Power Electronic Conversion
Technology Annex PECTA

European Conference on Power Electronics and Applications
Aalborg DENMARK
EPE'23
September 4th > 8th, 2023
ECCE EUROPE
www.epe2023.com

Energy saving potential of WBG-commercial power converters in different applications

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Acknowledgments

We acknowledge the financial support and the provision of information and contacts by PECTA, as well as the support provided by the Energy and Environmental Engineering program of the FHNW through student projects.

Keywords

«Silicon Carbide (SiC)», «Gallium Nitride (GaN)», «Power losses», «Efficiency», «Device application»

Abstract

This work estimates the yearly global energy savings potential of different power electronics applications featuring commercial wide bandgap (WBG)-based power converters. It is the first study analyzing real products in the market. We show that WBG-based products exhibit considerable energy-saving potential in all investigated applications. Further, because of the large annual increase of installed photovoltaic (PV) and electric vehicle (EV)-charger converters, we estimate future energy-saving potential.

Introduction

The implementation of WBG devices (Silicon carbide - SiC & Gallium nitride - GaN) has significant potential for efficiency improvement and footprint reduction of power converters [1,2]. Because of that, several manufacturers have increasingly developed power converters based on SiC and GaN technology. Applications such as PV inverters, motor drive inverters, uninterruptable power supplies (UPS), and laptop chargers are a few examples of available commercial WBG-based power converters.

Several studies [1,2] have reported the potential energy savings of WBG converters in specific applications. However, these investigations were based on power converters developed in academia rather than commercial products, often being incompatible with industry standards and commercial product requirements.

In this work, we estimate the yearly global energy saving potential in several applications considering the substitution of actual Silicon-based commercial power converters with their commercial WBG-based counterparts. It is the first study to assess the energy potential of commercial converters, yielding results compatible with state-of-the-art industrial technologies. We have searched manufacturers for each selected application in order to obtain the available products and associated technical information of the WBG-based systems. Our analysis provides the energy-saving potential of

WBG technologies with existing products that can serve to guide policymakers [3]. We have investigated six applications for SiC: data centers, PV inverters, drive inverters, HVAC (heating, ventilation, and air conditioning)-Appliances, EV off-board charging stations, and battery storage. In the case of GaN, laptop chargers were considered.

The results from this work were obtained as part of task A of the Power Electronic Conversion Technology Annex (PECTA) [3] aimed to collect and analyze information about WBG-based products and investigate their energy-saving potential in applications.

Methodology

A challenging part of this investigation was finding out which products feature WBG power semiconductors. We have contacted several commercial power electronics manufacturers, searched their websites and investigated press releases. Surprisingly, there was no mention of WBG in the product datasheet in several cases, but in the press release of the products with the partnership with WBG power semiconductor manufacturers. The list of the found manufacturers and their products for each application are shown in Table I. The goal was to gather as much technical information as possible about these products, particularly regarding converter efficiency.

In order to estimate the energy-saving potential, we have searched the annual energy consumption per application in the literature. With that, the yearly energy losses of each application featuring silicon (Si) and WBG-converters were calculated.

Our estimations have the following limitations:

1) Lack of information provided by the datasheets. In most cases, only the peak efficiency is provided by manufacturers, which can significantly reduce the potential advantages of WBG in applications where sub-load conditions prevail. In such cases, additional characterization and simulation work considering load profiles is required to improve accuracy.

Table I: WBG-based commercial products. The reported efficiencies can be peak (most cases), average or minimum efficiency values depending on the manufacturer. The PV inverters may have an integrated DC/DC converter.

