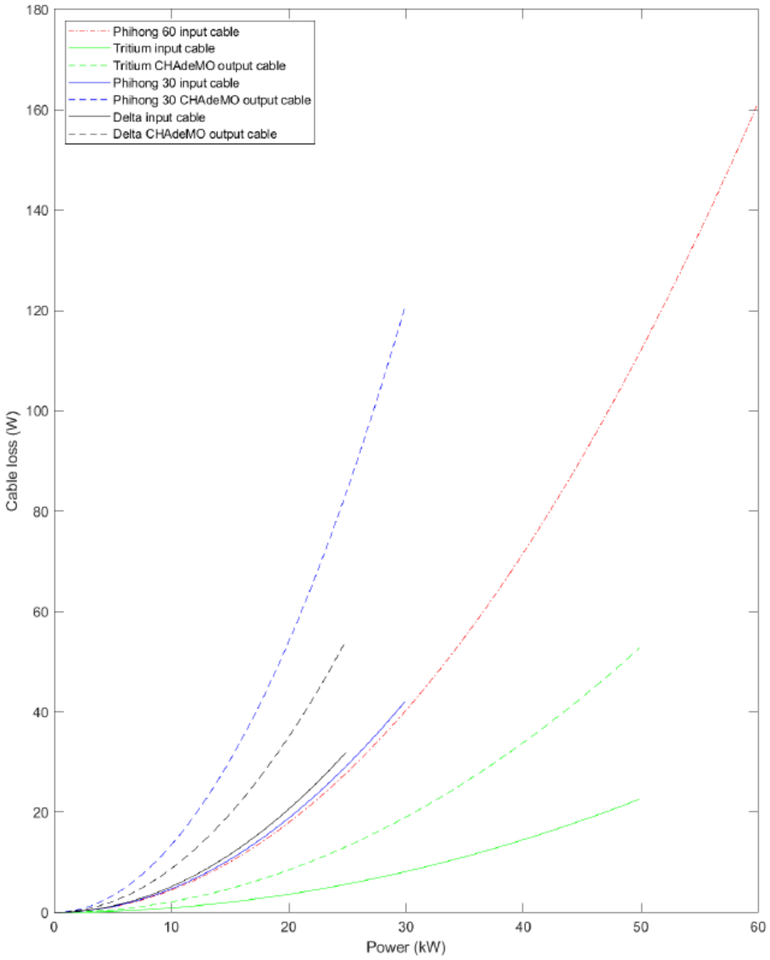


Fig. 17. Losses in DC charger test environment cables relative to load across cables [12]

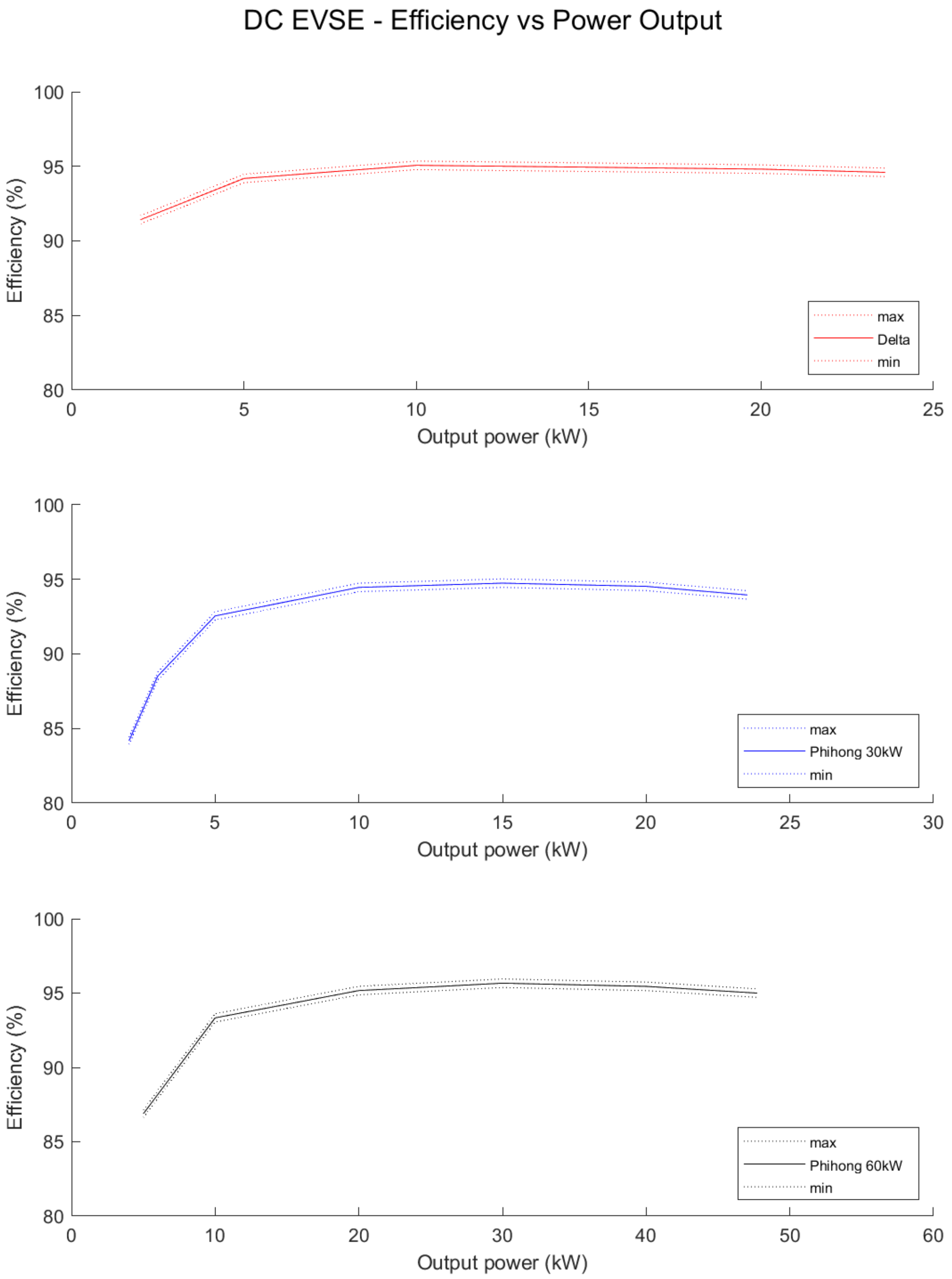


Fig. 18. DC charger efficiency using OCPP smart charging profile to control output power [12]

Fig. 18 shows the efficiency measurements for the Delta, Phihong 30 kW and the Phihong 60 kW, varying with output power. The graphs show an upper and a lower bound and these indicate measurement uncertainty of 0.3%. From the above figure, the Phihong 60 kW can be observed to have the best efficiency of 95-96%. However, the general efficiency over output power rating characteristic appears to be similar for both devices under test.

1.5.4. Vehicle Charging Profiles

Along with the efficiency calculations, it is also important to have a look into the DC charger vehicle charger profiles. Fig. 19 to Fig. 22 presents the efficiency curves for each charge cycle for each of the tested vehicles for each of the DC charges.

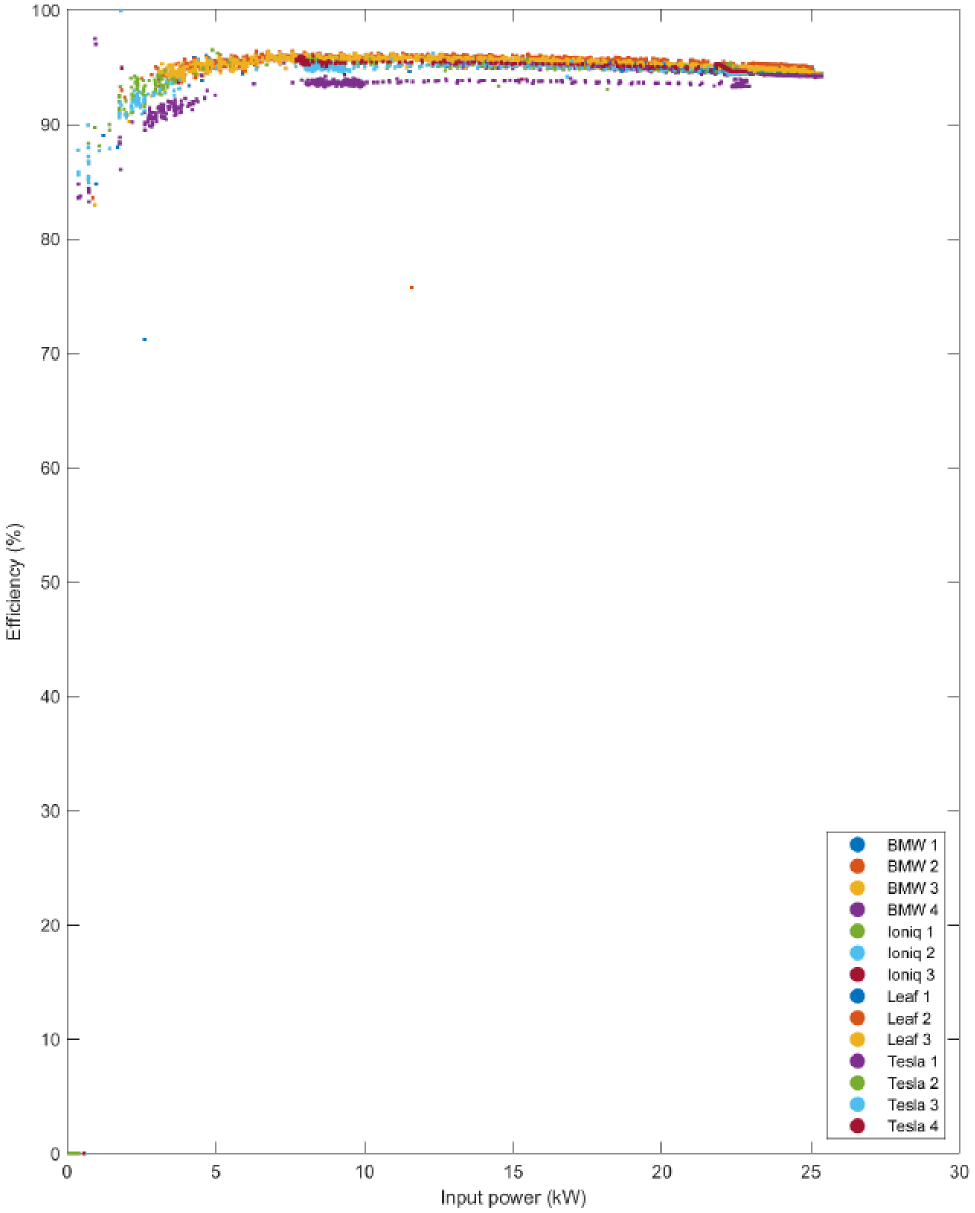


Fig. 19. Delta DC charger efficiency for each tested vehicle [12]

From the figure Fig. 19 it can be seen that beyond about 7 kW input power, the efficiency of the Delta DC charger is above 94% for all the vehicles used in the study. Below 7 kW of input power, the efficiency of the Delta DC charger becomes lower for all vehicles and falls below 90%.

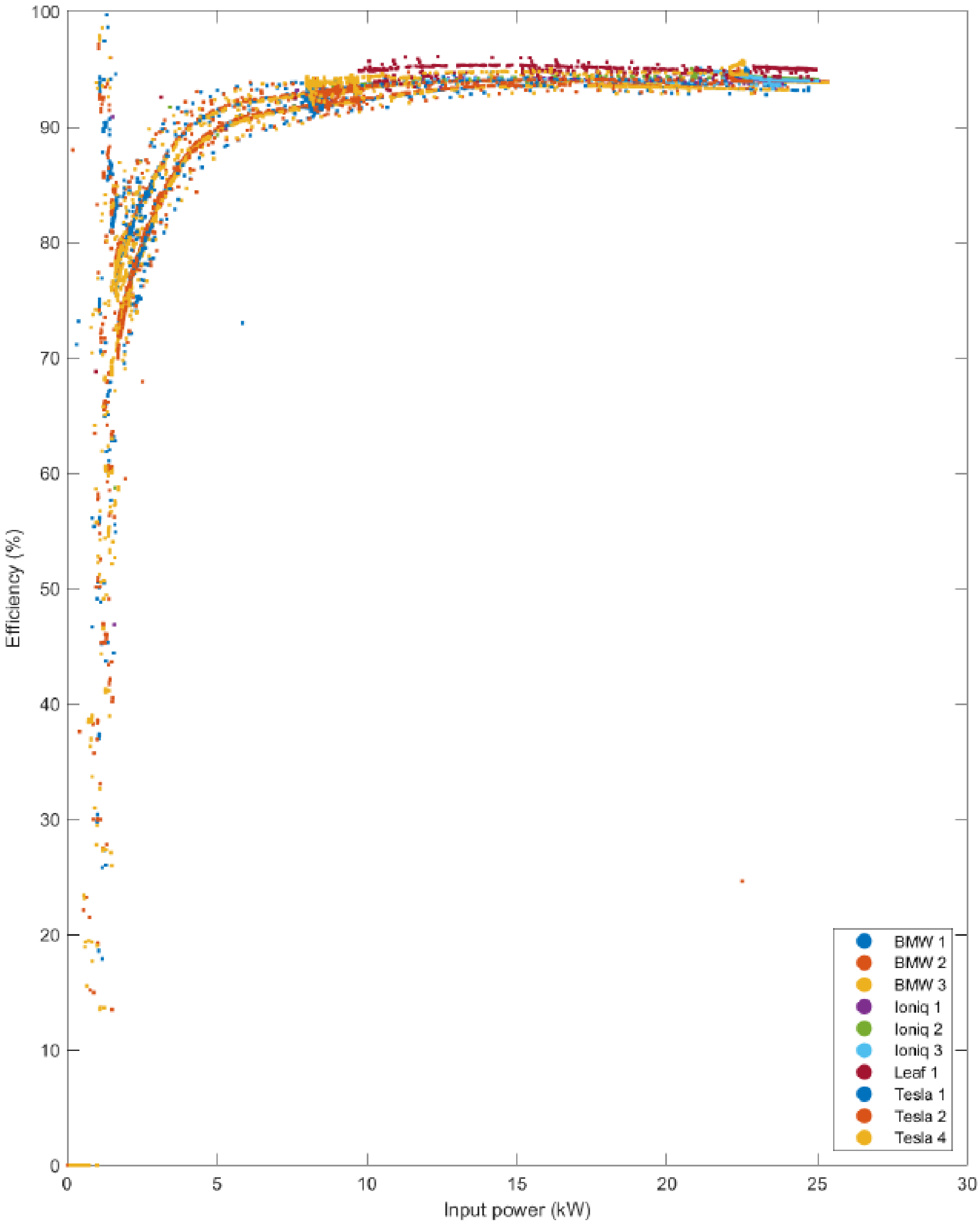


Fig. 20. Phihong 30 kW DC EVSE efficiency for each tested vehicle [12]

Fig. 20 shows the efficiency recorded, for the Phihong 30 kW DC charger, tested with the vehicles as mentioned in Tab. 6. It can be observed that beyond 12 kW input power, the efficiency recorded for the Phihong 30 kW for all the vehicles is more than 92%. However, at lower input powers of less than 5 kW, the efficiency of the Phihong 30 kW charger reduces significantly to less than 90% for most of the vehicles.

