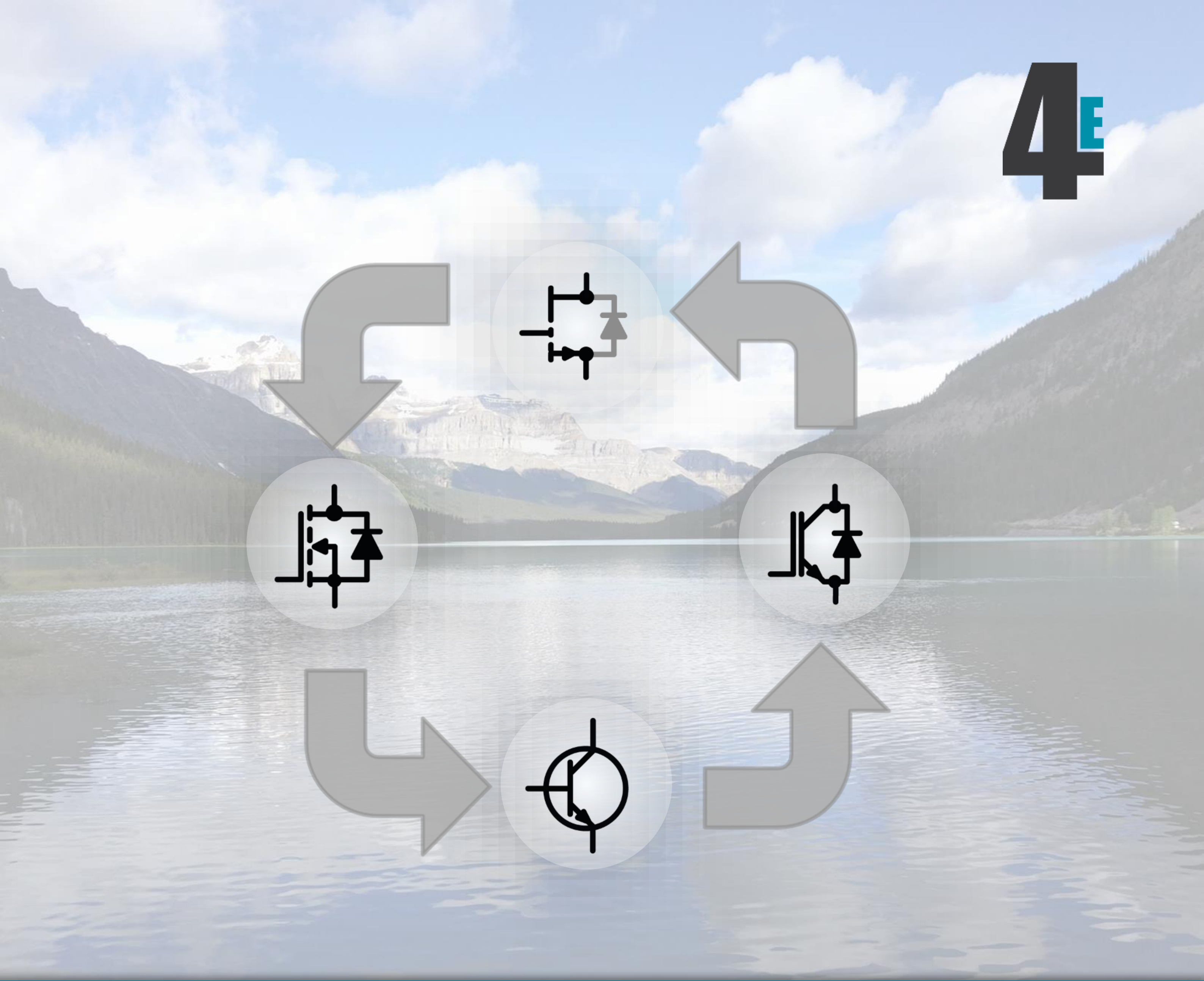

Energy saving potential of WBG-commercial power converters in different applications

4E Power Electronic Conversion Technology Annex (PECTA)

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Abstract:

This report explores the potential of wide bandgap (WBG) power semiconductor devices, such as SiC or GaN, in enhancing energy efficiency compared to traditional silicon-based systems. Estimating global energy savings, the research focuses on applications like data centers, photovoltaic inverters, low-voltage motor drives, electric vehicle charging stations, inverters for battery storage, and laptop chargers. Findings indicate substantial annual energy savings exceeding 120 TWh, equivalent to twice Switzerland's electric energy demand. The study acknowledges its conservative nature, not accounting for all WBG applications or potential future growth in sectors like photovoltaics. Despite uncertainties, the results underscore WBG power electronics' significant role in achieving global energy efficiency

About the IEA 4E Power Electronic Conversion Technology Annex (PECTA):

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

Further information on PECTA is available at:
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 TCP 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 a 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 Annex (EMSA)
- Solid State Lighting (SSL) Annex
- Electronic Devices and Networks Annex (EDNA)
- Power Electronic Conversion Technology Annex (PECTA)

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

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Executive Summary

Wide bandgap (WBG) power semiconductor devices (e.g. made of SiC or GaN) offer the potential of higher energetic efficiencies of power-electronic systems when compared to classic silicon-based power electronics. Nowadays, WBG devices are already used in numerous products, and more products are continuously brought to the market. This results in a general improvement in energy efficiency in the applications concerned and opens up the potential for considerable energy savings if these applications are equipped with WBG devices on a broad scale.

With this background, this study estimates the annual global energy saving potentials for selected power-electronics applications assuming that they would be entirely replaced by more efficient WBG – based systems.

To come to the results, the actual yearly global energy consumption was estimated for each considered application in the first step. Depending on the available data, different estimation approaches had to be employed. Secondly, the energetic efficiencies of silicon-based and WBG-based systems in the respective application fields have been researched in product datasheets and in the scientific literature. The global yearly energy saving potential of WBG power electronics has then been calculated based on the efficiency differences between silicon and WBG products, the global annual energy consumption per application, and (where possible) by considering typical application profiles.

It has been found that WBG power electronics enables a significant global energy saving potential. The annual global energy savings potentials for the considered applications are respectively:

- Data center / server power supplies (SiC): 4.6 to 6.7 TWh/year
- Photovoltaic inverters (SiC): 20.7 TWh/year
- Low-voltage motor drives (SiC): 103 TWh/year
  This value includes HVAC systems:
  fans: 20 TWh/y ; pumps: 20 TWh/y ; compressors: 33 TWh/y
- Electric vehicle charging stations (SiC): 0.8 TWh/year
- Inverters for grid-connected battery storage systems (SiC): 0.4 TWh/year
- Laptop chargers (GaN) (SiC): 3.2 TWh/year

When the individual saving potentials of the considered applications are summed up, this results in a total annual saving potential of:

> 120 TWh/year.