Appl.	*Manuf.*	*Product*	*Pwr*	*η (%)*
Data center	Eaton	Eaton 93 PR UPS [4]	300 – 1200 kW	99
	Mitsubishi	Summit series [5]	500 kW	98.2
	Toshiba	G2020 series [6]	500, 750 kW	98.2
	TMEIC	Next GEN UPS [7]	n/a	98
PV inverter	GE	LV5+ [8]	2.7 – 3.5 MW	98.9
	SMA	Sunny High power peak 3 [9]	150 kW	99
	Sungrow	SG250HX [10]	250 kW	99
	Fronius	Symo GEN 24 Plus [11]	3 – 5 kW	98.2
	REFUsol	020K-SCI [12]	20 kW	98.7
	Kaco	Blue Planet 150 TL3 [13]	150 kW	99.2
Drives	Infinitum	Aircore EC: Int. drive [14]	3 – 12 kW	n/a
	Plettenberg	MST 400-160 SiC [15]	66 kW	n/a
	APD	Aergility ATLIS UAV [16]	n/a	98
EV charger	Ingeteam	Rapid ST400 [17]	Up to 400 kW	n/a
Battery storage	Kaco	Blueplanet 92.0-137 TL3-S [18]	92 – 137 kW	98.8
Laptop charger	Hama	Hama Universal USB-C [19]	65 W	86
	Hyper	HyperJuice GaN 66W [20]	66 W	n/a
	Lenovo	Lenovo 65W USB-C GaN [21]	65 W	n/a

2) Potential energy savings were estimated from the different applications' total energy consumption, which are already estimations.
3) In general, manufacturers do not provide information about the products' topologies. Therefore, we do not know if these converters feature full SiC MOSFET (Metal-oxide-semiconductor field-effect transistor) topologies or SiC diodes with Si IGBTs (Insulated-gate bipolar transistors) in the so-called hybrid topology. If the latter case is used, the efficiency improvement will likely be underestimated.
4) Converter efficiencies are very dependent on further specifications (power rate, frequency, etc), as well as operation ranges.

Within the aforementioned limitations, we have focused on gathering available information only from commercial products found on the internet, and as such, some parameters needed to be estimated.

Silicon Carbide Applications

Data centers

According to the International Energy Agency (IEA), the worldwide energy consumption from data centers in 2021 was between 220 - 320 TWh [22]. This estimation excludes the energy used for mining cryptocurrencies, which is about 100 - 140 TWh [22].

Two scenarios have been considered: the first one represents the global energy consumption of data centers alone, with a value of 320 TWh used in the calculations, and the second scenario includes the energy used to mine cryptocurrencies, with a value of 460 TWh considered in the estimation. The energy consumption of the information technology (IT) equipment in a data center (without auxiliary systems) was estimated with the help of Eq. 1, where the power usage effectiveness (PUE) represents the effective amount of energy used in the IT equipment.

$$PUE = \frac{Total\,facility\,energy}{IT\,equipment\,energy} \qquad (1)$$

An average of 1.59 PUE is assumed for data centers worldwide [23]. Employing Eq. 1, the IT equipment energy consumption is 201 TWh for the first scenario and 289 TWh for the second scenario.

The input energy in a data center passes through uninterruptible power supplies (UPS) and power distribution units (PDUs) to power the servers. Due to a dual power source strategy for increased redundancy and reliability, many IT systems operate in loads ranging from 20 – 40 % [24] of the PDU's nominal values. To estimate the data center efficiency for silicon-based converters, experts rely on the efficiency values of aboutabout 95.8 % to 96.1 % in the 20 - 40 % load range [24]. Therefore, we can assume that silicon-based UPSs operate with an average efficiency of 96 %. Furthermore, SiC-based UPSs have a stable efficiency of aboutabout 98.3 %, based on the calculated average efficiency of four commercial SiC UPSs [4-7] in the 20 – 40 % load range. Thus, a possible global energy-saving potential was estimated with SiC technology implementation of 4.6 TWh/year for the first scenario and 6.7 TWh/year for the second scenario, respectively.

