Strategic Research Agenda

of

The European
Technology and Innovation Platform

“Electronics for Energy Efficiency and Sustainability (EEESy)”

The Strategic Research Initiative for Efficient Electric Power Conversion

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Content

1 Foreword

Power Electronics is the technology associated with the efficient conversion, control and conditioning of electric energy from the source to the load. It is the enabling technology for the generation, distribution and efficient use of electrical energy. It is a cross-functional technology covering the very high Giga Watt (GW) power (e.g. in energy transmission lines) down to the very low milli Watt (mW) power needed to operate a mobile phone. Many market segments such as domestic and office appliances, computer and communication, ventilation, air conditioning and lighting, factory automation and drives, traction, automotive and renewable energy, can potentially benefit from the application of power electronics technology.

The ambitious goals of the European Union to reduce the energy consumption and CO_2 emissions can only be achieved by an extensive application and use of Power Electronics, as power electronics is the basic prerequisite for:

- Efficiently feeding-in wind and solar energy to the grids,
- the stabilisation of the power grids with increasing share of fluctuating renewable energies,
- highly efficient variable speed motor drives,
- energy efficient and low-emission mobility with hybrid and full electric vehicles,
- an energy saving lighting technology,
- efficient recovery of breaking energy,
- energy management of batteries,
- control appliances and building management systems via the grid interface (smart grids)

The estimated energy savings potential that can be achieved by introducing power electronics into systems is enormous, more than 25% of the current EU-25 electricity consumption.

Since power electronics is a key technology in achieving a sustainable energy society, the demand for power electronics solutions will show significant growth in the coming decades. The European industry holds a strong position in the field of power semiconductors and modules and is establishing a wide band-gap semiconductors technology base. Europe also has high quality power electronics research groups at universities and research institutes with well established networks and associations in Europe to provide platforms for discussion, cooperation and joint research. On the other hand, outsourcing of research and technology to emerging countries, strong research increment in these countries, and the possibility of key European companies being taken over by competitors from Asia, make it even more critical for Europe to keep up with the technological development. This requires continuous investments in research and development.

This Strategic Research Agenda is intended to present a vision of the strategic research targets of key European industry and academic players for the next 20 years and provide a basis for future joint research activities in the area of power electronics.

I would like to acknowledge and express thanks to all the experts from the power electronics community for providing their valuable input and comments. Last but not least, I address my sincere thanks the European Commission as well as to the national authorities for their ongoing commitment to and support of the vision of an energy efficient more-electric society.

Dipl. Phys. Thomas Harder
ECPE General Manager

2 Power electronics – its relevance for Europe

2.1 Potential for energy efficiency

The ever-increasing demand for energy, the shortage of fossil fuels and the need for carbon footprint reduction have resulted in a global awareness of the importance of energy savings and energy efficiency. This topic is taking high priority in today's society, leading to many governmental policies and measures, industrial programmes and research, both in Europe and worldwide. Combating the energy and climate problem requires a complex, interdisciplinary approach involving technological solutions such as sustainable energy sources and more efficient energy use as well as political measures and general public commitment. In its Action Plan for Energy Efficiency, the European Commission presented an energy policy which seeks to enable the European Union to reduce greenhouse gases by at least 20%, to reduce energy consumption by 20% and increase to 20% the share of renewable energies in energy consumption by 2020. Furthermore, the European Union committed itself in 2009 to the reduction of its Greenhouse gas (GHG) emissions by between 80% and 95% by 2050. However, the interpretation of the energy savings target in EU law is much weaker than for the other two pillars of the EU climate package: greenhouse gases (GHG) and renewable energy. As a result, recent evidence suggests that the energy savings target will be missed by a wide margin even though it could be met largely through cost-effective measures. It should be noted that energy savings have the potential to cover half of the EU 80% emission reduction target for 2050.