This value approximately corresponds to twice the annual electric energy demand of Switzerland, to illustrate the order of magnitude of the potential energy savings. The presented savings potential represents a lower limit for the following reasons:

- Not all possible applications of WBG power electronics were considered in this study; another possible application would be wind turbines, for example.
- For some applications, such as photovoltaics, strong future growth is expected. This study has worked with the currently installed unit numbers. Thus, the possible future energy saving potential for growing applications is expected to be higher.

It should also be noted that the figures given in this report are based on a wide variety of estimates and therefore contain certain uncertainties. The magnitudes of the values given are therefore intended as a guide.

In summary, it has been shown that due to the large number of units, WBG power electronics enable remarkable global energy savings potential when rolled out on a broad scale.

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1. Introduction

1.1. Overview and Objectives of PECTA

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.

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. 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 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.

2. Advantages of WBG in the Applications

2.1. 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 1. Figure 1 shows some of the products available with their power and estimated switching frequency range. 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.

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.

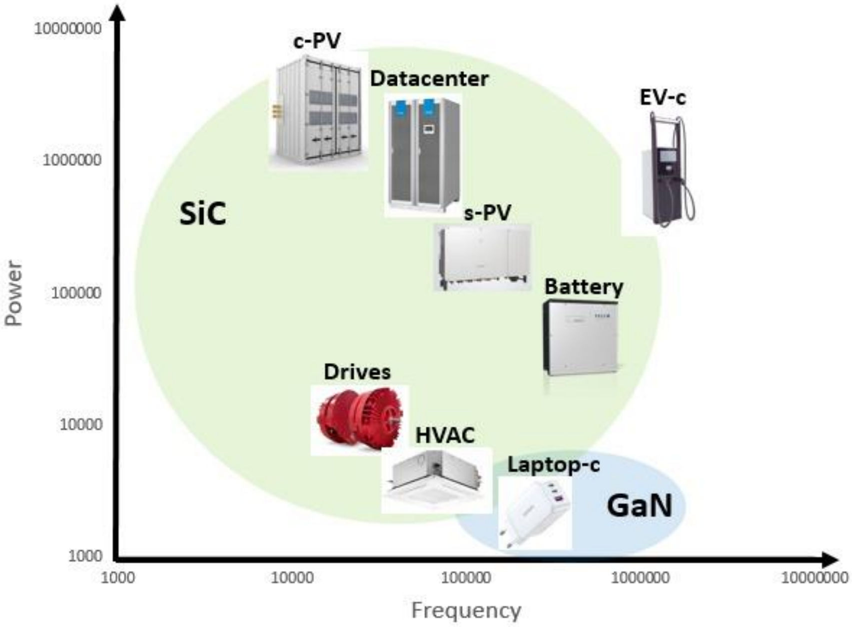

Figure 1: Power and switching frequency range from the available products. The frequency is estimated since this data is not available on datasheets.

Table 1: WBG-based commercial products..

Application	Manufufacturer	Product	Power	η (%)
Data center	Eaton	Eaton 93 PR UPS [4]	300 – 1200 kW	99.0
	Mitsubishi	Summit series [5]	500 kW	98.2
	Toshiba	G2020 series [6]	500, 750 kW	98.2
	TMEIC	Next GEN UPS [7]	n/a	98.0
PV inverter	GE	LV5+ [8]	2.7 – 3.5 MW	98.9
	SMA	Sunny High power peak 3 [9]	150 kW	99.0
	Sungrow	SG250HX [10]	250 kW	99.0
	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	98.0
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	86.0
	Hyper	HyperJuice GaN 66W [20]	66 W	n/a
	Lenovo	Lenovo 65W USB-C GaN [21]	65 W	n/a

2.2. Silicon Carbide Applications

2.2.1. 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 about 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 about 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.

2.2.2. PV Power Generation

As reported by the IEA, solar PV electricity generation has reached 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 extra energy generation 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 generate an extra ~4.5 TWh of energy, while Sweden and Denmark could achieve 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 extra energy-generation potential would be 338, 1117, 41, and 52 GWh, respectively.

Remarkably, detailed studies have been performed in Austria, in order to assess the potential of SiC technology for PV installations in the country. A detailed analysis can be found in Appendix A.

2.2.3. Motor drives

In order 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 [32]), 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 [33].

2.2.4. 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.

2.2.5. E-Vehicle Fast Charging Stations (off-board)

An electric electric car consumes in average approximately 0.2 kWh/km [34], and the average driving distance is 11,300 km/year for the European Union in 2019 [35], giving a total energy consumption of 2260 kWh per car annually. According to IEA [36], it is estimated that a total number of 16.5 million global EV cars are on the road in 2021. Considering 16.5 million e-vehicles, a global energy consumption of about 37.3 TWh is estimated. According to [37], SiC can achieve a peak efficiency of 97 %, depending on the used topology. The comparison was performed with the Terra charging station from ABB [38], 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.

2.2.6. Battery storage for residential

The estimated global energy storage capacity installed in residential segment in 2021 is about 56 GWh [39]. Assuming an average 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 [40] and 98.8 % [18] for SiC, yielding yearly energy savings of about 370 GWh/year.

2.3. Gallium Nitride Application

2.3.1. Laptop Chargers

The number of computers in use was over 1 billion by the end of 2008 and over 2 billion by 2015 [41]. 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 [42]. 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 [43] and 86 % for the GaN charger [19], the input energy required from both technologies are estimated as shown in Eq. 2.

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

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.

3. Discussion

Fig. 2 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. 2 due to its small energy saving potential (< 1 TWh).

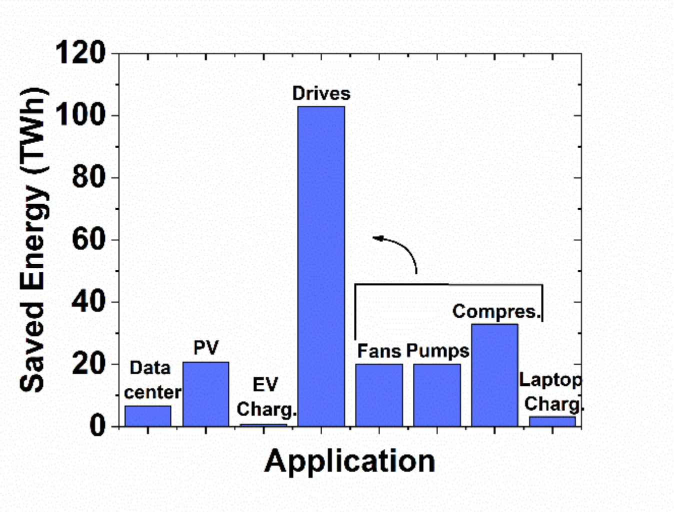

Fig. 2: Potential energy savings for different applications in the year 2021. As a comparison, a 1.2 GW nuclear power plant can produce about 10 TWh / year.

