ECPE Position Paper

The All-Electric Society - Enabled by Power Electronics

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Table of Contents

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1. Introduction and Motivation

1.1 Definition and scope of power electronics

Power electronics is an important subfield of electrical and electronics engineering dealing with the application of electronics to the control and conversion of electric power. According to the IEEE, power electronics can be defined as the use of electronic devices to control and convert electric power covering power conversion, power supplies and motion control [1.1].

Power electronics is a cross-sectional and ubiquitous field as it covers many disciplines, including material science, semiconductor physics and power devices, assembly and interconnection technologies, electrical circuit topologies, and control, in all systems and applications dealing with electric energy from the low Milliwatt range up to Gigawatt power, see figure 1.1.

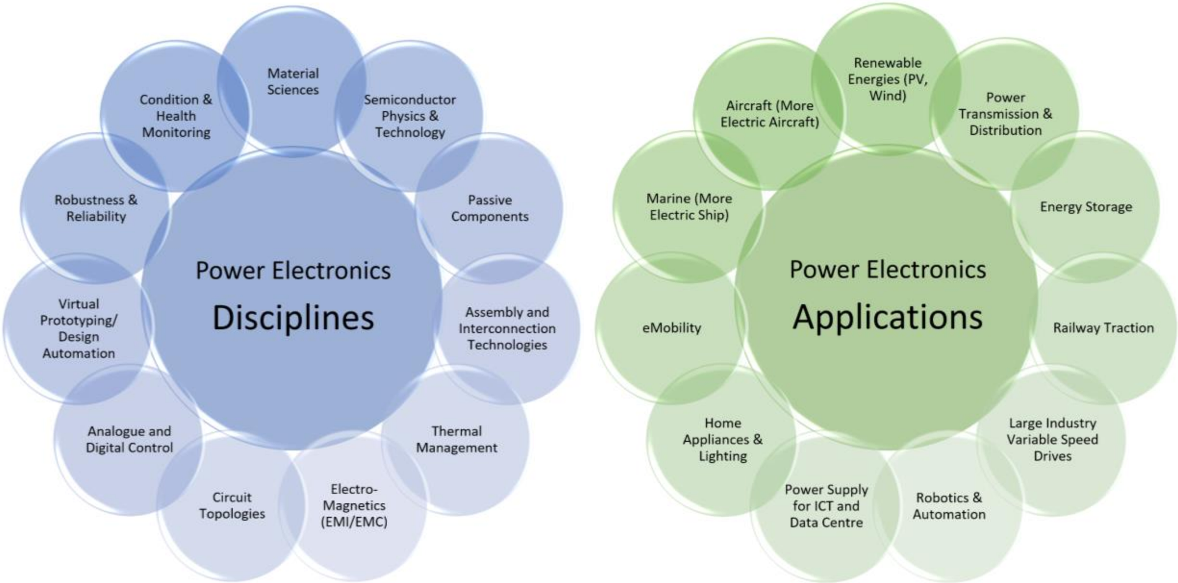


Fig. 1.1: Disciplines (left) and major applications (right) related to power electronics

The power semiconductor device is the key driver and enabler in power electronics systems. Today power electronics is dominated by semiconductors based on the material silicon (Si). This is a very mature technology which has been developed over decades with cost-efficient, high-volume production up to 300 mm wafer technology. Upcoming wide bandgap semiconductor devices based on silicon carbide (SiC) and gallium nitride (GaN) are gaining momentum in various power electronics applications due to their intrinsic advantages in energy efficiency and power density on the system level. For the economic impact, the leverage effect of the market sizes from the power semiconductors to the systems level must be considered with a typical factor of 100 from the power wafers to the electronics systems, see figure 1.2 [1.2].

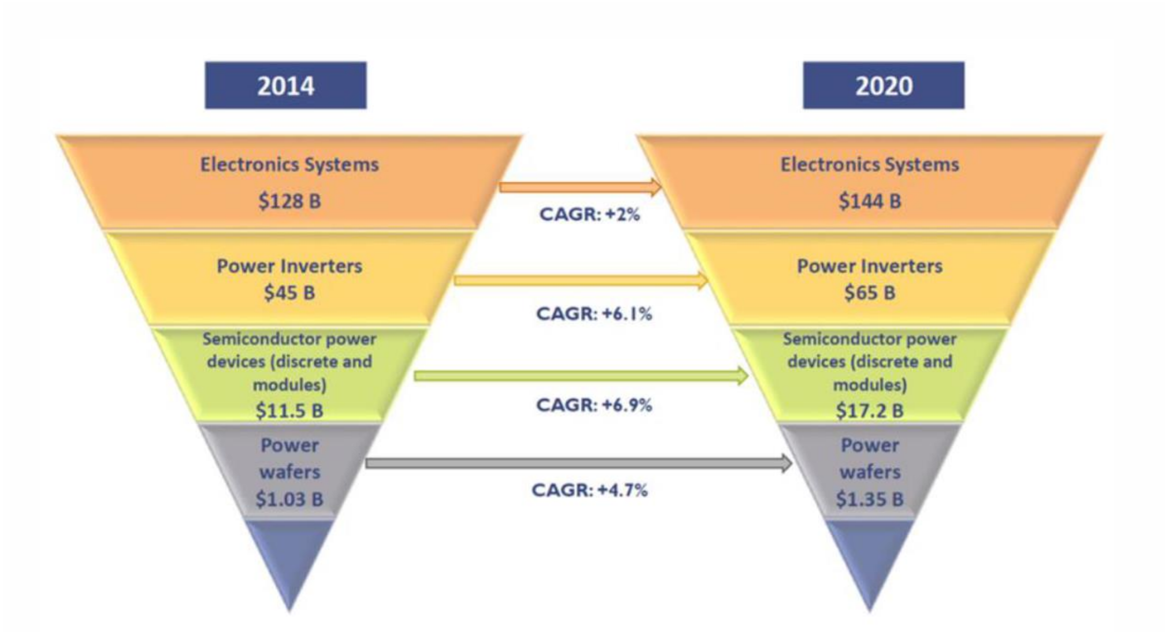


Fig. 1.2: Power electronics value chain analysis from wafers to systems [1.2]

1.2 Energy efficiency and sustainable energy supply

Power electronics is a key technology for increased energy efficiency along the full chain from generation, transmission & distribution up to the use of electric energy. Furthermore, it is an enabler for the grid integration of renewable energy sources, e.g., photovoltaics (PV) and wind power. E-mobility is boosting power electronics as it is a key technology on the vehicle itself as well as on the grid side when it should be charged. Power electronics can significantly contribute to the key issues of improved energy efficiency, reduced consumption of materials, and sustainable energy supply based on renewables.

The sustainable energy supply covers the grid integration of renewable energies, the low-loss power transmission, e.g., with High Voltage Direct Current (HVDC) lines and the power distribution, including local grids with bidirectional flow of power as well as integration of energy storage into the grid. Grid control and global stability with smart inverters, integration of energy storage, reduction of harmonic distortions, and improved power quality measures are important for a sustainable energy supply based on renewable energies.

Energy Efficiency can be improved on all levels, from the components to the modules and converters and finally on the systems and applications level [1.3]. Examples will be presented in the following chapters.

- On the component level with low-loss wide bandgap (WBG) devices and new materials to advance passive components.
- On the module and converter level with new circuit topologies, proper circuit design to eliminate distributed parasitics and applying digital control. Advanced integration technologies, including power embedding and smart thermal management, to fully exploit the potential of the new devices applied in the converter and at system level.
- On the system and application level e.g. by the elimination of redundant power conversion steps through introduction of efficient DC grids e.g. for buildings, industry plants, ships and

airplanes. Further savings can be achieved by introducing power electronics where it is not yet used today because it is too bulky or too expensive. Key enablers are miniaturization, system integration and cost reduction. Smart solutions on the system level provide energy savings by smart integration of power electronics and information & communication technologies (ICT).

1.3 Power electronics value chain in Europe

Historically, Europe has a strong position in power electronics on the technology side with power devices and modules but also on the application side with industry and traction drives. In recent decades Europe has taken a leading role in further important application areas like automotive power electronics, renewable energies and smart grids. On the other side, the mass market of power supplies for computer and telecom applications has mainly moved to Asia.

It is worth mentioning that the full power electronics value chain is present in Europe with strong industrial players, and excellent research infrastructure with universities and R&D institutes. The value chain starts with materials, substrates and wafers, before moving up to power devices, modules and converters, and concludes with the systems in the numerous applications mentioned in this position paper. It is accompanied by equipment manufacturers for production and testing equipment as well as by providers of software tools.

It is key for the future to maintain and strengthen Europe´s position in power electronics technologies and applications, since other regions in the world, e.g., China and US have also identified the importance and the potential of power electronics.

2. Energy Transition from Fossil to Renewable Energies

2.1 Reduction of CO_2 emissions, climate change

Climate change is clearly progressing and visibly affects life on earth. With the Paris Agreement, governments have agreed to fight global warming and reduce greenhouse gas emissions in order to keep the global average temperature increase to below 2°C compared to the pre-industrial levels, with the goal to further limit this increase to 1.5°C [2.1]. In addition to mitigation, the agreement further addresses adaptation to climate change. However, adaptation strategies can be associated with notable energy consumption and therefore be contradictory to the greenhouse gas reduction targets. The use of renewable-energy-based technologies is the way to resolve this conflict [2.2].

Various scenarios on future energy consumption and supply have been proposed over the past years. They make clear that changes in all energy sectors e.g. heating, transportation and electricity are needed, and that renewables-based electrification together with energy storage and energy efficiency technologies, is the major step towards greenhouse gas reduction and climate change mitigation.

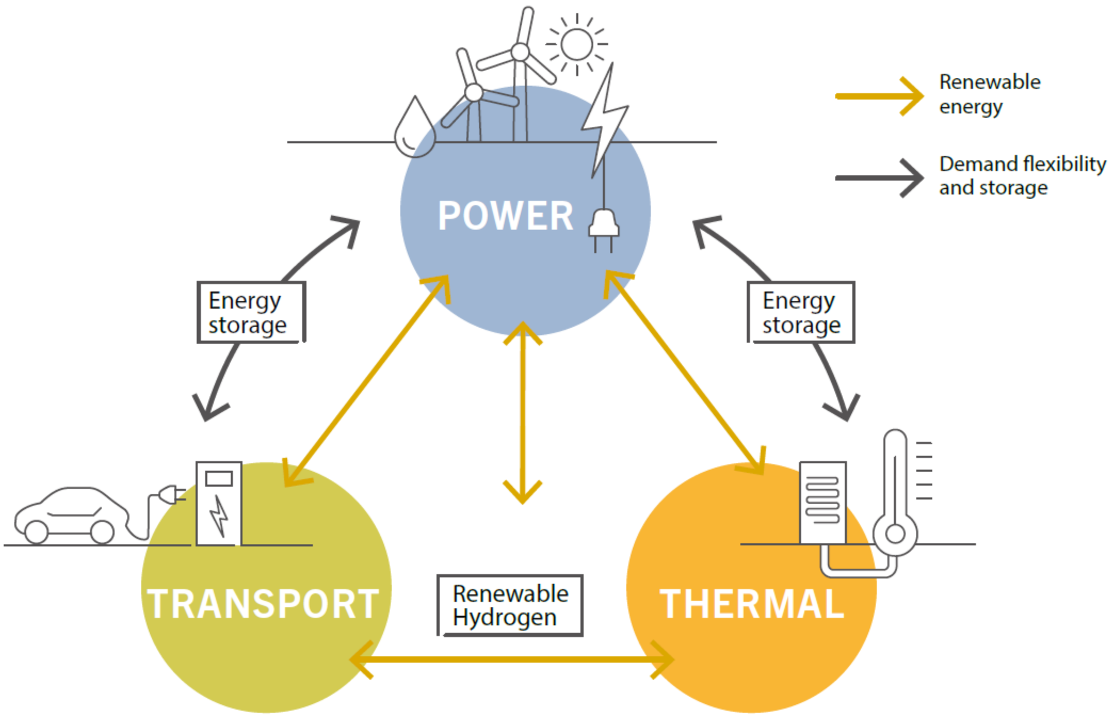


Fig. 2.1: Coupling of power, thermal and transport sectors, [2.4], p. 204

According to an exemplary scenario proposed by "IRENA" (Fig. 2.2, [2.3]), the worldwide total final energy consumption (TFEC) needs to decrease from 378 EJ in 2018 to 348 EJ in 2050. In the same time period, the share of electricity in the TFEC is supposed to increase from 21% to 51%, with a renewables share of 90% in direct electricity, in order to reach the 1.5°C goal by 2050.

Overall, the share of renewables in the worldwide total primary energy supply (TPES) in the IRENA scenario amounts to approximately 75%. A summary of several other scenarios in figure 2.3 ([2.3], p. 92) shows that an average of 60% or more renewable energy share in the TPES is projected in all 1.5°C case studies, compared to the current level of less than 20% in 2018. Significant efforts to increase the renewable energy capacity are therefore urgently needed.

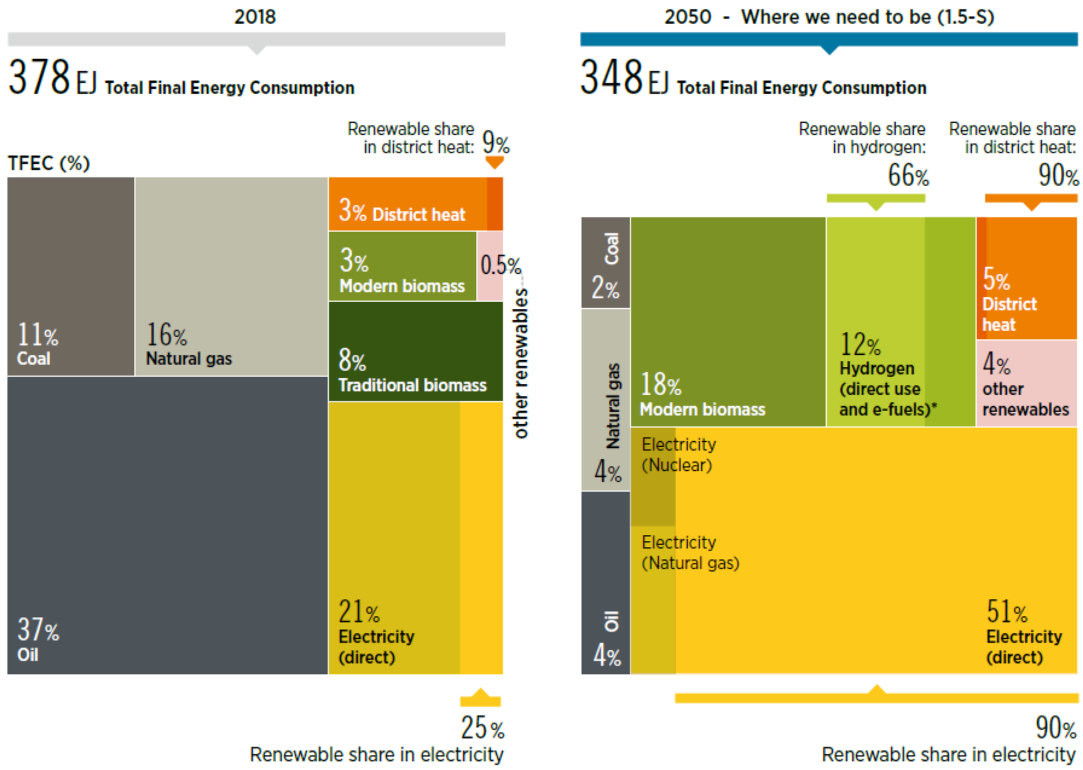
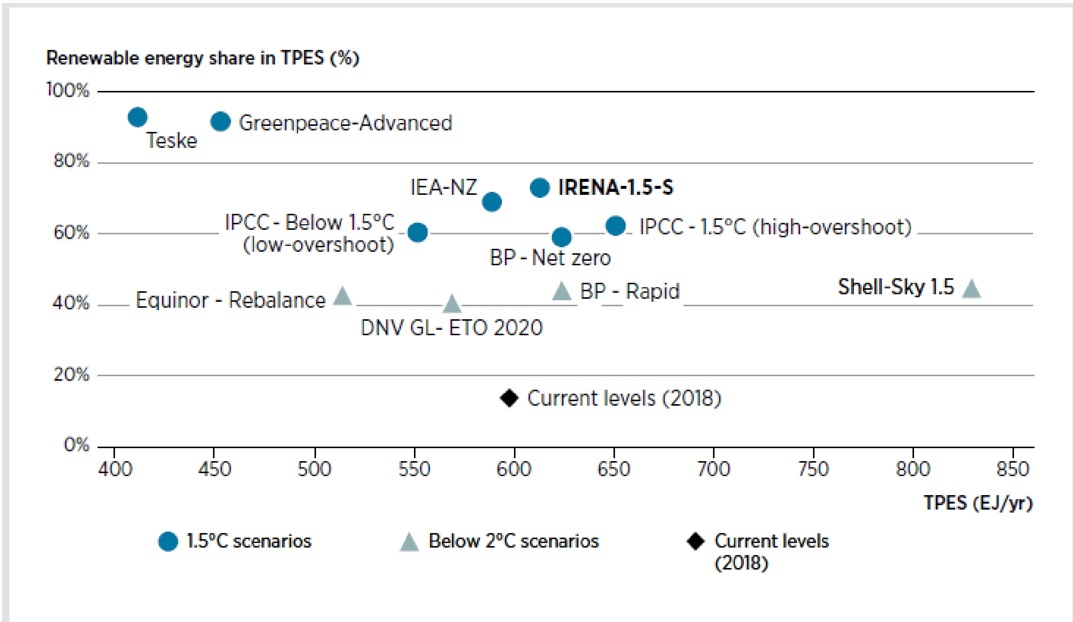