The demand for electricity is continuously growing and will continue to do so at a much faster rate than other energy sources over the coming decades, twice that of the overall energy consumption. Today 20% of final energy consumption in EU is electrical energy (which translates into up 40% of total primary energy), but this is predicted to grow significantly in the next few decades. Power Electronics is the technology associated with the efficient conversion, control and conditioning of electric energy from the source to the load. It is the enabling technology for the generation, distribution and efficient use of electrical energy. It is a cross-functional technology covering the very high Giga Watt (GW) power (e.g. in energy transmission lines) down to the very low milli Watt (mW) power needed to operate a mobile phone. Many market segments such as domestic and office appliances, heating, ventilation and air conditioning, lighting, computers and communication, factory automation and drives, traction, automotive and renewable energy can potentially benefit from the application of power electronics technology.

Table 1 Power electronics applications and electrical energy-saving potential

Application		Electricity consumption [% of EU consumption]	Electrical energy saving potential	Energy saving potential [% of EU consumption]
Motor control **- industrial applications** **- appliances, HVAC, lifts** **- traction drives**		~50%	30-40% (feasible in ~50% applications)	5-6%
Lighting		21%	>70%	>14%
ICT	**Data centres and servers**	2%	50%	1%
	Radio base stations	1%	30%	0.3%
	Standby consumption	4%	80-90%	3.6%

Table 1 shows the large electrical energy consuming sectors that have significant energy-savings potential. A few major areas can be identified:

- Motor control – It is estimated that motor-driven systems account for more than 50% of total electricity consumption (65% of industrial electricity, 38% of tertiary and 35% of residential). The energy-saving potential of Variable Speed Drives (VSDs) comes from the ability to control the motor speed to match the output with the system needs at very high efficiencies. The energy savings potential by introducing VSDs is estimated to be 30–40% for most applications. The technical potential for energy savings is for about 40–50% of all motors depending on the application, and given that VSDs have already been applied to about 15–20% of all motors the remaining potential is estimated to be about 30%. Combining all these figures, the total electrical energy-savings potential of VSDs is about 5–6% of the current electrical energy consumption.
- Buildings (Commercial, Industrial and Residential)
    - Lighting – Currently 21% of total electrical energy is consumed by lighting. Savings of up to 70% of this can be achieved using technology solutions which are already on the market, such as replacing traditional fluorescent sources by high-efficiency ones using electronic ballasts (>90% efficiency), and intelligent dimming based on data for occupancy and daylight (collected by wireless sensors). This translates into 14% of the total electricity consumption. The savings will be greater with new technologies based on solid-state lighting (i.e. LEDs).
    - Heating, ventilation and air conditioning (HVAC) – HVAC accounts for 40% of the total energy consumption in buildings (including electrical and non-electrical heating). Using advance control together with energy-efficient appliances it is possible to save around 20% of total energy consumption (electrical and non-electrical).

- ICT
    - Electrical energy demanded by *data centres and servers* in the Western Europe was 56 TWh in 2007 and is forecast to increase incrementally to 104 TWh in 2020. In a typical data centre, less than half of this power is delivered to the compute load, which includes microprocessors, memory and disk drives. The rest of the power is lost in power conversion, distribution, and cooling. The use of advanced power electronics techniques, like new DC distribution networks, can lead to a 10% reduction of the required energy. The integration of ICT technologies and power electronics and improving energy management can save an additional 20%, and the implementation of best practices can lead to a 50% reduction, which translates into 1% savings of the total electricity consumption. Further research on reliability, implementation and cost reduction can further improve these numbers.
    - Estimates indicate that the telecom industry consumes 1% of the global electricity consumption, and more than 90% is consumed by networks operators. Almost 30% of electrical energy savings can be achieved in *radio base stations* (RBS) by employing efficient power electronics technologies such as efficient power amplifiers and techniques for low consumption in standby mode. If we take the annual electrical energy consumption of a 3G RBS of 20MWh and estimate the number of RBS in Europe to be 20 000 per operator for the 30 largest operators and predict the growth of 3 times until 2010 this gives the total savings of 10TWh or ~0.4% of the total electricity consumption.
    - The annual electricity consumption related to standby functionalities and off-mode losses in the EU was estimated to have been 47 TWh in 2005. It has been estimated that the total annual energy savings potential for standby consumption in the EU is 35TWh, and power semiconductor manufacturers claim that more than 90% standby consumption reduction is feasible.

To summarise: the estimated energy savings potential that can be achieved by introducing power electronics into systems in the shown areas only is enormous: 25% of the current EU-25 electricity consumption.