PV renewables and E-vehicle fast 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 [44]. The global electrical vehicle fleet may achieve a value of 672 million vehicles in 2050 [45]. 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. 3 shows the saved energy for these applications in the year 2050, demonstrating the great potential of SiC implementation in such applications.

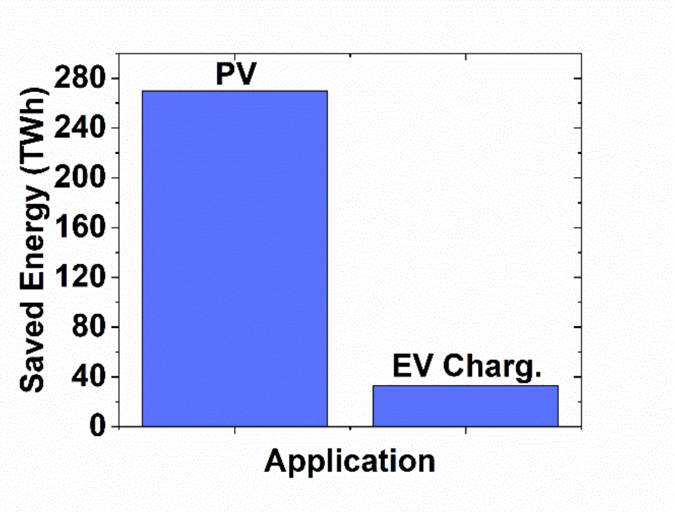

Fig. 3: Potential energy savings for PV and EV Chargers applications in the year 2050. The PV application increased from 20.7 TWh/year to 270 TWh/year and the EV charger application from 0.81 TWh/year to 33 TWh/year compared to 2021.

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 regime are dominant, 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 could. 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. Whereas some PV manufacturers makes some efficiency curves available, this is rather an exception compared to other applications such as air conditioning systems. 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 affect societal economics.

4. 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 based on statistics of 2021. Drive applications presented a huge potential to implement SiC technology due to their large global energy consumption. Furthermore, our study highlights the 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 towards the increased incorporation WBG technology into products, providing a forecast on the potential of such technologies. We expect to promote greater understanding and action amongst policymakers to identify the main applications where WBG devices may significantly affect 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+qeUck79UGJRQh1vGG-TEnJ30jMRDw1lk4bmV0

[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] P. Steimer, Energy savings by means of Medium voltage power electronics, ABB, Private communication.

[33] 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

[34] 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

[35] 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

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

[37] 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).

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

[39] 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/

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

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

[42] 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

[43] 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

[44] 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

[45] 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

Appendix – Potential energy savings for WBG in PV and Wind Power in Austria

According to Austria's Climate and Energy Strategy #mission2030[1], an ambitious objective of electricity generation based on 100 % of renewable energy sources is formulated. This is also supported by the renewable expansion act (Erneuerbaren Ausbau Gesetz)[2]. Furthermore, different scenarios on how to reach these goals are elaborated in the "integrated national energy and climate plan for Austria"[3].

This appendix is focused on energy savings for PV and wind power applications and is highlighting the potential impact of WBG semiconductors and its adoption in both applications based on different scenarios which are backed by historical data for a time horizon of 10-20 years from now.

PV

According to the integrated national energy and climate plan for Austria, the planned PV based energy production should reach 42 Petajoule per year until 2030. Based on data from "Statistik Austria"[4], "Solar Power Europe"[5] and the "International Renewable Energy Agency"[6] the following base scenario has been documented as follows:

Forecast PV Austria 2030

- Expected energy production: 42 PJ or 11.7 TWh[7]
- Expected installed capacity: 9.7 GW
- Expected operated hours/year (OH): 1203 h/y

The operating hours highly depend on the weather during the year. Looking into historical data from 2019 and 2020 the following situation has been documented:

PV Austria 2019

- Produced Energy: 1.7 TWh
- Installed capacity: 1.7 GW
- Effectively operated hours/year: 1000 h/y

PV Austria 2020

- Produced Energy: 2.04 TWh
- Installed capacity: 2.22 GW
- Effectively operated hours/year: 919 h/y

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[1] bmvit. #mission2030–Die österreichische Klima- und Energiestrategie; Bundesministerium für Nachhaltigkeit und Tourismus & Bundesministerium für Verkehr, Innovation und Technologie: Vienna, Austria, 2020.

[2] Federal Ministry for Digital and Economic Affairs, "Renewable Energy Expansion Act Law", Feb. 2022, Online: https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20011619.

[3] Federal ministry republic of Austria, "Integrated National Energy and Climate Plan for Austria 2021-2030", Vienna, Dec. 2019, Online: https://energy.ec.europa.eu/system/files/2020-03/at_final_necp_main_en_0.pdf.

[4] Statistik Austria, "Energiebilanzen (Energie und Umwelt)", accessed online: March 2022, online: https://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/energie_und_umwelt/energie/energiebilanzen/index.html

[5] Solar Power Europe, "Country Profiles: Austria", accessed online: March 2022, online: https://www.solarpowereurope.org/austria-country-profile/.

[6] International Renewable Energy Agency, "Energy Profile, Austria", accessed online: March 2022, online: https://www.irena.org/IRENADocuments/Statistical_Profiles/Europe/Austria_Europe_RE_SP.pdf.

[7] Conversion factor: 3.6 PJ = 1 TWh

Thus, it is obvious that the current yields from PV in Austria will require a higher share of installed capacity until 2030 to meet the PV energy targets of 11.7 TWh/year if similar weather conditions are anticipated. Therefore, a forecast based on 3 different scenarios is derived:

- OH Scenario 1 (optimistic): 1250 h/y
- OH Scenario 2 (main): 1050 h/y
- OH Scenario 3 (conservative): 900h/y

Moreover, the required compound annual growth rate (CAGR) to meet 2030 PV energy targets (forecasted PV energy production from 2020-2030 to meet 2030 objectives as shown in **Fig. 1**) calculates to

$$CAGR_{PV,2020-2030} = 19.65\ \%.$$

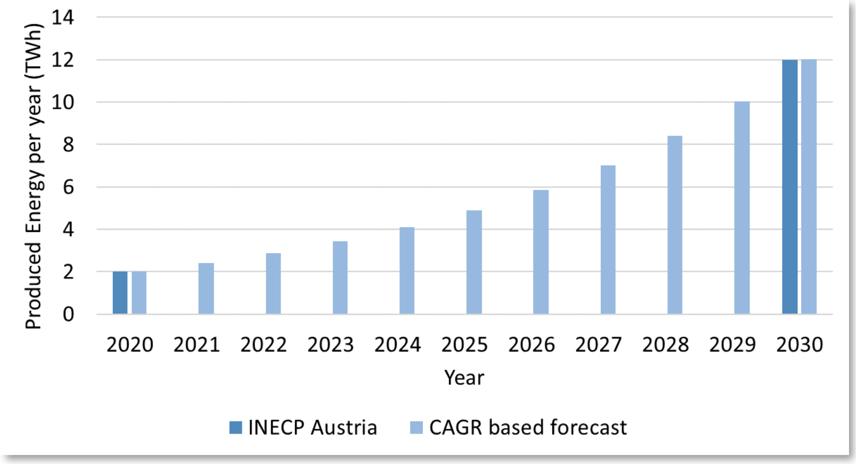

Fig. 1: PV energy forecast for Austria considering the years 2020 to 2030.