Fig. 2.2: Breakdown of the total final energy consumption (TFEC) by energy carrier: the share of electricity is supposed to increase from 21% in 2018 to 51% in 2050, with a total renewables share of 90%, in order to reach the 1.5°C goal by 2050 ([2.3], p. 71)

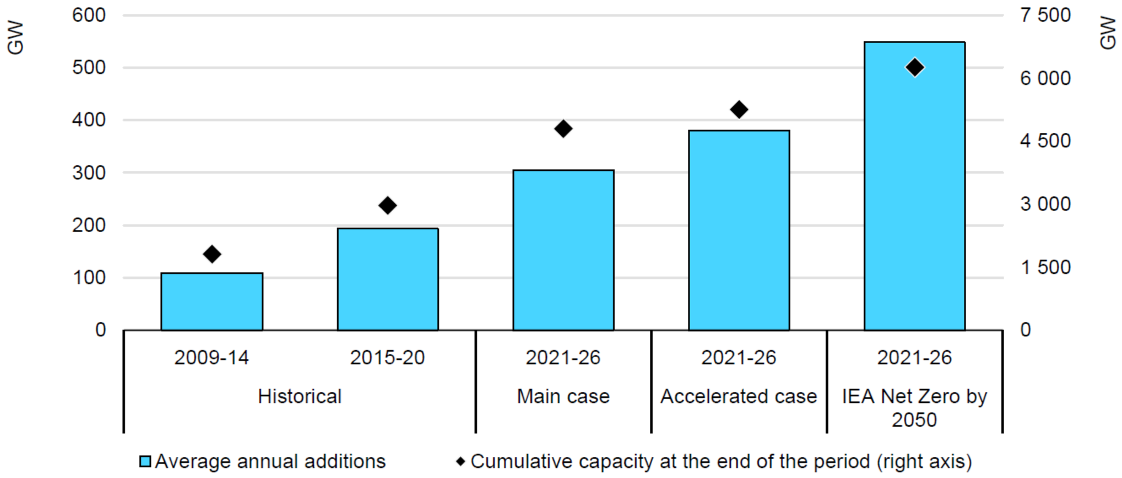


Sources: Shell's 2021 "Sky 1.5" scenario (Shell, 2021); BP's "Rapid Scenario"(BP, 2020); the "Below 1.5°C" and "Above 1.5°C" scenario from the Intergovernmental Panel on Climate Change (IPCC, 2018); Greenpeace's 2015 "Advanced" scenario (Greenpeace, 2015); Teske's "Achieving the Paris Climate Agreement Goals" (Teske, 2019); Equinor's "Rebalance scenario" (Equinor, 2020); DNV GL's Energy Transition Outlook 2020 (DNV GL, 2020) and IEA's Net Zero by 2050 (IEA, 2021b).

Fig. 2.3: According to different studies, an average of 60% or more renewable energy share in the total primary energy supply (TPES) is needed to reach the 1.5°C goal in 2050 ([2.3], p. 92)

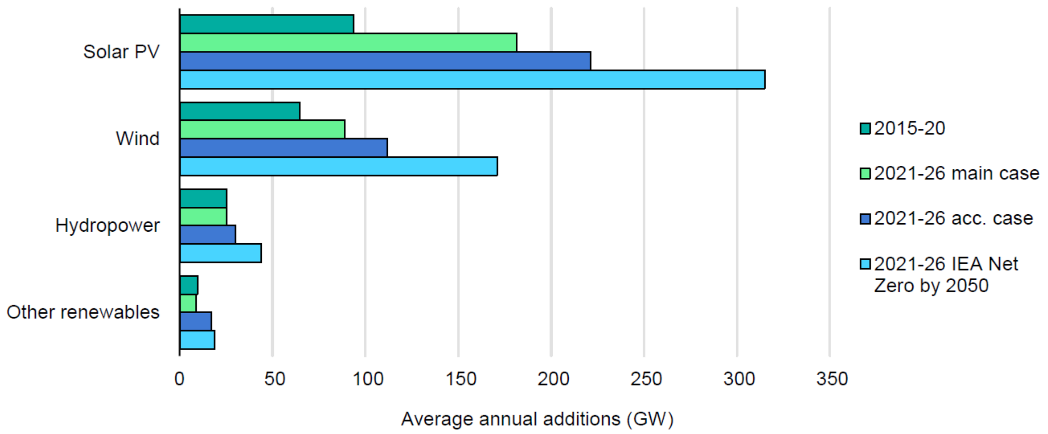
2.2 Renewable energies are electric

The global installed capacity of renewable power and the renewable share in electricity have notably increased in the last decade, with hydro power, wind (on- and offshore), photovoltaics and bioenergy being the main sources that substantially contribute to the electric energy sector. While the average annual growth of installed power was ~100 GW/year in the period from 2009 to 2014, an average of ~200 GW were added each year between 2015 and 2020 [2.5, 2.6]. To meet the climate change mitigation targets, the trend needs to further develop and speed up notably, specifically concerning the contributions of wind and photovoltaic power sources.



Source: IEA (2021a), Net Zero by 2050.

Fig. 2.4: Average annual renewable capacity additions and cumulative installed capacity from 2009 to 2020, and forecasts till 2026 by the IEA based on current and predicted governmental and regulatory decisions ("main case", "accelerated case") and the "Net Zero by 2050" scenario [2.6]



Note: acc. case = accelerated case.

Fig. 2.5: Average annual renewable capacity additions by technology from 2015 to 2020, and forecasts till 2026 by the IEA based on current and predicted governmental and regulatory decisions ("main case", "accelerated case") and the "Net Zero by 2050" scenario [2.6]

The forecast of the necessary capacity increase till 2026 presented by the International Energy Agency (IEA) (Fig. 2.4 and 2.5) considers three different cases [2.6]: the "main case" and the "accelerated case" based on current and predicted governmental and regulatory decisions, and the "Net Zero" case by 2050. While the main and accelerated cases already assume an average of 305 GW[1] respectively 380 GW annual renewable power additions between 2021 and 2026. However, to reach Net Zero in 2050 would require average annual capacity additions of approx. 550 GW for the next five years. This means that governments need to act and formulate more ambitious goals to reach the necessary annual capacity growth under the IEA Net Zero Scenario during 2021-2026 [2.6].
Comparable to these worldwide analyses and forecasts, ENTSO-E has developed three main scenarios on the European scale, comparing the national trends in line with the EU's and the member states' action plans with a centralized and a decentralized power generation scenario compliant with the 1.5°C target [2.7]. However, all three scenarios rely on notable gas import share, and in the current situation (2022) geopolitical conditions need to be revised.

2.3 The role of power electronics in renewable energy generation, transmission and energy storage

Power electronic inverters are indispensable for the future power system based on renewables. The projected 250 to 480 GW average additional capacity of wind and photovoltaic installed power [2.6] demands roughly the same amount of installed inverter power. By way of example, figure 2.6 depicts the basic structure of a wind power generator which uses a power electronics inverter as interface to the electric power system. Controlled appropriately, the back-to-back inverter enables either maximum power infeed to the grid ("grid following control") or active and reactive power infeed according to the grid operator requirements ("grid forming control"). In the same way, power electronic inverters are used to fully control the infeed of photovoltaic power to the grid.

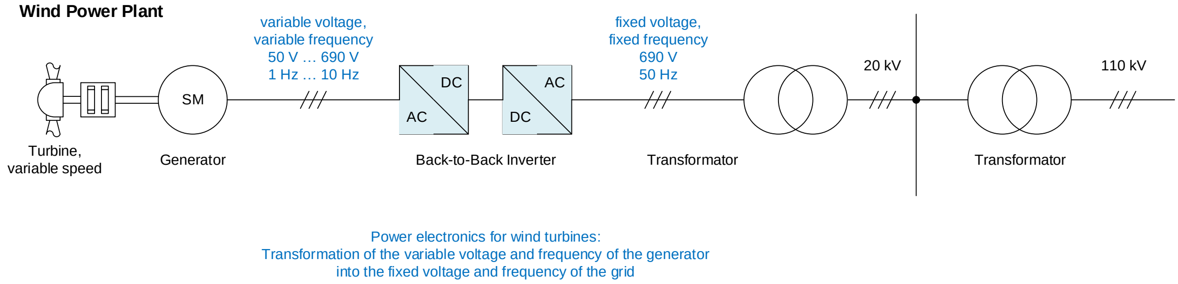


Fig. 2.6: Wind power plant based on synchronous generator and back-to-back power electronics inverter technology, enabling full control of power infeed to the electric grid electronics

It is obvious that conversion efficiency, cost, reliability, resource-efficiency, re-use and recycling of power electronics are major driving forces of future developments. The current trend towards applying low-loss, fast-switching wide bandgap semiconductors in power electronic converters is one approach among others to increase efficiency and reduce filtering and cooling efforts and thus material expense. Design for reliability and predictive maintenance are further paths towards more environmentally friendly technical solutions.

[1] "This implies an acceleration of almost 60% compared to renewables' expansion over the last five years."[2.6]

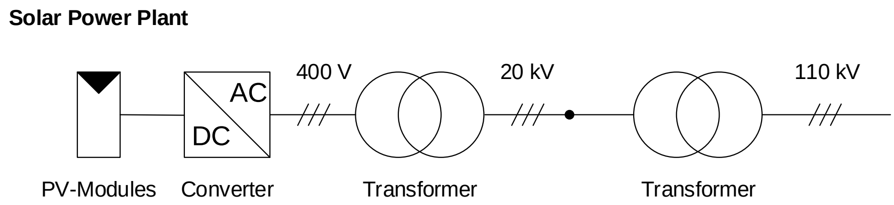


Fig. 2.7: Basic structure of a solar power plant with power electronics inverter to convert dc to ac power, enabling full control of power infeed to the electric grid electronics

Power electronics plays a major role not only in energy generation based on renewables, but also in maintaining stable electric power systems including transmission-level technologies like HVDC or STATCOMs, and in controlling energy storage components. An upcoming development specifically in Germany is Hydrogen electrolysis. Figure 2.8 below presents the necessary installation of H_2-electrolysis in Germany till 2045, and the associated amount of renewable power installations to supply these systems which also need approximately the same amount of installed converter power.

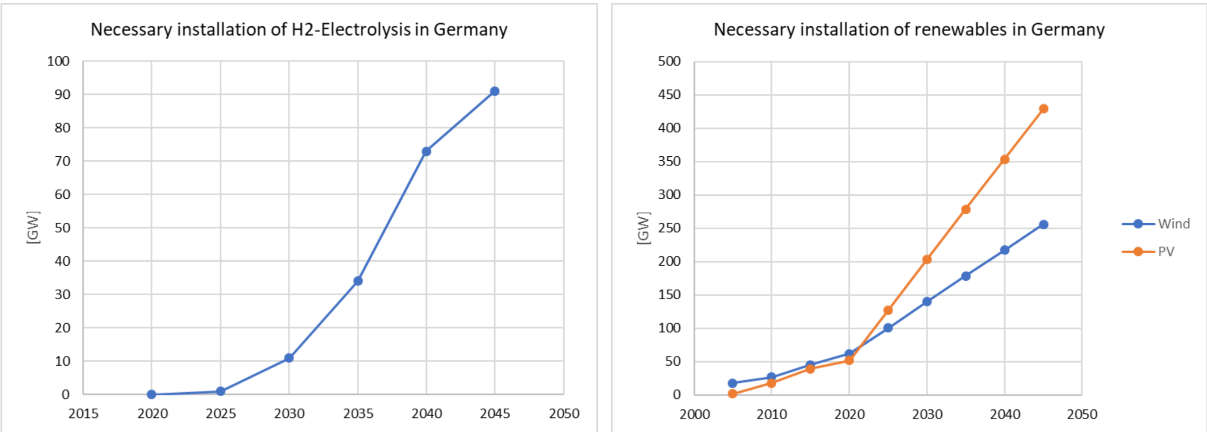


Fig. 2.8: Necessary installation of H_2-electrolysis in Germany till 2045, and the associated amount of renewable power installations (source: based on data from [2.8])

3. Power Electronics for the Future Electronic Grid System

3.1 Power electronics in the AC and in the DC transmission grid

Power electronics is not only necessary when it comes to the integration of renewable energies (like wind or photovoltaic sources), or of charging stations in the electric grid but also when it is needed to create light transmission and transformer infrastructures which offer low losses and control capabilities. Among these technologies HVDC is reported as an example of low-loss transmission whilst Flexible Alternating Current Transmission Systems (FACTS) can contribute to make HVAC transmission systems more efficient. Moreover, the Smart Transformer is reported as an example to introduce additional system level controllability of DC-distribution though meshing possibilities at low and medium voltage levels. Both are system level solutions which could interact with distributed control possibilities embedded in the inverters that are already used for integration of sources and new loads (like charging stations).

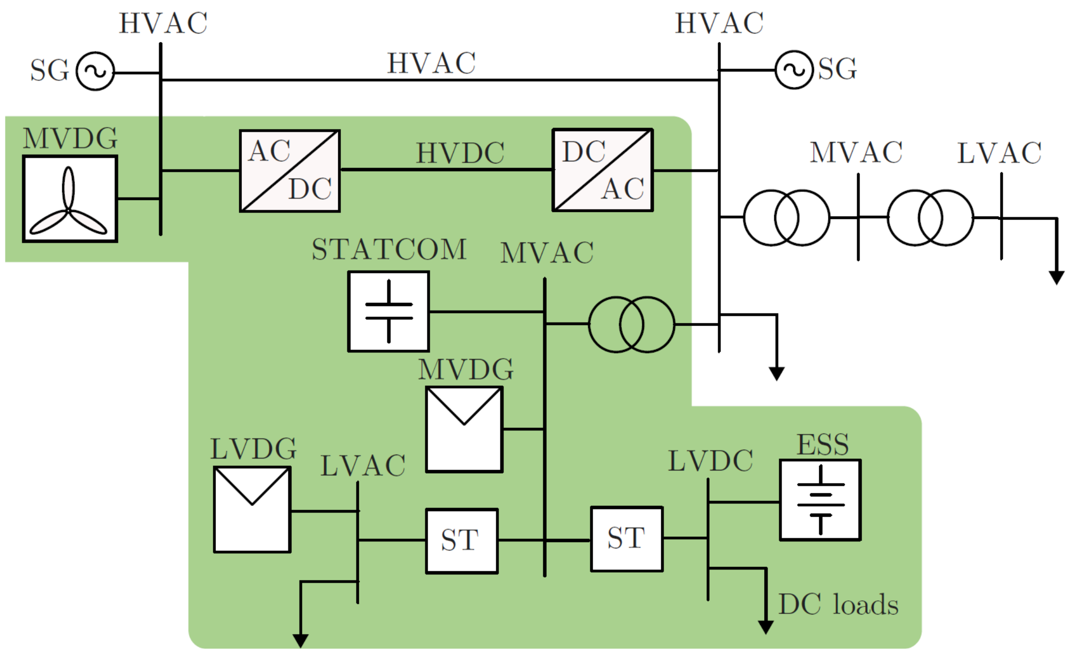


Fig. 3.1 Power electronics contributing to the future electronic grid systems.
(HVAC / HVDC: High Voltage Alternating/Direct Current) [3.25]

3.2 Low-losses power transmission (HVDC)

HVDC is a key enabler for a carbon-neutral energy system. It is highly efficient for transmitting large amounts of electricity over long distances, allowing integration of renewables and interconnecting grids. HVDC technology has been recognized as a key technology for enabling the clean energy transition, contributing to the UN's Sustainable Development Goal 7: increasing access to affordable, reliable, sustainable and modern energy for all [3.1]. A 2000-km long DC transmission line at 800 kV loses about 5% of its power, while the power losses in an AC line of similar voltage are about twice as high [3.2].

Compared to conventional HVAC transmission, HVDC transmission has approximately half the carbon footprint [3.2].

Industrial studies did show that carbon footprint of the latest HVDC power converter technologies is one-third of what it was ten years ago [3.3]. For example, the HVDC connection with latest transmission technology between the UK and France could cut the CO_2 emissions by 1 million tons per year.

By 2030, 65% of electricity consumed in Germany is to derive from renewables and by 2050 it will increase to 80% generated by renewable sources. This requires improvements to the transmission network to carry the wind energy produced in the north towards the load centres in the south, at the same time allowing improvements in the system stability [3.4].

3.3 Smart transformers for meshed and hybrid grids

Smart Transformers are based on so called Solid-State Transformers (SST) which are power-electronics-based conversion systems which use a high frequency transformer. The volume of such high-frequency transformer could be 97% smaller with respect to a low frequency one [3.5] and consequently its production leads to a reduction of CO_2 emissions. For example, 100 tons of CO_2 can be saved per each installed 1 MVA assuming the use of 10 times less copper. The overall SST can be 80% smaller in volume with respect to a low frequency transformer [3.6] and have perhaps 3 times higher losses in comparison but it should be noted that an SST offers functionalities that a low frequency transformer does not offer and the use of WBG devices will lead to a significant reduction of these losses and/or volume.