2.2 Power electronics – an enabling technology

Table 2 shows several societal megatrends and their relation to power electronics. Some of these trends are enabled and only possible by using power electronics. Let us take a more detailed look at the role that power electronics plays in these trends.

Table 2 Societal megatrends

Megatrends	Consequences for Power Electronics
Mobility & Transport	Hybrid and electric vehicles, urban transport, more electric aircraft/ships
Information & Communication Society	PC, internet, data servers, telecom, body area networks
Energy supply – security, availability and reliability	Energy efficiency, power quality, electrification, system reliability
Energy-efficient buildings and homes	HVAC, lighting
Industrial manufacturing	Automation, process control

Mobility

The transport sector is the fastest-growing sector in the European economy and, being responsible for above 30% of total primary energy consumption, represents the largest primary energy consumer in the EU. Final energy consumption in the transport sector grew 28.6% in the EU-25 between 1990 and 2004. Increasing fuel prices and the global energy situation have triggered worldwide investment in **electric and hybrid vehicles** and increasing penetration of these vehicles into the market. Power electronics is an enabling technology for the development of drive trains and battery-charging for these cleaner and more fuel-efficient vehicles. Furthermore, the increasing electrification of previously mechanical and hydraulic vehicle functions, such as x-by-wire applications like electric power steering or electric braking are only possible through the use of power electronics.

Hybrid electric buses using hybrid electric vehicle propulsion technology are increasingly becoming part of public transport in cities around the world. They offer considerable fuel savings, as high as 75% compared with a modern bus, and reduce emissions by as much as 60%. Power electronics is a necessary part of the drive train of these buses.

Aviation is responsible for ~12% of the transport energy consumption and is the fastest-growing energy consumer in the EU, with an increase of 73% between 1990 and 2006. Air transport demand is predicted to double in the next 10–15 years and triple in 20 years. **More electric aircrafts (MEAs)** where bleed air and hydraulic power sources are replaced with electrical equivalents, thus enabling a significant improvement in efficiency, system flexibility, aircraft reliability and specific fuel consumption, also depend on power electronics as an enabling technology. Boeing's More-Electric-Aircraft 787 Dreamliner has achieved a 20% reduction in fuel and CO_2 compared to its conventional counterpart 767 primarily due to its efficient no-bleed engines and the composite airframe. Power electronics systems are crucial for the aircraft's distributed power system and the total power electronic load is 1MW compared to several kW in conventional aircrafts.

Information and communication society

The impact of the information and communication society on the global economy has continuously increased over the last decades. The social benefits of this advance have also been translated into a proportional increase in the energy demanded by this sector.

In Western Europe the demand for IT services was about 60 TWh of electricity consumption (with another 20 TWh in the residential sector) and it is expected to rise to 104 TWh per year by 2020. In 2006, the power use associated with **servers and data centres**, including storage and network equipment, was about 1.5% of total US electricity consumption, and it is projected to increase to 2.5% of total electricity consumption by 2011. The peak load consumption of US data centres is around 8 GW, equivalent to 16 baseload power plants. The use of advanced power electronics techniques, like new DC distribution networks, can lead to a 10% reduction of the required energy. The integration of ICT technologies and power electronics, improving energy management, can yield an additional 20% energy saving, and the implementation of best practices can lead to a 50% reduction.

Today microprocessor industry is not only focused on the performance per euro but also on the performance per watt. Load consumption can be dramatically reduced by appropriate power supply strategy. Techniques like Dynamic Voltage Scaling that adjust the supply voltage of the microprocessor as a function of the work load can achieve significant reduction on the consumed power. Further improvements can be achieved increasing the efficiency of the power converters under light load conditions (e.g. when the processor is in idle mode) by means of reconfigurable power stage as a function of the load, adjustable digital control and optimization of dead times.

The annual electricity consumption related to **standby functionalities and off-mode** losses in the EU was estimated to be 47 TWh in 2005. Without taking specific measures, the consumption is predicted to increase to 49 TWh in 2020. An important portion of these losses is related to power supplies hence novel power electronics techniques for achieving high efficiencies at low loads are necessary. Further savings can be expected from the application of efficient power supplies in electronics appliances, such as TVs, VCRs, microwave ovens, etc.