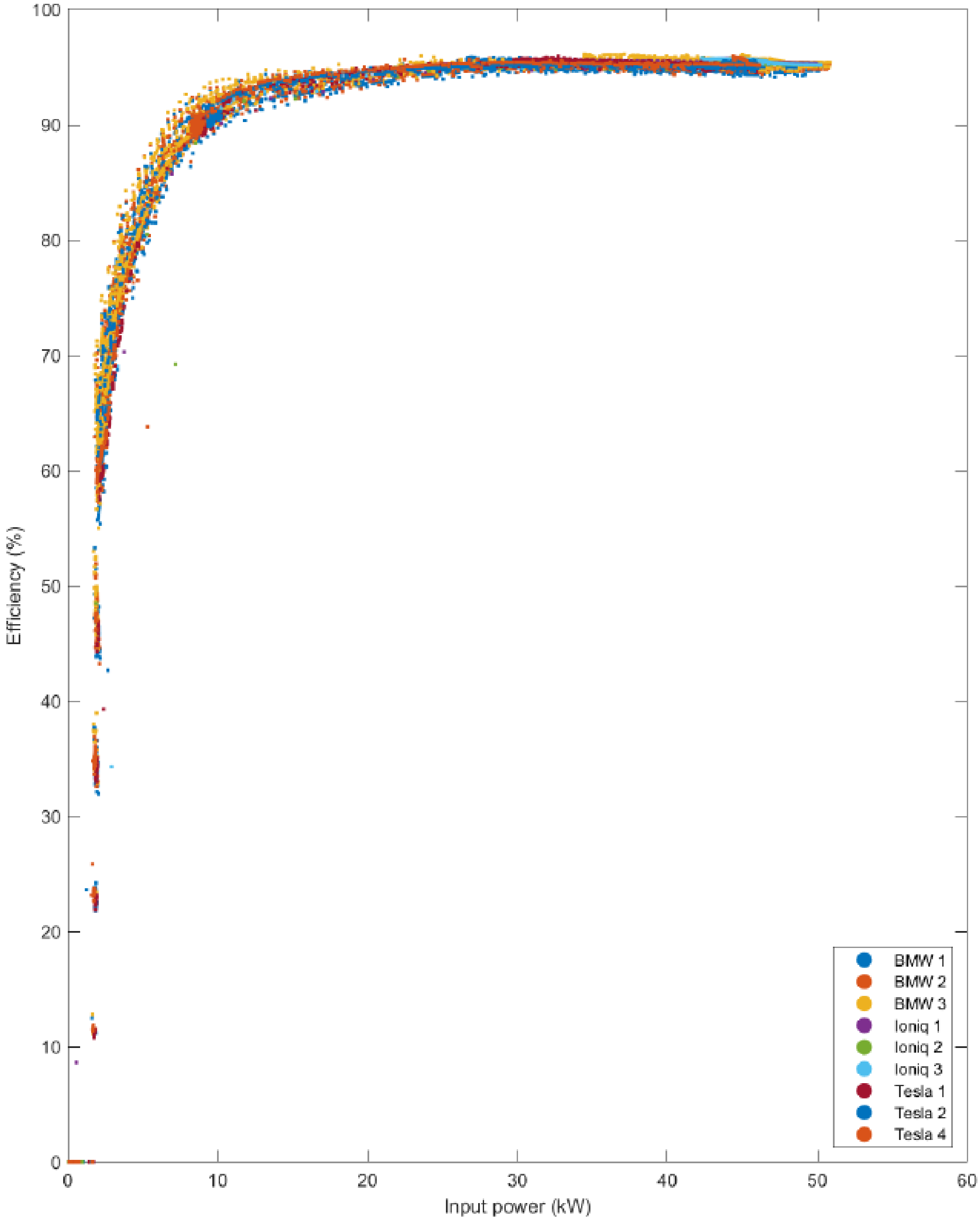


Fig. 21. Phihong 60 kW DC EVSE efficiency for each tested vehicle [12]

Fig. 21 depicts the efficiency of the Phihong 60 kW charger, when tested with different vehicles. At higher input power, the Phihong 60 kW shows very good efficiency values of around 95% and more, while the efficiencies observed at lower input power (less than 10 kW) is below 90%.

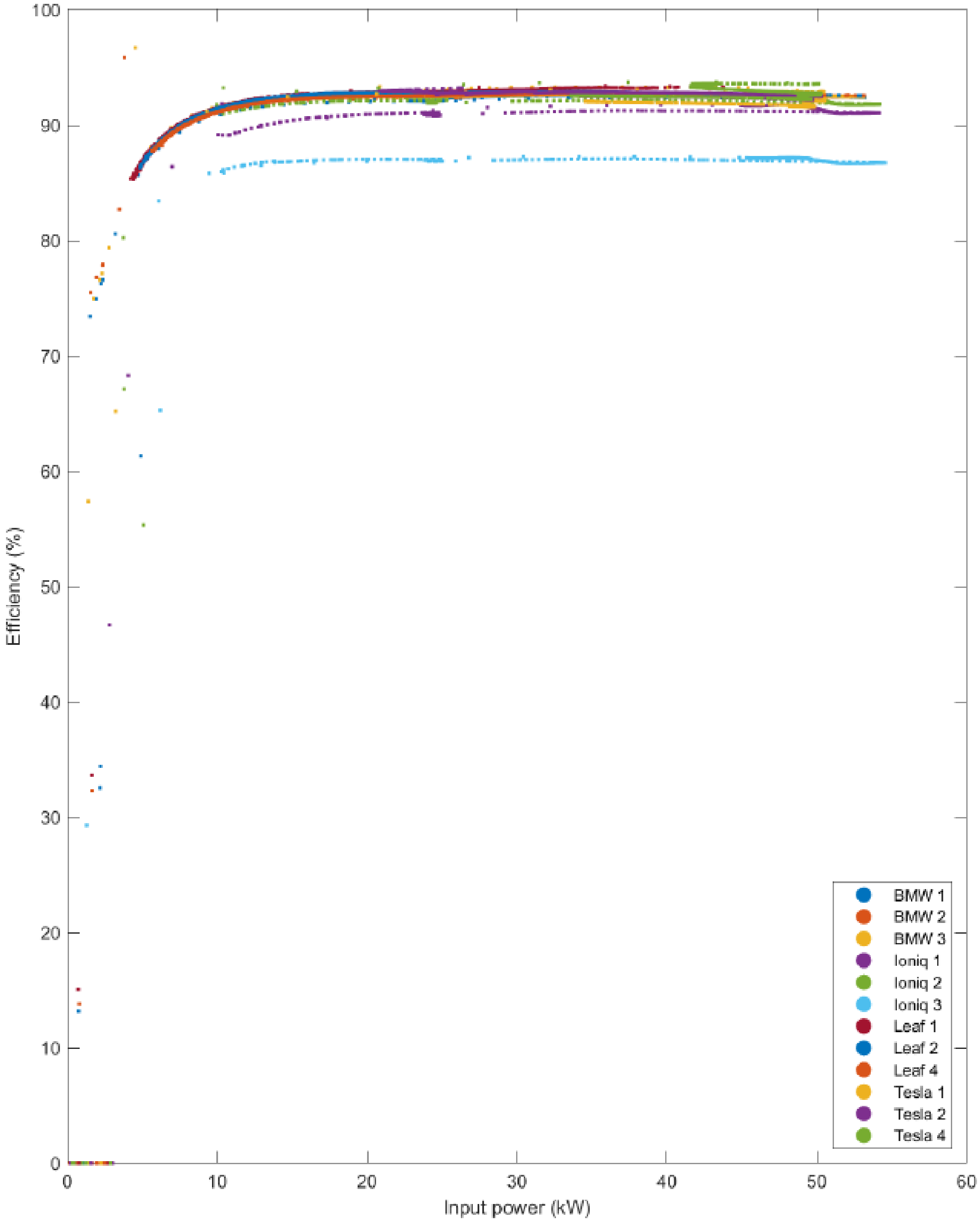


Fig. 22. Tritium DC EVSE efficiency for each tested vehicle [12]

Fig. 22 shows the efficiency figures of Tritium charger, when tested with different vehicles. The efficiency varies for different vehicles and has the lowest values for the leaf at under 90%. At input powers less than 10 kW, the efficiencies dip to much lower than 90%.

1.5.5. DC charger efficiency under EV charging

The following figures, from Fig. 23 to Fig. 26 presents the total charge cycle efficiency of each of the Chargers in study, tested for each vehicle for each charge cycle. In the figures, the circles represent the average efficiencies, and the whiskers present the maximum and minimum efficiency values recorded for the charger/vehicle combination plus the measurement uncertainty of 0.3%.

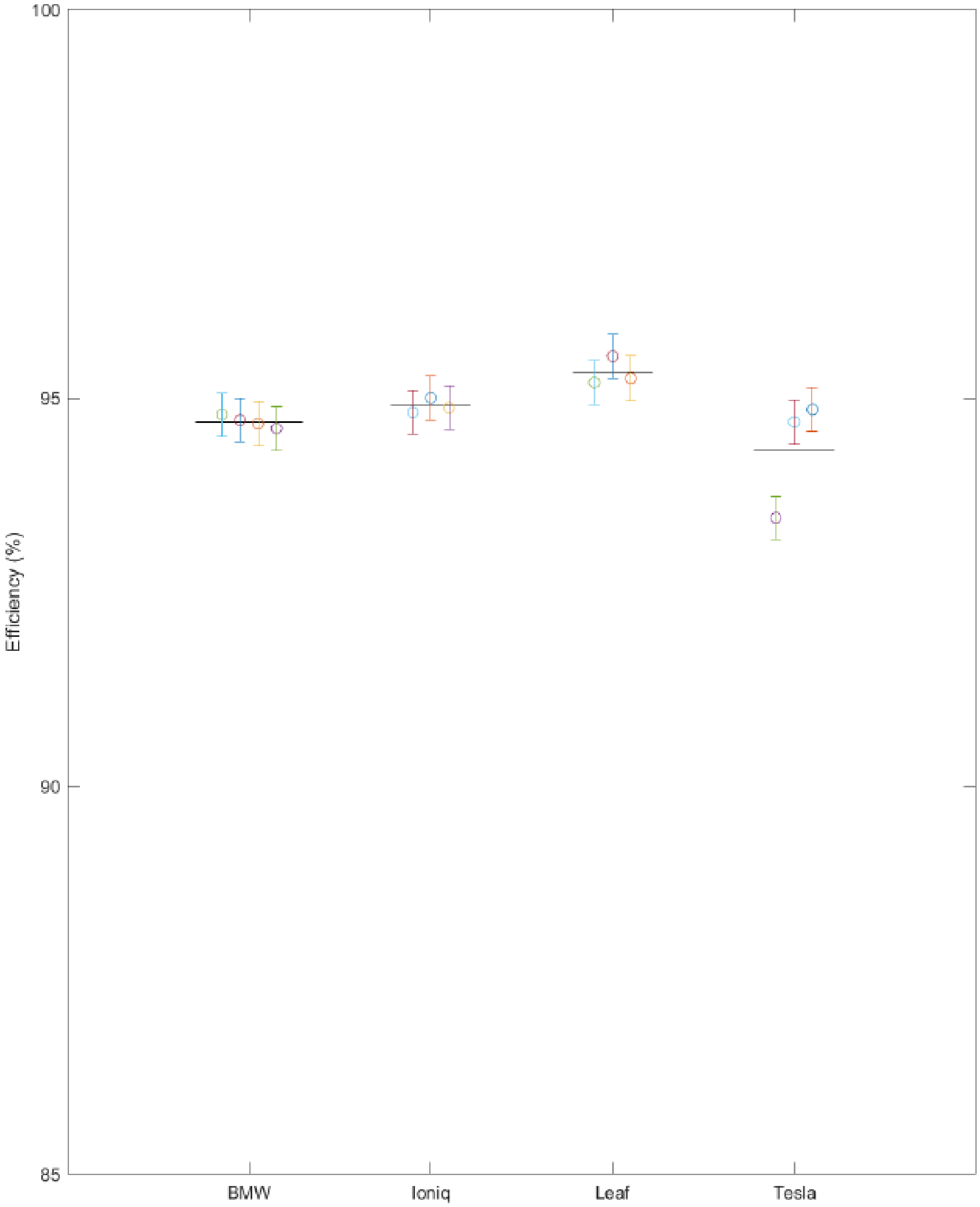


Fig. 23. Delta DC charger efficiency summary for each tested vehicle [12]

Fig. 23 shows the charge cycle efficiency for the Delta DC charger, tested with different vehicles. It can be seen that the Tesla exhibits a wide variation in efficiency spread when used with the Delta DC charger.