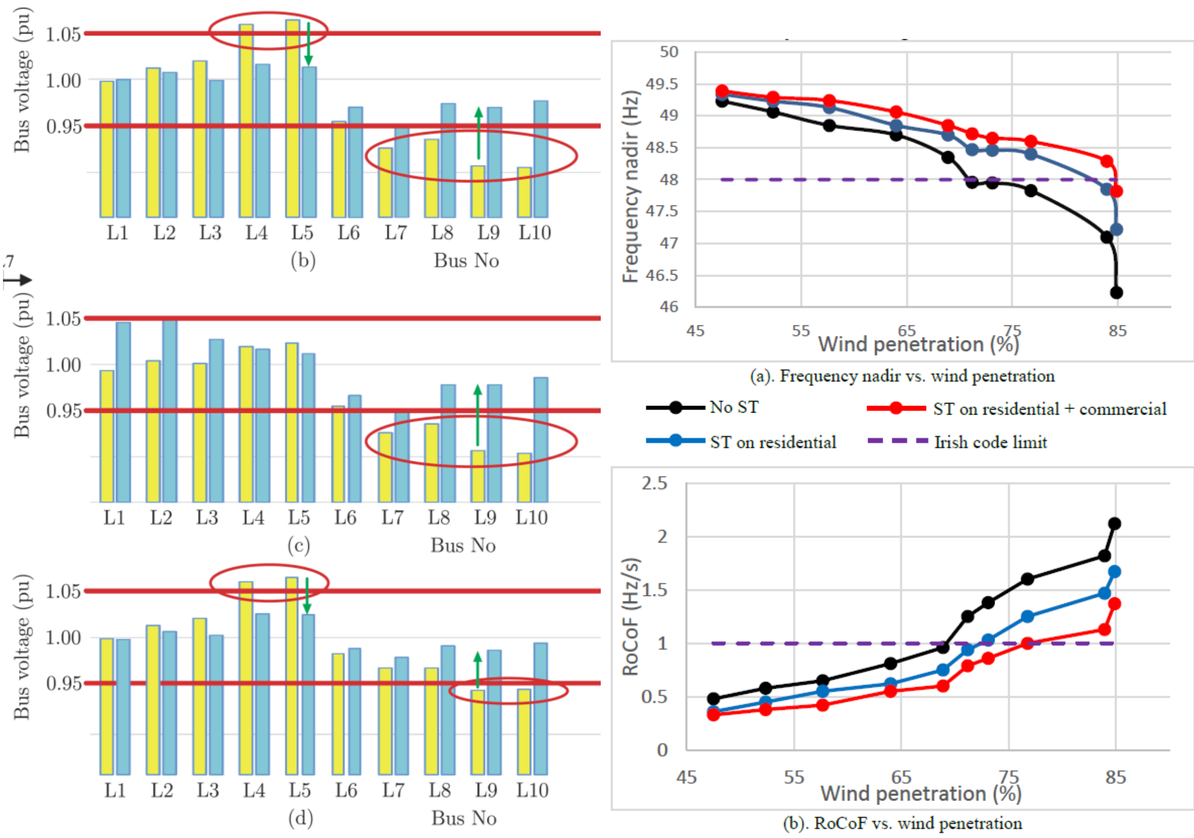


Fig. 3.2 Potential of Smart Transformers (ST) by mashing a distribution grid (a: yellow radial grid, blue with ST-meshing) [3.8] and by controlling voltage-sensitive loads (b: impact on Ireland-grid [3.13])

SST enables DC grids in Medium Voltage (MV) and Low Voltage (LV) levels leading to hybrid grid and will allow meshing of grids, typically not done at distribution level which is mostly radial. This offers more controllability both of active power flow and of voltage/reactive power [3.7]. This controllability is needed to allow photovoltaic and charging station installation even at the end of the feeder avoiding voltage violations [3.8].

MVDC could be a crucial technology for integration of PV and wind turbine parks also thanks to the use of SiC devices in the kV range. In fact, already the use of 3.3 kV Si IGBTs leads to an efficiency of 99% for the Modular Multilevel Converter which converts MVAC into the MVDC [3.9] - 3.3 kV SiC have 25% lower voltage drop and 7.5 times lower switching losses in comparison to Si [3.10].

Additionally, it should be noted that the voltage controllability which power electronics offers could be used for the untapped potential associated with voltage-dependent loads [3.11]. For example, it has been demonstrated that the improvement of voltage controllability can unlock up to 3.2 GW of untapped potential [3.12]. This increment of grid capacity can be done through smart transformers which can control the voltage profile, increasing the damping in case of power mismatch. Consequently, the larger damping reduces the frequency nadir and Rate of Change of Frequency (ROCOF), allowing the increase of wind penetration by approximately 10% [3.13].

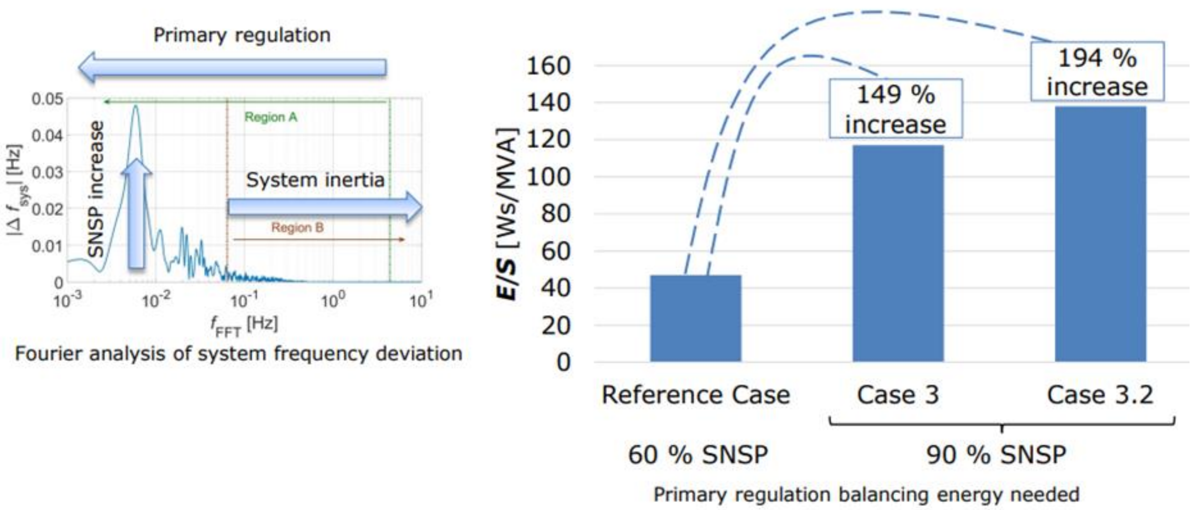


Fig. 3.3 Learning of the project Migrate from Ireland network study, request of primary regulation when System Non-Synchronous Penetration (SNSP) increases from 60% to 90% [3.18].

3.4 Stabilization measures in a power electronics dominated grid

Despite power electronics being a key technology for guaranteeing integrations of renewable energies, electrification of transport sector as well as enabling a more efficient energy system, several concerns exist regarding stability of a power-electronics-dominated-system. Sometimes these concerns are too restrictive as shown in [3.14] regarding Japan where it is demonstrated that renewables in Japan can easily satisfy more than 40% of annual demand (or 30% if hydropower and biomass are excluded), while still maintaining grid stability within tolerable ranges and maintaining the surplus/curtailment of variable renewables at a low level of around 4%, being significantly higher that governmental goal of 22%. Renewables penetration levels over 40% may require additional technical measures to ensure grid stability and maintain renewable energy generation curtailment at acceptable levels. In [3.15] the problems of integrating Non-Synchronous Generation (NSG) based on power converters are identified and it is pointed out that they can lead to a critical situation as consequence of a fault if System Non-

Synchronous Penetration (SNSP) is above 65 %. TSOs ranks the decrease of inertia, which leads to frequency variation, and consequently to problems for classical synchronous generator-based generation which shall be anyway present to supply 20 % base load, as the most severe issue of a power electronics dominated grid - as shown in table 5.1 of [3.15]. Moreover, a case study of the Irish transmission grid has revealed that almost three times the primary frequency balancing energy is needed in relation with the installed capacity of synchronous generators if the share of non-synchronous generation is increased from 60% to 90% [3.17].

On the other hand, the grid code of National Grid ESO [3.15] identifies in the grid forming control of power converters that avoiding the use of Phase Locked Loop (PLL) to synchronize to the electric grid is the key to the stability issues associated with faults [3.18]. Moreover, the authors of [3.19] identify that optimal placement of 30 % grid forming converters (or even 20% if grid voltage support is enabled) could be the key to lead to a stabilization of the grid since grid forming converters are showing inherent damping capability [3.20].

The power electronics converter-fed load can also contribute to the stabilization measures as well. Initially, the converter is used to support grid under disturbance by feeding reactive power [3.21], [3.22]. The study in [3.21] shows that using the converter interfaced components to provide reactive power can significantly increase the post-fault electromagnetic torque in induction machine (IM) loads and hence contribute to its reacceleration. The analysis has demonstrated that, in a grid of 20 MW load and with IM loads penetration of less than 36.5%, a 12 MVA converter of a Battery Energy Storage System (BESS) can provide sufficient reactive power for IM re-excitation and prolong the Critical Clearing Time (CCT). In [3.22] the reactive power is provided by exploiting the spare capability of the fast-charging stations. The analysis shows that the reactive power from fast charging stations can help load-levelling, reducing at least 20% of power mismatch between the real-time consumption and dispatching plan. The converter can provide significantly high controllability. As a consequence using the converter-fed loads to emulate the behaviours of conventional loads, such as synthetic inertia or demand-voltage sensitivity, has been proposed to enhance the grid stability. In Ireland, a 480 kVA rated flywheel/ battery hybrid energy storage has been installed. The aim is to provide frequency services up to 20 minutes when the frequency is less than 49.8 Hz [3.23]. The stability issue of interaction between converters has arisen within the power electronics dominated grid. Consequently, the universal model-based stability analysis should be done for the power electronics dominated grid where coordination of converters is a potential solution [3.24].

4. Power Electronics and e-Mobility

4.1 Summary

Mobility is key for global growth and societal wealth. In 2020 world citizens moved distances of 23 billion km in total; by 2050 that figure will grow to 105 billion km [4.1]. This number does not include movements of freight and goods. The demand on mobility mounts with the growth of the world population as every single citizen needs to travel and needs to send and receive goods. In 1999 the size of the world population was 6 billion. By 2050 the world will count over 9 billion people [4.2].

Today most vehicles are based on power trains using fossil fuel. Over the last decades enough evidence has been provided showing that burning fossil fuel has a direct and indirect impact on the health of people. As such, mobility is undergoing a transformation from fossil fuel mobility to sustainable and environmentally friendly electric mobility. Electrification does not only reduce CO_2 and other harmful gases, but it also drives the need for renewable energy and therefore independence from oil and gas. In addition, electrification allows the rise of new mobility concepts such as drones and high-speed transportation like the hyperloop concept for example.

Historically, mobility was defined as transport moving people, animals and goods from A to B. Future mobility, however, is fueled by three key technology-driven disruptive trends: electrification of vehicles, connected & autonomous vehicles and mobility-as-a-service [4.3].

The following gives a brief overview in seven sectors and their trend towards electrified vehicles.

4.2 Micro-mobility

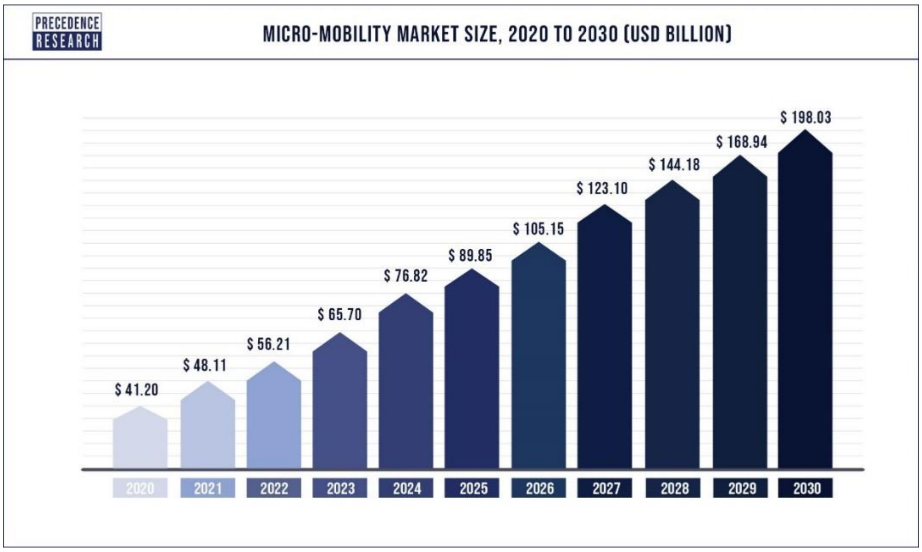


Fig. 4.1: Global micro-mobility market growth [4.4]

Micro-mobility covers small mobility vehicles such as e-bikes, scooters, cargo bikes, light quadracycles etc. Although those mobility vehicles existed in the past, electrification has made them more popular and there is a growing demand in this sector. Figure 4.2 [4.4] shows a global market size of 56 billion USD in 2022 with a compound annual growth rate (CAGR) of 17% until 2030. The power demand is relatively low and the biggest challenge for this sector is to achieve low cost. Many of these vehicles have low mechanical damping meaning power electronic devices must withstand high mechanical vibrations and forces. Also, most commonly, air-cooling systems are required which can lead to design challenges. Therefore, new integration concepts for highly efficient power systems like embedding and multifunctional integration are necessary.

4.3 Automotive

The global trend is already pushing towards greater electrification within the automotive sector. In 2019 1% of the global car stock were electric cars [4.5]. The EU proposes a ban of new petrol and diesel cars by 2035 requiring the need for electric vehicles [4.6]. In general, power electronics for electric vehicles have progressed well with the transition from Silicon based switching devices to SiC WBG switching devices. The voltage range is commonly 400 V but is likely to move towards 800 V. Integration of the electric motor and the inverter is seen as a key development to achieve better integration. Challenges here are new active or hybrid EMC filter technologies to reduce size, weight and costs. New SiC and upcoming GaN power devices with their high switching speeds make new isolation concepts for motor windings necessary to withstand high dv/dt values of up to 100 kV/µs. A high level of mechatronic integration gives new challenges to the thermal management and cooling.

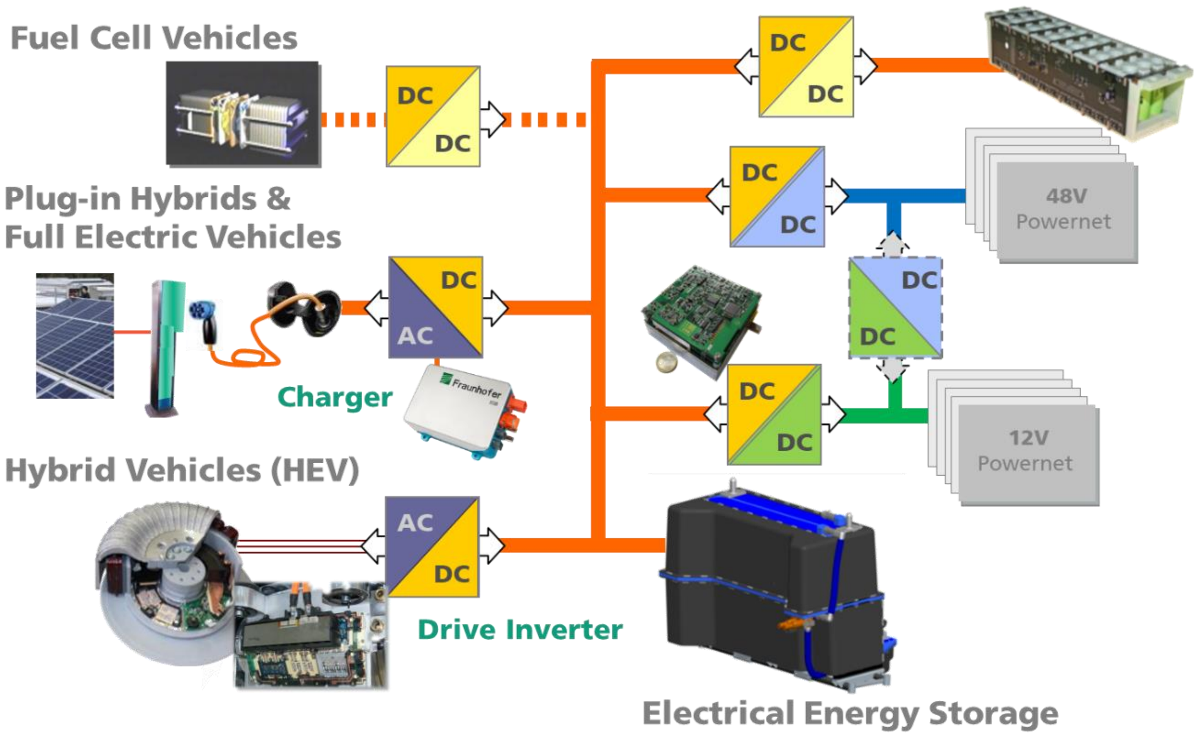


Fig. 4.2: Power train of electrified cars (hybrid, full-electric or fuel cell vehicles), electronics

One of the most researched activities is the battery charger. Depending on the power level, electric cars have on-board chargers for power levels up to 22 kW. High power DC-chargers are placed outside the vehicle and are more and more established. There can even be seen a trend to more DC-charging even at low power level with DC-charge wall boxes. Charging connectors still vary between continents and should be harmonized. There are also new trends emerging with battery chargers. Vehicle-to-grid charging is one trend that needs new bidirectional charging stations or on-board chargers with adapted power electronics with a high overall and standby efficiency as well as an intelligent control concept for energy flow management. Wireless charging will give more comfort and enable autonomous vehicles to charge. Beside static conductive and static wireless charging, early concepts on dynamic conductive charging are tested in the field allowing to reduce or even eliminated the on-board traction battery.

For autonomous vehicles, new energy supply concepts are necessary for a save and fail operational power supply of sensors and actors. This can be achieved by redundancy concepts or by intelligent power electronics with failure detection and segregation.