It is estimated that European consumption of **broadband equipment** will be up to 50 TWh per year by 2015. Power amplifiers are one of the main building blocks of all modern wireless communications systems. They are used in all base stations and all the mobile units which are currently available. To maintain the required levels of system performance current commercially available amplifiers are designed to operate with extremely poor levels of efficiency, which means they consume far more energy than is strictly necessary. For example, current base stations in the UK operate at an efficiency level of approximately 12%. This results in over 609,000 tons of CO_2 emissions into the atmosphere on an annual basis. If these base stations were to be 50% efficient CO_2 emissions could be cut by over 450,000 tons per year. Power electronics techniques are also here crucial for reducing the energy consumption.

Energy supply – security, availability and reliability

The increasing energy demand, the shortage and finiteness of fossil fuels and the need for carbon footprint reduction in order to prevent hazardous climate changes have brought the issue of energy into the spotlight of political and public attention. Electrical energy is one of the cleanest, most efficient and versatile forms of energy and it is predicted that its demand will continue to grow at a much faster rate than other energy sources in the coming decades. In recent years there has been a growing awareness within the electricity supply industry of the need to reinvent Europe’s electricity networks in order to meet the demands of twenty-first-century customers. In 2005 the European SmartGrids Technology Platform was established as a coherent approach to meet the challenges envisaged by network owners, operators and particularly users, across the EU. In the EC paper “Vision and Strategy for Europe’s Electricity” it was concluded that future electricity markets and networks must provide all consumers with a highly reliable, flexible, accessible and cost-effective power supply, fully exploiting the use of both large centralised generators and smaller distributed power sources across Europe. End users will become significantly more interactive with both markets and grids; electricity will be generated by centralised and dispersed sources; and grid systems will become more interoperable at a European level to enhance security and cost-effectiveness. This new concept of electricity networks is described as the ‘SmartGrids’ vision.

One of the priority actions of the EC Action Plan for Energy Efficiency is to make power generation and distribution more efficient. Transmission and distribution (T&D) losses of electrical energy are typically between 6% and 8%. In the US alone, this translates into $19.5 billion. Business Roundtable’s Energy Task Force T&D Working Group, which ABB chairs, identified a number of energy-efficient technologies for grids, including power electronics technologies such as HVDC, FACTS, power electronic transformers, distributed generation/microgrids (power electronics is necessary to interface distributed generators such as wind turbines, solar cells etc. to the grid) etc. ABB identifies power electronics as a key technology in all four pillars of Smart Grids:

- **Integration of renewables** (wind turbine converters, HVDC for offshore wind park connection, SVC/STATCOM for grid code compliance, energy storage for improving stability and decreasing power fluctuations, solar converters etc.)
- **Integration of electric vehicles** ((fast) charging of electric vehicles, traction drive for hybrid (electric) vehicles, dynamic energy storage to absorb peaks due to simultaneous (fast) charging of electric vehicles)
- **Reliability and efficiency** (efficient long distance transmission with HVDC, variable speed drives in industrial plants and pumped hydro stations, energy storage for emergency and peak power, power quality solutions for industry etc.)
- **Demand response** (converter interface to distributed generation with built-in load management capability, drives in pumped hydro station with remote control from control centre).

Sustainable buildings and homes

Energy use in residential and commercial buildings is responsible for about 40% of the EU's total final energy consumption and CO_2 emissions of which more than 50% is electrical energy. The cost-effective energy-saving potential by 2020 is significant: 30% less energy use within the sector is feasible. This equals a reduction of 11% of the EU's final energy use. The sector has significant untapped potential for cost-effective energy savings which, if realised, would mean an 11% reduction in total energy consumption in the EU by 2020.

Smart Homes, also known as automated homes, intelligent buildings, integrated home systems or domotics, have been gaining in popularity in the past few years. Smart homes incorporate common devices that control features of the home. Originally, smart home technology was used to control environmental systems such as lighting and heating, but recently the use of smart technology has developed so that almost any electrical component within the house can be included in the system. A reliable source of energy is mandatory for all these developments. Home energy management relying on power electronic systems is therefore one of the key issues for home automation. Such a distributed energy management would also interface the local renewable energy sources such as solar panels and the home loads.