PV Power Generation

As reported by the IEA, solar PV electricity generation will reach almost 1000 TWh in 2021 [25]. A typical SiC-based PV inverter may present a peak efficiency in the range of 98.2 up to 99.2 % (Table I). As such, we selected the commercial converter from Kaco [13], with a peak efficiency of 99.2 % for the calculations. An efficiency improvement of about 2 % using the SiC technology may be expected [26], resulting in a global potential energy saving of 20.7 TWh per year. In Europe, the PV electricity generation was about 215.9 TWh in 2022 [27], with Sweden presenting a solar energy generation value of 1.963 TWh [27] and Denmark with 2.181 TWh [27]. Considering a 2 % efficiency improvement using SiC technology, the European continent could save about 4.5 TWh, while Sweden and Denmark could save up to 40 and 44 GWh, respectively. For the year 2023, solar energy generation for the Netherlands, Germany, Switzerland and Austria is expected to be 16.3, 53.9, 2, and 2.52 TWh [27], respectively. With SiC technology implementation, an energy-saving potential would be 338, 1117, 41, and 52 GWh, respectively.

Motor drives

To calculate the energy-saving potential of motor drive inverters using SiC technology, we first estimated the total energy consumption of this application.

Electric motors account for 40 - 45 % of global electricity consumption [28]. These motors can be divided into three different categories according to their power rating: Small (10 – 750 W), Medium (0.75 – 375 kW) and Large motors (> 375 kW), which account for about 9 %, 68 % and 23 % of the energy used by electric motors, respectively [28]. According to [28], 30 % of all electric motors in Germany are sold with a variable frequency drive (VFD). Implementing VFDs can enable up to 40 % energy savings [29] of the motor consumed energy that, combined with SiC topologies, may reach a further 5% increase in efficiency depending on the used topology and application [29,30].

The global electricity use in 2021 was about 25000 TWh [31]. Electric motors account for about 45 % of global electricity utilization [28], corresponding to an estimated energy of 11250 TWh. Because 30 % of the motors are sold with VFDs, we roughly assume a direct correlation between the percentage of motors sold with VFDs and their energy consumption without a VFD implemented, leading to a value of 3375 TWh. If the VFD implementation reduces energy consumption by 40%, we end up with an energy consumption of 2025 TWh/year. Such a value is the energy consumption of all motors using Silicon VFD which are already in place. If we assume 93% efficiency of Si inverters, and 98% of SiC inverters (SiC has 5% higher efficiency than Si), we come to an energy saving potential of SiC vs. Si of 103 TWh/year. Such saved energy can be improved if the rate of adoption of VFDs increases. According to industry experts, roughly 50 % of industrial motors could benefit from VFD systems [32].

HVAC

HVAC applications also use VFDs to reduce power losses and are included in motor drive applications. The energy consumption for HVAC applications is estimated as 19 % for pumps, 19 % for fans and 32 % for compressors of the total global energy consumption by motors (11250 TWh). Such percentages correspond to the estimated share of the global motor electricity demand for HVAC applications [28]. We considered the same assumptions from the previous section with a direct correlation between the percentage of motors sold with VFDs (30 %) and their energy consumption without a VFD implemented.

The global saving energy potential of HVAC applications using the SiC technology in VFDs is 20 TWh for fans, 20 TWh for Pumps, and 33 TWh for Compressors.

E-Vehicle DC Fast Charging Stations (off-board)

An average electric car consumes approximately 0.2 kWh/km [33], and the average driving distance is 11,300 km/year for the European Union in 2019 [34], giving a total energy consumption of 2260 kWh per car annually. According to IEA [35], it is estimated that a total number of 16.5 million global EV cars are on the road in 2021. Considering 16.5 million vehicles, a global energy consumption of about 37.3 TWh is estimated. According to [36], SiC can achieve a peak efficiency of 97 %, depending on the used topology. The comparison was performed with the Terra charging station from ABB [37], which uses Si technology and presents an efficiency of about 95 %. The SiC efficiency improvement may lead to a potential energy saving of 0.81 TWh for EV chargers compared to Si chargers.

Battery storage

The estimated global energy storage capacity installed in 2021 is about 56 GWh [38]. Assuming a 50% depth of discharge for each day in a year, the energy savings for the charge and discharge cycles were estimated for Si and SiC-based commercial inverters. The assumed efficiencies are 97 % for Si [39] and 98.8 % [18] for SiC, yielding yearly energy savings of about 370 GWh/year.