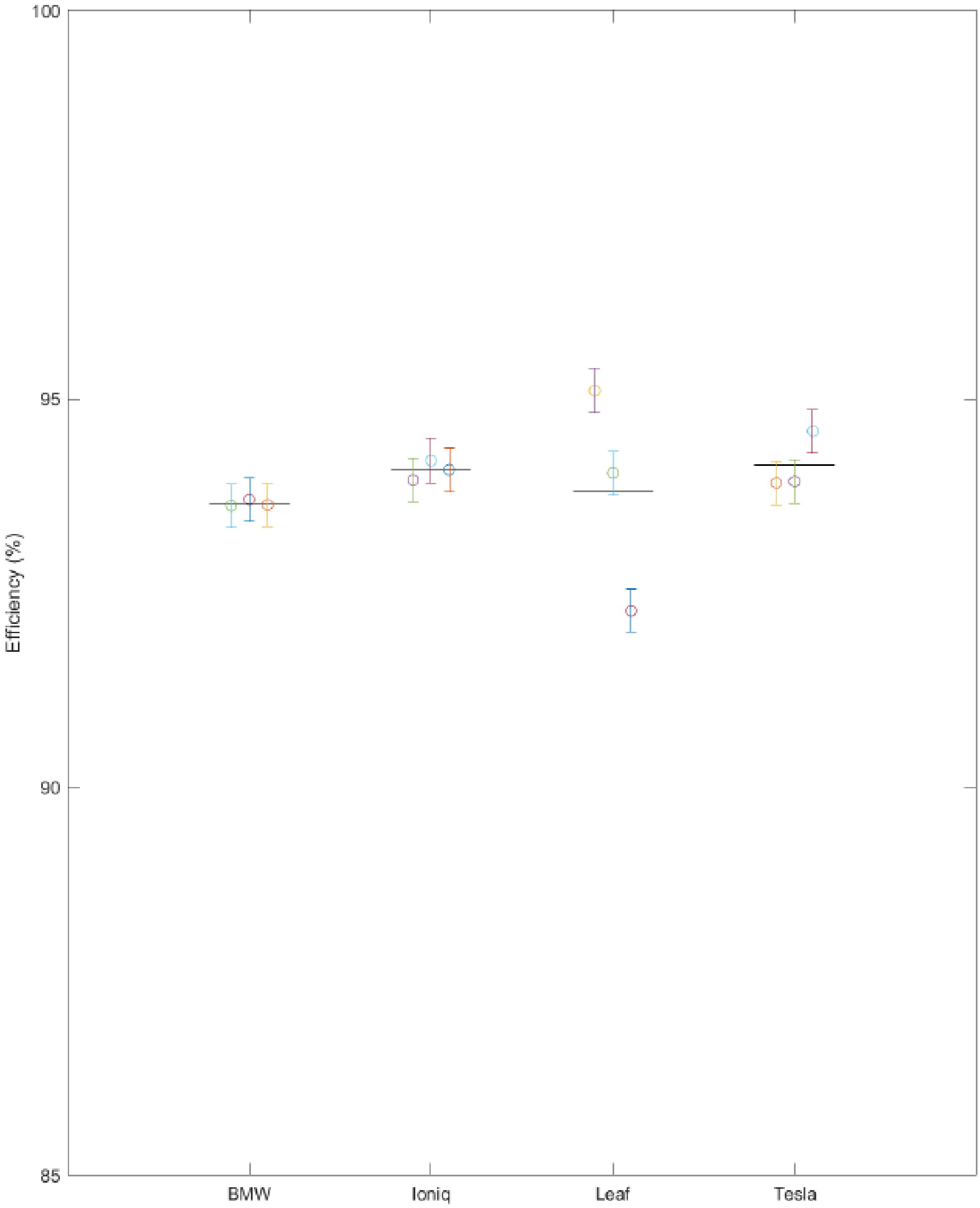


Fig. 24. Phihong 30 kW DC EVSE efficiency summary for each tested vehicle [12]

Fig. 24 shows the charge cycle efficiencies for the Phihong 30 kW charger, when tested with the selected vehicles and it can be observed that the Leaf exhibits a wide efficiency spread. The BMW and Ioniq show constant spread of efficiency.

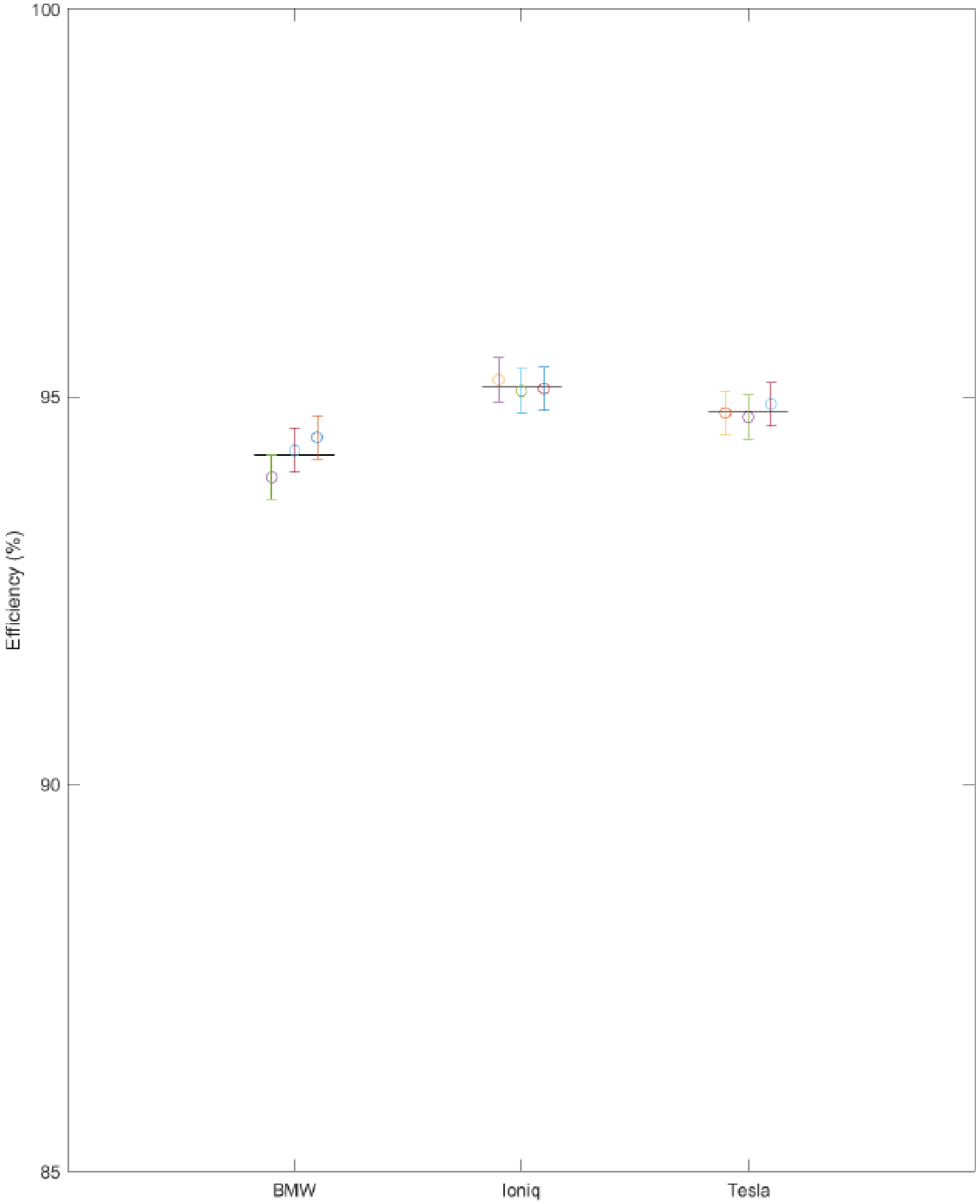


Fig. 25. Phihong 60 kW DC EVSE efficiency summary for each tested vehicle [12]

Fig. 25 shows the efficiency of the charge cycle of the Phihong 60 kW charger tested with all the selected vehicles. The Phihong 60 kW charger shows almost constant spread for the maximum and minimum efficiencies for all the vehicles.

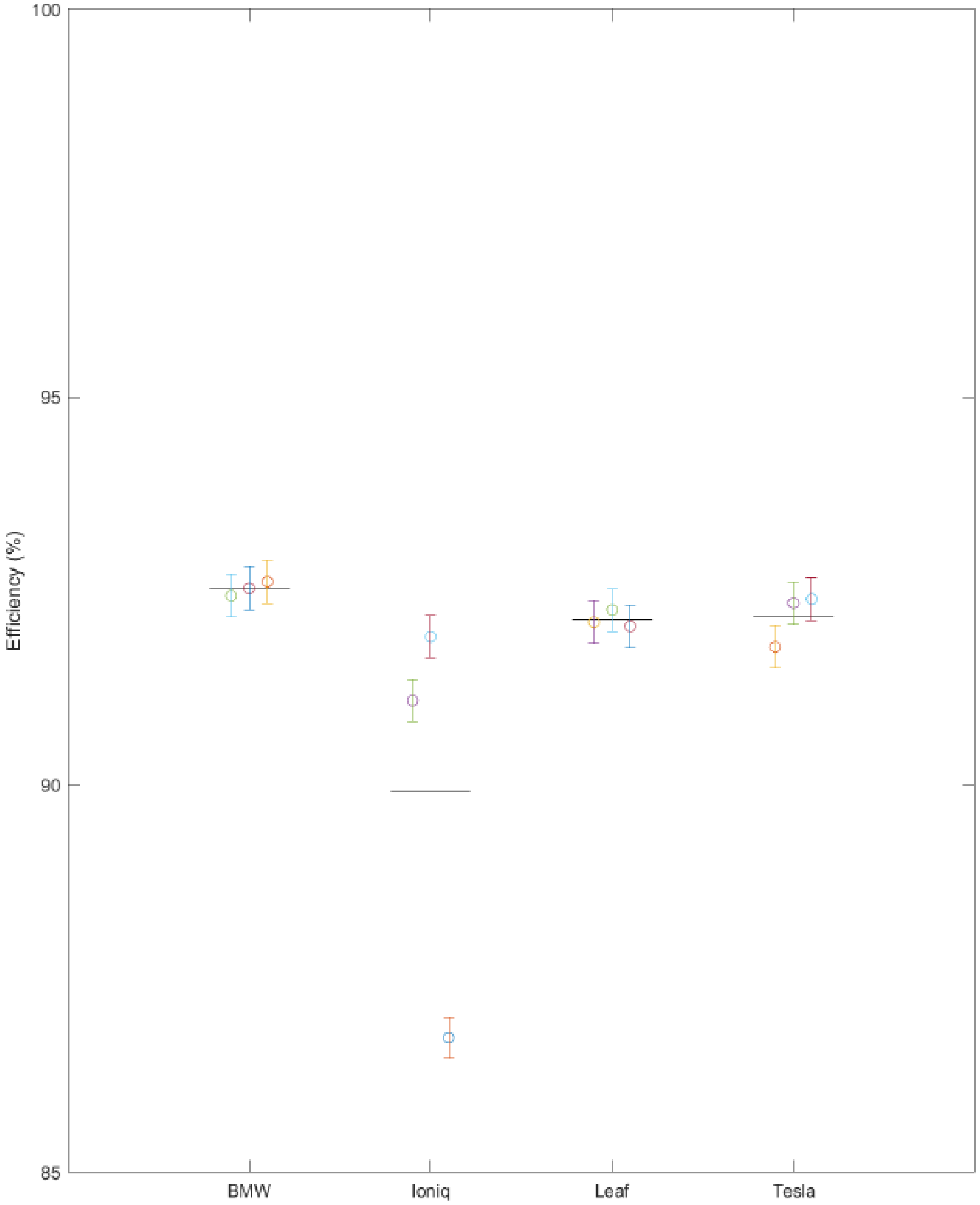


Fig. 26. Tritium DC EVSE efficiency summary for each tested vehicle as published in [12]

Fig. 26 Depicts the charge cycle efficiency of the Tritium DC Charger for each of the tested vehicles. The Ioniq shows wide variations in terms of energy efficiency while other vehicles have similar energy efficiencies.

1.5.6. DC Chargers Power Factor

The measured power factor for each charger, tested with each of the vehicles as shown in the figures below (Fig. 27 to Fig. 30):

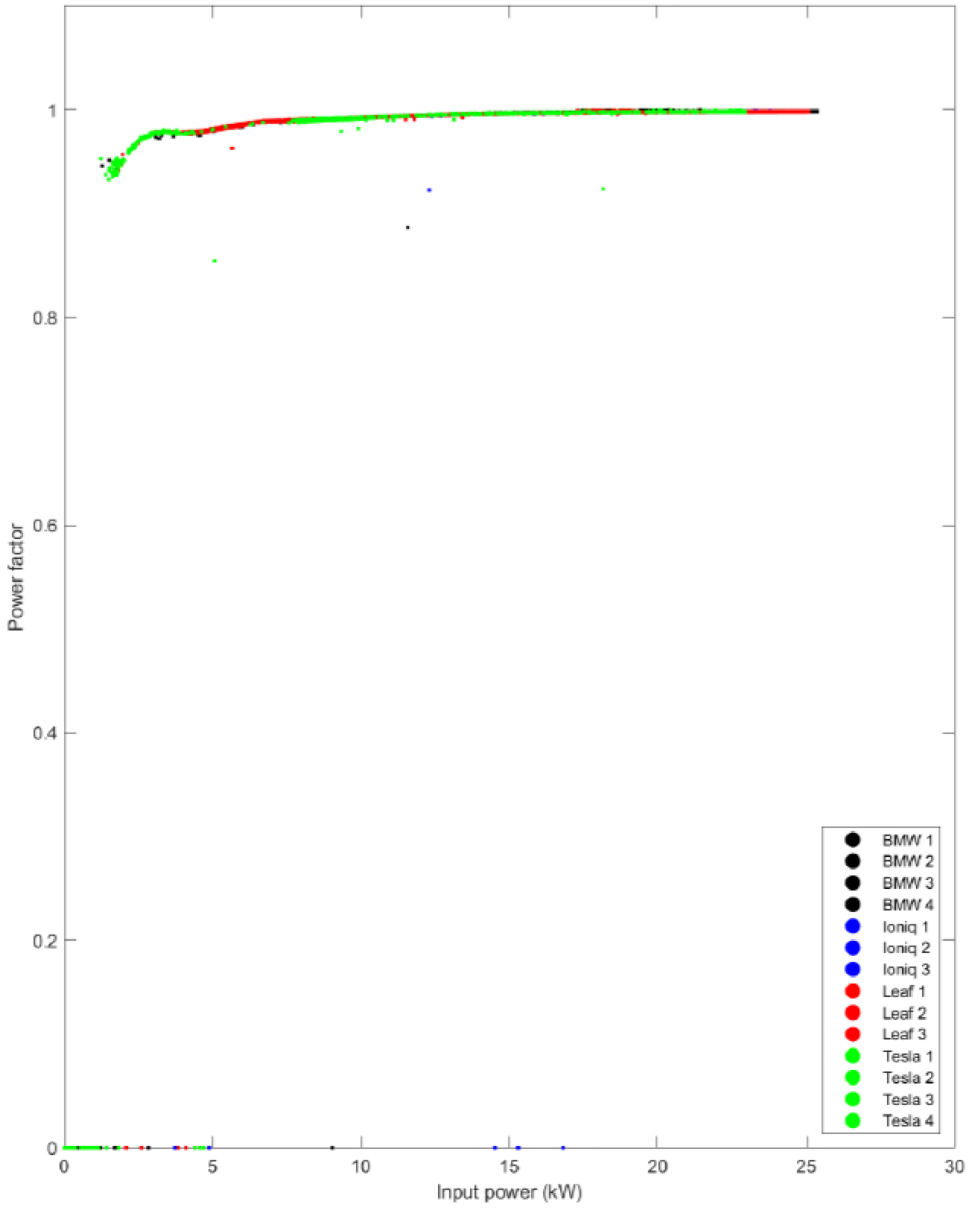


Fig. 27. Delta DC charger true power factor as published in [12]

Fig. 27 shows the measured power factor of the Delta DC charger, when used in combination with each of the selected vehicles. The results show that at more than 5 kW of input power, the Delta DC charger has very good power factor for all the vehicles. At less than 5 kW, the power factor drops by a small margin.