Energy-positive buildings are those that generate more power than their needs. They include the management of local energy sources (mainly renewable, e.g. solar, fuel cells, micro-turbines) and the connection to the power grid in order to sell energy if there is excess or, conversely, to buy energy when their own is not sufficient. They use systems and components such as advanced Heating, Ventilating and Airconditioning (HVAC) and highly efficient lighting. They are equipped with intuitive devices that not only meter the energy consumed but also provide real-time information (e.g. on incentive pricing, deviations from standard consumption) to help people living in (or managing) these environments save energy while maintaining the desired comfort levels. They include Plug-in Electric Vehicles infrastructures in order to facilitate not only clean transport but also alternative local energy storage.

In order to achieve energy-positive buildings and neighbourhoods, a multidisciplinary innovation approach is needed. Examples are: decentralised monitoring and control systems for power quality management, communication protocols, power electronics, e-trading platforms for dynamic pricing, virtual power plants, multi-agent systems, and service architectures. Some of these technologies are mature; others in early stages of development and some still need research.

Lighting consumes more than 20% of all electricity generated in the European Union (EU). The situation is similar in the United States and the percentage is even higher in some developing countries, since lighting is one of the largest uses of electric power. Power electronics is an enabling technology for new energy efficient lighting technologies. Gas discharge lamps such as fluorescent and HID lamps cannot be operated directly from the mains, because they have negative incremental impedance, and therefore, must be operated in series with current controlled ballast. To improve the efficiency of gas discharge lamps, the traditional magnetic ballasts can be replaced by high-efficiency electronic ballasts. The use of high-frequency electronic ballasts results in significant ballast volume and weight reduction and improves the performance of the discharge lamp. The high-frequency operation also makes the lamp start easily and reliably, and eliminates audible noise and flickering effects. In addition, due to the advances in power electronics, power regulation can be easily incorporated into the ballast, making intelligent energy management feasible. LED technologies and in some case plasma technology is being used for both indoor and outdoor next generation high efficiency lighting solutions and power electronics is playing a key role in developing high efficiency drivers for optimising their operation.

Industrial manufacturing

Nearly one-third of the world's energy consumption and 36% of its carbon dioxide (CO_2) emissions are attributable to manufacturing industries. Manufacturing is still the driving force of the European economy, contributing over 6 500 billion euro in GDP. It covers more than 25 different industrial sectors, largely dominated by SMEs. There is an increasing demand for greener, more customised and higher quality products. The European manufacturing sector faces an intense and growing competitive pressure in global markets. European companies are faced with continuous competition in the high-tech sectors from other developed economies, such as the U.S, Japan and Korea. Manufacturing has to address the challenge of producing more products with less material, less energy and less waste. Together with other industrial technologies, ICT and advanced materials, power electronics-enabled variable-speed control of motors as an enabler for higher automation and better process control will improve the competitiveness of the companies. Power electronics in combination with wireless sensor technology can also be utilised for machine conditional monitoring applications, checking that electrical machines are operating in accordance with expected efficiency norms as well as enabling predictive maintenance to ensure machines are repaired/maintained in advance of breakdown thereby minimising downtime and associated losses.

3 EEESy ETP – motivation, objectives and structure

The main drivers behind starting a European Technology & Innovation Platform on “Electronics for Energy Efficiency and Sustainability” are:

- Achieve awareness & acceptance of Power Electronics as a key technology to solve energy related challenges. This important area has to be on the agenda of EC policy.
- The European power electronics community must agree on a common vision for the future role of power electronics (Strategic Research Agenda).
- Presently, the contacts of the power electronics community to the European Commission are lacking sustainability. We need this official ETP status to be in the information loop.
- Other ETPs with non-power electronics experts try to cover our topics of efficient power conversion but it lacks co-ordination and vision.
- Intensify the cooperation with other stakeholders, joint roadmap or position papers with other ETPs e.g. on e-mobility or renewable energies. Today, these joint activities are done without power electronics involvement.

As the industrial power electronics network in Europe with more than 100 member organisations, companies as well as university and research institutes (Competence Centres), the ECPE (European Center for Power Electronics) is driving the ETP and provides the organizational platform for the EEESy Technology and Innovation Platform.