Gallium Nitride Application

Laptop Chargers

The number of computers in use was over 1 billion by the end of 2008 and over 2 billion by 2015 [40]. According to the previous trend, we have assumed that the number of active PCs (personal computers) in 2021 is about 3 billion. It is worth noting that this estimation includes both laptops and desktop computers. Thus, it was assumed that 50 % of the total number of computers is composed of laptops, providing a value of 1.5 billion active laptops in 2021. Furthermore, it was considered a typical 65 W charger with a laptop battery that can run 1,000 charging cycles until the end of its life [41]. Finally, a typical 2-hour charging time required for a full charge (1 charge cycle) and a battery life expectancy of 4 years to complete the 1000 cycles is used, giving an average of 250 charging cycles per year.

The global installed power is calculated by multiplying the number of active laptops (1.5 billion) and the individual charger power (65 W), leading to 97.5 GW. Then, one unit's charging time per year can be estimated as the average of charging cycles per year (250) multiplied by the typical charging time (2h), leading to 500 h/year. Finally, with the datasheet average efficiencies of 81.4 % for the Si charger [42] and 86 % for the GaN charger [19], the input energy required from both technologies are estimated as shown in Eq. 2.

$$E_{in} = (Global\ installed\ power \times Charging\ time\ per\ year)/Efficiency \tag{2}$$

The estimated input energy required is 59.9 TWh/year and 56.7 TWh/year for the Si and GaN chargers, respectively. Subtracting the values, we can obtain the saved energy of 3.2 TWh/year by implementing GaN technology.

Discussion

Fig. 1 shows the global yearly energy savings potential estimated by fully replacing commercial Si-based converters with WBG ones for different applications. The motor drive application (HVAC included) displays the largest potential saved energy (103 TWh/year) because of the motors' high global electricity consumption. Applications such as Data centers, PV, EV Charger Stations and Laptop Chargers display smaller potential energy savings (< 20 TWh/year) due to their lower share in global energy consumption. Battery storage application is not shown in Fig. 1 due to its small energy saving potential (< 1 TWh).

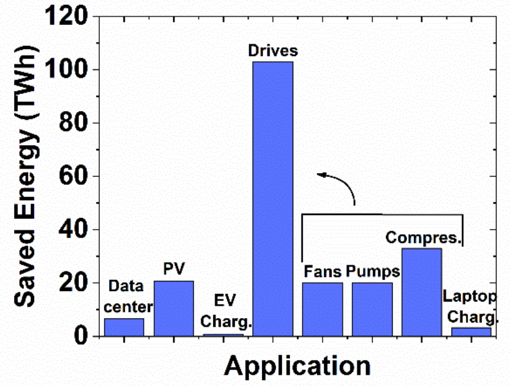

Fig. 1: Potential energy savings for different applications in the year 2021. As a comparison, a 1.2 GW nuclear power plant can produce about 10 TWh / year.

PV renewables and E-vehicle charge stations are expected to massively expand in the next decades, driven by aggressive market growth. Therefore, evaluating the energy-saving potential is essential when the technology is expected to be broadly adopted. We thus have performed estimates of the potential energy savings of such applications for the year 2050 based on the estimates of the annual consumption/generation in the same year. Photovoltaics is expected to generate electricity of about 13000 TWh/year in 2050 [43]. The global electrical vehicle fleet may achieve a value of 672 million vehicles in 2050 [44]. Considering the assumptions performed in previous sections (PV power generation and E-vehicle fast chargers), potential energy savings of 270 TWh/year and 33 TWh/year for the PV and EV charger applications have been calculated, respectively. Fig. 2 shows the saved energy for these applications in the year 2050, demonstrating the great potential of SiC implementation in such applications.