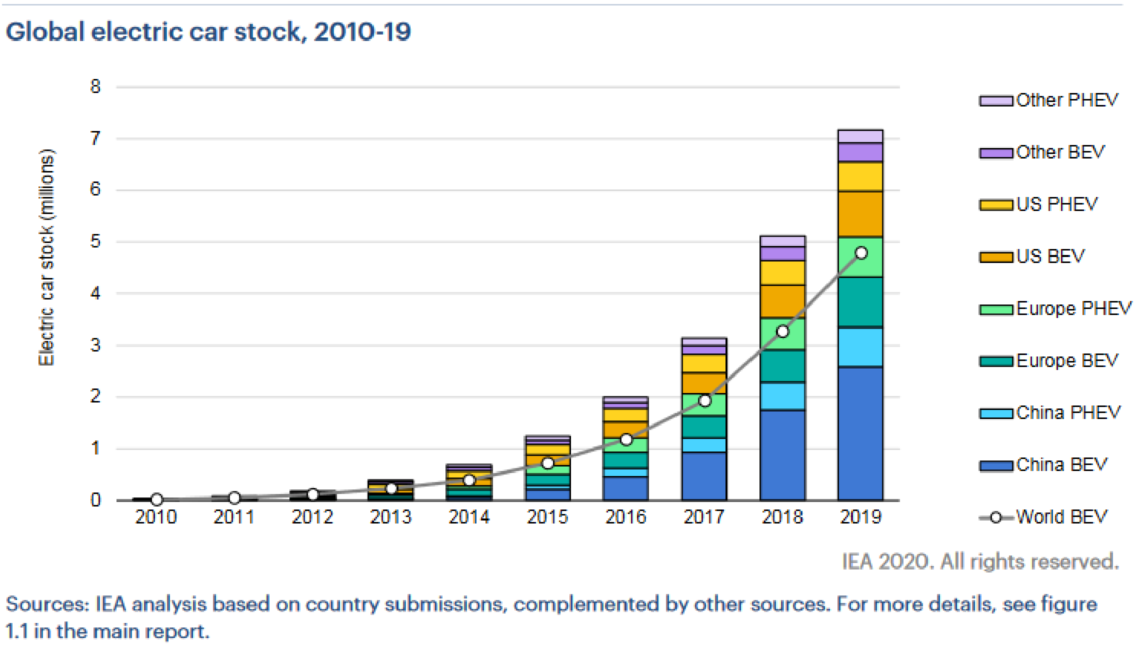


Fig. 4.3: Global electric vehicle car stock [4.5]

4.4 Trucks and busses

Trucks and busses share the same roads as cars, but energy and power demands are higher and the operation time is much longer. To cover the long and continuous operation time intelligent power electronics are needed for predictive maintenance. Power electronics are therefore designed to deal with higher lifetime requirements. Due to the high-energy demand, the applications will be covered by fuel cell powertrains in the future or by opportunity-charging and dynamic road charging. To operate a fuel cell many auxiliaries controlled by power electronics are required. Highly efficient and powerful DC/DC converters are needed to couple the fuel cell with a battery system and drivetrain. For the oxygen supply an electric turbocharger with approximately 10% of the nominal fuel cell power is needed. The drive inverter must handle very high rotation speeds of more than 150 000 rpm requiring inverter switching frequencies of around 100 kHz. Dynamic road charging requires large amounts of power electronics embedded within or beside the road. Depending on the technology used, technologies used in the railway industry can be used and modified for dynamic conductive road charging and technologies used for static wireless charging can be transferred to dynamic wireless charging.

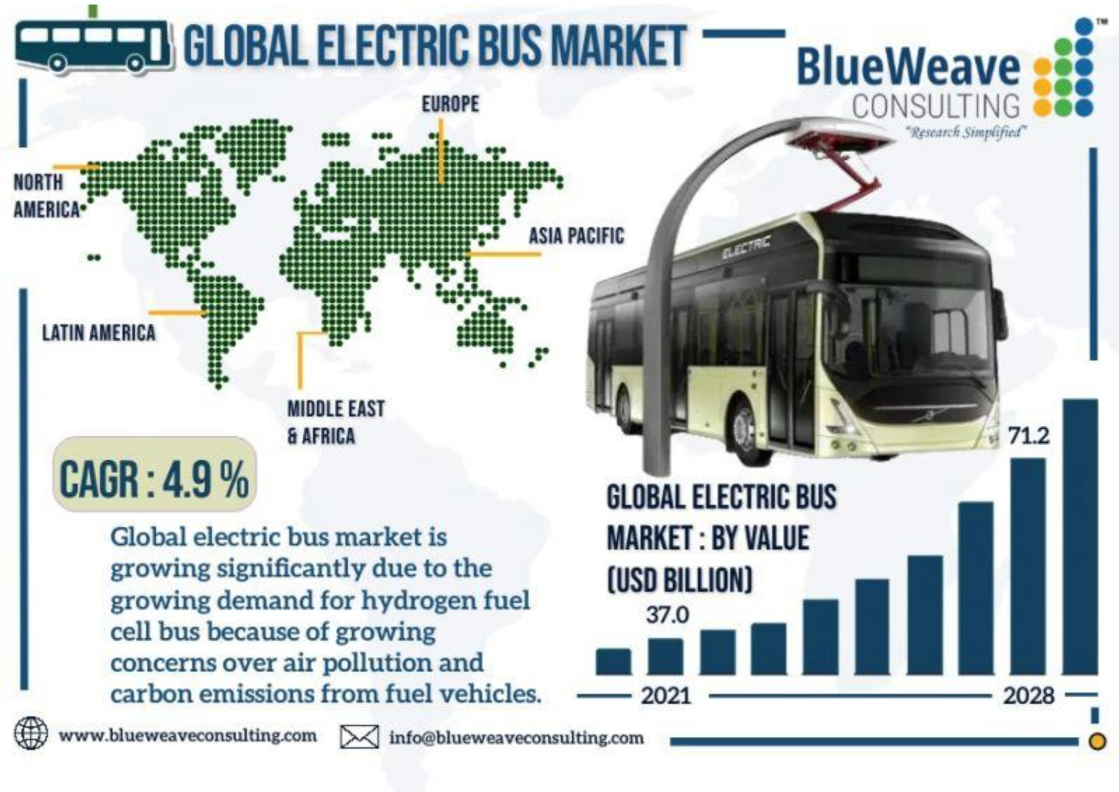


Fig. 4.4: Global electric bus market [4.7]

4.5 Off-highway

Off-highway vehicles cover those used for construction and agriculture. Today only 3% of the off-highway global powertrain market is hybrid. Large constructional vehicles operate the engine 24 hours a day contributing significantly to global warming. The off-highway sector is the most unexperienced sector in terms of electrification. The power level required is bigger compared to trucks and busses and therefore off-highway vehicles are also suitable to be powered by hydrogen or if available directly from the grid. Also, power electronics is not only required for the traction but also for the functions that off-highway vehicles are designed. For example in case of an excavator, power electronics must move the boom, stick, bucket and also swing the cabin. For these applications power electronics must be designed to withstand short, high bursts of power as well as periods of no or low-power activity putting a constraint on the thermal power cycle which impacts on the lifetime of the power semiconductor switches and components. Also, the weight of actors, in particular if loaded (e.g. full bucket) offer substantial energy recovery. Therefore, for off-highway applications power electronics should be designed to optimize recuperation. Finally, many off-highway vehicles are working in harsh environments dealing with dust, dirt and water. Power electronics components need to be designed to withstand these conditions.

4.6 Railway

From all transport modes railway is the mode that has experienced most electrification so far. However, of the approximately 1.3 million km of track worldwide just under 30% is electrified [4.8]. In railway applications power electronics is experiencing two trends. Trains and infrastructure are expected to last decades and as such power electronics must offer high reliability and long lifetime. The need for very high-speed trains is growing, resulting in the development and implementation of

MAGLEV trains (magnetic levitation) and Hyperloop trains (pods travelling within vacuum tubes). MAGLEV is based on superconductive technologies and as such requires power electronics switching devices, components and materials that can operate at cryogenic temperatures. In Hyperloop trains, power electronics components exposed to the vacuum have no medium for conductive or convective heat transfer.

4.7 Marine

Worldwide, maritime transport is responsible for almost 2.5% of total greenhouse gas emissions, according to the International Maritime Organization. It produces one billion tons of CO_2 each year [4.9]. Electrification is seen as an enabler technology to reduce CO_2 and power electronics plays a pivotal role within this transition. In 2020 the global electric ship market was sized at about 4.6 billion USD and was projected to grow at a compound annual growth rate (CAGR) of almost 12% until 2026 [4.10]. Electrification on vessels, ferries and ships also provide performance gains such as maneuverability. Power electronics in marine applications must be designed for long lifetime and robustness. For example, the indirect exposure to salt water requires good encapsulations of power electronics components. Due to the amount of power and energy required in marine applications, hydrogen powered fuel cells are seen as an alternative to classical batteries. As such power electronics are required to operate the entire fuel cell system. In addition, due to the large scale of loads in large vessels, power needs to be efficiently distributed in a controlled manner. Consequently, in maritime there is a large overlap between power electronics engineering and power systems.

4.8 Aviation and aerospace

Emissions and noise from aircrafts must be reduced by 2040 [4.11] and electrification will undoubtedly help in achieving these targets. Aviation will have a high potential impact in CO_2 reduction as the aircraft fleets worldwide are expected to grow again after the Covid-19 crisis with highest growth rates in Asia Pacific.

The aerospace sector is one of the most challenging sectors when it comes to electrification. That is because not only should power electronics be highly efficient to reduce weight of cooling systems, but it also has to provide an extreme high power-to-weight and sufficient power-to-volume ratios. Traditional power electronics using silicon (Si) based power modules cannot achieve these target values. Therefore, new wide bandgap (WBG) semiconductors like SiC and GaN are needed and for the future even ultra-wide bandgap semiconductors (UWBG) will give an additional benefit. Due to the extreme environmental temperature cycles, passive components must withstand harsh temperatures. In addition, reliability is very important in aerospace and as such bespoke power modules and components need to be developed to fulfil aerospace criteria. Traditional circuit topologies such as three phase inverters supplied from one dc-link can be a single-point failure. Therefore, fault tolerant power electronics circuits are considered. For future short and medium range airliners superconducting power trains are under investigation. This gives new challenges like operating power electronics at very cold environments of -200°C. Also, special inverters with high frequencies for superconducting electric motors must be investigated.

Power electronics is also required for new sectors that in some cases do not have even standards yet. For example, power electronics is required for vertical take-off and landing vehicles and unmanned aerial vehicles.

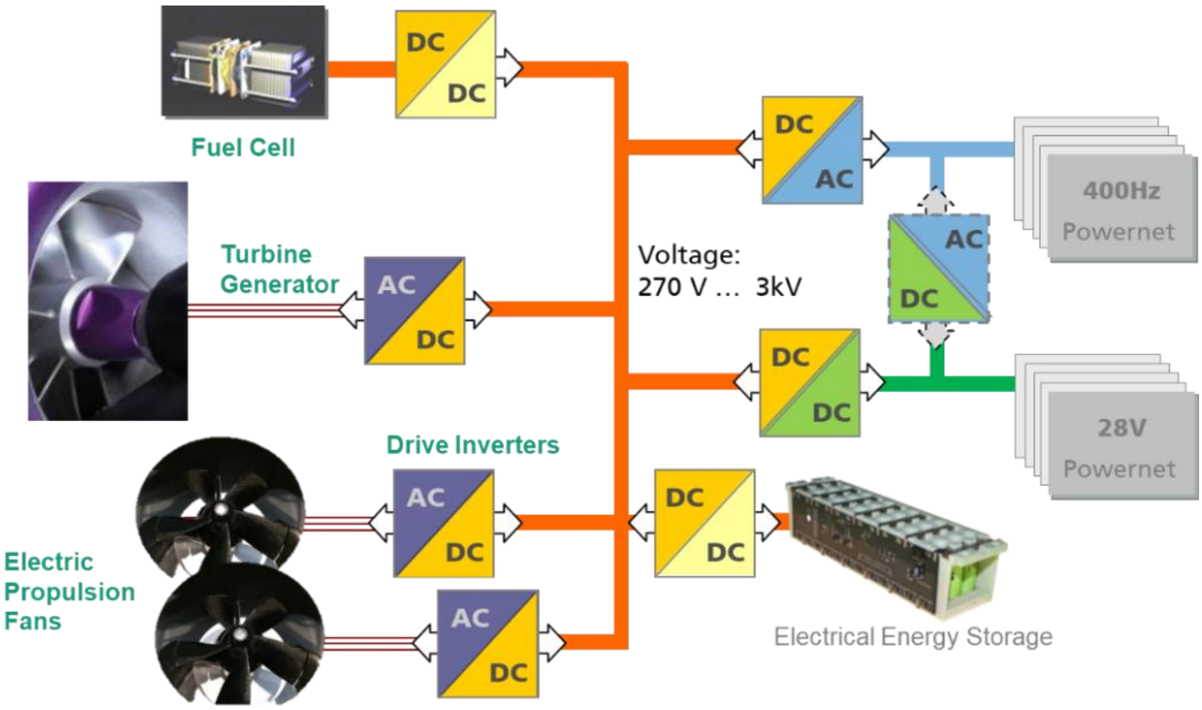


Fig. 4.5: Future electric power train of electric propelled aircrafts

4.9 Conclusion

In general, the role of power electronics in e-mobility is to provide the charging and discharging of the battery, to provide control of the traction drive, to power vehicle ancillaries and in multi-level voltage systems to connect different voltage systems using DC/DC converters. Today most commonly Si IGBTs and Si MOSFETs are used depending on the power level. The rise of WBG devices have several benefits that are vital in the mobility sector. High switching frequencies will lead to significant rise of power-to-weight and power-to-volume factors. Beside cost, these two factors are critical in most mobility sectors.

5. Power Electronics in Industrial Manufacturing

5.1 Summary

Power electronics in industrial manufacturing is closely related to the Industry 4.0, or even its larger concept, the Fourth Industrial Revolution (4IR), as the lines between the physical and digital worlds blur.[2] Smart and integrated drives may seem naturally associated with this movement, but condition monitoring and smart maintenance, as well as power supplies for industrial processes have become equally important elements of this transition. DC industry grids offer further possibilities to make overall industrial processes more efficient. The focus is not only on energy efficiency, but also on minimizing the use of energy-intensive and limited raw materials such as copper and aluminum.

In summary, power electronics is one of the key enablers for the transition of many industrial processes to a sustainable, energy-efficient and digitalized mode of production.

5.2 Smart and integrated drives (Industry 4.0)

With the advent of advanced system control and monitoring, inverters as used within Industry 4.0 may not only be required to fulfill its formerly main task, i.e., to supply the driven electric motor with electric power in the desired form but it may also become an element that is at the heart of the control and monitoring of the overall process. Thereby, a "smart inverter" has been defined as an inverter that "… controls and looks into the process, collects information and offers it to the digital world." [5.2]. Therefore, in addition to its fundamental function of driving the motor, it provides a key element of the process automation. To ensure interoperability and integration of the digital information, key requirements have been defined in the Asset Administration Shell (AAS), the central concept of Industry 4.0 [5.3]. Accordingly, as summarized in [5.2]:

- use of standardized formats is required to ensure interoperability
- the smart inverter can be clearly identified (asset information)
- it provides correct process data
- and it enables or automatically connects to Industry 4.0 services (e.g., condition monitoring)

Based on their integration into the automation systems and the direct measurement of significant process parameters (e.g. motor voltage and currents), the smart inverters form the core of the smart and integrated drive systems. Thus, the power electronics and their related signal processing serve as an interface between the drives and the automation level above. This applies to the entire range of drive technology, from highly integrated drives [5.4] in the W and kW range to applications in the medium-voltage range, where the power can reach up to 100 MW.

5.3 Condition monitoring and smart maintenance

As per the previous section, a smart converter may act as intelligent sensor for collecting and evaluating of process and internal data and thus may serve condition monitoring and predictive maintenance functions.

[2] For further information in 4IR and the focus of its component Industry 4.0 on digitization, organizational transformation and productivity enhancement see [5.1].

As per [5.5], the benefits both for the manufacturers of power electronics systems and for the customer are manifold, as the smart inverter allows obtaining general information about the system, such as load and ambient conditions, so as to detect possible weaknesses and dynamically optimize the system performance. The recorded measurement data also provides detailed information of the mechatronic drive system in case of faults, which can be used for root cause analysis and further product improvement. It also features condition monitoring and predictive maintenance capabilities, not only of the inverter, but of the entire system/process, enabling a reduction in downtime and overall service costs.

Such advanced condition monitoring and predictive maintenance comes with strong requirements, such as the ability to clearly indicate and analyze the occurring failure(s). The aim of these condition monitoring systems is to predict upcoming failures, including the prediction of the remaining useful lifetime of the components being monitored [5.6]. In doing so, the reliability of the drive systems should not be compromised by the use of condition monitoring and the system costs should not be increased, which is why additional sensors should be avoided as far as possible. A further key challenge is the pre-processing of the measurement data in the signal processing of the smart inverter and its further processing and storage in the components of the higher-level automation system.

5.4 Power supplies for industrial processes

The demand for converters in the low and medium voltage range continues to increase across the entire power range and is determined by several factors. This is mainly due to the possibility to both increase the system energy conversion efficiency and the process flexibility offered by variable frequency based industrial drives. In addition to the already well-established low-voltage drives below 1 kV, multilevel converters in the medium-voltage range above 1 kV have seen increasing popularity and market acceptance over the last two decades [5.7]. This trend is supported both by the rapid development of Si-, SiC-, and GaN-based power semiconductors (IGBTs and MOSFETs), that have replaced thyristor-based solutions by self-commutated voltage source inverters, and by an increasing interest in grid-related applications for LV and MV converters for power transmission and distribution. These latter are both driven by the energy generation from renewable sources such as PV and onshore/offshore wind and the demand for power quality services at all voltage levels in the transmission and distribution grids. In addition, some industrial processes are experiencing an immense upswing due to the conversion of the energy system to sustainable technologies and thus represent a revived, new application for power electronics. One example is the integration of large-scale electrolyzers to produce green hydrogen, which in the future will have to be integrated into the power grids in the multi-GW range via power converters.