As the period until 2040 is split into two different substages (2030 target: 12 TWh; 2040 target: 13 TWh[8]) the CAGR for 2030-2040 adapts to

$$CAGR_{PV,2030-2040} = 0.8\ \%.$$

The transition towards a higher PV energy production for a time horizon of 20 years is given in **Fig. 2**.

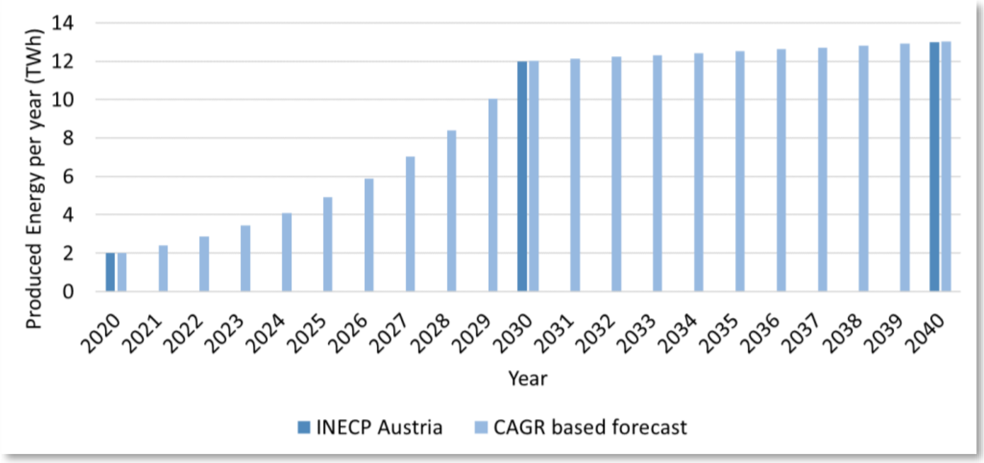

Fig. 2: PV energy forecast for Austria considering the years 2020 to 2040.

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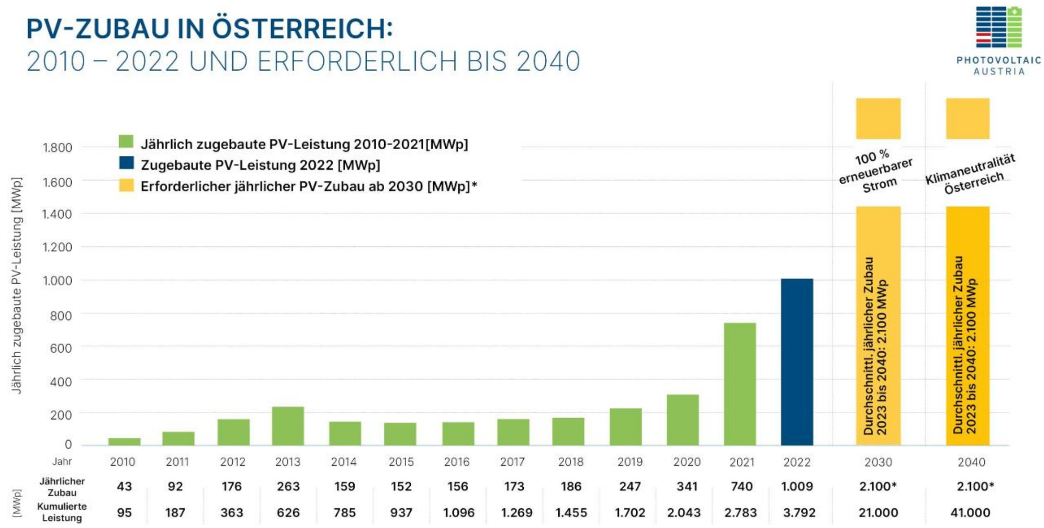
[8] Federal ministry republic of Austria, "Integrated National Energy and Climate Plan for Austria 2021-2030", Vienna, Dec. 2019, Online: https://energy.ec.europa.eu/system/files/2020-03/at_final_necp_main_en_0.pdf.

It should be noted that a more recent publication from Bundesverband Photovoltaic Austria (2023)[9] expects even larger figures for an Austrian related PV expansion (2030: 21 TWh; 2040: 41 TWh) for PV (see **Fig. 3**). This updated targets in a relation to possible energy savings for WBG based PV inverters, however, could not be considered in this report, due to its recent release. However, it should be noted, that higher absolute values in electricity generation of PV systems also result in larger energy savings (absolute values).



Quellen: Aktuelle Leistung: Innovative Energietechnologien in Österreich Marktentwicklung; Hrsg. BMK 2023. Erforderlicher PV-Zubau bis 2030/2040: Integrierter österreichischer Netz-infrastrukturplan (ÖNIP); Hrsg. BMK 2023. *Prognose: Durchschnittlicher Jahreszubau lt. ÖNIP – Ableitung PV Austria. Grafik: © PV Austria

Fig. 3: PV energy forecast for Austria as published by Bundesverband Photovoltaic Austria. The figure can be accessed via https://pvaustria.at/grafiken/.