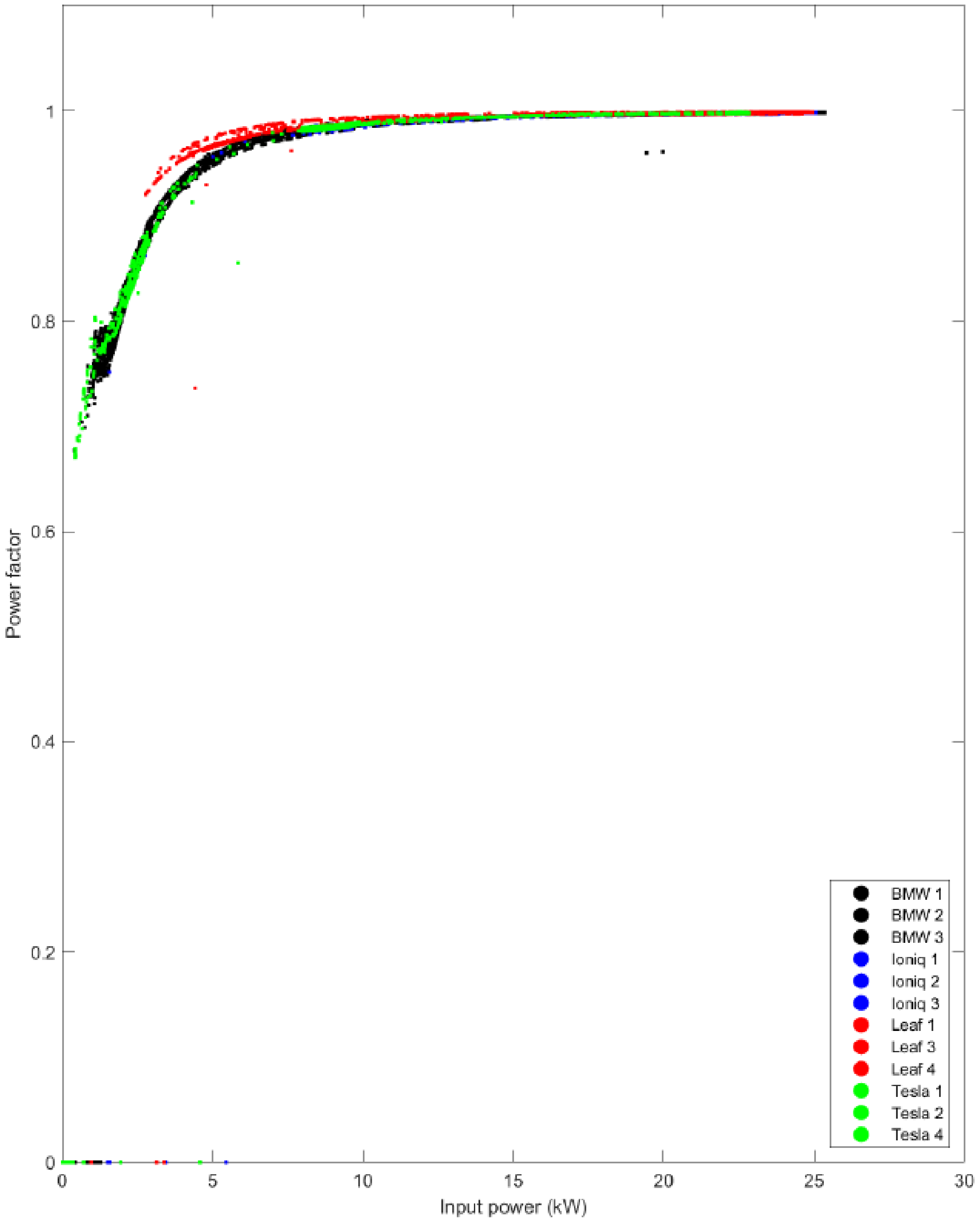


Fig. 28. Phihong 30 kW DC charger true power factor as published in [12]

Fig. 28 shows the power factor measured for the Phihong 30 kW charger, when used with all the selected vehicles. Beyond about 7 kW of input power, it is observed that the Phihong 30kW charger shows a high power factor operation. However, below 7 kW, there is a considerable fall in the measured power factor.

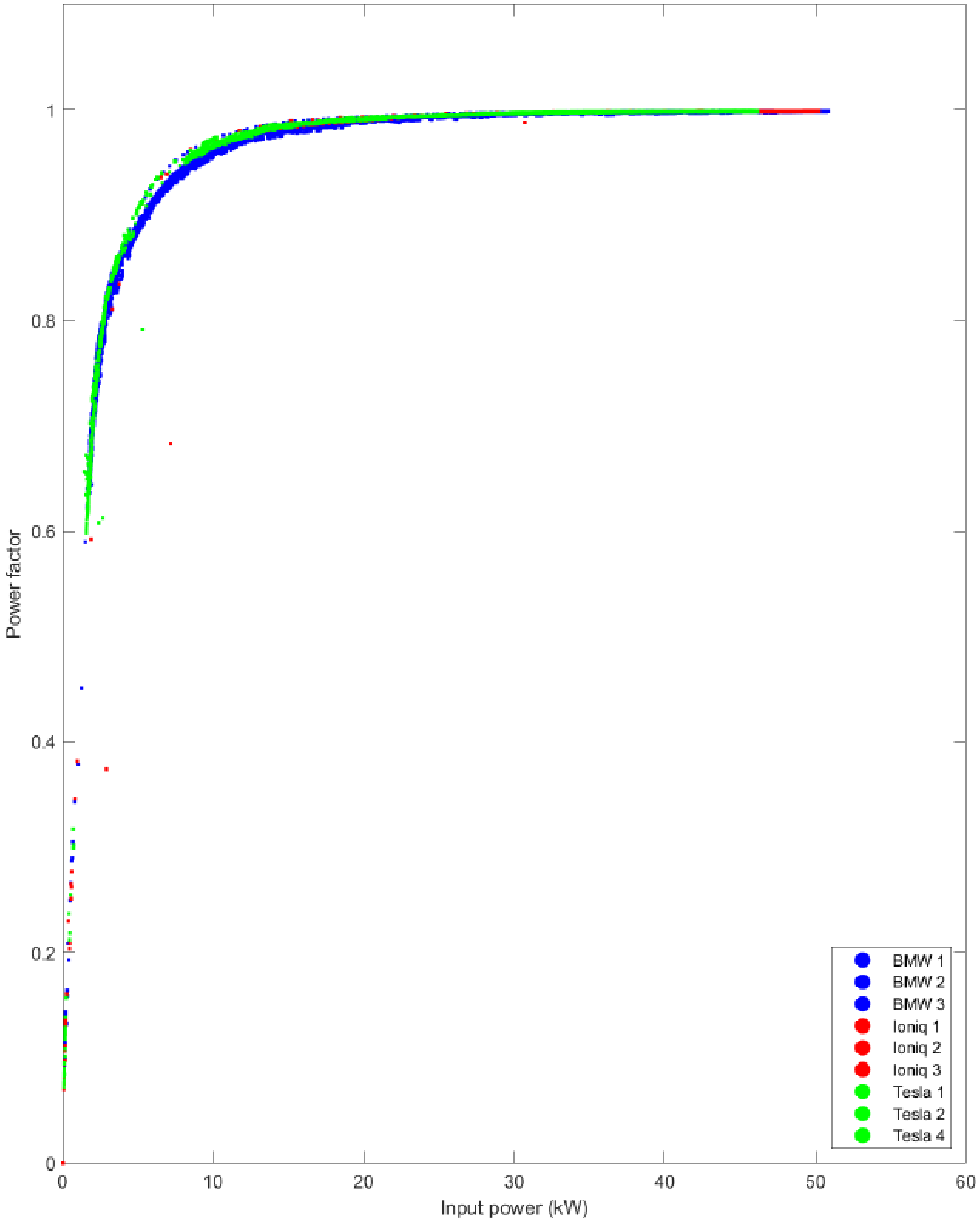


Fig. 29. Phihong 60 kW DC EVSE true power factor as published in [12]

Fig. 29 shows the power factor measurements for the Phihong 60 kW when used with the selected vehicles. It is observed that beyond about 15 kW, the Phihong 60 kW shows high power factor but below 17 kW, the power factor reduces drastically to much lower values.

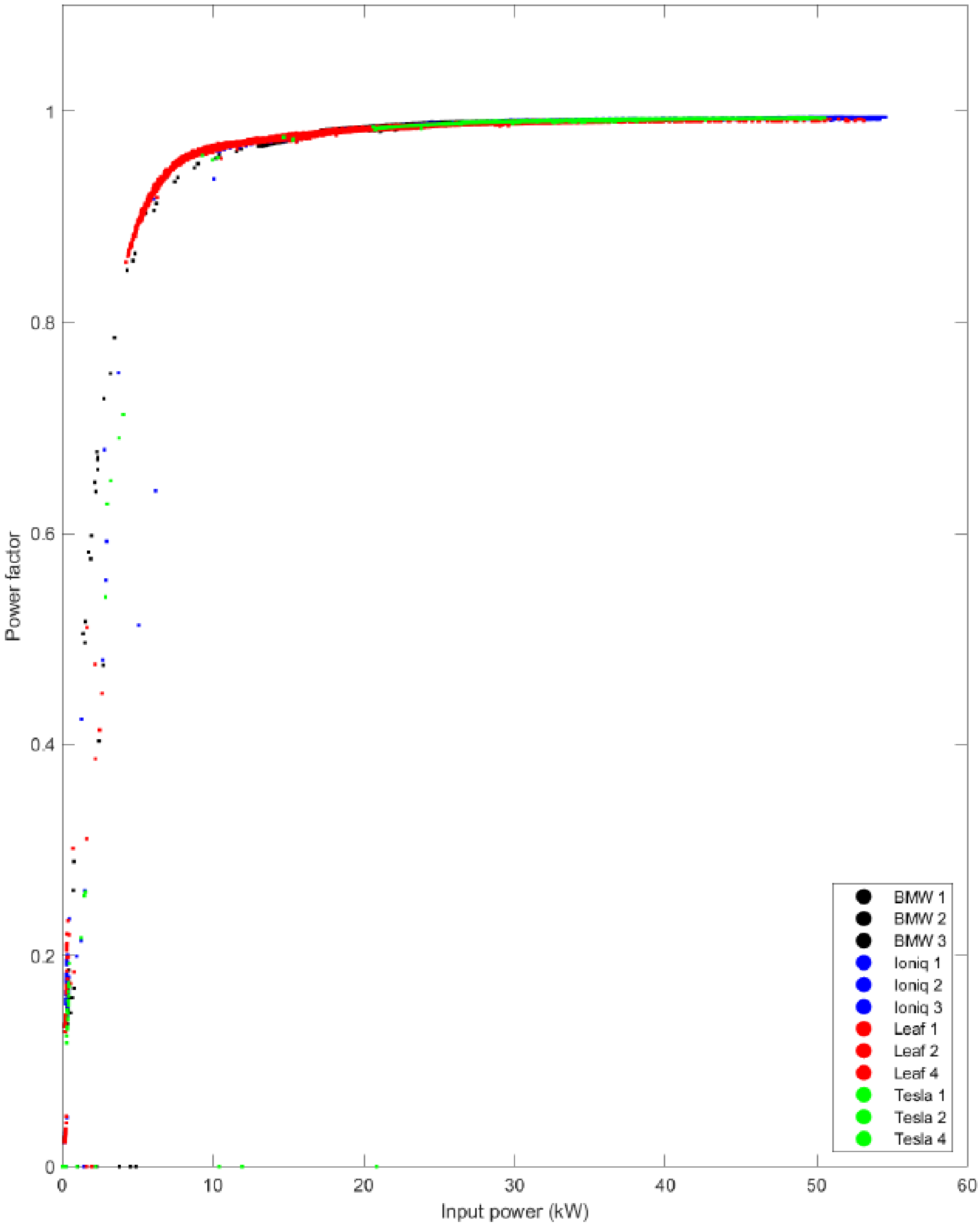


Fig. 30. Tritium DC EVSE true power factor as published in [12]

Fig. 30 presents the power factor measurement values for the Tritium DC charger, when used with all the selected vehicles. It can be seen that beyond 12 kW, there is charging at high power factor, However, below 12 kW, the power factor reduces considerably.

1.5.7. DC Chargers Efficiency Summary

The results obtained through experiments for the DC chargers will now be summarized. Tab. 8 lists the peak and average efficiency for all the four DC chargers, tested with preset output load.

Tab. 8. DC charger peak and average efficiency under controlled loads as published in [12]

Charger	Peak Efficiency	Average efficiency
Delta	95.07% ±0.3%	94.85% ±0.3%
Phihong 30 kW	94.75% ±0.3%	94.42% ±0.3%
Phihong 60 kW	95.66% ±0.3%	95.32% ±0.3%

Tab. 9. DC charger efficiency summary under vehicle charging as published in [12]

Charger	Leaf	Ioniq	Tesla	BMW	Average
Delta	95.33% +0.5-0.42%	94.90%+0.39-0.37%	94.33%+0.80-1.16%	94.69%+0.38-0.37%	94.81%
Phihong 30 kW	93.81%+1.58-1.81%	94.08%+0.40-0.41%	94.15%+0.72-0.51%	93.65%+0.33-0.31%	93.92%
Phihong 60 kW	-	95.13%+0.37-0.34%	94.81%+0.38-0.36%	94.25%+0.51-0.57%	94.73%
Tritium	92.13%+0.40-0.36%	89.91%+2.27-3.43%	92.17%+0.50-0.67%	92.53%+0.37-0.37%	91.68%

In Tab. 9 , the efficiency figures of DC chargers under vehicle charging are presented. It can be observed that the Delta has the best efficiency figures for both controlled load operation as well as vehicle charging operation.

Though not a scope of this study, it is important to have a look at the energy efficiencies of the AC chargers (also included in the New Zealand Report).

1.5.8. Charging Power

The average charging power measured during the tests are presented in Tab. 10. This was determined by averaging the cumulative power output from the individual chargers and the duration of the charging for each vehicle and charger combination, generating a charge rate measured in kilowatts per hour. In [12] it is stated that the presented data in kW/hr is a result of the averaged cumulative power output from the EVSE and duration of the charge time for each vehicle-charger combination.

Tab. 10. Average observed vehicle internal charging rate as published in [12]

All units are in kW/hr	Ioniq	Tesla	BMW	Leaf
25 kW DC	21.8	20.4	21.9	15.3
30 kW DC	21.1	20.2	17.4	14.4
50 kW DC	38.4	42.8	30.7	14.8
60 kW DC	39.9	37.2	26.3	-

Apart from the average charging rate, the maximum charging power was also recorded for each DC charger, for each vehicle and the results are tabulated in Tab. 11.