The work of the ETP will focus on the development of a common strategic research agenda based on the structure and knowledge of the ECPE Network. This includes the ECPE Programme on Research and Technology Roadmaps and the results of the European E4U Project on “Electronics Enabling Efficient Energy Usage” that ran from May 2008 to November 2009 and was funded by the European Commission´s ICT programme in Framework Programme 7 (FP7).

The list of the contributors is provided at the end of the document.

4 EEESy 2030 Vision

The ‘More or All Electric World’: by 2030 the share of green electricity in overall energy consumption will significantly increase. Power electronics will be a dominant enabling technology in the “More or All Electric World”.

The finiteness of fossil energy sources and the necessity to reduce our CO_2 emissions are pushing forward the electrification of our society. In the next decades, we will see a transition from the burning of fossil fuels towards green electricity, step by step. For example, Japan is aiming for a fully electrified society in 2050, and complete independence from fossil materials. Power electronics will be a dominant technology in the ‘More or All Electric World’.

In the EEESy vision of a ‘More or All Electric World’, the green electricity is produced in the South (solar energy) and the North (wind energy) and directly transported to the areas where it is consumed. The long-distance energy transmission is performed by a super grid using low-loss HVDC (High Voltage Direct Current) technology.

By 2030:

- *Three technologies: information processing, power processing, and sensors & actuators will converge to enable smart, energy-efficient systems*. A major impact lies in the integration of power electronics, ICT and sensors to save electrical energy with more intelligent systems in various power electronics applications. Some examples of smart (remote) controlled power electronic systems are smart battery management systems or smart homes including lighting, heating and cooling.
- *Smart Grids in 2020 will able to handle a 20%-plus share of fluctuating renewable energy in an economical and efficient way*. The high complexity of future smart-grid and plug-in electric vehicles to support the grid will be handled by the integration of three main technologies: new smart and efficient power electronics systems, seamless monitoring systems and communication and information-processing technologies. A significant effort in research in all these technologies will enable the high penetration of renewable energy sources, the extensive introduction of more efficient electric vehicles and the interaction of both concepts to optimise the energy-processing chain.
- *Low-emission e-mobility will dominate automotive market*. Plug-in hybrid and full electric cars are increasingly entering the European and worldwide markets. More serial production highway capable electric cars available for sale are expected to enter the European market towards the end of 2010 and early 2011. The German “National Development Plan on Electric Mobility” announced a plan to put a million plug-in cars on the roads by 2020. It is expected that by 2030 more than 50% of the market will be accounted for by plug-in hybrids and electric cars. Technologies and infrastructure for ultra-fast battery-charging combined with on-

board charging with widely spread charging points, both enabled by power electronics, will eliminate the driving range aspect.

- *Energy positive buildings will allow for halving of building life cycle.* 80% of the lifecycle costs of a building are after the building has been commissioned. About 50% of this is electrical energy. Hence energy savings achieved during the total life of the building will halve the lifecycle costs. This will be achieved by a combination of having buildings generate energy for their own consumption from renewable energy sources and power electronics enabled energy efficiency measures in the main power consumers: lighting and HVAC.
- *Industry in Europe will take global leadership in smart, energy-efficient systems and products based on the converging technologies.* European industry has an excellent starting position to take global leadership in smart energy systems. Europe has both a strong component and module industry (power semiconductors, driver and control ICs, integrated smart power, modules and IPEMs) and a very strong system industry covering many application areas for intelligent power electronics for energy efficiency: power supplies and power management; electronic lighting (smart control combining power electronics, sensors and control); automotive power electronics (emerging technologies e.g. x-by-wire, hybrid and electric traction); industrial applications (smart drives, energy recovery, energy-efficient industrial processes); renewable energy (PV inverters and power optimisers, converters and generators for wind turbines and biogas turbines).
- *Universities and research centres in Europe take global leadership in research and innovation in electronics, enabling efficient energy usage.* Europe has a strong tradition in research on power electronics and related areas. Proactive policies should be introduced to improve the uptake of science and engineering subjects in secondary schools and therefore increase the number of students doing engineering in university. This will ensure keeping the innovation and research pace of the EU research in top position compared to the emerging countries with fast research and innovation development and other strong world centres. Long-term research will receive more investments necessary for breakthroughs and paradigm shifts in contrast with today’s primarily short- to medium-term, project-oriented research, resulting in incremental advances.