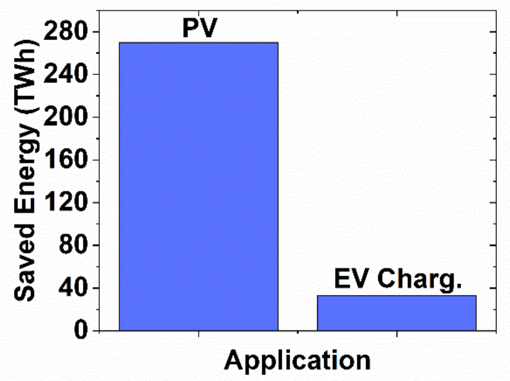

Fig. 2: Potential energy savings for PV and EV Chargers applications in the year 2050. The PV application increased from 20.7 TWh/year to 270 TWh/year and the EV charger application from 0.81 TWh/year to 33 TWh/year compared to 2021.

It is important to highlight that the estimates performed in this work are, in most cases, based on datasheet information. In general, using peak efficiencies provided by the selected products will underestimate potential savings in all applications where sub-load conditions are strongly featured, such as PV and VFD motors. This is because SiC MOSFETs exhibit lower conduction losses compared to Si IGBTs for sub-load conditions. Based on our simulations using professional PV design software, for example, we have verified that SiC PV inverters could exhibit up to 5% higher efficiency than their Si counterparts. In order to achieve better estimation accuracy, we need (at least) to have access to the efficiency curves of commercial converters and to further implement them into simulations considering representative load profiles. We expect that the results will nevertheless stimulate the industry to provide more data for the academy and customers, in order to improve potential savings estimations.

An important takeaway from this study is that more and more power electronics companies are starting to implement WBG devices into their next-generation power converter products, showing a positive trend towards energy efficiency improvement. Within this scope, SiC dominates the higher power segment of converters and is featured in many more products than GaN, possibly because of its longer market maturity.

Finally, beyond the energy-saving potential estimated here, it is essential to highlight that the electricity cost savings obtained by adopting WBG converter technologies will further impact societal economics.

Conclusion

This work reports on the energy saving potential of substituting commercial Si-based converters by commercial WBG-converters in different applications. We focus on commercial products in order to provide a more realistic global estimation of the energy saving potential. Drive applications presented a huge potential to implement SiC technology due to their large global energy consumption. Furthermore, our study highlights the future potential of PV inverters and EV chargers based on SiC switches, where their aggressive expansion places SiC as a key candidate for reducing power losses. Finally, the market research performed in this work shows the industrial trends with WBG technology, indicating the prospects for such technology. We expect to promote greater understanding and action amongst policymakers to identify the main applications where WBG devices may significantly impact the future energy landscape.

References

[1] X. Yuan, I. Laird, and S. Walder.: Opportunities, Challenges, and Potential Solutions in the Application of Fast-Switching SiC Power Devices and Converters, IEEE Trans. Power Electron., vol 36, no. 4, pp. 3925-3945, April 2021, doi: 10.1109/TPEL.2020.3024862

[2] G. Iannaccone, C. Sbrana, I. Morelli, and S. Strangio.: Power Electronics Based on Wide-Bandgap Semiconductors: Opportunities and Challenges, IEEE Access., vol 9, pp. 139446-139456, Oct 2021, doi: 10.1109/ACCESS.2021.3118897

[3] PECTA.: Power Electronic Conversion Technology Annex. Accessed 12 June 2023. Available: https://www.iea-4e.org/pecta/

[4] EATON.: Eaton 93PR UPS Range Brochure. Accessed 12 June 2023. Available: https://www.eaton.com/content/dam/eaton/products/backup-power-ups-surge-it-power-distribution/backup-power-ups/eaton-93pr/eaton-93pr-300-1200kw-ups-brochure-en-us-east-asia.pdf

[5] Mitsubishi.: Summit series datasheet. Accessed 12 June 2023. Available: https://www.mitsubishicritical.com/media/6317/sa-enl0048-summit-series-data-sheet.pdf

[6] Toshiba.: Uninterruptable Power Systems G2020 Series. Accessed 12 June 2023. Available: https://www.toshiba.com/tic/datafiles/brochures/G2020_Series_ESSENCE_101619_nocrop.pdf

[7] TMEIC.: TMUPS Next Generation UPS for Business Critical Loads. Accessed 12 June 2023. Available: https://5.imimg.com/data5/SELLER/Doc/2021/4/DQ/BE/TJ/60336995/tmups-w250-series-ups.pdf