Tab. 11. Maximum observed vehicle internal charging power as published in [12]

All units are in kW	Ioniq	Tesla	BMW	Leaf
25 kW DC (Delta)	23.6	21.6	24.0	23.7
30 kW DC (Phihong 30 kW)	23.5	21.6	23.8	23.7
50 kW DC (Tritium)	49.5	46.6	49.0	45.9
60 kW DC (Phihong 60 kW)	47.5	43.9	48.5	-

Tab. 12. Maximum rated vehicle charging power as published in [12]

Maximum rate **All units are in kW**	Ioniq	Tesla	BMW	Leaf
DC	69	170	49	46

Tab. 12 shows the maximum rated charging power for all the selected DC chargers, as mentioned in the product specification from their manufacturers. It can be found that the Phihong 60 kW and the Phihong 30kW chargers are not able to provide the maximum power to the vehicles, in accordance with their specifications.

Tab. 13. Maximum observed vehicle internal charging current as published in [12]

DC Charger Type	**Ioniq**	**Tesla**	**BMW**	**Leaf**
25 kW DC (Delta)	61.0	60.1	60.9	60.8
30 kW DC (Phihong 30 kW)	60.9	60.1	60.7	60.7
50 kw DC (Tritium)	130.1	129.3	127.2	128.8
60 kW DC (Phihong 60 kW)	122.8	121.6	122.8	-

Tab. 13 presents the maximum recorded vehicle internal charging current for each of the charger vehicle combination.

Tab. 14. Maximum specified DC charger charging current as published in [12]

DC chargers Type	Maximum available output current (A)
Delta (25 kW DC)	60
Phihong 30 kW (30 kW DC)	47
Tritium (50 kW DC)	n/a
Phihong 60 kW (60 kW DC)	118

Tab. 14 shows the maximum rated current for the selected DC Chargers. The data is obtained from the product specifications by the manufacturers.

Tab. 15. Average to maximum power ratio under charge as published in [12]

Maximum rate	Ioniq	Tesla	BMW	Leaf
DC	0.99	0.97	0.90	0.91

It is important to investigate the ratio of average power to peak power since it provides an understanding of the utilization capacity of the charging power, by the vehicles. For example, a ratio of 1:1 would indicate that the vehicle is able to consume charging power, at the rated capacity of the charger. Lower ratios would mean that the vehicle in unable to consume power continuously, at the rated maximum. Tab. 15 shows the ratio of average to maximum power for each of the vehicles.

1.5.9. Vehicle internal energy use and efficiency

In the previous sections, efficiency and energy usage were discussed for the charger and discussions were limited to the internal structure of the charger. However, the internal efficiency of the vehicle is also important since it affects the overall power transfer efficiency from the grid to the battery. The vehicles have their own electrical systems that have different control objectives like the battery pack temperature. The losses in cables also contribute to the total vehicle internal energy loss. The results of experiments on the AC chargers will also be presented here, such that an analysis may be drawn in later sections.

Tab. 16. Vehicle internal charging efficiency as published in [12]

	Ioniq	Tesla	BMW	Average
AC Charging	91.5±0.4%	92.7±1.7%	91.0±4.1%	91.7%
DC Charging	98.1±0.5%	906±3.3%	97.3±0.5%	95.3%

Tab. 16 shows the vehicle internal charging efficiency, indicating the total energy input (derived from the AC or DC charger output measurements) delivered to each vehicle, relative to the total energy absorbed by the battery for each test (derived from the onboard BMS). Interestingly, it may be seen that the internal charger efficiency of vehicles is much higher for DC chargers, in comparison with AC chargers.

1.5.10. Grid to battery charging efficiency

The summary of all the previous sections is to understand the power transfer efficiency from the grid to the battery. This involves considerations of all previous data where the Charger efficiency, loss and internal vehicle efficiencies.

Tab. 17. Grid to Battery charging efficiency as published in [12]

Charger type	Leaf	Ioniq	Tesla	BMW	Average
Average AC		90.7%	92.6%	90.4%	
DC Delta	n/a7	93.1%	85.46%	92.2%	90.2%
DC Phihong 30	n/a7	92.3%	85.3%	91.1%	89.6%
DC Phihong 60	n/a7	93.3%	85.9%	91.7%	90.3%
DC Tritium	n/a7	88.2%	83.5%	90.0%	87.2%
Average DC		91.7%	85.0%	91.0%	

Tab. 17 presents the Grid to Battery charging efficiency for all the DC chargers in the New Zealand Report. For further analysis, the average AC charger efficiency is also presented. It may be seen that the overall system efficiency figures, for power transfer from the grid to the battery speaks an interesting story. The DC chargers have higher efficiency than the AC chargers and this is mainly due to the reduced efficiencies for AC chargers, in the case of vehicle internal efficiency.

1.5.11. Summary of the Testing results in New Zealand Report

The New Zealand report discusses various aspects of vehicle charging and finally presents a detailed test report on four commercially available DC chargers. The DC chargers are tested with both controlled load as well as with vehicle charging. For vehicle charging, four models of EVs were selected and used in the experiments. The major findings are listed below:

1. The efficiency range varies from 94% to 96% for controlled loads and 91% to 95% for vehicle charging mode. This is considerably lower than AC chargers, which typically exhibit efficiencies of 99% and above.
2. Below 25% of the maximum power output, efficiency reduces considerably. However, peak efficiency has been recorded at about 50% of the rated output power.
3. Power factor drop was observed with a decrease in output levels.
4. A major variation was observed in the standby power. Poor power factor values were observed at standby which suggest capacitive effects of high-efficiency switch-mode power converters.

5. Another important finding of the New Zealand report is the efficiency of the internal charging of vehicles, when operated with AC and DC chargers. It is found that when operated with the AC chargers, the vehicle internal energy losses are quite high when compared to DC charger operation. The difference in energy loss can be attributed to the design and function of AC and DC chargers:
    a. **AC Chargers**: These chargers do not contain energy conversion stages (power electronics) themselves. Instead, the power electronic converters, are located inside the vehicle (in this specific case also designated as on-board charger). Although AC chargers are highly efficient with only negligible losses from cabling and protection circuits, the major energy losses occur within the car due to the on-board charger.
    b. **DC Chargers:** These chargers include the necessary power electronics, cabling, and protection circuits etc. within the charging unit itself. Therefore, the energy conversion happens outside the vehicle, resulting in minimal internal energy losses within the car.

   Consequently, looking at the whole energy transmission chain (from grid to better), both, AC and DC-chargers come with similar energy efficiency performance depending on the power electronics design.

In

Tab. 9 it is observed that the DC charger efficiency ranges from 89-96% when in operation with vehicle charging. For AC chargers, the efficiency for vehicle operation is much higher, at more than 99% (root cause as previously discussed). However, looking at the final Grid to battery efficiency values, it is observed that the DC charger's overall efficiency is higher than that of the AC charger for some chargers. This finding hints at the superiority of the DC chargers over the AC chargers.

2. DC-Wallbox Measurement Test Setup for PECTA Wallbox Pre-Scoping Study

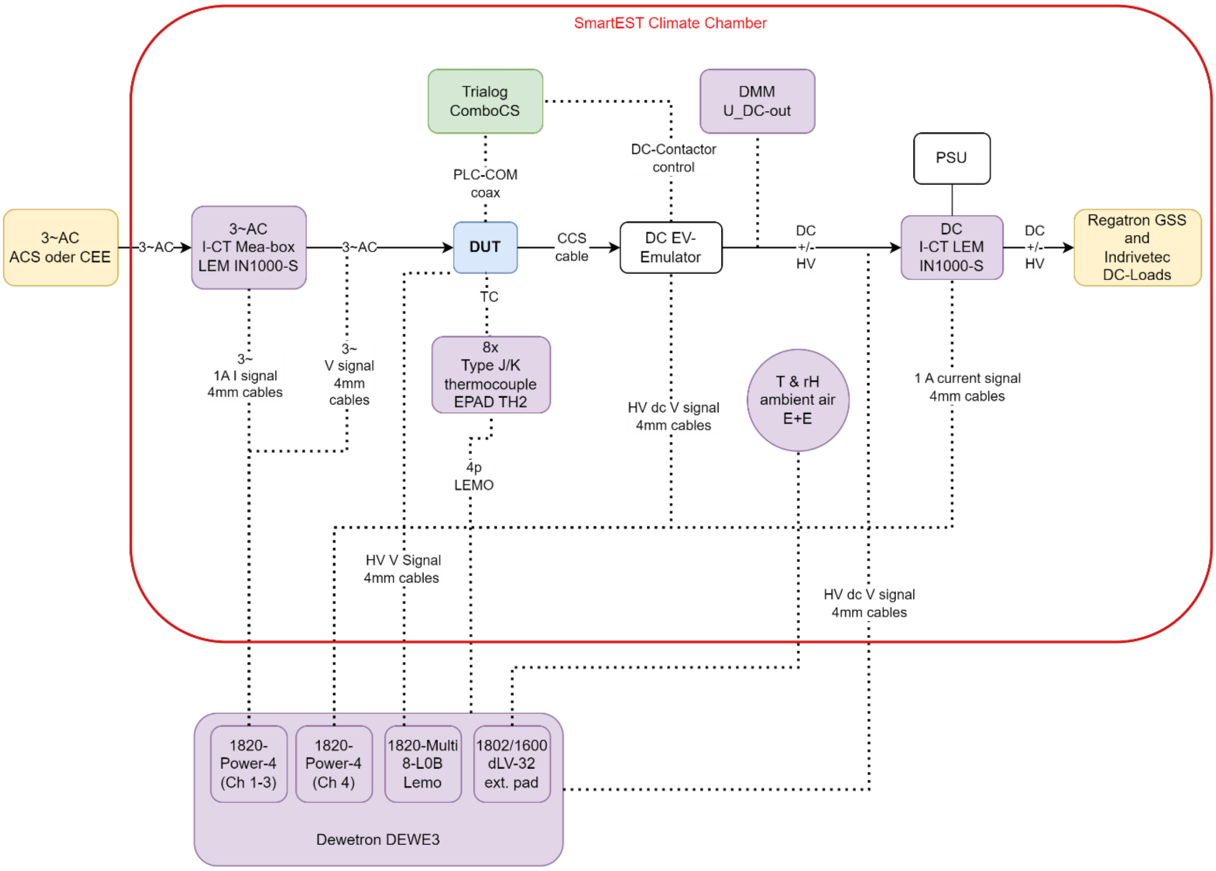


Fig. 31. Schematic representation of the basic measurement setup for Wallboxes

For an adequate measurement, it is essential to know the exact measuring points and thus be able to estimate the corresponding measurement parameters. Fig. 31 shows a schematic representation of the basic measurement setup for measurements on DC-Wallboxes intended for measurements in a high-capacity temperature chamber at the AIT SmartEST laboratory site.

2.1. Measurement test setup

Prior to moving into the measurements, the measuring equipment shall be discussed, which will help to understand the ecosystem in which the experiments were performed. Tab. 18 lists the different measurement equipment used for the test.

Tab. 18. Measurement Equipment used for the Test

Measurement Type	Device
Input Voltage Measurement	Dewetron (Designation) Channel
Input Current Measurement	3x Hall Sensor (Designation) – Dewetron Channel
Output Voltage Measurement	Dewetron (Designation) Channel
Output Current Measurement	Hall Sensor (Designation) – Dewetron Channel
Temperature Measurement	3x Temp Sensor (Designation) – Dewetron Channel

2.1.1. Emulated Vehicle (feeding power back to the grid)

A power bidirectional power supply is used (Regatron TC.GSS), to act as the load (i.e., electric vehicle). The Regatron is a power supply and recuperation system, operating as a power sink and feeds back the energy to the grid. The Regatron is a modular 32 kW with a voltage range of 65 V to 1,500 V_{DC} (nominal), a three-phase mains input of 400 V_{AC} (line to line), and operating modes in CV (constant voltage), CC (constant current), CP (constant power), and "internal resistance mode". The source/sink is capable of handling fully digital controls and peripheral operations. To achieve different voltage and current profiles, the system can be operated in parallel, series, or mixed configuration modes. The Regatron TC.GSS comes with an RS232 interface standard. The applications range from testing and qualification of battery systems, development and testing of vehicle drives, simulation of vehicle electrical systems, test benches for electric drives, elevators, tower crane drives, cable cars, evaluation and testing of hybrid concepts, general electrical process engineering, and Energy buffer systems. Fig. 32 shows the Regatron 32 kW Modular Grid-Tie Source/Sink system.

Fig. 32. Regatron Modular Grid-tie Source / Sink system 32 kW

2.1.2. Measurement Equipment

The Dewetron DEWE3 RM8 is a data acquisition system and was used for power measurement of DC chargers and Fig. 33 shows the measurement setup along with the PC. The DEWE3 RM8 offers a power module and unique combination of flexible hardware and intuitive software for high-precision power measurement, performance analysis, and evaluation. It enables the measurement of high voltage and current in perfect synchronization together with additional analog inputs such as temperature, vibration or noise as well as other data sources such as CAN, SCPI or FlexRay.

The Dewetron setup is used to measure several system-relevant variables, these include: The Input voltage of the Wallbox as three-phase grid connection, the RMS input current, consumed power, DC EVSE load voltage, output charging current, output power, efficiency and temperatures at cooling intake, cooling outlet as well as the top-housing temperature.

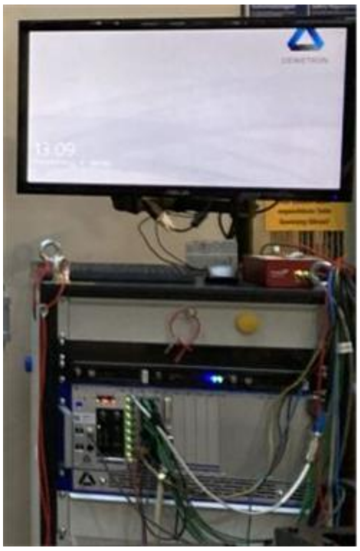


Fig. 33. Dewetron Measurement System PC Setup

The Dewetron DEWE3 RM8 data acquisition system (DAQ) was used to measure AC and DC voltages and currents. The integrated power module calculates all AC and DC power and efficiency of the DUT.

2.1.3. Climate Chamber

Fig. 34. Large-capacity climate chamber

The large-capacity climate chamber shown in Fig. 34 is equipped with temperature and humidity controls. The temperature range extends from -40 to +60 °C and was preset to the following temperatures to determine the efficiency for the corresponding series of measurements: -35 °C, -15 °C, 0 °C, 25 °C and 55 °C.

3. DC-Charger Experimental studies

3.1. Device Overview

One of the DC chargers commercially available in the market was procured and several experiments were performed to measure the efficiency. The reports on the efficiency tests will be presented in later sections of this document.