In addition to the conversion of energy generation and new technologies for energy storage and conversion, the classic applications on the consumer side must not be forgotten. An estimated 65% to 70% of the electrical energy consumed in industry is converted into mechanical energy by drive systems [5.9]. As a result, the energy efficiency of these applications in particular is increasingly in the spotlight. Due to the significant increase in energy costs, which are expected to continue rising, any improvement in energy efficiency will not only lead to more sustainable but also to economically attractive solutions.

In addition to the drive components (i.e. motors and converters) themselves, the focus is increasingly on the holistic optimization of industrial processes. This is the only way to successfully exploit the entire energy-saving potential. This development is also increasingly reflected in standardization and the definition of energy efficiency standards contained therein [5.10].

Among other things, this also leads directly to the following section, in which the potential of power electronics-based DC grids in the industrial environment is addressed.

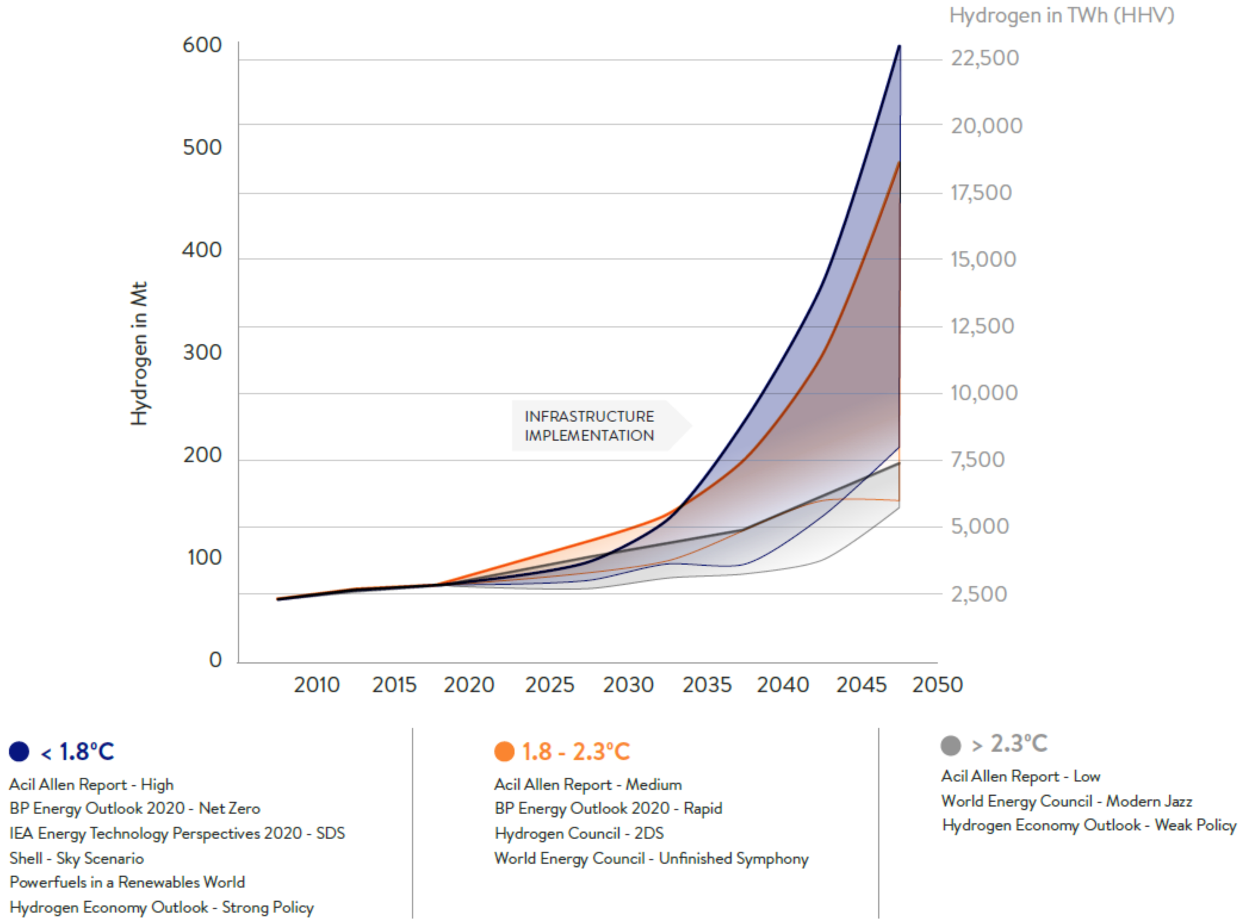


Fig. 5.1: Range of Hydrogen demand assessment by 2050 [5.8]

5.5 DC industry grids

Most equipment within homes and offices, but also larger scale applications, such as factory automation are supplied by DC voltage. When compared with AC, power electronics-controlled devices directly connected to the DC grid operate at very high efficiency levels and draw from other advantages of DC power supply mentioned below.

One of the main advantages of DC grids is mainly due to the greatly reduced number of energy conversion stages resulting in increased energy efficiency. Although a DC/AC converter can already achieve efficiencies of more than 99% when using modern SiC power semiconductors, especially in the partial load range, a reduced number of power converters still means significant energy and resource savings over the entire product life cycle.

Together with further energy saving potentials at system level, e.g. the use of braking energy, this results in efficiency gains of up to 10% (sometimes even 25% depending on the system configuration and load cycles) compared to conventional AC coupled systems [5.11]. For operators, the use of modern DC systems also results in further advantages. Due to the reduced number of system components, the footprint of the systems can be reduced[3]. The use of (galvanically isolated) DC/DC

[3] E.g., [5.12] reports on a reduction in size of the converters by up to 25%.

converters also makes it easy to integrate DC-coupled energy storage and power infeed e.g. from photovoltaics. This allows the peak load required from the AC grid to be reduced or - in the event of a breakdown of the AC grid - the DC grid can also be operated autonomously. This makes the systems robust and fail-safe, as the power converters themselves are able to detect these operating states and the DC grid can continue to be operated in a stable manner. No dedicated, higher-level communication infrastructure is required. An additional supervising energy management system to optimize the cost and energy efficiency of the DC grid thus makes it possible to provide customized solutions for energy supply.

If the DC grids are connected to the AC grid via active DC/AC inverters, these can actively support the AC grid by providing grid services such as frequency and voltage support [5.12]. This is an advantage that is becoming increasingly important in the course of the gradual conversion of the AC grid to a purely power electronics-dominated grid in the "All Electric Society".

Finally, it should be noted that DC grids will only become established if there is manufacturer-independent standardization of power electronic components and systems. This process has only just begun and must be pursued consistently. This is essential to ensure the long-term success of DC grids [5.11].

5.6 Pulsed power (e.g. in medical or food treatment)

While pulsed power technologies have been used in medical applications for some time, more and more power electronics-based applications are also being added in the fields of food processing and water treatment. These so-called solid state pulse generators produce repetitive unipolar or bipolar high voltage pulses based on semiconductor devices. The increased demand for high-voltage generators for the generation of repetitive high-voltage pulses requires special circuit topologies and opens up new optimization possibilities in the field of power semiconductors to enable the requirements for the efficient generation of steep-edged high-voltage pulses.

One application example is the electro-pulse treatment (electroporation) of plant tissue for the energy-efficient extraction of valuable ingredients from plant raw materials. In this process, high-voltage pulses are generated by a modern, energy-efficient and low-maintenance pulse generator based on power electronics and used to decompose the biological cells.

Among many examples in the field of juice extraction from fruit, processing of potatoes, the example of sugar extraction from sugar beets should be mentioned as an example of increasing energy efficiency in food processes by using power electronics based high voltage generators. Electroporation of sugar beets can replace thermal disintegration of the biological cells. Here, sugar is usually extracted from the beets at a temperature between 69°C and 73°C after the cells have been thermally disintegrated at a temperature between 70°C and 78°C. Experimental investigations have shown that electro-pulse treatment of sugar beet pulp in combination with the alkaline extraction process could lower the extraction temperature down to 60°C. In addition, less water is required for the extraction. Therefore, the downstream evaporation process to concentrate the sugar requires less thermal energy, the dry mass of the electroporated material increases (here, by 5%), reducing in turn the energy requirement for the following shred drying for livestock feed production. The results of the study suggest energy savings of at least 20% for the overall process of a sugar factory [5.13, 5.14].

6. Energy Savings in Smart Home & Office and Data Centers

6.1 Summary

The Smart Home & Office is driven from a DC source directly and addresses a large variety of different loads from lighting to home appliances, computing and communication devices. The digitalization and optimized fast switching power semiconductor devices enabled highly efficient, low volume power converters to penetrate in this cost sensitive mass market application. The driving force for this field of application is power density and energy saving. Despite this fast-increasing number of electrical devices there was a continuous decrease in energy consumption. Based on the new technology developed, the following numbers in the individual application segment shows the world energy saving potential:

- Lighting devices: 1 200 TWh/year
- Home appliances and HVACR systems**:** 340 TWh/year
- Computing and Communication equipment: 7.8 TWh/year
- Data Center: 28.4 TWh/year

6.2 Introduction to the individual fields of application

Power electronics is the key technology to control the flow of electrical energy between the energy source and the consumer with great precision, extremely fast control times, high efficiency and high-power density on all power conversion stages. There is a huge variety of different loads in the home & office applications starting from lighting to home appliances e.g. washing machines and induction cookers, HVACR (heating, ventilation, air condition, refrigeration), consumer, computing and communication equipment, etc. which are needed to be precisely controlled on demand, maximized in energy efficiency, minimized in size and weight, at the same time working at the highest level of reliability and to be competitive on the market. And all these applications are extremely cost sensitive.

Electricity generation is currently the largest source of energy-related CO_2 emissions, accounting for 41% of the 34 Gt of CO_2 emitted worldwide in 2020. More than 40% of the current electricity energy consumption is for just four end uses – industrial electric motor systems, air conditioners, refrigeration and lighting. These four uses also contribute over 5 Gt of CO_2 emissions a year – roughly equal to the United States' current total CO_2 emissions [6.2]. Energy saving is realized on three levels:

- component level (e.g. semiconductors, LEDs, sensors)
- system level (e.g. motor controlled HVACR, digital controlled power supplies, low stand-by power
- building, facility level (e.g. smart control and emerging autonomy coordination of multiple components/systems towards a common goal)

The leverage factor for added value from power devices to power converters is a factor of 5 to 10, from power devices to final systems even a factor of 20 to 100 depending on the system and application (Source: Siemens, Infineon and ZVEI). For the European economy it is important to cover the whole value-added chain from the component level to the final system and from hardware to software.

6.3 Energy saving benefits by applying power electronics in home & office equipment

Lighting

The migration from incandescent and fluorescent lighting to LED relies on dedicated power electronic drivers to carefully manage flicker on the one side but improve light quality for various purposes of illumination. Reduction of power consumption is achieved significantly from 100% consumption in the case of incandescent to less than 10% in the case of LED. Smart power electronic drivers cover all options of illuminations from dimming to different colors, intensity and spectral compositions up to autonomous lighting in public areas. Even they can be powered by photovoltaic panels directly. Indoor lighting in residential and commercial buildings significantly contributes to global energy as well as peak demand. Efficiency gains in lighting can deliver substantial energy savings, while allowing access to and improved quality of energy services in developing countries. Therefore, lighting is an essential target for demand-side energy efficiency initiatives due to its relevance and cost-effectiveness. Following the study in SEAD 2021 (SEAD is an initiative of the Clean Energy Ministerial) in which the efficiency of all new indoor lighting sold globally doubled from 2022 onwards, the potential global annual electricity reduction by 2030 could be 1200 TWh, resulting in approximately 550 Mt of CO_2 emissions reductions.

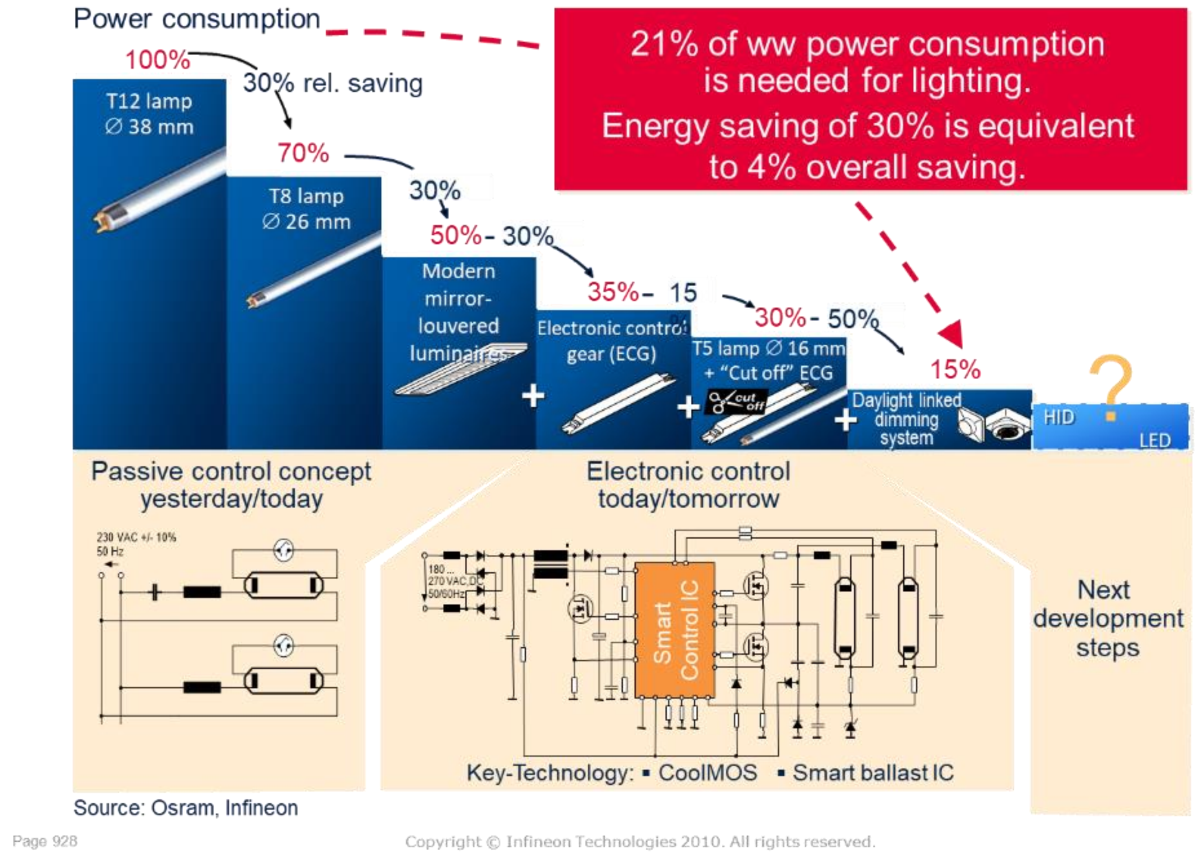


Fig. 6.1: Lighting systems: energy savings with electronic control

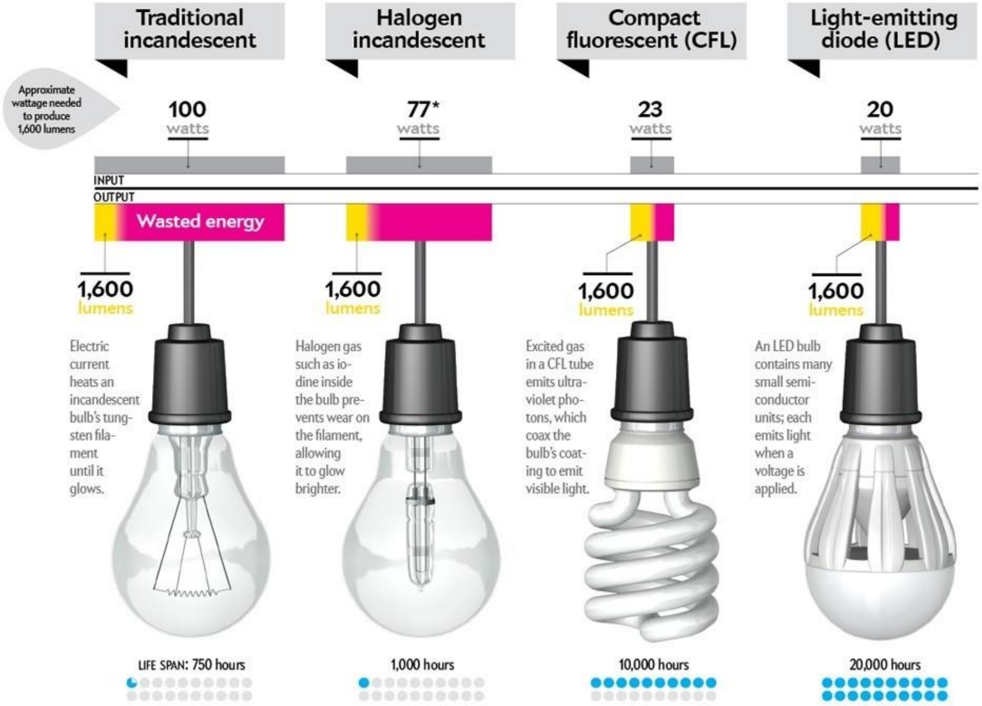


Fig. 6.2: Lighting systems: efficiency and longevity [6.12]

Home appliances and HVACR systems

Heating, ventilation, air conditioning and refrigeration systems usually use some sort of heat transport medium which needs to be circulated by pumps as well as heat pumps for shifting thermal energy from lower to higher temperature levels. These heat pumps typically involve compression of a working medium, condensation at higher pressure and temperature, and expansion and evaporation at lower pressure and temperature [6.1]. Basically, all this equipment is using a variable speed drive today. Moving from the old DC motor with very simple electronics to a variable speed drive with today's power electronics, there is an efficiency increase from less than 60% in the past to higher than 95% with today's power converters. A variable speed drive is an electronic device that can be used to adjust the rotation speed of an electric motor according to the needs of the application. There are about 8 billion electric motors in use in the EU [6.10].