Based on the three different scenarios in terms of effectively operated hours (OH scen. 1, OH scen. 2, OH scen. 3), the required total installed PV capacity should reach at least 9.6 GW and in a best-case scenario results in 14.1 GW until 2030 (see **Fig. 4**). In order to benchmark the potential of WBG over silicon in terms of efficiency and energy savings, 3 scenarios are defined:

- EE WBG Scenario 1 (optimistic): 2.5 percent points efficiency improvement
- EE WBG Scenario 2 (main): 1.5 percent points efficiency improvement
- EE WBG Scenario 3 (conservative): 0.5 percent points efficiency improvement

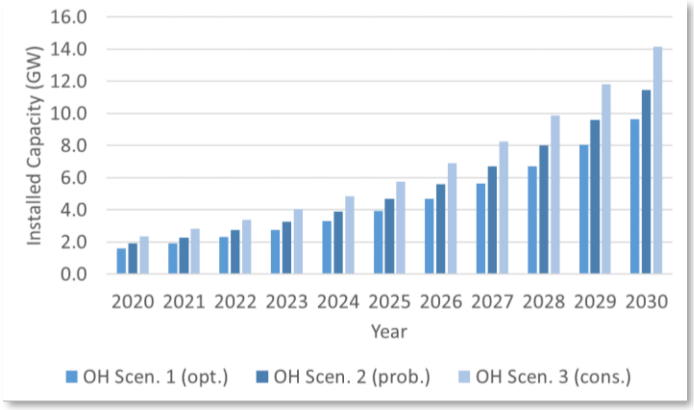


Fig. 4: Calculated installed PV-based capacity forecast for Austria considering the years 2020 to 2030. Three different scenarios are included OH scen1: 1250 h/y, OH scen2: 1050 h/y, OH scen3: 850 h/y.

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[9] Bundesverband Photovoltaik Austria, "Grafiken und Darstellungen", Online: [https://pvaustria.at/grafiken/.](https://pvaustria.at/grafiken/)

The different scenarios can depend on many different parameters. One specific quantity is the topology itself. Energy conversion concepts based on DC/DC converters in conjunction with DC/AC inverters are normally prone to higher efficiency improvements compared to sheer AC/DC solutions when adopting WBG. There are more Si semiconductors involved in a DC/DC plus DC/AC conversion concept compared to the pared-down version, thus higher energy savings can be expected. Furthermore, another difference is the voltage i.e., DC-link or grid voltage level which could exclude GaN as competitive device if the DC-link voltage exceeds 400-500 V. Exceptions are multi-level or multi-cell converters. Also, the applied switching frequency can impact the facilitated energy savings. Converters which are running on a rather low switching frequency are normally coming with lower energy savings when adopting WBG as the switching losses are already only a minor part of the total system losses. Conduction losses can be reduced as well but will mainly benefit from operation under light or no-load conditions. However, even though lower energy savings might be achieved by replacing Si via WBG at lower switching frequencies, this might allow a redesign of the converter, increasing the operating frequency while maintaining similar shares of semiconductor losses and reducing the volume of the total system.

Considering aforementioned scenarios, energy savings for different types of energy savings for WBG semiconductors are listed in **Table 1**. This list is furthermore split into 2 main categories:

- Assuming that all PV inverters will be based on WBG devices
- Assuming that only newly adopted PV systems will be based on WBG semiconductors.

Coming back to the ambitious goal of Austria to increase the installed capacity of 2020 by 6 times until 2030, the difference in savings between these two categories lies only at approximately 35 %.

Table 1: WBG energy savings forecast for PV applications - Austria.

	ALL PV Inverters		**Newly installed PV inverters**	
	Total energy savings (TWh) 2020-2030	Total energy savings (TWh) 2020-2040	Total energy savings (TWh) 2020-2030	Total energy savings (TWh) 2020-2040
EE WBG Scen. 1:	1.58	4.67	1.03	3.67
EE WBG Scen. 2:	0.95	2.8	0.62	2.2
EE WBG Scen. 3:	0.32	0.93	0.21	0.73

Assuming that Austria will meet its PV energy targets in 2030, the expected yearly energy savings then will sum up to 251 GWh/year for newly adopted and 301 GWh/year for all installed PV capacities based on WBG over Si solutions. A summary of results of the three different scenarios is depicted in **Fehler! Ungültiger Eigenverweis auf Textmarke.**.

Table 2: WBG energy savings forecast for PV applications in 2030 - Austria.

	ALL PV Inverters 2030	***Newly installed PV inverters 2030***
	Energy savings (GWh)	Energy savings (GWh)
EE WBG Scen. 1:	301	251
EE WBG Scen. 2:	180	150
EE WBG Scen. 3:	60	50

To relate these types of energy savings to an equivalent reduction of GHG emissions per year, it is assumed that this available energy can be alternatively used to substitute available energy from those technologies coming with a higher carbon footprint. Thus, again three different use cases for 2030 are derived. The first use-case assumes an averaged grid related GHG-Emission of 220 gCO_2eq/kWh (**UC1:** worst case)[10]. The main scenario (**UC2**) is defined by 130 gCO_2eq/kWh and as best-case (**UC3**) scenario 70 gCO_2eq/kWh is considered. The different values have been chosen based on day-by-day observation according to "electricity maps" data points.

Table 3: CO_2 savings (t CO_2eq/year) if all PV Systems would be based on WBG semiconductors - 2030.

	WBG Scen. 1 (t CO2eq/year)	WBG Scen. 2 (t CO2eq/year)	WBG Scen. 3 (t CO2eq/year)
UC1	66 148	39 689	13 230
UC2	39 088	23 453	7 818
UC3	21 047	12 628	4 209

Thus, depending on the aforementioned scenarios (inverter design, efficiency of the original silicon-based PV system, wide bandgap technology – SiC or GaN, etc.) the CO_2 savings can vary from 4.2 kt CO2eq/year to 66 kt CO2eq/year.

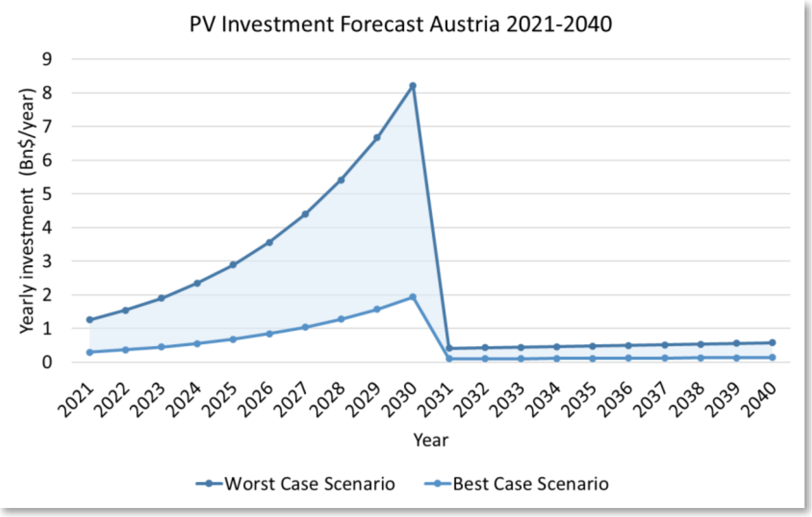

Fig. 5: Worst case (OH 3 + 100% residential PV) and best case (OH 1 + 100% utility-scale PV) scenarios for PV investments (in billion $ including 3 % of yearly inflation rate) required to meet Austrian PV targets.