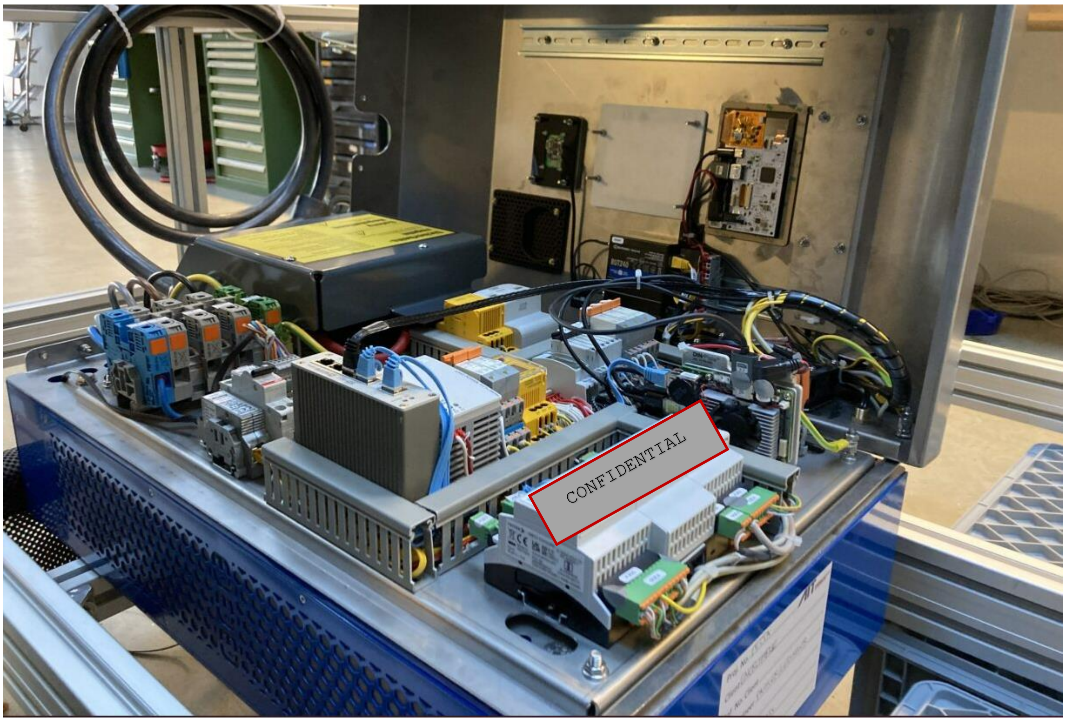


Fig. 35. Side View: Interior of the DC-Wallbox

Fig. 36. Top View: Interior of the DC-Wallbox

In the images shown in Fig. 35 and Fig. 36, the DC Charger under test is shown in the open state. Small signal electronics for controlling the contactors and the display electronics can be seen on the side of the hinged cover.

For simplicity, the illustration is divided into 3 sections from left to right in the below Tab. 19. The internal details are listed for each of the three different sections. The sections are shown in Fig. 36. The power electronic components of the charger, however, are located in the enclosure at the bottom part seen in Fig. 35 .

Tab. 19. Internal details of DC Charger

Section of the Charger 1	▪ **Internal details**
Left Section Top	▪ Protective cover for rectifier stage
Left Section Bottom	▪ Terminal Blocks for 3-phase mains connection
Center Section Top	▪ Raycap PROBLOC B 1000 DC Surge Protective Device (SPD) for DC Systems ▪ BENDER AGH420 Part 2 of BENDER isoEV425
Center Section Bottom	▪ Terminal Blocks for electrical installations ▪ ABB SN201 C6 - Miniature Circuit Breaker (MCB) for Protection against overcurrent (overload and short circuit) ▪ Raycap RayDat NET 6 POE - Surge Protective Device (SPD) for LAN Category 6 Networks
Right Section Top	▪ Phoenix Contact - Changeover Relais ▪ +24V-GND Terminal Blocks
Right Section Bottom	▪ BENDER isoEV425 Isometer ▪ Phoenix Contact - Changeover Relais ▪ Phoenix Contact UNO POWER- Power Supply for Electrical Cabinets

3.2. Specific Test Setup

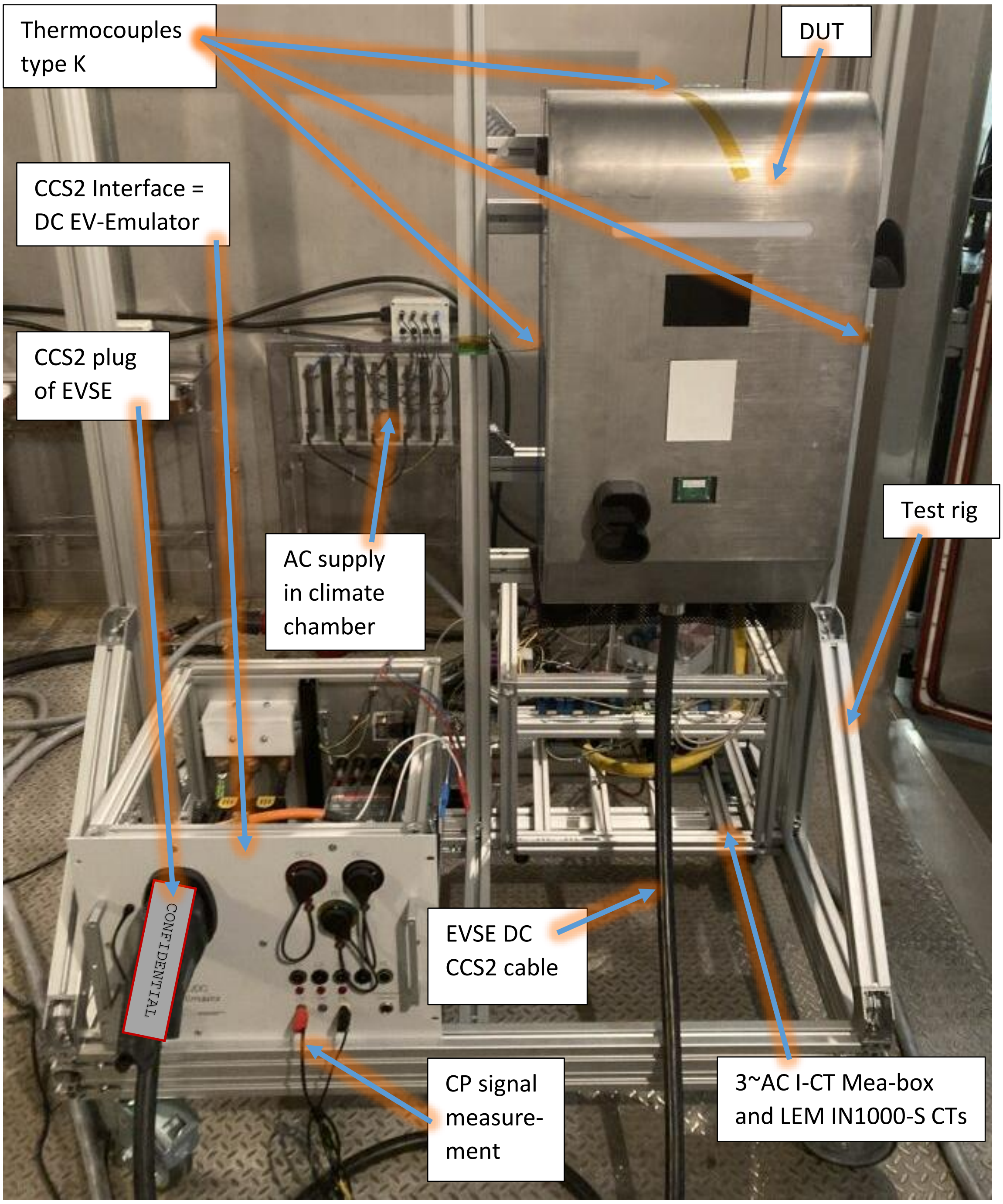


Fig. 37. Front View: Full setup of all measuring devices on power input as well on power output side

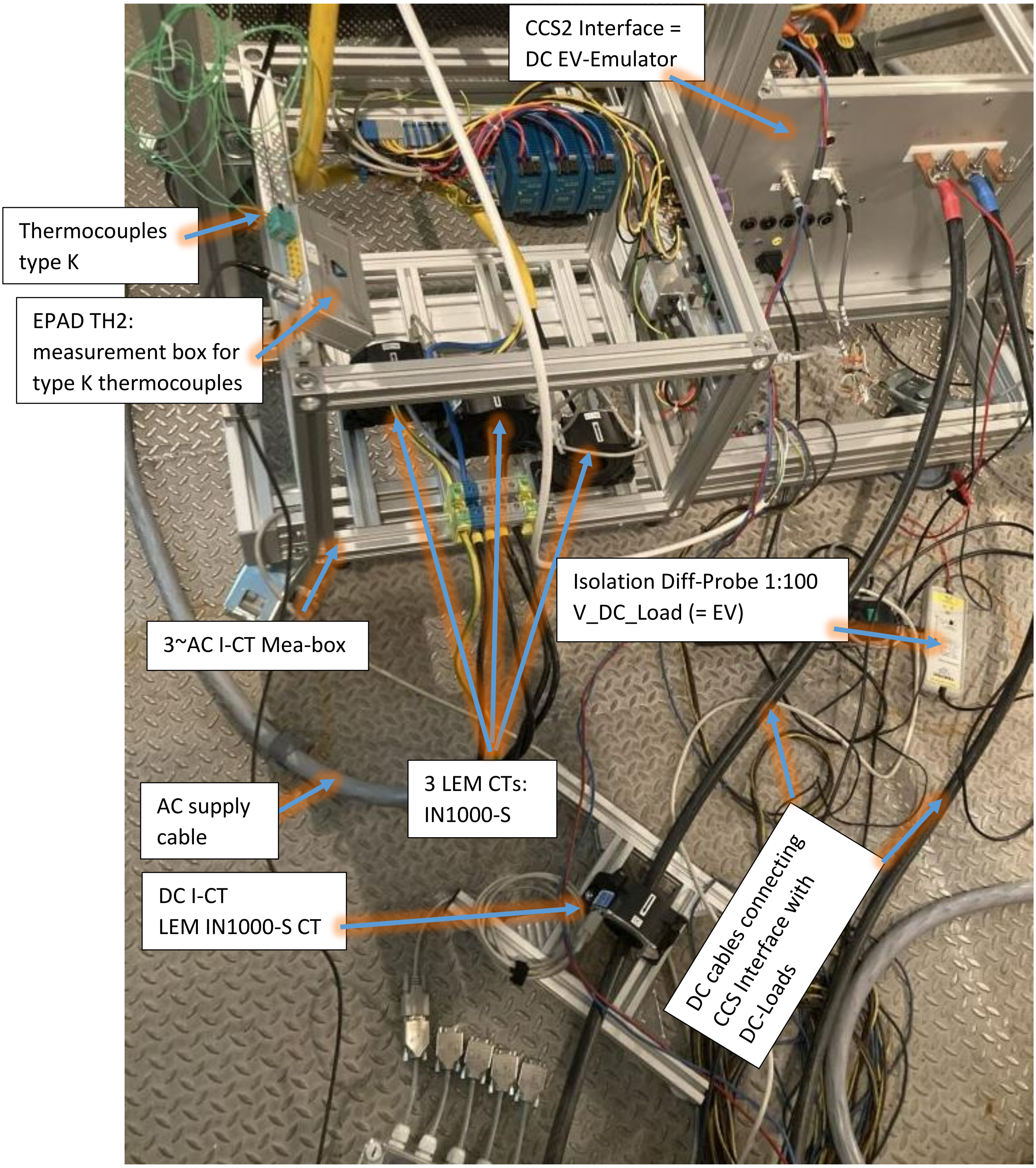


Fig. 38. Rear View: Full setup of all measuring devices on power input as well on power output Power Density

The specific test setup is shown in Fig. 37 and Fig. 38. The test rig supports the Device under Test and the other testing accessories. The different sensors and cables can also be seen in the images above.

3.2.1. Power Density from Datasheet Dimensions

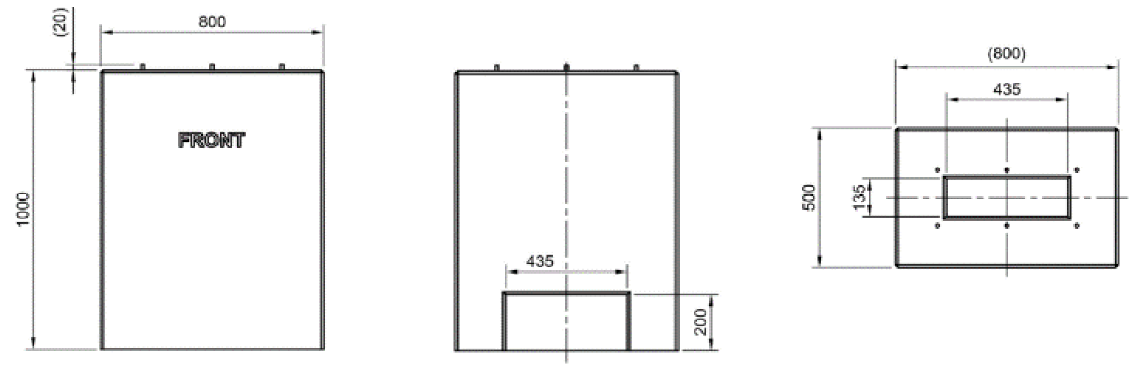


Fig. 39. Datasheet overview of Dimensions

The dimensions of the charger are obtained from the datasheet and presented in Fig. 39. After the dimensions are known, it is important to calculate the power density of the power electronics inside the charger.

To calculate the power density, initially, the dimensions from the datasheet are chosen as an example to explain the theory of the power density calculations. Therefore, from Fig. 39, it follows:

$l = 500\text{mm}$ $w = 800\text{mm}$ $h = 1000\text{mm}$

$$v = l.w.h \tag{1}$$

And thus, gives with a power rating of 40 kW a power density of:

$$v = 500 * 800 * 1000$$

So, with a power rating of 40 kW, the power density is calculated as:

$$Power\ Density = 40 * \frac{1000}{50*80*100} \tag{2}$$

Therefore, the calculated power density of the combined product is $0.1\ \text{kW}L^{-1}$.

The above calculations denote the power density of the entire charger and may seem to be quite low for such applications. However, the volume of the power electronic circuit within the charger is to be looked upon, such that the power density of the power electronic circuit can be calculated.

3.2.2. Power Density for Power Electronics of the Charger

This section calculates the actual measured values for the power electronics of the DC Charger.