There are several different motor drives using power electronic converters e.g. in washing machines, dishwashers, refrigerators, freezers, heating systems (pumps, fans), heat pumps for heating and/or cooling. Modern refrigerators may have fans inside and outside the cooling compartment for improved heat exchange and valves and flaps for controlling the coolant and air flow for maintaining the desired temperature distribution. On top of this with the faster switching and lower loss devices, the size of the power converter could be reduced by a factor of up to 10 which is going along with significantly less material consumption, leading to overall energy saving, precise control of speed and torque, more compact and powerful motors, smaller power converters and altogether lower system cost. Depending on the smartness of the control for all this equipment there are different "Energy Levels" available on the market.

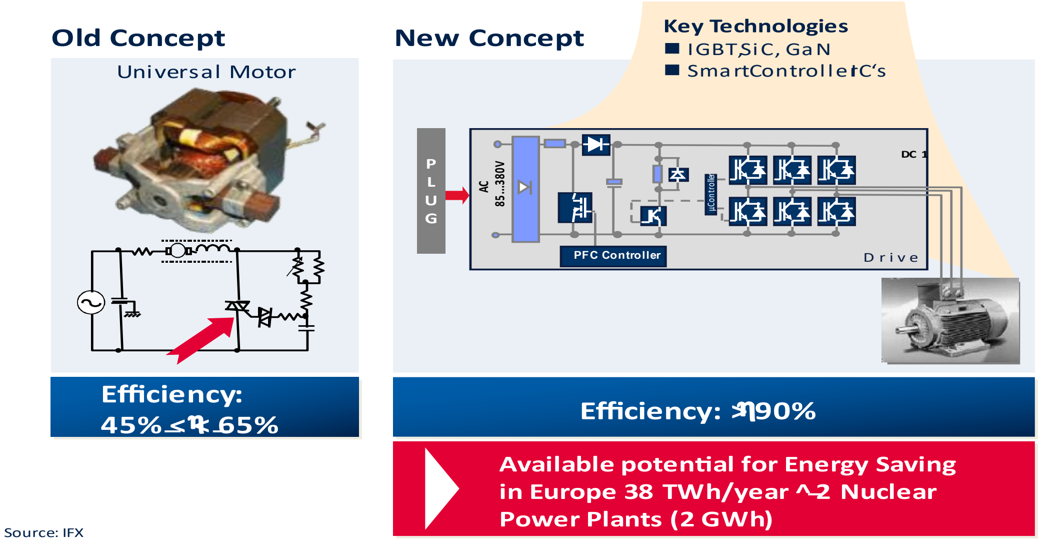


Fig. 6.3: Motor drive concepts for home appliances

A more efficient motor can generate savings ranging from a few euros to several tens of thousands of euros over its lifetime, depending on its power and use pattern. Considering that the new regulation (application of modern power electronics) is consequently applied in all motor drives, the annual savings will increase to 110 TWh by 2030 in the EU. This means that 40 million tons of CO_2 emissions per year will be avoided and that the annual energy bill of EU households and industry will be reduced by approximately € 20 billion by 2030. Following the well-known assumption that the European market share is approximately 30%, the USA market share is 30% und Asian market share is 40% the worldwide energy saving by applying the variable speed drives with modern power converter technologies in all appliances the worldwide energy saving potential is 370 TWh per year.

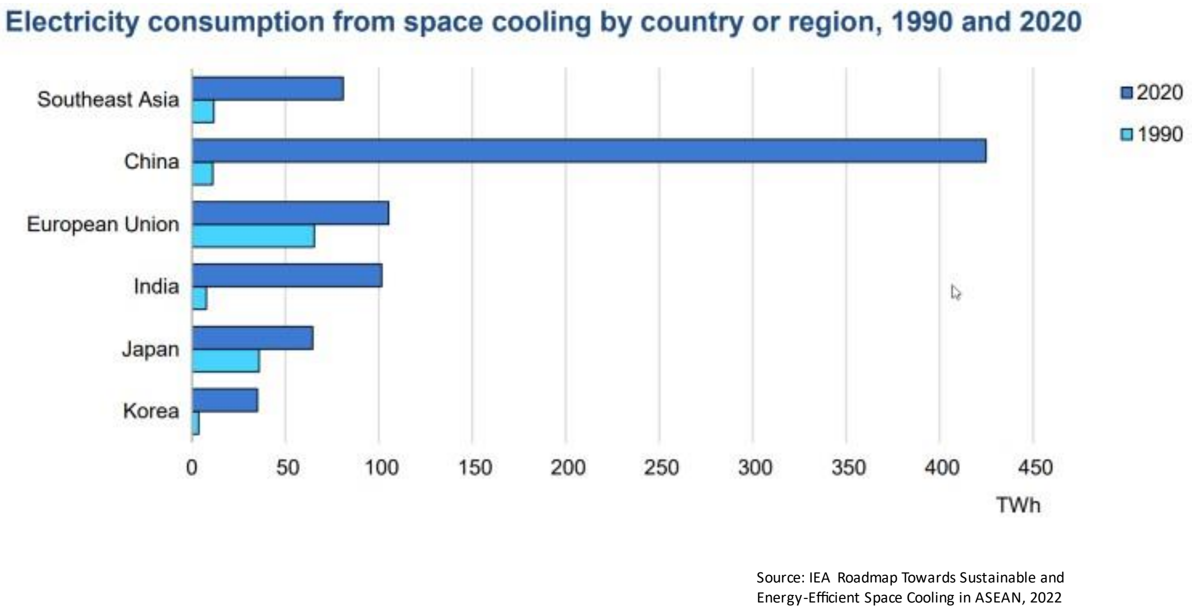


Fig. 6.4: Electricity consumption from space cooling in different regions [6.13]

Computing and communication equipment

All this equipment needs to be powered by a Switch Mode Power Supply (SMPS) and a special attention is paid to the stand-by power losses. The driving force behind these SMPS is to miniaturize the size and volume and at the same time achieve an increase in efficiency. Efficiency and cost reduction are the key figures to evaluate SMPS. SMPS represent by far the biggest industrial sector and market by the number of sold units. These power converters are the key elements inside all equipment in the home and office area like consumer electronics (e.g. induction cookers, TV sets, satellite receivers, tuners, DVD players, electric toothbrushes), computers, mobile phones just to mention some important examples.

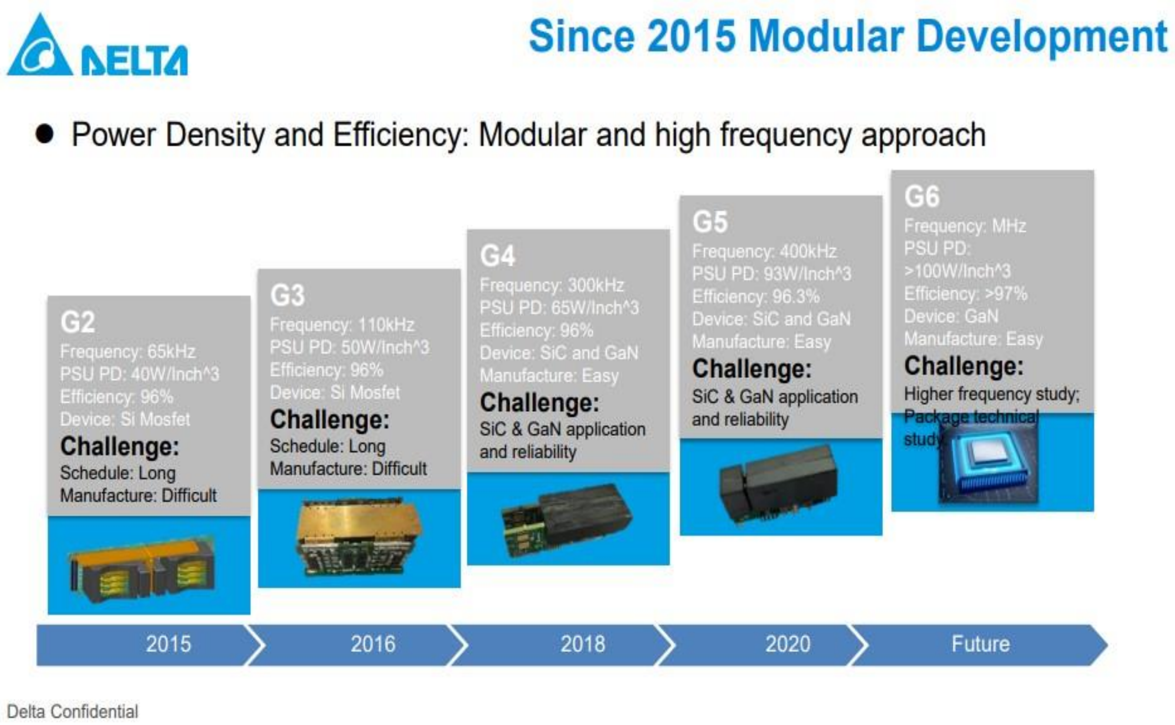


Fig. 6.5: Modular development of power supplies since 2015
(source: in courtesy Peter Wallmeier, Delta Energy Systems)

Mobile devices, being powered by a battery of modest capacity, with compact form factor and with severe space constraints, require extremely efficient power electronic converters. Taking a mobile phone as an example there are dozen SMPS' integrated inside, providing voltage regulation for the various sub-circuits: WIFI, audio, screen backlighting, processors, etc.

To give an example for energy saving by applying wide bandgap (WBG) power devices: Following a white paper published by Google in 2006 [6.10], the efficiency increases from 70% in 1994 to above 90% in 2010 (today 96%) based on new power semiconductor devices reduced loss energy by a factor of 4. Assuming the new power supply design gets deployed across 100 million PCs (this is the demand of Germany) estimates a saving of 40 TWh over 3 years which translates to 5 billion EURO at current Germany energy rates. The energy saving potential based on highly efficient power supplies with the new power devices for Delta products delivered in the timeframe from 2010 to 2019 is calculated to 30 TWh which stands for 16 million tons CO_2 reduction (Source: Delta with more than 40% market share). The world market is calculated to be a factor of 2.5 higher. In addition, we must see that with these ultra-fast and low-loss switching devices the size of the power converters could be scaled down by a factor of 50 or even more which is reducing the material consumption tremendously. These new types of ultrafast switching devices are the key element in all SMPS (DC/DC and AC/DC) converters.

The worldwide energy saving potential is calculated to 7.8 TWh per year [6.1].

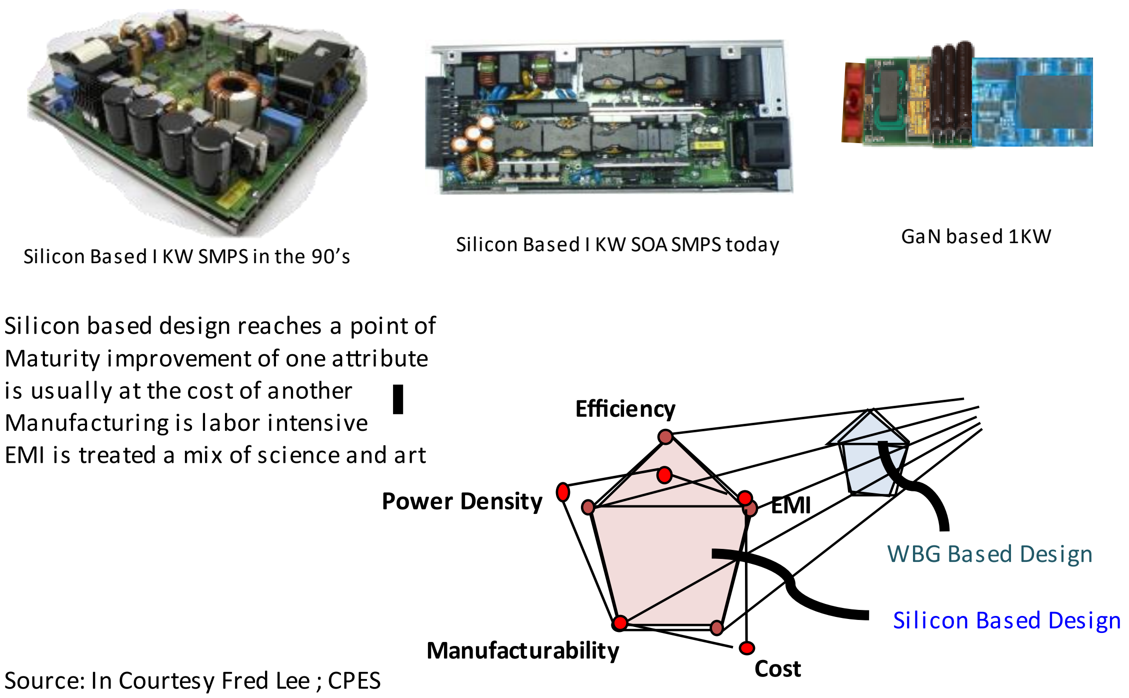


Fig. 6.6: Power supply development trend (source: in courtesy Fred Lee, CPES)

Data centers

Beside e-mobilty and renewable energy technologies the fastest growing field is data centers. With the development of the information society, tremendous amounts of data exceeding traditional expectations will be handled, and this trend will continue to expand in the future. This is having a big impact on energy consumption. It is expected that the world information volume (IP traffic) in 2030 will reach 30 times more compared to the present day and 4000 times more in 2050. Following a study from Japan Science and Technology Agency 2019 - Center for Low Carbon Society Strategy, the electric power consumption concerning information will reach 42 000 TWh annually in 2030 and 5 000 000 TWh in 2050 which is much greater than the current world electric consumption of 24 000 TWh. In these applications efficiency increases from the conventional solution today with an average efficiency rating of 84% to the future solution with appropriate topologies and the application of the new type of power semiconductor devices could go up to 96%.

By connecting data centers directly to a DC grid the energy saving potential in Germany is 5 to 10%. Assuming a total energy demand of 15 TWh per year in Germany [6.8], i.e. annual savings of 0.75 TWh to 1.5 TWh or 375 000 t to 750 000 t of CO_2.

The worldwide energy saving potential total is calculated to 28.4 TWh per year [6.1].

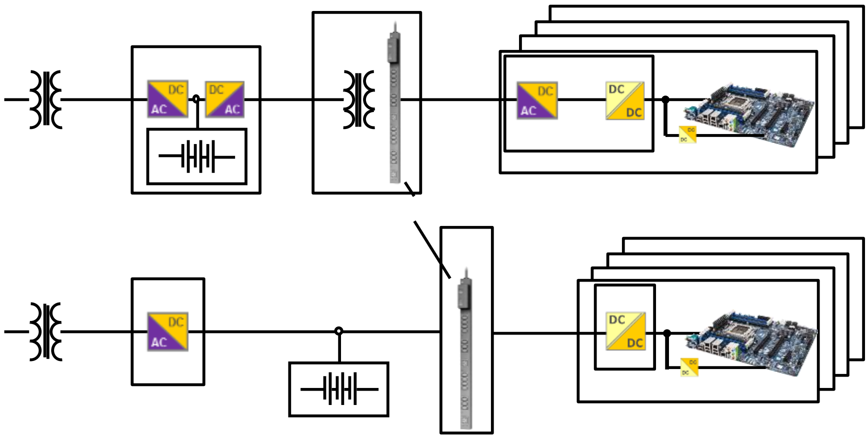


Fig. 6.7: DC grids for decentral energy systems

DC Grid for home & office, shopping centers and production plants

Most of the equipment we are operating in the home & office, factory automation and in shopping centers are supplied by a DC voltage. All devices are directly connected to the DC grid and controlled by power electronics converters operating at very high efficiency levels and sense the stability and behavior of the DC power supply. Furthermore, the DC power grid in the factory supports the transformation towards digitalization, communication of electrical systems and devices and the application of artificial intelligence (AI). In addition, the transparency of energy flow offers - beside energy efficiency - many other advantages listed below. All power supplies today are having an AC/DC converter in the input followed by one or multiple stages of DC/DC converters. Also, variable speed motor controls are having a 2-stage power conversion system AC/DC followed by a DC/AC converter. Connected by DC grid directly, early machine aging effects are sensed and predictive maintenance can be applied easily by using the current waveform. The DC/DC converters today with new generation pf power devices operate significantly above 95% while the AC/DC converter are large in volume and low in efficiency (below 85%). This is saving space, material, cost, and increases reliability and efficiency. DC grid is also the basic for powering all future e-propulsion systems [6.7].

Direct Current (DC) advantages [6.6]:

- Peak power reduction (up to 80% by a much simpler integration of battery storage)
- Increase in energy efficiency (reduction in AC-DC/DC-AC conversion processes, use of braking energy) with energy savings of 6% to 10%
- Increase in security of supply (easier battery storage integration)
- Easier implementation of intelligent grid structures
- Easier integration of renewable energy
- Grid friendly support of AC utility grid
- Smaller, lighter, cheaper (the converters required for energy-efficient drives are becoming simpler, smaller and cheaper. Many components that are required for AC are no longer required for DC. Converters can save 25% and more in volume and weight. The same applies to other electronic devices that are connected to the DC grid).

A comparison of AC and DC grid connectivity is shown in figures 6.7 and 6.8, highlighting the beneficial bidirectionality inherent in the DC grid.