5 Strategic Research Agenda

The main application areas of interest for EEESy given the electricity consumption, energy savings potential and the market size are:

- Smart e-drives;
- Power supplies for green ICT, industrial and medical applications;
- Electronic lighting;
- Power grid infrastructure and renewable energy sources;
- Automotive and avionics.

Each chapter outlines specific priorities along a timeline including technological requirements to reach the identified goals. Where appropriate, a preliminary roadmap is presented.

Application fields

5.1 Smart e-drives

5.1.1 Field definition

Motor driven systems are widely present, their applications ranging from the low power area e.g. in home appliances over medium power in industrial and automotive up to the large MW power in the field of generation. It is estimated that motor driven systems account for more than 50% of total electricity consumption. In EU, motor driven systems are the largest consumer of industrial electrical energy, accounting to around 65% of the total EU industrial electricity consumption. The main applications of low voltage industrial drives are pumps, fans and compressors. The main application areas of industrial medium voltage drives are pumps and fans (70%) in Energy, Oil & Gas, Water, Metals, Mining, Marine, Chemistry, Cement, Pulp & Paper industry.

The energy saving potential of Variable Speed Drives (VSDs) comes from the ability to control the motor speed to match the output with the system needs. This is enabled by power electronic inverters that supply variable frequency voltage to the motor thus changing its speed. This is particularly beneficial in fluid and motion applications such as pumps and fans where the flow or speed vary over time. The estimated energy efficiency potential that can be achieved by using VSD is estimated to be around 30-40% on average and in pump driven systems can be as high as 60-70% depending on operation and load cycle of the drive. Many of today's unintelligent fixed-speed drives can be substituted economically by electric variable-speed drives due to:

- high automation and flexibility in production;
- maintenance-free, self-adjusting operation;
- reduced energy costs during operation.

The field of smart electrical drives (smart e-drives) as presented in this SRA includes:

- Industrial low voltage drives (0.2kW to 500kW, <690V)
- Large drives for industry and traction (100 kVA - 100 MVA, 1 kV – 25 kV)

5.1.2 Objectives

The main objectives in the field of smart e-drives are:

- *Increase market penetration of inverter drives to 40% by 2030* - Currently, in Europe, 15-20% of motor drives use VSDs (5% worldwide). The estimated potential is that 40-50% of motor drives in EU could be driven by inverters in the future.

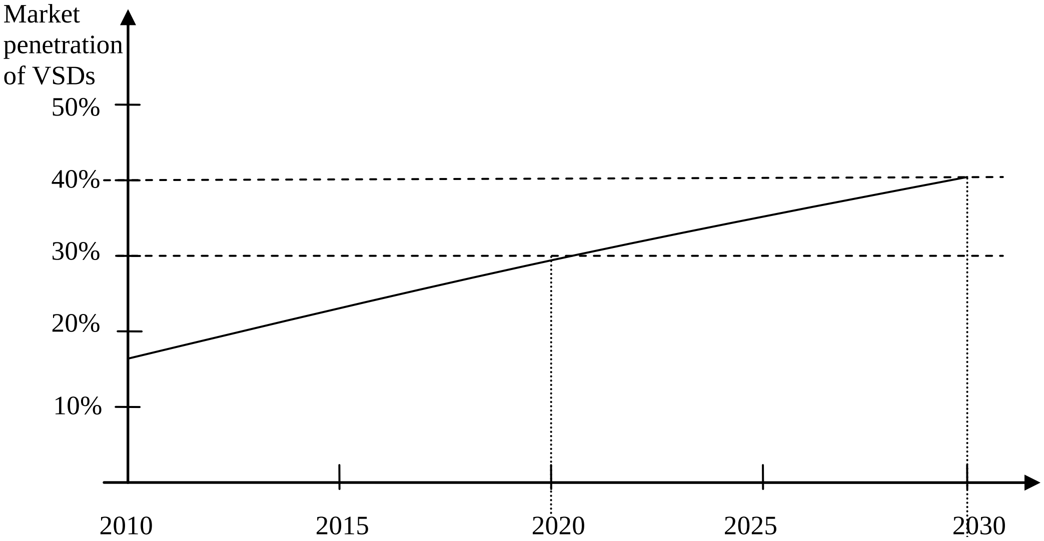


Figure 1 Market penetration of VSDs (2010-2030)