From the measurements it therefore follows:

$l = 142\ \text{mm}$ $w = 800\ \text{mm}$ $h = 1000\ \text{mm}$

$$v = l \cdot w \cdot h \tag{3}$$

$$v = 142\ \text{mm} \cdot 800\ \text{mm} \cdot 1000\ \text{mm} = 113.1706\ \text{dm}^3 \tag{4}$$

And thus, gives with a power rating of 40 kW a power density of:

$$^{40\ \text{kW}}\!/_{113.6\ \text{dm}^3} = 0.352\ \text{kW L}^{-1} \tag{5}$$

Hence, the power rating of the 40 kW charger (of the power electronic circuit) is $0.352\ \text{kW L}^{-1}$

3.3. Discussion on potentially implemented topologies

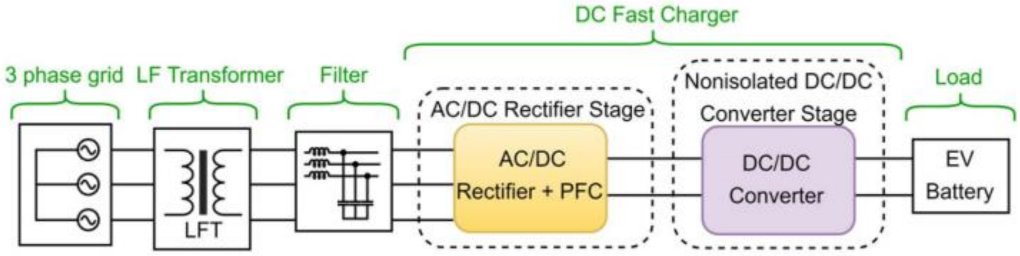
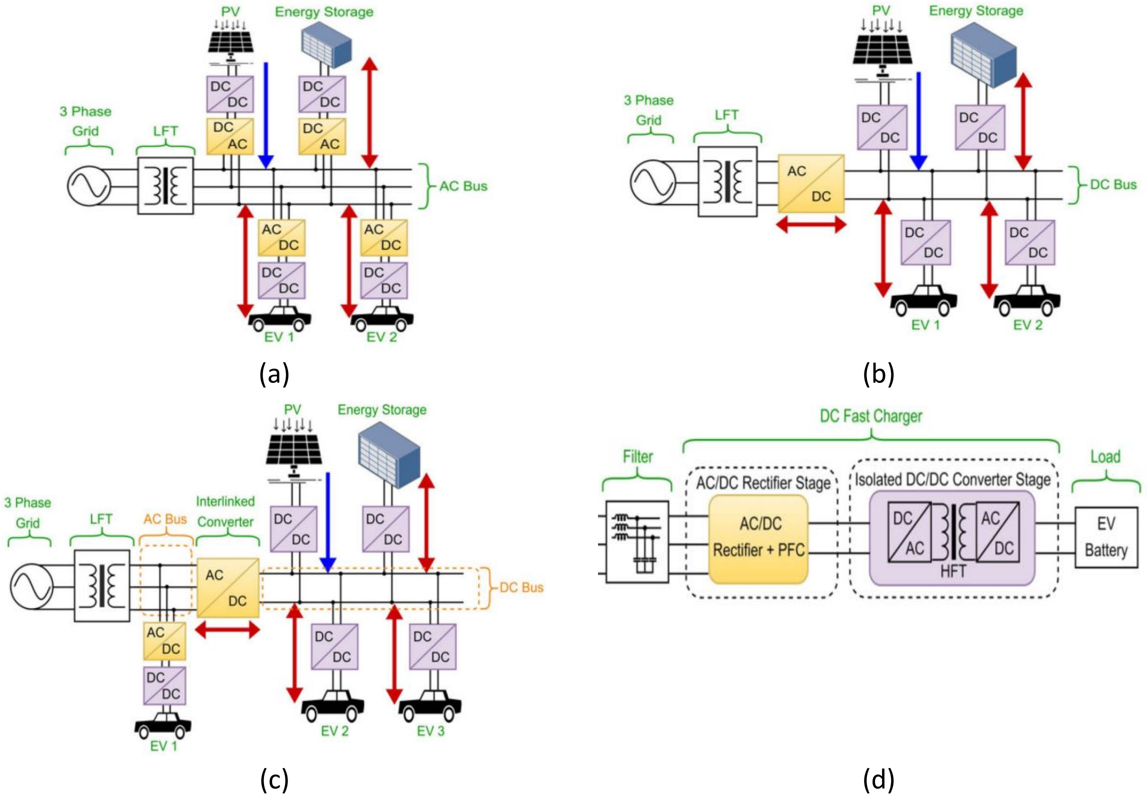


Fig. 40. Non-Isolated DC-DC converter with Low Frequency Transformer [21]

Fig. 40 [21] depicts the block diagram of the non-isolated chargers with low frequency transformer (LFT). Especially, first generation fast chargers, where utilizing LFT technology to provide galvanic isolation.

In recent years, DC chargers transformed towards medium frequency isolation, which benefit from a lower transformer volume and weight. Also, battery voltages for EVs evolved from 400 V, to recently, commercially available 800 – 920 V.

For fast-charging applications, different configurations can be used [21]. Fig. 41 describes the (a) AC bus (b), DC bus (c) Combination of AC and DC bus and (d) high frequency transformer configurations for DC chargers.



(a) (b)

(c) (d)

Fig. 41. Different Configurations for Fast Chargers [21]. (a) AC bus, (b) DC bus, (c) Combination of AC and DC bus, and (d) HFT configuration

In Figure (a) above, the AC power is distributed through the bus. Individual sources and charger terminals have their own AC-to-DC converters and subsequent DC-to-DC converters. The above figure (b) demonstrates a single AC to DC converter, and a subsequent DC bus. Therefore, the individual sources and loads have their own DC to DC converters. This scheme saves the cost of multiple AC to DC converters but needs more complicated protection devices for DC network systems. The configuration in (c) above shows a hybrid structure of both AC and DC buses, where the Renewable Energy Sources (RES) are connected to the DC bus and there is an interlinked AC to DC converter which is bidirectional. The bidirectional DC/DC converters between EVs and the DC bus are responsible for DC fast charging/discharging with the help of a V2G, S2G or V2V operation. This configuration uses the advantages of the simplicity of the AC bus structure and the cost effectiveness of the DC bus architecture. For all of the three configurations (a), (b), and (c), the transformers used are line frequency transformers.

Out of the configurations shown in Fig. 41, the high frequency transformer configurations shown in (c) have become the most popular solution recently, owing to the compact transformer size. The are two stages of conversion for this charger configuration:

1) Different options for the AC/DC rectifier stage (not limited to these solutions):
   a) 6 pulse diode bridge rectifier (unidirectional)
   b) Vienna Rectifier (unidirectional)
   c) Six-switch rectifier (bi-directional)
   d) Multi-Level rectifier such as Neutral point Clamped Rectifier (bi-directional)

Out of the above, the diode bridge and the Vienna rectifier are suitable for unidirectional Grid-to-vehicle power flow, while the six-switch rectifier and the Neutral point Clamped topologies are suitable for the bidirectional power flow. The efficiency of the Vienna, PWM and NPC topologies, which supply 22 kW output power for high power on-board chargers, can be tuned to achieve approximately 98 - 99 % efficiency, for parameters as for example 20 kHz switching frequency, 400 V AC input voltage, and 800 V DC output voltage.

2) DC/DC power Stage: The major converter topologies that are most suitable for the DC/DC power stage for isolated converters are:
   a) LLC converter.
   b) Dual Active Bridge Converter (DAB).
   c) Phase Shifted Full Bridge Converter (PSFB).

All the three converters mentioned above provide galvanic isolation. Soft switching methods like Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) are the most important advantages of the LLC topology. However, the wide range of operating modes with nonlinear loads (battery characteristics of EV charger is nonlinear) and nonlinear resonant components result in a very complex analysis of the LLC converters. For example, it can become difficult to ensure ZVS condition for the LLC converter at light load conditions.

For the Dual active Bridge Converter, the transformer leakage inductance serves as the main power transfer element. The advantages of the DAB are high efficiency, high power density, bidirectional operation, symmetric structure, low device stress, and soft switching possibilities. When the DAB is operated using high frequency switching, the parasitic leakages and stray inductances affect the converter operation and leads to worsened reactive power and reduced efficiencies. Fig. 42 shows the DAB topology.

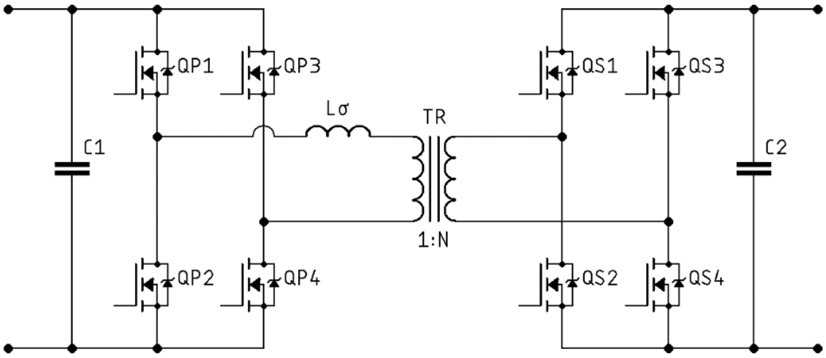


Fig. 42. Dual Active Bridge Topology

The PSFB topology is quite similar to the LLC topology, with the only absence of passive and resonant components. PSFB advantages include soft switching, simple phase shift PWM control, low EMI and decreased current stress on devices. However, the secondary side has diodes which result in hard switching. Additionally, there are high voltage stresses on the rectifying bridge and high circulating current on the primary side during freewheeling.

3.4. Efficiency Overview and Characteristic DC-Wallbox Curve Field

In this section, the efficiency of the charger 1, as measured, will be discussed. In order to illustrate the electrical efficiency for different operating points, a graphical illustration is introduced that should highlight electrical efficiencies for different voltage and current levels simultaneously (Fig. 43). The dashed lines show a specific power level (e.g., 5 kW, 10 kW, 15 kW, etc.) which is constant along that line (even though voltage and current levels are changing). The black line illustrated the theoretical maximum limits of the charger based on defined output limits such as maximum voltage, maximum current, and maximum power level. The red line identifies the maximum operating area based on the actual obtained response of the charger during operation.

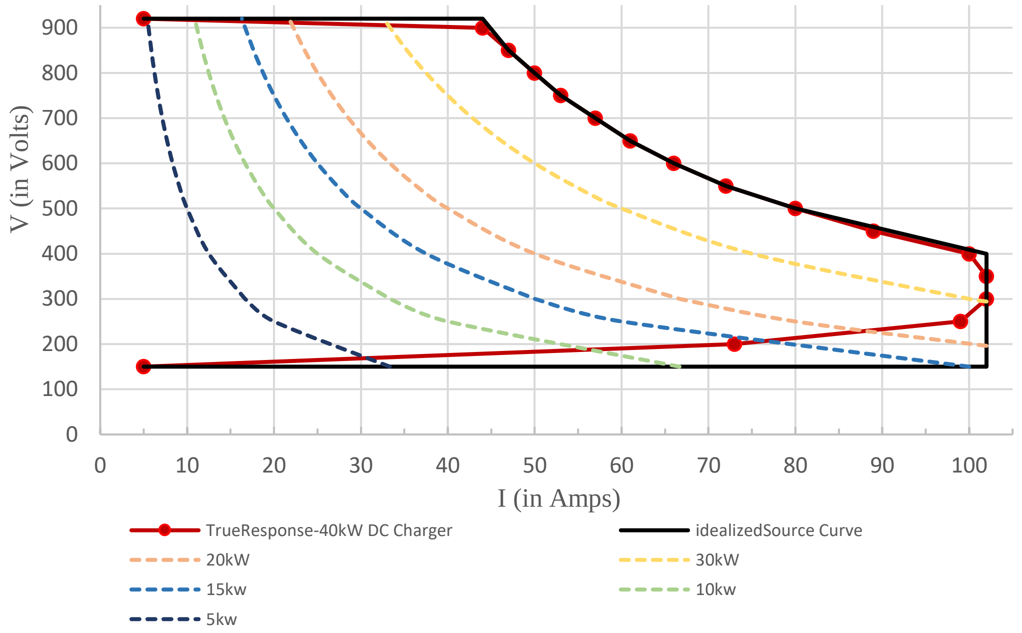


Fig. 43. Comparison of calculated 40 kW and System response OAR

The illustration above (Fig. 43) shows the source characteristic curve of the measured Wallbox. The black frame represents the ideal calculated values of the EVSE as a source. The actual operating points reported back via the Wallbox communication are shown in dark red. For simplification, parabolic curve sections are shown from left to right, indicating power steps in 5, 10, 15, 20 and 30 kW. The horizontal axis represents the output current in Amperes and the Vertical axis represents the output voltage in Volts.

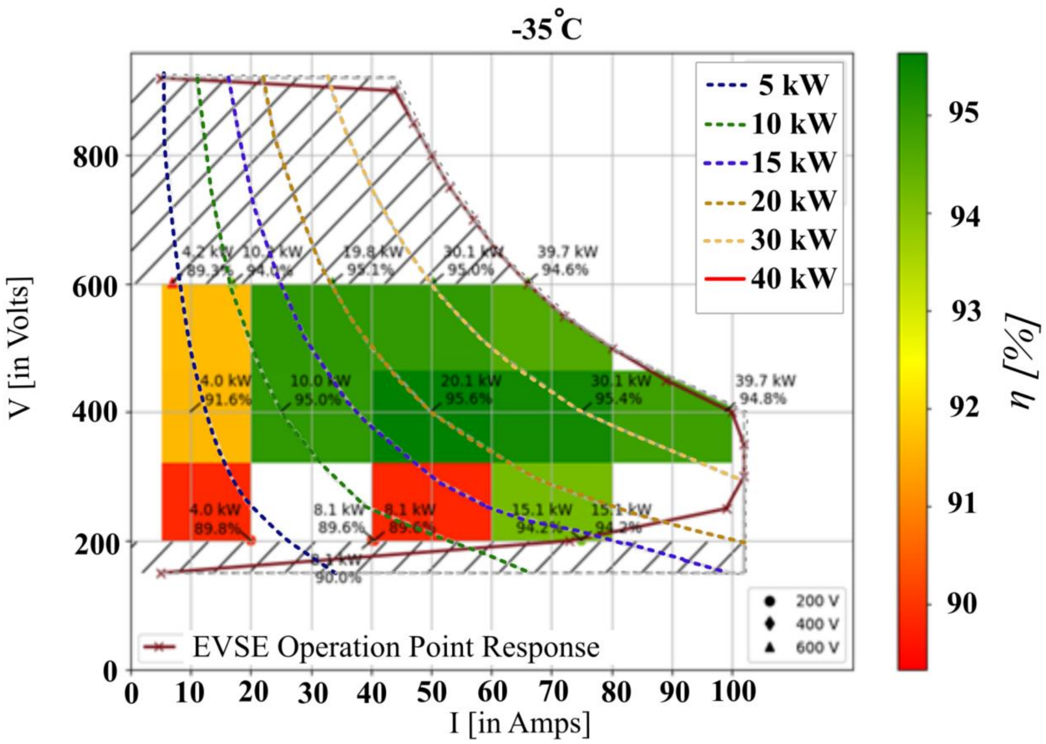


Fig. 44. Efficiency of different operating points with output voltages up to 600V @-35°C

Fig. 44 shows the highest efficiencies for the series of measurements at -35°C in the range of 20 kW to 30 kW and achieve efficiencies of 95.4 to 95.6% at the operating point of 400 V.