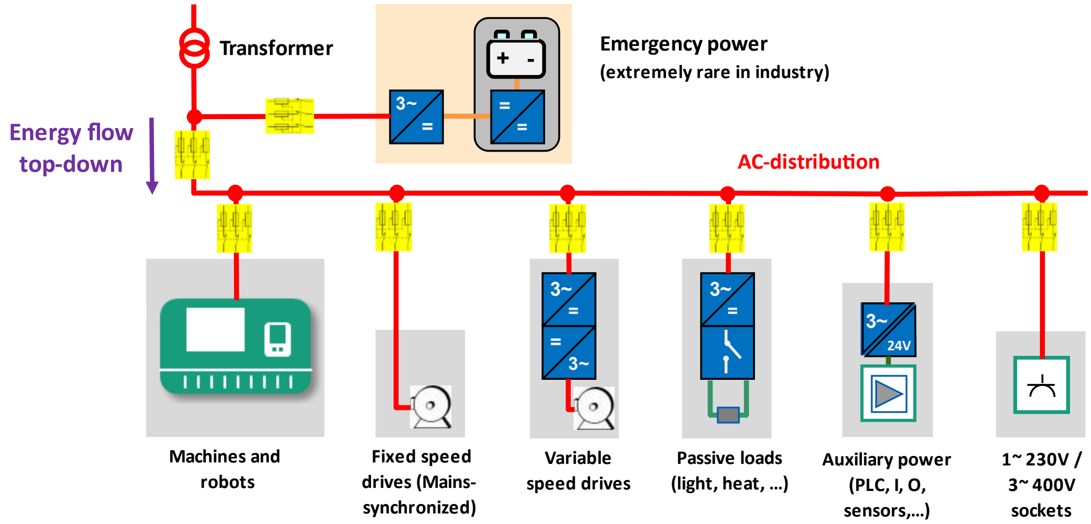


Fig. 6.8: Status quo: topology of an industrial AC grid [6.11]

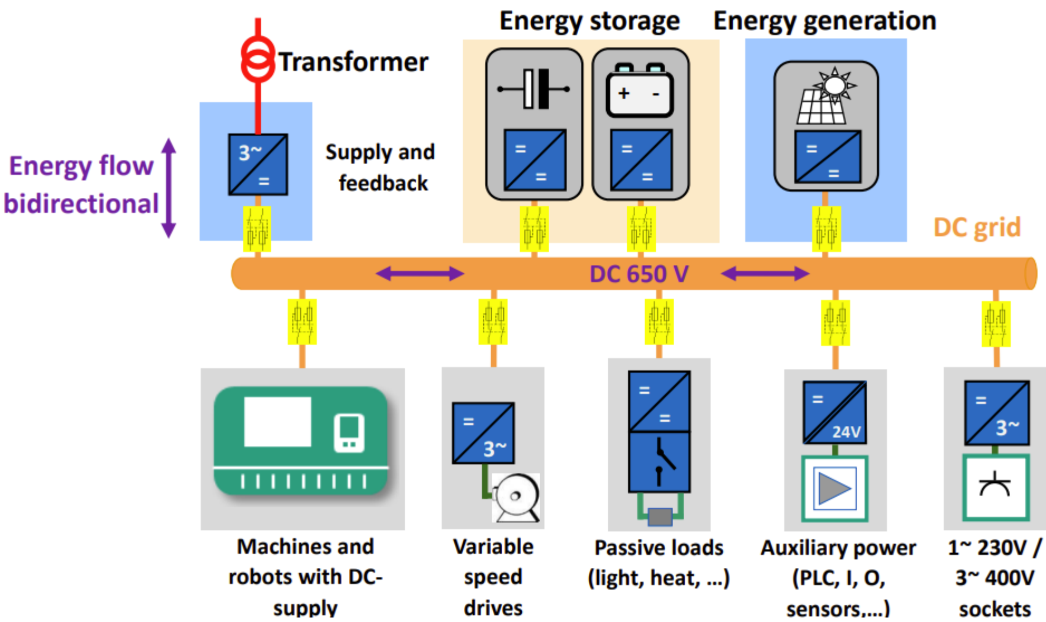


Fig. 6.9: Topology of an industrial DC grid [6.11]

7. Trends in Power Electronics

7.1 Power devices

The performance of active and passive power devices has always been a limiting but also enabling factor for power electronics. Therefore, the progress on these devices has usually triggered a corresponding progress in power electronics. Likewise, this will happen in the future with new or advanced devices. In recent years, semiconductors, especially those made of wide bandgap (WBG) materials, have shown significant progress on this track whilst their packaging and the associated passive components have lagged behind. Thus, innovation in packaging and passives is most desired.

Semiconductors

Silicon (Si) devices have been the workhorses of power electronics and will remain just that for quite a while. The low voltage MOSFET, the super junction MOSFET, the IGBT and thyristor-based devices have reached a level of maturity that ground-breaking improvements are not to be expected. However, theoretical borders like the Nakagawa-limit [7.1] for IGBTs still identify room for improvements and thus, gradual progress, usually driven by process technology, e.g. feature size or aspect ratio, will extend the life of silicon as the innovation driver at least until the end of the decade [7.2]. At the same time prices are coming down due to growing market volume and production on 300 mm wafers. In this way, silicon will remain a strong player at least in the “bread and butter” sector.

Two decades ago, the first **silicon carbide (SiC)** Schottky diode became commercially available, and one decade ago, the first SiC MOSFETs appeared on the market. In the meantime, SiC devices have conquered a considerable market share and made the step out of the high-end niche into the mainstream, with the e-mobility becoming a strong driving force (Tesla Model 3 with SiC-based propulsion converter). While the economy of scale is driving down prices (introduction of 200 mm wafers around 2025), SiC devices become viable for more and more applications and the variety of available devices, packages and topologies is steadily growing. On the one hand, the MOSFET is widening its voltage range upwards (6.5 kV) and downwards (650 V) and on the other hand, advanced device structures like the super junction MOSFET, the FinFET or even bipolar devices are attracting more and more attention. Furthermore, SiC devices are building up a track record of reliability and the remaining reliability concerns, like the threshold instability/hysteresis or bipolar degradation are eliminated or at least suppressed to a non-critical level. Therefore within a decade, SiC will become the primary player in most of the power electronics applications, at least for power levels above 10 kW [7.3].

Lateral gallium nitride (GaN) devices with voltage ratings up to 650 V are now established for applications up to a few kW. There is currently a strong focus for consumer electronics chargers (USB-C, laptops) but also for power supplies in data communication and storage centers. Automotive on-board chargers are currently under development. All these applications take benefit from the low parasitic capacitances and the low gate charge of lateral GaN transistors. GaN-based converter circuits can operate at higher switching frequencies with high efficiency and their volume and weight can be reduced as compared to Si-based converters with similar performance. The established GaN-on-Si hetero epitaxy growth is based on Si substrates with wafer diameters of currently 200 mm in commercial production with developments towards 300 mm. This is a key to allow for competitive GaN device costs. Lateral GaN devices suffer from a few drawbacks in performance where some are intrinsic to the device concepts, and some may be solved with good engineering. The transistor channel region and drift region are limited to a very small device volume (basically the 2-dimensional electron gas - 2DEG channel layer) which makes energy dissipation inside the device very difficult. Device ruggedness under short circuit conditions is thus very poor as compared to Si- or SiC-based competitors. For the same reason and due to the high GaN material defect density, device breakdown does not start via avalanching but happens spontaneously and is destructive. This requires an exceptionally high safety margin between rated voltage and real breakdown voltage. The p-GaN gate approach is used in most commercial transistors to obtain normally-off characteristics with threshold voltages of 1-2 V. Special gate drivers that are adapted to the limited voltage swing (typically 5-6 V) and that supplies the needed on-state gate currents have to be considered for optimum fast switching. GaN devices using an insulated gate (MISFETs) are still rarely seen on the market due to dispersion and reliability challenges with the non-native gate insulator materials needed in GaN technology.

Monolithic integration is an important advantage in lateral GaN technology. Integrated gate driver circuits with less parasitic inductances lead to cleaner switching transients of the power switches on one hand but also allow for a simpler and only voltage-based gate control in the system. Monolithic power switch integration of i.e. a half bridge is currently limited to ~100 V applications since the conductive Si substrate would lead to significant transistor channel depletion when the substrate becomes negatively biased with respect to the source of the high-side switch (backgating effect). Using SOI substrates or electrically insulating so called engineered substrates may reduce this issue but would significantly increase the thermal impedance. New promising approaches use pre-structured pn-wells in the Si substrate to electrically isolate the high-side from the low-side GaN switch [7.4].

In explorative research, the lateral GaN-HEMT device concept is now extended by stacking multiple 2DEG channel layers on top of each other [7.5]. This further reduces the on-state losses on one hand but the 2-dimensional hole gas layers (2DHG) generated in parallel allow for a more constant electric field strength along the drift region and – similar to super junction devices – to higher blocking voltages. A prerequisite is the implementation of a new tri-gate gate module where fins are etched into the heterostructure layers at the gate position to modulate the stacked channel layers from the side [7.5].

Vertical GaN transistors are recently considered for voltage ratings > 1000 V and for higher device current capabilities since they are also expected to have less capacitances and gate charges as compared to their SiC-based counterparts. The straightforward choice is GaN substrates which are currently available up to 100 mm wafer size but they are still prohibitively expensive. Their low defect density and the feasible GaN homo-epitaxy may allow for high reliability devices. Alternative substrate approaches with either substrate transfer or approaching the drain contact through big Si substrate vias for a GaN-on-Si concept, could give the vertical GaN devices a commercially more attractive perspective. In academic research 1200 V transistors based on the current aperture (CAVET), Trench-MISFETs, Fin-MISFETs and Fin-JFETs have been demonstrated. It is the Fin-JFET where the n-GaN fin is overgrown with p-GaN for the gate junction where repetitive avalanching with energies comparable to Si and SiC devices and a very competitive short-circuit ruggedness was recently demonstrated [7.6]. The technology is currently on its way to commercialization in the US. Vertical GaN transistors are in direct competition to SiC transistors but area-selective doping by implantation is a challenge in GaN due to its relatively low decomposition temperature of ~900°C. Engineering efforts are needed here to allow for well-designed channel structures that reduce internal electrical field peaks. But a 1200 V planar gate MOSFET based on n-type and p-type doping by implantation has already been demonstrated recently [7.7].

Gallium oxide (Ga_2O_3) with a band gap of 4.8 eV is considered as a very promising semiconductor material for power-electronic devices. The material breakdown strength is estimated as 8 MV/cm and the resulting power figure of merit ($R_{ON}A$ vs. V_{Br}) is higher than for SiC and GaN, even when considering the moderate electron mobilities of 150-180 cm^2/Vs. N-type doping in epitaxy can be controlled over a wide range of 10^{15} - 10^{19} cm^{-3} and low-resistive ohmic contacts have already been realized despite the high bandgap [7.8]. The thermodynamically stable polytype β-Ga_2O_3 crystal can be grown from a melt, which would allow for relatively cheap substrates as compared to SiC and GaN. A considerable material-based drawback is the very low thermal conductivity of ~0.2 W/(cm K), which is 7-10 times smaller than for silicon. P-type doping is not possible and, consequently, no avalanching was observed in Ga_2O_3.

While there were only lateral Ga_2O_3 transistors with average drift zone breakdown fields < 1 MV/cm demonstrated up to 2018 the situation gradually improved since then and a higher breakdown strength with respect to GaN is proven yet. Lateral transistors demonstrated up to 5 MV/cm [7.9] and up 8000 V breakdown voltage were reported in the meantime. However, the power figure of merit of GaN devices is not reached yet due to the limited on-state conductivity. Most lateral devices are MOSFETs with a threshold voltage often beneath -10 V, because the moderate electron mobility calls for a high channel electron density. Attempts for normally-off devices use hetero-contact gates with i.e. NiO or SnO as p-type structure [7.10]. There are a few reports on vertical Ga_2O_3 transistors with 1000 V blocking capability using the CAVET or Fin-MOSFET concept. Despite very active research activities on Ga_2O_3 devices in the last 5 years there are almost no reports on power-electronic switching above 100 V. 400 V / 0.2 A switching transients with lateral Ga_2O_3 MOSFETs recently revealed severely increased dynamic R_{ON} numbers [7.11]. It is not clear if their origin is inside the Ga_2O_3 material or related to the extrinsic gate insulator material. It seems that the expected very high breakdown field strengths of Ga_2O_3 devices can be realized in the next few years. However, dynamic switching under such high electric fields inside the device may become a severe burden for introducing Ga_2O_3 devices into real applications. More research and reports on switching properties are urgently needed before Ga_2O_3 can be considered as a serious competitor against Si, SiC or GaN in power electronics.

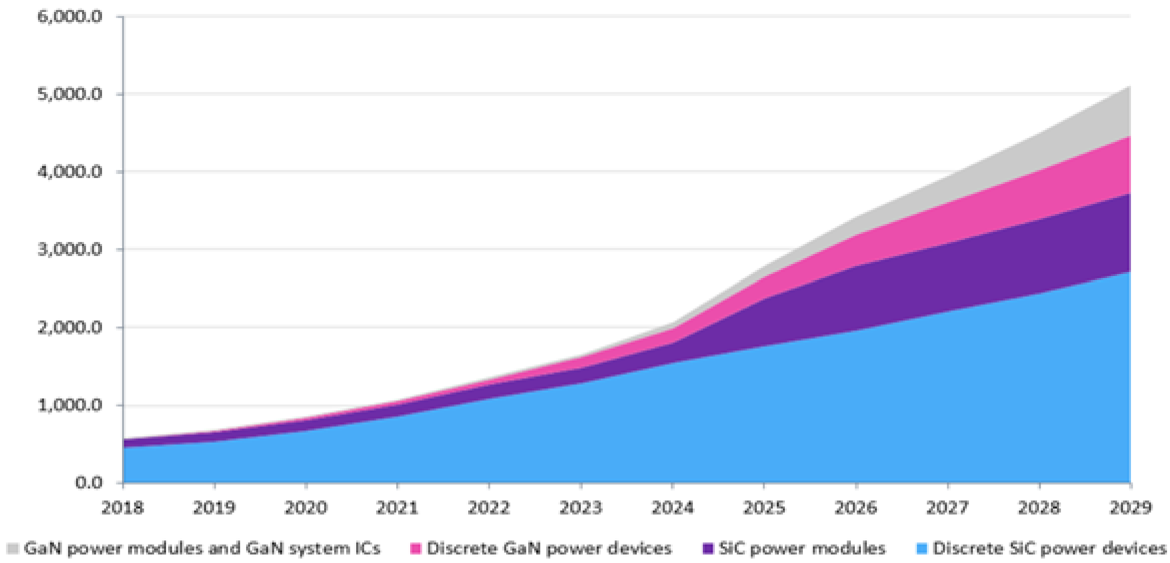


Fig. 7.1: Market volume of SiC and GaN devices in million USD by device type [7.12]

The different semiconductor technologies are in different stages of their life cycle and thus, the semiconductor mix will change significantly over time. Silicon technology is quite mature and profits a lot from other fields like processors and other logic circuits. Thus, the main step forward is the

transition to 300 mm wafers, currently being implemented and a gradual decrease of price per chip area. The silicon market will only profit from a general increase in market volume.
In contrast, the manufacturing process of SiC wafers is quite complex and – mainly Japanese – attempts to develop a melt-growth process have never yielded power grade wafers. Thus, SiC chips will remain more expensive per area than silicon, though the raw wafer prices are coming down especially when 200 mm will be introduced in large scale by the mid of the decade. On the one hand, smaller junction terminations and higher current densities compensate for that such that in the future SiC chips will beat silicon ones even in price per amp. On the other hand, achieving system advantages have been an important argument to apply SiC devices. Both trends will continue, particularly fostered by progress in packaging and with passives, and will grow the market volume of SiC devices by a factor of about ten within a decade (see figure 7.1). All this has to go hand in hand with an improvement of the wafer quality, i.e. further reduction of the defect density and new techniques for wafering. The conventional sawing process for wafers is quite expensive, time consuming and limited to thick wafers. Therefore, new technologies have to be investigated to realize SiC thin wafers for the next generations of power MOSFETs. This is a prerequisite to improve production yield, reliability and performance and might allow for a reduced screening effort. Altogether, an improved wafer production and quality will reduce device cost dramatically.