Additionally, a recently published US report on PV related capital expenditures (CapEx) from Q1 2020[11] mentioned, that the average price per Watt ($/W) for installing a PV system highly varies on the type of installation (residential PV (worst case 2020: 2.71 $/W), commercial rooftop PV and utility-scale PV (best case 2020: 0.94 $/W) fixed tilt vs one-axis tracker). Moreover, it is confirmed that the prize of PV installations in $/W reduced considerable during the last decade. This was mainly driven by cost optimization of inverters and efficiency improvements of solar modules. Thus, the inverter's cost itself already represents a small fraction of the total cost per installation. As WBG devices currently come with higher cost per component for similar current ratings compared to their silicon counterparts, it is important to exploit all benefits offered by WBG semiconductors (besides improved efficiency also

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[10] Electricity map, "CO2 Emissions - Austria", Online: https://app.electricitymaps.com/zone/AT

[11] Price reference 2020: https://www.nrel.gov/news/program/2021/documenting-a-decade-of-cost-declines-for-pv-systems.html.

e.g., smaller passives, reduced cooling efforts etc.), when employing these devices into new PV inverters. The worst case and best-case investment scenario for Austria based on installed capacity scenarios OH 1 and OH 3 for different pricing schemes (100 % residential vs 100 % utility-scale PV) is depicted in **Fig. 5**. Considering a yearly inflation rate of 3 %, the overall investments until 2030 are varying between 9 bn $ (best case) to 38 bn $ (worst case) assuming that potential higher investments due to WBG can be compensated via the redesign of passives and an improved cooling concept.

Wind Power

The Austrian energy production based on wind power should reach 16 TWh[12] per year until 2030 which equals to 24.5 PJ. Similar to the PV use case, different scenarios have been derived for the wind power regime. Gathered data to derive several different scenarios is based on sources as "Statistik Austria"[13], austrian power grid AG[14], the international renewable energy agency (IRENA) [15] and the international energy agency wind technology collaboration programme (IEA wind TCP)[16].

Forecast wind power Austria 2030

- Expected energy production until 2030: 58 PJ or 16 TWh[17]
- Expected energy production until 2040: 72 PJ or 20 TWh
- Required additional energy production until 2030 (compared to 2020): 9.2 TWh
- Required additional energy production until 2040 (compared to 2030): 4 TWh
- Energy production in 2020: 6.79 TWh
- Installed Capacity in 2020: 3.13 GW
- Operated hours in 2020: 2168 h

In order to reach the energy targets for 2030 a compound annual growth rate (CAGR) of 7.85 % is required (calculated value). For energy targets until 2040, this value can be split based on two different periods:

- $\text{CAGR}_{\text{wind}}$ for the period 2020 -2030: 7.85 %
- $\text{CAGR}_{\text{wind}}$ for the period 2030 - 2040: 1.63 %

The wind energy forecast for 2020 to 2030 and 2020 to 2040 for Austria is illustrated in **Fig. 6** and **Fig. 7**, respectively.

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[12] Federal ministry republic of Austria, "Integrated National Energy and Climate Plan for Austria 2021-2030", Vienna, Dec. 2019, Online: https://ec.europa.eu/energy/sites/ener/files/documents/at_final_necp_main_en.pdf.

[13] Statistik Austria, "Energiebilanzen (Energie und Umwelt)", accessed online: March 2022, online: https://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/energie_und_umwelt/energie/energiebilanzen/index.html

[14] Austrian Power Grid APG, "Installed Power Plant Capacity 2017-2022", Online: https://www.apg.at/en/markt/Markttransparenz/erzeugung/installierte-leistung.

[15] International Renewable Energy Agency, "Energy Profile, Austria", accessed online: March 2022, online: https://www.irena.org/IRENADocuments/Statistical_Profiles/Europe/Austria_Europe_RE_SP.pdf.

[16] IEA Wind Power TCP, "Wind Energy in Austria", Online: https://iea-wind.org/about-iea-wind-tcp/members/austria/.

[17] Conversion factor: 3.6 PJ = 1 TWh

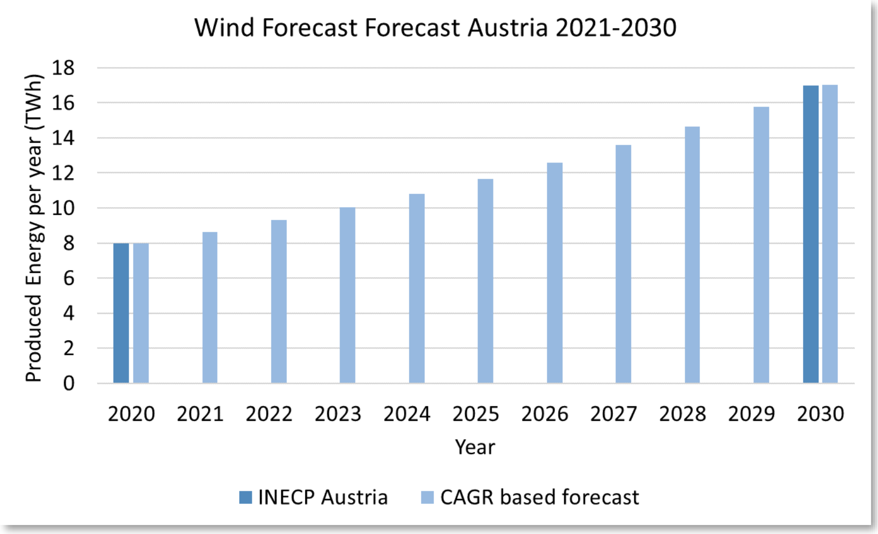

Fig. 6: Calculated wind energy forecast for Austria considering the years 2020 to 2030.