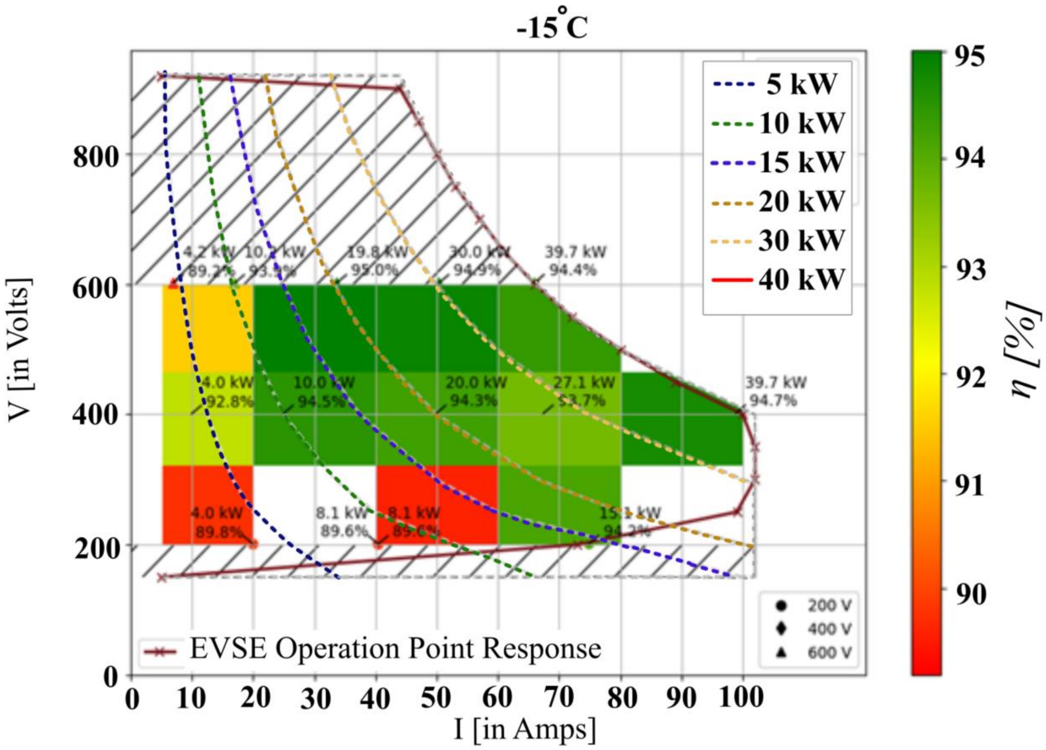


Fig. 45. Efficiency of different operating points with output voltages up to 600V @-15°C

For the series of measurements at -15°C, the Fig. 45 shows the highest efficiencies in the range of 10 kW-20 kW and achieves efficiencies of between 94.5 to 95.0% at operation points of 10 kW@400 V and 20 kW@600 V.

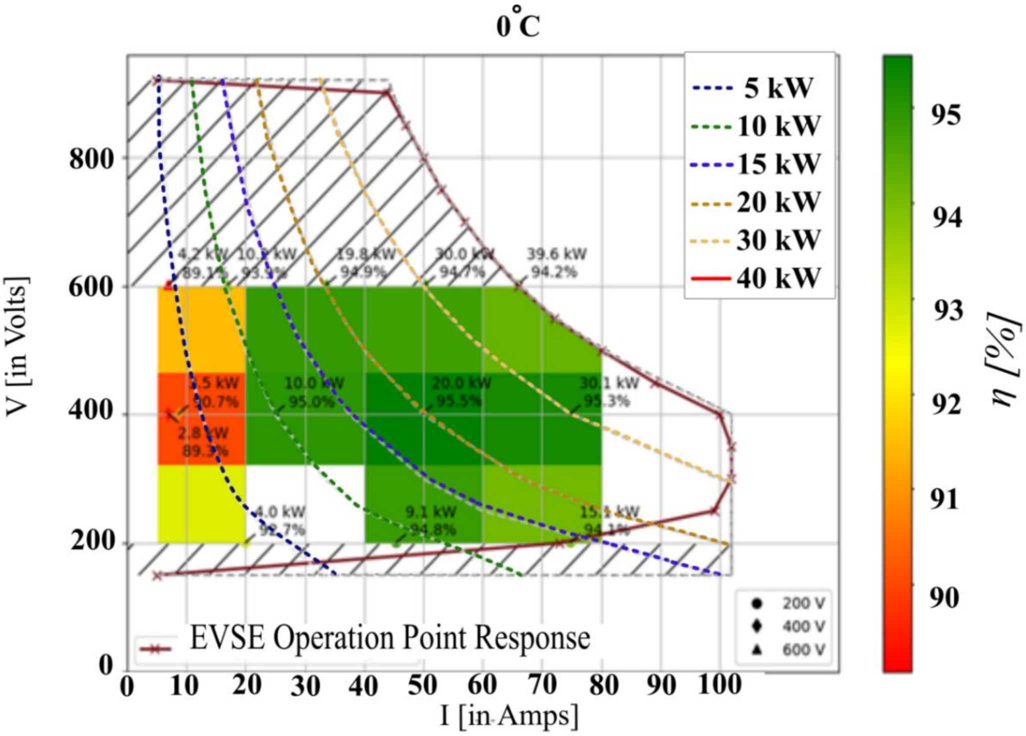


Fig. 46. Efficiency of different operating points with output voltages up to 600 V @ 0 °C

The diagram in Fig. 46 shows the highest efficiencies for the series of measurements at 0°C in the range of 20 kW-30 kW and achieves efficiencies of between 95.3 and 95.5% at the operating point of 20 kW and 30 kW@400 V.

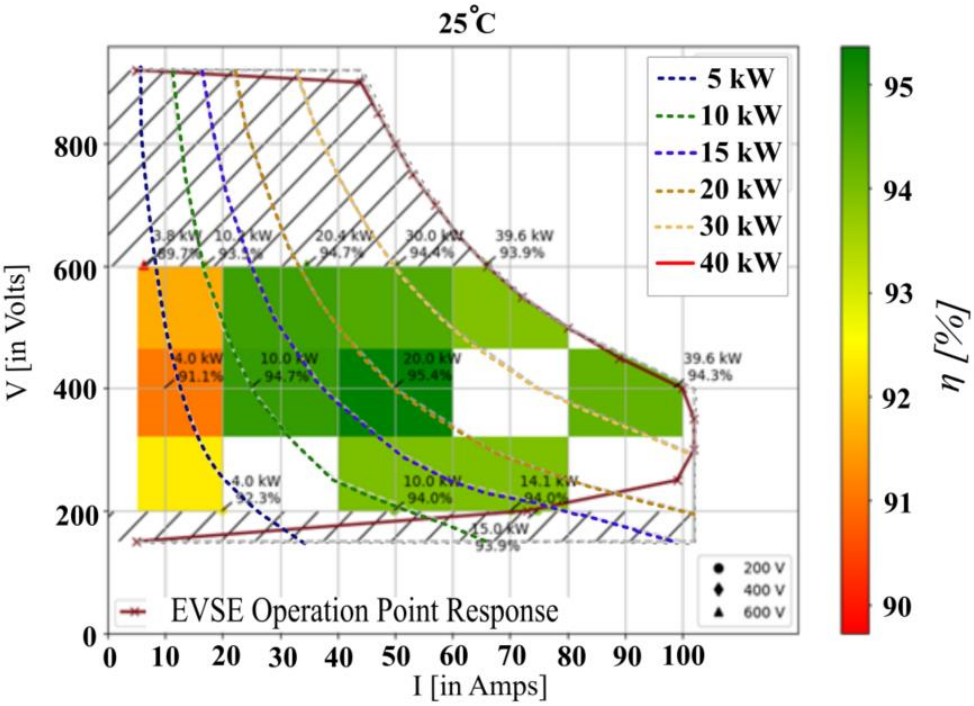


Fig. 47. Efficiency of different operating points with output voltages up to 600V @25°C

Fig. 47 the highest efficiencies for the series of measurements at 25°C in the range of 10 kW-20 kW and achieves efficiencies between 94.7 and 95.4% at the operating point of 10 kW and 20 kW@400 V.

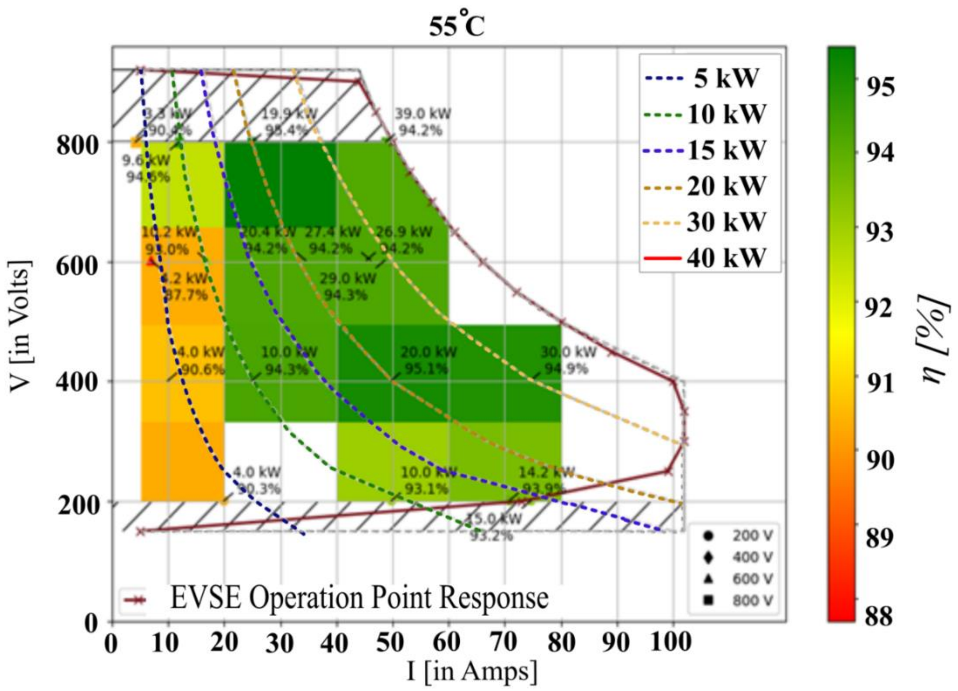


Fig. 48. Efficiency of different operating points with output voltages up to 800V @55°C

The diagram in Fig. 48 shows the highest efficiencies for the series of measurements at 55°C in the range of 20 kW-30 kW and achieves efficiencies of between 95.1 and 95.4% at the operating point of 20 kW@800 V and 20 kW@400 V and 94.9% at the operating point of 30 kW@400 V.

For the present study, with an aim to look closely into the efficiencies of the DC chargers, we came across a popular commercially available DC charger, which claims an estimated efficiency of 97%. However, from our communication with the manufacturer, we understand that the figure of 97% refers to the efficiency of the rectification stage only. Some other commercially available DC fast chargers rated at 100 kW, 690 V AC-DC Cabinet claim energy efficiencies of more than 98%. Upon contacting the manufacturer in this case, we were informed that the figure mentioned was referring to the rectifier stages “only” and that the DC/DC, if any, was not considered.

Therefore, during this study, it was not possible to access any clear information about the efficiency of the DC/DC conversion stage of the commercial charger. This remains a hurdle in the investigation into the efficiencies of commercially available DC fast chargers.

3.5. Switching Frequency

The switching frequency of the DC charger could not be determined since no communication was available from the manufacturer on the switching frequency used for the charger. Due to the complex setup, it was also not possible to extract it during operation.

4. Conclusions and Outlook

The report provides a detailed overview of the electric charger market and the efficiencies of commercial products, with a focus on DC chargers. The DC chargers are expected to increase in demand in the future and therefore, they have been studied in more detail in this report. It includes take-aways from the recent European Commission report on the charger market and a study recently published by the government of New Zealand and provides an overview of the roadmap ahead. Analysis and data of the DC charger market is presented, and a view of the future is also drawn from statistical data. Driving forces that help the DC charger market to grow exponentially have also been studied. It has been observed that the DC chargers are commercially available for a higher range of power from 20 kW to 350 kW and more. The major reason for high power for DC chargers arises from the fact that DC chargers primarily aimed for fast charging. Fast charging of batteries mandates higher current values, which in turn result in high power output. Experiments on commercially available chargers (DC charger) revealed maximum efficiency figures of around 95 %. This is still low when compared to AC chargers and increased efforts must be extended to increase the efficiency of DC chargers. However, the overall Grid to Battery charging efficiencies revealed that the DC chargers emerged at least as efficient as AC chargers (considering all conversion stages). It is predicted that the demand for high-power DC chargers (fast chargers with more than 350 kW output power) will rise steadily in the near future. Future DC chargers must target fast charging and higher efficiencies as their primary goal. The secondary features of grid stability, renewable integration and Vehicle to Grid technologies shall also remain as focus areas. In addition, it should be noted that as of now the market for low power DC-charges < 11 kW is in a very early phase. At present, there are only a few companies at present committing to and working on solutions for these lower power levels for DC-Wallboxes. Thus, at the time of the publication of this report, it is still unclear which power levels will be relevant in the future for this specific type of market (3 kW, 5 kW, 7.5 kW, 10 kW etc.). However, voices from industry (questionaires) see low power DC-chargers as interesting alternative to high-power on-board chargers. In addition, it should be noted that it was identified that relatively significant stand-by losses can occur during EV-Wallbox idle mode operation.

Possible proposed PECTA follow-up activities, based on results of the pre-scoping DC-Wallbox study:

- **Market analysis and monitoring:**
    - Conduct regular reviews of the energy efficiency of low-power DC-Wallboxes in the market to identify change of trends or technological breakthroughs.
    - Whenever it becomes obvious that the market is moving into a specific direction: Endorsing measurements and investigation of commercially DC-Wallboxes to better understand the semiconductor utilization and relevant dedicated parameters such as energy efficiency under charging conditions (different power and voltage levels).
    - Deeper analysis of AC vs DC chargers in terms of cost, efficiency, circular economy, life cycle analysis etc.
    - Investigation of EV-Wallbox stand-by losses.
- **Regulatory Framework:**
    - Support the development of more complete guidelines DC-charger datasheets dedicated to energy efficiency.
    - Supporting policy formulations for incentivizing DC-Wallbox with highest efficiency levels.
    - Focus on emerging trends, technological breakthroughs, and shifts in consumer demand. Adjust policies to support the most efficient technologies.

The study reveals that the DC charger market is getting ready to witness major changes in terms of technology innovation, charging power demand, fast charging time reduction, and market growth. As the market is expected to more than double in the coming 5 years, it is clear that the DC chargers will see major modifications and advancements to cope with the rapidly increasing number of EVs in the world markets. Therefore, it may be too early to act in this regard such that the policy formulations or the development of standards can accommodate the major changes that will be witnessed in the near future. Prudent measures by energy authorities may be to closely monitor the major trends and break-throughs in the DC charger market and act when greater market penetration of DC chargers also in the lower power area has been observed.

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