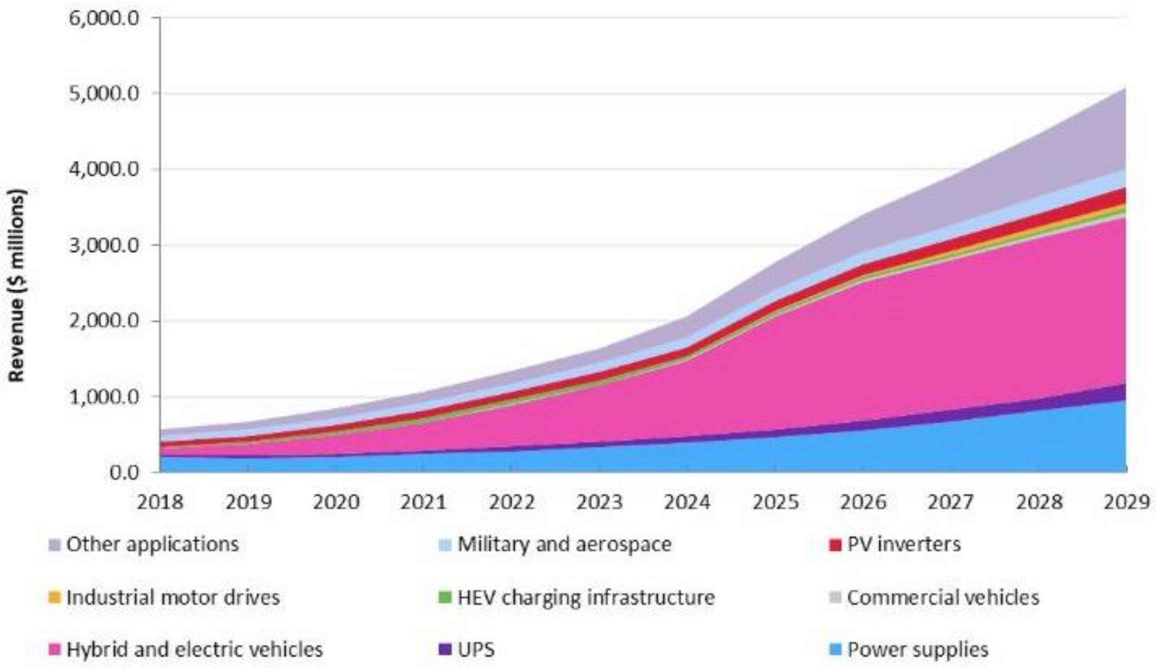


Fig. 7.2: Market volume of SiC and GaN devices in million USD by application [7.12]

The next step will be ultra-wide bandgap semiconductors (UWBG) made of Ga_2O_3, AlGaN, AlN or diamond crystals as base material. These promising materials with very wide bandgap of 4 to 6 eV are still under development and many challenges have to be tackled but these materials have very promising electrical characteristics. There seems to be significant improvements up to a factor of 37 possible comparing AlN to available GaN [7.14]. To bring this into application, the quality must be improved to a low defect rate and the size of the crystals must be increased to at least 100 mm or 150 mm. Beside this new device concepts and processing technologies must be developed for these promising new semiconductors.

Gate control

State of the art GaN enhancement HEMTs exhibit gate threshold voltage in the range 0.7 - 3 V, with a recommended operating voltage close to 5 V. The consequently very low voltage margin, both on the on- and off- states, render the device highly sensitive to EMI, leading to electrical stress and false turn-ons. This is accentuated by the devices high switching speeds and low parasitic capacitances, which tend to increase the quality factors of parasitic resonators. Negative off-state polarisation voltages, which is a common practice with Si-IGBTs and SiC-MOSFETs, are furthermore impractical for current GaN-HEMTs due to the extra conduction loss during the reverse conduction phase.

As a mitigation mean, intensive research is being carried out both by industry and academia in the direction of die- or package- embedded drivers to reduce parasitic inductances and magnetic couplings to a minimum. Smart drivers with active gate control are also being investigated.

Packaging

In the past decades, big investments in packaging were made in cost reduction of the expensive semiconductors by shrinking the chip area. Work was carried out on three main tracks. The power cycling capability of semiconductors was heavily increased by new technologies like silver or copper sintering, diffusion bonding, new solder materials, copper wires, chip top side clip designs instead of wire bonding and transfer moulding. The longer theoretical lifetime was then translated into applicable performance or reduced chip size. The thermal design was improved, and double-sided cooled modules came up. Importantly, the thermal spreading was introduced by thick copper layers for WBGs to enhance the thermal resistance. Lastly, huge efforts were made to design low parasitic inductance packages. The switching losses are reduced, and efficiency is increased. All of these developments lead to reduction of the chip size and cost (and beneficially also to the passive components). Key technologies are busbar-like designs for the chip top side connection as well as the load terminals to the dc link, multilayer circuit carriers such as all kinds of printed circuit board embedding.

Packaging of power semiconductors is now in upheaval. In the future the semiconductors (Si, SiC and GaN) will become cheaper. The reduced semiconductor cost will move the focus from lowest chip size to other interesting new trends. Power electronics becomes a commodity resulting in high quantities. On the other hand, the technology pull will hand over from automotive to other applications with special demands. Electrical energy production and transmission needs highest efficiency and well-known reliability. The aviation industry move towards all electric aircraft will demand for extreme power at lowest weight.

The integration of functionality into one component will move forward. Especially for the WBG devices, drivers, sensors, snubbers, and capacitors should be located near the power switch. The high number of paralleled semiconductors must be controlled smoothly under all conditions. The current density will increase beyond the limits of today's top side semiconductor contacts like bond-wires. Integration will demand for special joining technologies like direct bonding [7.17] or velcro-welding [7.18] made for signals and power at the same time. The interconnections must perform well for large joining areas as well as fine pitch layouts at high temperature and high temperature swings. The integration of capacitors needs improved housings and deep understanding of failure mechanisms [7.16]. Reduction of material layers and process steps will therefore save cost [7.15].

Regarding on-resistance values, new generations of SiC semiconductors will be thinned down to thicknesses known from silicon. For GaN, vertical concepts there will be a demand for special packaging technologies.

Some "harsh" industrial applications (wind, PV) demand for improved life cycle quality. In these applications, traditional wear out is not an issue. Most failures arise at switch on after a longer period of shut down or at full load. Packaging technologies are needed to cover these mostly humidity or corrosion triggered failures. New test methods have to be found.

A challenging trend is design optimization by simulation. Especially the thermo-mechanical management will be a key. This digital twin approach needs a power electronics material database. Together with transparent and efficient material models. Process history must be included. Reliability testing and qualification of products would speed up at reduced cost [7.19].

Magnetics

Magnetic components are used to store energy, to transform voltages, to damp interferences or to provide galvanic isolation. The variety of conductor and core geometries as well as their different materials enable an optimisation for each application and requirement. Often, the magnetics are the largest, most complex to design and most expensive components in power electronics. Here, the increasing switching frequencies enabled by WBG semiconductors lead to a reduction of size, weight and cost, but also come along with challenges.

To realise higher switching frequencies, the rise and fall times have to be short. The transient voltage distribution in the windings is determined by the parasitic stray capacitances, which have to be minimised by construction and need to be adjusted to enable a uniform voltage distribution [7.20]. The trend is towards higher voltage levels and reduced component size leads to smaller insulation distances, which have to support the high electrical field and have to prevent partial discharges. This is only achievable with new insulation materials, which can also cope with higher frequencies, usually leading to faster aging. Furthermore, the increasing switching frequencies lead to increased winding losses (skin, proximity) and core losses (hysteresis, eddy currents and residual). A reduction of the losses can be achieved by sophisticated designs, e.g. laminated ferrite cores, but still need to be dissipated by innovative cooling concepts and have to characterised accurately.

For higher frequency topologies the trend is for interleaved winding structures (with litz wire) to minimise proximity losses in the winding or winding arrangements to control the transient potential distribution or distributed air gaps to reduce the proximity losses in turns and windings, but the measure has its limits when surface losses of small segments dominate the bulk losses [7.21], or when manufacturability is compromised by deformation during sintering. In any case, the dissipation of power losses from the inner segments is crucial, as they are separated by insulators, i.e. materials with low thermal conductivity.

Integration is another trend, when parasitic capacitances are included in the circuit design or the magnetic components are mounted onto the cooling plates of the semiconductors. Using coupled inductors in multiphase converters or in LCL-filters can reduce the material effort by using compensating magnetic fluxes. In other applications pre-magnetised inductors [7.22] with magnets in air gaps can reduce the volume. Planar inductors are another trend because they are less expensive to manufacture and have better heat dissipation due to a higher surface to volume ration [7.23].

AI and neuronal networks are used for the design of magnetic components [7.24] and the handling of material data [7.25]. The design process is increasingly supported by 3D printing. It is state of the art to print prototypes of coil formers using fused deposition modelling or selective laser sintering and windings can be formed by selective laser melting of copper.

Capacitors

Capacitors are a fundamental passive component and are used in many power electronic applications. The workhorses in terms of technology are aluminium electrolytic capacitors, metallised film capacitors and ceramic capacitors. However, the progress in active devices also calls for improved capacitors.

The higher switching speeds possible through use of WBG devices require a mechanical and electrical construction of the capacitors which provides low parasitic inductances. This implies that the capacitor elements must be mounted very closely to the hot switching devices. As a consequence, the requirement for the temperature stability of the capacitor materials will increase. Furthermore, the ripple current load and the overall voltage level will increase to realise higher energy and power densities.

These trends require capacitors with lower losses, i.e. lower ESR values and a high breakdown strength of the dielectric materials. Additionally, the lifetime requirements and general reliability are expected to rise. New dielectric materials e.g. nano-doped polymer or solid-state polymer electrolytes in combination with new mechanical constructions of the connection of the capacitors toward the power devices are supposed to reach those goals [7.26, 7.27, 7.28].

7.2 Life cycle costs of power electronics

The main side-effect of an ever-growing global power electronics market is the waste produced once lifetime of components/systems ends. This trend poses growing ecological problems. In [7.29] it is reported that in 2019 the global electronic waste generated worldwide was 53.6 million tonnes. Although power electronics is not fully responsible for this amount, it is a contributor.

5R-Sustainability of power electronics

Recycling (R1) is the first answer that comes to mind helping with the electrical and electronic waste. Today only a fraction of waste is recycled. Recycling, however, has its own challenges. For example, recycling requires energy for the dismantling process and energy to transport waste. In many cases this energy still comes from CO_2 intensive power plants. In addition, some recycling processes require chemicals and most importantly water depending on the hardware and components that need to be recycled. Adding chemicals and using fresh water are not environmentally friendly. Another layer of complexity is added by the trend of high-power electronics integration. High integration does make it much more difficult to break down integrated devices into raw materials. Recycling is not only about extracting and separating materials, but also about traceability. As such, AI, IoT, Big Data, Blockchain, Smart Sensors and Diagnostics are seen as key enablers of a circular economy. They gather, explore and disseminate knowledge related to dynamic manufacturing processes of circular systems. They allow for improved communication across the whole ecosystem and supply chain (suppliers, manufacturers, re/users, disassemblers and recyclers).

To reduce recycling efforts power electronics should **Replace** (R2) rare-earth material with abundant materials. Another step is the introduction of biodegradable organic electronic materials, which are considered safe and nontoxic.

Right-to-repair (R3) is seen as a new trend when helping to reduce waste. The aim is to stop electrical items becoming obsolete. According to the UK government, right-to-repair will reduce 1.5 million tonnes of electrical waste generated each year. At the moment, right-to-repair is slowly implemented into the consumer markets [7.30].

Reuse (R4) and **Repurpose** (R5) are two additional contenders helping to reduce waste. Reuse deals with monitoring and upgrading hardware to increase lifetime of a system. Repurpose deals with upgrading hardware and implementing the hardware for a different function that is less technical demanding or operates in a less harsh environment. Power electronics has not entered the market of reuse and repurpose unlike that seen in the battery market, where many start-up companies have started working in both fields. Possibly standardisation can promote repurposing, such that subsystems can be easily reused for other applications when the original system is decommissioned.

In order to achieve a true sustainable NetZero future, power electronics must put more emphasis in sustainable engineering solutions.

Lifetime increase

With the electrification of society, power electronics addresses mission critical applications, where failures must be avoided, either for safety reasons (e.g. aerospace), or due to high downtime costs (e.g. datacentres, offshore wind generators, etc.). On the other hand, power electronics have been identified as a highly prone to failure element [7.31] – new high-density components do not tend to have significantly higher reliability than previous generations. Active methods to ensure availability must therefore be thought after, in the form of three main paradigms: condition monitoring (CM) to predict failures, reliability driven control to delay failures, and fault tolerance to maintain operation despite failures.

Condition monitoring consists of estimating or observing the state of health (SoH) of a power system, possibly measuring thermal parameters, switches' on-state voltage, inverter output voltage spectrum, etc. In particular, digital twins, implementing either electrical or thermal observers, are gaining strong interest for CM. Remaining useful life estimation remains challenging to estimate, due to the lack of accurate lifetime models. CM can nonetheless guide conservative actions to prevent failures due to wear-out, whilst minimising the time to maintenance.

Furthermore, SoH estimate can be used to actively influence the component's degradation. As temperature and thermal cycling constitute the main stressors for PE systems artificially increasing losses under light load can reduce thermal cycling – thereby trading lifetime for efficiency. In case of parallel sub-systems, active thermal control can consist in sharing the total loading according to SoH, so as to unload weak elements and extend the system-level remaining useful life (RUL) [7.32]. These paradigms can be applied from die- to system- level [7.33].

The ability to maintain operation in case of fault is paramount to critical applications. This is commonly achieved through redundancy (e.g. 2N or 2N+1), which is a costly and bulky paradigm. Self-healing electronics can reduce the amount of redundancy using fault-tolerance strategies, such as topology morphing, whereby part of the system can be disconnected or reconfigured to maintain operation of the healthy elements [7.34].

7.3 Make energy efficiency and green energy affordable

Green and energy efficient power electronics must not be more expensive than conventional solutions. Especially reduced losses lead to reduced cooling effort and new integration concepts that have the possibility even to reduce cost compared to traditional solutions.

System advantages due to integration

Power electronics building blocks (PEBBs) or Intelligent Power Modules (IPMs) constitute active sub-systems comprising power devices and some low power control electronics, such as isolation stages, low parasitic gate-drivers, sensors, and logic, as well as a standardised control interface. Such power-module level integration results in an increased power density, and enables the implementation of some degree of control and smartness, such as protections (thermal, short circuits, etc.), supervision (e.g. state of health estimation), and control (dead-time, die-level reliability-driven control, etc). PEBBs are designed as versatile sub-systems that can be used in a variety of applications. As such, economies of scale lead to lower costs than custom solutions

The concept has been intensively investigated; in particular since the 2000s and is currently gaining particular interest in fields such as consumer electronics and e-mobility, where moulded technologies enable an additional degree of heterogeneous integration.

System advantages due to better components, and new production possibilities

Power electronic systems advance in power to weight and power to size ratings due to new components like semiconductors and passives like inductors and capacitors. This is also a benefit of improved efficiency and lower thermal losses. The necessary cooling system of air or water cooling can be smaller, more lightweight and consumes less resources for production. Materials like aluminium and copper as well as iron or ferrite for the inductive components are safe. Due to the smaller size even the use of plastic materials for isolation can be reduced.

Another approach to reduce the needed materials is 3D printing of different components to realize a higher level of integration [7.35]. This can be used for different plastic parts for isolation and mounting but also for metals and ceramic materials. With this technology also small quantities of power electronic systems can be produced with a reduced amount of materials. Also, for large production quantities the 3D printing technology will increase the level of mechatronic integration, especially with the upcoming possibilities of printing different materials like plastic, metal and ceramics together and realize cooling, electric isolation and conducting parts in the same process step.

7.4 Conclusions

Even after the very fast development during the last 20 years and the availability of wide bandgap SiC semiconductors there are many promising technologies arising. These new technologies will give power electronic a further technology push. Enabling even more new electric powered, highly efficient applications and generating an additional application pull for new solutions. Europe is at the forefront of power electronic development. To stay there, further focused research on these promising topics must be facilitated.

8. Executive Summary and Conclusions

Today´s economy is still based on fossil energy sources, which are burned to generate heat and electricity, and to fuel transport and mobility. In the last years, it became obvious that this system is not sustainable due to the limited fossil resources and especially due to the dramatic effects of the climate change owing to human-caused CO_2 emissions. Presently, we observe a transition to a More-Electric Society with the final goal of an All-Electric Society, in which the electrification is based on the use of renewable energies. In the energy transformation (German “Energiewende”) we see a transition to decentralized power generation based on renewable energy sources on the generation side, and a transition to energy efficient power conversion and control on the use side. In parallel, a fundamental transition in transport and mobility is proceeding by an advancing vehicle electrification based on variable speed motor drives.

All these transitions are based on the efficient conversion and control of electrical energy, or in other words, on power electronics.

Another megatrend supported by power electronics, apart from the sustainable and highly efficient energy supply, is the resource efficiency related to the consumption of materials. The miniaturization of converter systems and increased power density, enabled by modern wide bandgap power semiconductor devices, lead to significant materials savings, e.g. on copper and aluminium. Further innovations are needed in life-cycle assessment and circular economy with a focus on reuse and recycling in power electronics.

Major innovations on the system level are driven by digitalization and artificial intelligence where smart power electronics can provide extended functionalities to the user, and exploit energy savings on the system level far beyond the converter efficiency itself.

Finally, the importance of reliability and availability should be mentioned as reliability is a key differentiator for Europe´s power electronics industry. Reliability is a cross-sectional and multi-disciplinary topic starting from the material science behind the degradation mechanisms, covering technology and product qualification and testing, and addressing also intelligent reliability concepts including condition and health monitoring.

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Fig. 2.1	REN21
Fig. 2.2	IRENA
Fig. 2.3	Shell
Fig. 2.4	IEA
Fig. 2.5	IEA
Fig. 2.6	Courtesy of ECPE network
Fig. 2.7	Courtesy of ECPE network
Fig. 2.8	Courtesy of ECPE network
Fig. 3.1	M. Liserre, University of Kiel
Fig. 3.2	M. Liserre, University of Kiel, based on R. Zhu and J. Chen
Fig. 3.3	Grid Code (GC) GC0137
Fig. 4.1	Precedence Research
Fig. 4.2	B. Eckardt, Fraunhofer IISB
Fig. 4.3	IEA
Fig. 4.4	BlueWeave Consulting
Fig. 4.5	B. Eckardt, Fraunhofer IISB
Fig. 5.1	World Energy Council
Fig. 6.1	L. Lorenz, Infineon
Fig. 6.2	G. Retseck and J. Christiansen, US Department of Energy
Fig. 6.3	L. Lorenz, Infineon
Fig. 6.4	IEA
Fig. 6.5	P. Wallmeier, Delta Energy Systems
Fig. 6.6	F. Lee, CPES
Fig. 6.7	M. Maerz, Fraunhofer IISB
Fig. 6.8	H. Borcherding, OWL University of Applied Sciences and Arts
Fig. 6.9	H. Borcherding, OWL University of Applied Sciences and Arts
Fig. 7.1	Omdia
Fig. 7.2	Omdia

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