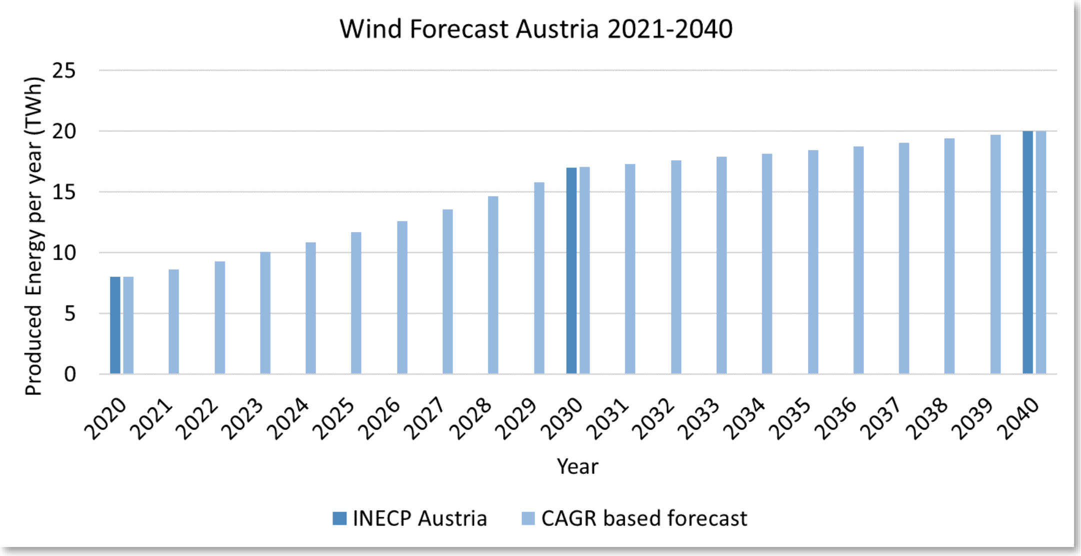

Fig. 7: Calculated wind energy forecast for Austria considering the years 2020 to 2040.

Again a more recent publication on Bundesverband Photovoltaic Austria[18] expects 21 TWh until 2030 and 29 TWh until 2040. Similar to latest statistics for PV these targets have not been considered in this report, but are mentioned for the sake of completeness. Likewise, to the comment in the PV section, it should be noted, that higher absolute values in electricity generation of wind power systems also result in larger energy savings for wide bandgap technology (absolute values).

Similar to PV, the operating hours for wind power depend on specific weather conditions during the year. Looking at some data from 2017 – 2020, the operated hours for wind power in Austria was varying between 2100 h – 2430 h.

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[18] Bundesverband Photovoltaik Austria, "Grafiken und Darstellungen", Online: https://pvaustria.at/grafiken/.

Table 4: Historically produced energy and installed wind power capacity in Austria [19],[20].

	2017	2018	2019	2020
Produced energy (TWh)	6.57	6.03	7.45	6.79
Installed capacity (GW)	2.70	2.89	3.04	3.22
Operated hours (h)	2438	2089	2455	2107

Based on those aforementioned inputs in terms of historically produced energy and installed capacity, the following 3 scenarios for operated hours (OH) of wind power systems in Austria have been derived:

- OH Scenario 1 (optimistic): 2500 h/y
- OH Scenario 2 (expected): 2150 h/y
- OH Scenario 3 (conservative): 1800 h/y

Using the different scenarios 1 - 3 predicting the required minimum installed capacity for wind power energy generation, the require operating power capability varies from 6.8 GW to 9.5 GW. Until 2040 at least 8 GW of installed power plant capacity in the wind power sector in Austria is required. Considering the worst-case scenario OH 3 even approximately 11 GW are mandatory to guarantee 20 TWh/year. Current data from 2020 to 2022 of installed wind power plants in Austria unveil that Austria is slightly behind the minimum required installed capacity interim target values (3.2 GW versus a minimum of 3.5 GW for 2021). However, looking into latest numbers from March 2022 already an increase installed capacity of 0.3 GW is noticed and expected to further increase in the course of the year. **Fig. 8** highlights the forecasted installed power capacity based on scenarios OH 1 -3, benchmarking it against historical data from 2020 up to March 2022. As most wind power systems in Austria are large scale-power plants feeding energy directly into the distribution grid, the installed wind power capacity in Austria is accurately tracked by APG with only minor deviations of < 5 % compared to available data from the IEA wind power TCP or IRENA.

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[19] Statistik Austria, "Energiebilanzen (Energie und Umwelt)", accessed online: March 2022, online: https://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/energie_und_umwelt/energie/energiebilanzen/index.html

[20] Austrian Power Grid APG, "Installed Power Plant Capacity 2017-2022", Online: https://www.apg.at/en/markt/Markttransparenz/erzeugung/installierte-leistung.

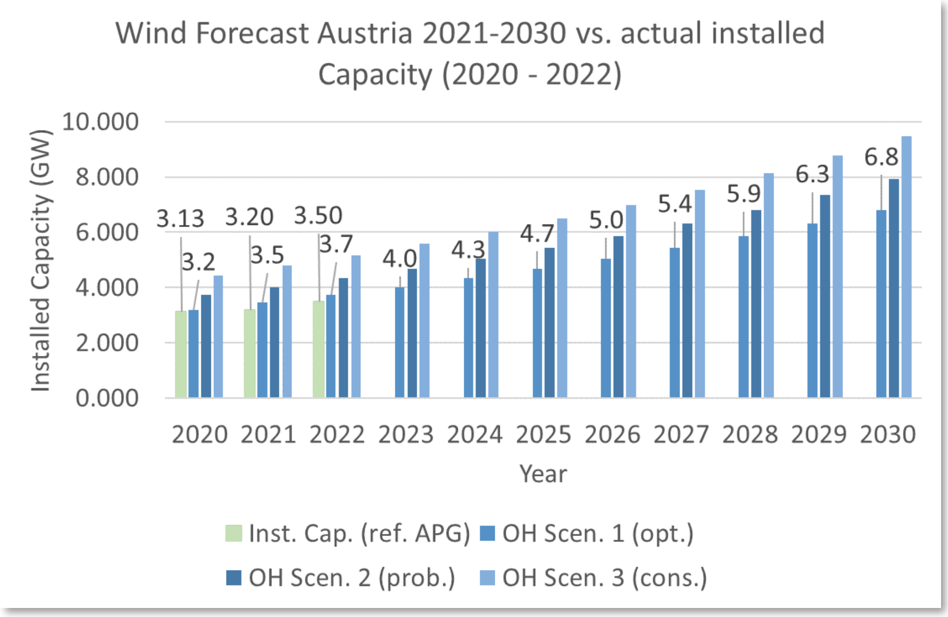

Fig. 8: Installed wind-based capacity forecast for Austria considering the years 2020 to 2030. Three different scenarios are included OH scen1: 2500 h/y, OH scen2: 2150 h/y, OH scen3: 1800 h/y. Furthermore, the current total installed capacity based on data from APG[21] is incorporated (green).