[8] General Electric.: LV5+ Solar Inverter Datasheet. Accessed 12 June 2023. Available: https://www.ge.com/renewableenergy/sites/default/files/related_documents/lv5plus-solar-inverter-datasheet.pdf

[9] SMA.: SMA and Infineon reduce system costs for inverters. Accessed 12 June 2023. Available:

https://www.sma.de/en/newsroom/news-details/sma-and-infineon-reduce-system-costs-for-inverters

[10] Sungrow.: SG250HX Datasheet. Accessed 12 June 2023. Available: https://en.sungrowpower.com/upload/file/20210108/DS_20201121_SG250HX%20Datasheet_V1.5.4_EN.pdf.pdf

[11] Fronius. : Fronius Symo GEN24 Plus Datasheet.

[12] REFUsol.: *REFUsol 020K-SCI Datasheet*. Accessed 12 June 2023. Available: https://cdn.enfsolar.com/Product/pdf/Inverter/507280bfa89a8.pdf

[13] Kaco.: Blueplanet 150 TL3 Datasheet. Accessed 12 June 2023. Available: https://kaco-newenergy.com/index.php?eID=dumpFile&t=f&f=2768&token=bce54fc792e4f842a145ac1f0891d739d95f95e4

[14] Infinitum.: Infineon collaborates with Infinitum for the new Aircore electric motor with aircore. Accessed 12 June 2023. Available: https://goinfinitum.com/infineon-collaborates-with-infinitum-for-the-new-air-core-electric-motor-with-air-core/

[15] Plettenberg.: MST 400-160 (SiC). Accessed 12 June 2023. Available: https://plettenbergmotors.com/product/mst-400-160-sic-silicon-carbide/

[16] APD.: Aergility ATLIS UAV. Accessed 12 June 2023. Available: https://www.unmannedsystemstechnology.com/company/advanced-power-drives-apd/silicon-carbide-sic-inverters/

[17] Ingeteam.: Rapid ST 200/400. Accessed 12 June 2023. Available: https://www.ingeteam.com/en-us/sectors/electric-mobility/p15_58_686/ingerev-rapid-station.aspx

[18] Kaco.: Blueplanet Gridsave 92.0 – 137 TL3-S. Accessed 12 June 2023. Available: https://kaco-newenergy.com/products/blueplanet-gridsave-92-TL3-S/

[19] Hama.: Universal USB-C Notebook Power Supply – GaN. Accessed 14 June 2023. Available: https://ch.hama.com/webresources/article-documents/00200/man/00200016man_bg_cs_de_el_en_es_fi_fr_hu_it_nl_pl_pt_ro_ru_sk_sv_tr.pdf

[20] Hyper.: HyperJuice GaN 66W USB-C Charger. Accessed 14 June 2023. Available: https://www.hypershop.sg/products/hyperjuice-gan-66w-usb-c-charger

[21] Lenovo.: Lenovo 65W USB-C GaN Adapter. Accessed 14 June 2023. Available: https://www.lenovo.com/us/en/p/accessories-and-software/chargers-and-batteries/chargers/40awgc65ww

[22] IEA.: Data Centres and Data Transmission Networks. Accessed 12 June 2023. Available: https://www.iea.org/reports/data-centres-and-data-transmission-networks

[23] Statista,.: Data Center average annual power usage effectiveness (PUE) worldwide 2007-2022. Accessed 12 June 2023. Available: https://www.statista.com/statistics/1229367/data-center-average-annual-pue-worldwide/

[24] ABB,.: How data centers can minimize their energy use. Accessed 12 June 2023. Available:

https://library.e.abb.com/public/ffa3a0ef7d7245b79807eeae2eaf7879/How%20data%20centers%20can%20minimize%20their%20energy%20use.pdf?x-sign=a+ZdVrPy6ESg6HKPF+tn0b08WMF+qeUck79UGJRQh1vGGTEnJ30jMRDw1lk4bmV0

[25] IEA.: Global Energy Review 2021 - Renewables. Accessed 12 June 2023. Available: https://www.iea.org/reports/global-energy-review-2021/renewables

[26] T. Eskilson, A. Jehle, P. Schmidt, M. Makoschitz, and F. Baumgartner.: Identifying the potential of SiC technology for PV inverters, EPE 2023

[27] Statista.: Solar Energy - Worldwide. Accessed 12 June 2023. Available: https://www.statista.com/outlook/io/energy/renewable-energy/solar-energy/worldwide?currency=usd

[28] P. Waide, and C. U. Brunner.: Energy -Efficiency Policy Opportunities for Electric Motor-Driven Systems - IEA, 2011. Available: https://iea.blob.core.windows.net/assets/d69b2a76-feb9-4a74-a921-2490a8fefcdf/EE_for_ElectricSystems.pdf

[29] P. K. Steimer.: Energy savings by means of Medium voltage power electronics - presentation.

[30] Personal communication with P. K. Steimer - ABB

[31] World Energy & Climate Statistics – Yearbook 2022.: Accessed 12 June 2023. Available: https://yearbook.enerdata.net/electricity/electricity-domestic-consumption-data.html

[32] ABB Whitepaper.: Achieving the Paris Agreement. The vital role of high-efficiency motors and drives in reducing energy consumption. Accessed 12 June 2023. Available: https://www.energyefficiencymovement.com/wp-content/uploads/2021/03/ABB_MotionEnergyEfficiency_WhitePaper.pdf

[33] Virta Global.: EV Charging – How much electricity does an electric car use ?. Accessed 12 June 2023. Available: https://www.virta.global/blog/ev-charging-101-how-much-electricity-does-an-electric-car-use

[34] Odyssee-Mure.: Sectoral Profile – Transport. Accessed 12 June 2023. Available:

https://www.odyssee-mure.eu/publications/efficiency-by-sector/transport/distance-travelled-by-car.html

[35] IEA.: Electric Vehicles. Accessed 5 July 2023. Available: https://www.iea.org/reports/electric-vehicles

[36] Wolfspeed.: Fast charging. Accessed 12 June 2023. Available: https://www.wolfspeed.com/applications/power/automotive/fast-charging/#:~:text=Wolfspeed%20Silicon%20Carbide%20power%20modules,frequency%20(45%2D250kHz).

[37] ABB.: Terra 360 charger. Accessed 12 June 2023. Available: https://search.abb.com/library/Download.aspx?DocumentID=9AKK107992A8963&LanguageCode=en&DocumentPartId=&Action=Launch

[38] BloombergNEF.: Global Energy Storage Market to Grow 15-Fold by 2030. Accessed 14 June 2023. Available: https://about.bnef.com/blog/global-energy-storage-market-to-grow-15-fold-by-2030/

[39] SMA.: Sunny Boy Storage. Accessed 12 June 2023. Available: https://www.sma.de/en/products/battery-inverters/sunny-boy-storage-25

[40] Worldometer.: Computers sold this year. Accessed 12 June 2023. Available: https://www.worldometers.info/computers/

[41] Jennifer Allen.: How Long Does a Laptop Battery Last ?. Accessed 14 June 2023. Available: https://www.lifewire.com/how-long-does-a-laptop-battery-last-5186206

[42] Hama.: Universal USB-C Notebook Power Supply. Accessed 14 June 2023. Available: https://ch.hama.com/webresources/article-documents/00200/man/00200006man_bg_cs_de_el_en_es_fi_fr_hu_it_nl_pl_pt_ro_ru_sk_sv_tr.pdf

[43] Irena insights.: Wind and Solar PV – what we need by 2050. Accessed 14 June 2023. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Webinars/07012020_INSIGHTS_webinar_Wind-and-Solar.pdf?la=en&hash=BC60764A90CC2C4D80B374C1D169A47FB59C3F9D

[44] J. Wiklund.: Electric Vehicles Expected to Comprise 31% of the Global Fleet by 2050. Accessed 14 June 2023. Available: https://www.globalfleetmanagement.com/10159371/electric-vehicles-expected-to-comprise-31-of-the-global-fleet-by-2050