In order to benchmark the potential of WBG over silicon in terms of efficiency and energy savings, again 3 different scenarios are defined:

- EE WBG Scenario 1 (optimistic): 2.5 percent points efficiency improvement
- EE WBG Scenario 2 (main): 1.5 percent points efficiency improvement
- EE WBG Scenario 3 (conservative): 0.5 percent points efficiency improvement

Similar to PV converters, the efficiency improvements depend on the wind power technology and how many converters are involved in the energy conversion transfer. Currently many different types of wind power solutions exist. The two most prominent and efficient solutions on the market are:

- the permanent magnet excited synchronous generator with AC/DC and DC/AC converter (wind power generator fully decoupled from the 50 Hz grid)
- the doubly fed induction generator (stator directly connected to the grid, rotor connected to the grid via AC/DC plus DC/AC converter while only processes approximately 20 -30 % of the total power)

Based on the aforementioned scenarios, the energy savings for a transition from Si-based to WBG semiconductors can vary from 85 GWh per year to 426 GWh per year (shown in **Table 5**) assuming that all wind power converters will be based on WBG and Austria reaching its wind power energy targets of 16 TWh until 2030. If only newly installed wind power systems will adopt WBG semiconductors the energy savings will reduce to 45 GWh to 226 GWh. Due to the fact that Austria is already benefiting from a high share of wind power systems especially in the area around Vienna (Lower Austria, Burgenland etc.) retrofitting WBG with existing solutions is an attractive option.

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[21] APG, „Installed Power Plant Capacity“, Online accessed at 25.03.2022: https://www.apg.at/en/markt/Markttransparenz/erzeugung/installierte-leistung

Table 5: WBG energy savings forecast for wind power applications in 2030 - Austria.

	ALL Wind Power Inverters 2030	*Newly installed Wind Power inverters 2030*
	Energy savings (GWh)	Energy savings (GWh)
EE WBG Scen. 1:	426	226
EE WBG Scen. 2:	255	135
EE WBG Scen. 3:	85	45

Table 6: WBG energy savings forecast for wind power applications - Austria.

	ALL Wind Power Inverters		**Newly installed Wind Power Inverters**	
	Total energy savings (TWh) 2020-2030	Total energy savings (TWh) 2020-2040	Total energy savings (TWh) 2020-2030	Total energy savings (TWh) 2020-2040
EE WBG Scen. 1:	3.30	7.76	1.10	3.76
EE WBG Scen. 2:	1.98	4.66	0.66	2.26
EE WBG Scen. 3:	0.66	1.55	0.22	0.75

Furthermore, it should be noted, that if all newly installed wind power inverters since 2020 will adopt WBG semiconductors, up to 1.1 TWh of energy could be saved from 2020-2030. Moreover, even a total of 3.76 TWh in energy savings could be realistic until 2040 by just adopting WBG semiconductors to newly installed wind power systems (best case scenario, as listed in

Table 6).

Similar to the PV use case, also the improved energy generation of wind power, quantified by the achieved energy savings via WBG semiconductors is reflected in CO2 savings. Therefore, different scenarios (optimistic, expected and worst case) are anticipated and highlighting potential future grid situations in terms of GHG Emissions per drawn kWh from the grid, as defined in the following:

- Worst case (**UC1**): 220 gCO_2eq/kWh
- Expected (**UC2**): 130 gCO_2eq/kWh
- Best case (**UC3**): 70 gCO_2eq/kWh

Table 7 lists dedicated potential energy savings based on the assumption, that this additional allocated energy comes with distinctly lower CO2 emissions due 0 emissions during energy production and rather low emission per kWh including the life cycle assessment.

Table 7: CO_2 savings (t CO_2eq/year) if all wind power plants would be based on WBG semiconductors (2030).

	WBG Scen. 1 (t CO2eq/year)	**WBG Scen. 2 (t CO2eq/year)**	**WBG Scen. 3 (t CO2eq/year)**
UC1	93 682	56 209	18 736
UC2	55 357	33 214	11 071
UC3	29 808	17 885	5 962

Finally, worst and best case required investments (capital expenditure – CapEx) financed or partially subsidized by the Austrian government to realize the denoted wind power objectives of 16 TWh until 2030 and 20 TWh until 2040, is estimated. Therefore, the two critical scenarios i.e., lowest installed required capacity (OH 1) vs. highest installed capacity (OH 3), weighted by the documented price policy for wind power projects in US in 2021, ranging from **1 $/W to 2 $/W** (averaged price: 1.44 $/W)[22,23], leads to a worst-case investment of 11.7 $ until 2030. **Fig. 9** highlights the yearly CapEx considering an inflation rate of 3 %.

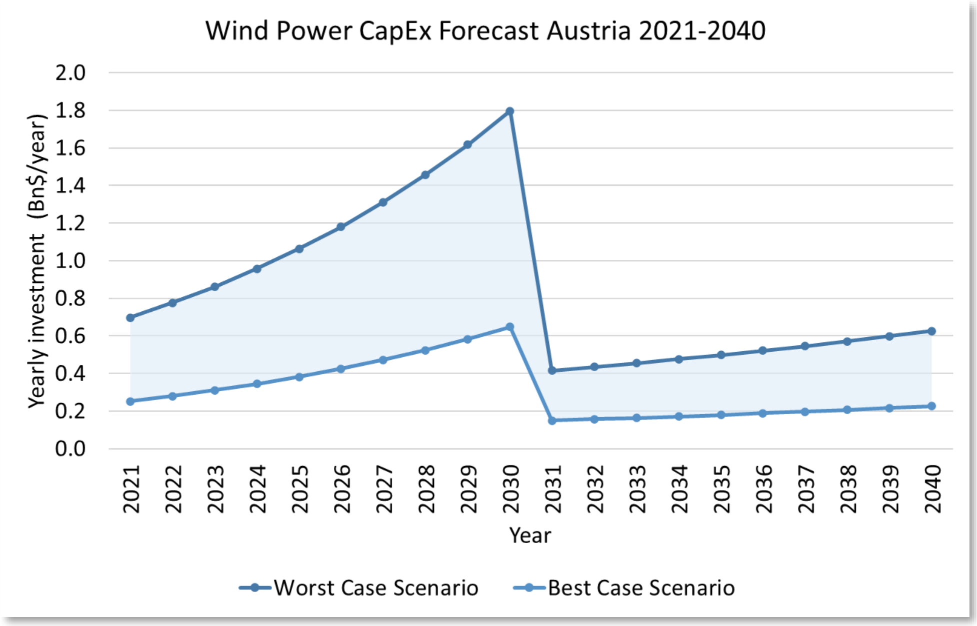

Fig. 9: Worst case (OH 3 and 2$/W CapEx) and best case (OH 1 + 1$/W CapEx) scenarios for wind power investments (in billion $ including 3 % of yearly inflation rate) required to meet Austrian wind power targets.

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[22] NREL, „2020 Cost of Wind Energy Review", accessed online at 30.3.2022, Link: https://www.nrel.gov/docs/fy22osti/81209.pdf

[23] Berkeley lab, WLand-Based Wind Market Report", accessed online at 30.3.2022, Link: https://emp.lbl.gov/wind-technologies-market-report