- *Increase efficiency of drives by reducing the losses to 50% of 2010 level* - The efficiency of commercially available VSDs of today is already high, in the 97-98% range. Looking at the complete system including the drive, motor and load (pump, fan etc), in order to make sensible system efficiency improvements, more attention must be paid to increasing the efficiency of the other system components (for example, the motor produces double or triple the losses in the inverter - the inverter efficiency is ~96% vs motor efficiency ~88%).

- *Increase power density of drives to 400% of 2010 level* - The potential to realise this goal for the inverter lies in system integration, high temperature technologies and passive components and for the motor in speed increase and magnets technology. The absolute value of power density depends strongly on the cooling system. Here the importance of increasing the efficiency of inverters comes in, since if the efficiency increases from 96% to 98% the losses will drop 50% which reduces the cooling effort and increases the power density.

- *Enhanced performance, intelligence and communication goal* - The 2030 smart e-drives will have: automatic initialization, power management, optimized operation with respect to application requirements e.g. maximum efficiency tracking by changing flux level, diagnosis functions, (wireless) sensors, communication between multi motor drives.

- *Increased reliability and fault tolerance – "Reduce failure rate to 10 % at same hardware functionality"*. The 2030 smart e-drives will have reduced amount of components, minimum sensor count, ability to reconfigure system in case of a fault, diagnostics and prognostics functions.

5.1.3 Research priorities

In order to meet the objectives presented in the previous section, technology advancements in the following areas will need to be made:

- New semiconductor materials with broad applications, such as SiC – due to their properties, these devices allow for lower losses and thus higher efficiency. Possibly even more important, these devices can operate at much higher operating temperature which translates into better semiconductor utilisation and less semiconductor material which brings the cost down. If one takes into account that ~50% of the cost in MV drives is power semiconductors the benefits are clear.
- New packaging and interconnection technologies (high temperature properties etc) – this issue goes together with the high temperature semiconductors. Furthermore, interconnection technologies that allow for double sided cooling lend themselves to better thermal management and higher power densities.
- High temperature technologies such as high temperature passives (power capacitors for high temperatures > 150°C), high temperature insulation materials etc – again goes together with higher operating temperature of the system enabled by high temperature semiconductors.
- Cooling technology – thermal management is a crucial part of the system, since it influences the cost, power density and reliability. Further developments in high performance cooling technologies such as active (forced/spray) cooling, phase change/heat pump technologies, conductive thermal transfer; new materials etc that allow for high power densities but are currently expensive are needed.
- System integration aspects, including passive components suitable for high density integration, integrated electrical, thermal & electromagnetic design tools, topologies suitable for high power density, increasing the integration level for reducing the components number etc.
- Sophisticated control platforms and integration of self powered sensors with wireless communication including enabling complex control tasks, automated start up and extended parameter identification procedures; control, lifetime monitoring and prediction of critical components, enabling plant monitoring and process energy consumption via wireless communication would increase reliability, availability and robustness of VSDs, standardisation of protocols etc.
- New converter topologies or configurations – in MV drives minimization or avoidance of gears, transformers and filters as well as increase of voltage and power of PWM converters are among main challenges for system efficiency and power density.
- Redundancy concepts (electrical machines, converter, control) and analysis of reliability and robustness including design for reliability are critical for reliability.

- Minimising sensor count – “sensorless” methods to reduce number of failure-critical parts or to have a quasi-redundance to supervise sensors (mathematical models for speed, position, torque, temperature etc.);
- Fault tolerant inverter and machine designs;
- Diagnostic and prognostics: thermal sensors/observers in devices, observers and other algorithms for diagnostics.

5.1.4 Impact

It is estimated that motor-driven systems account for more than 50% of total electricity consumption (65% of industrial electricity, 38% of tertiary and 35% of residential). The energy-saving potential of Variable Speed Drives (VSDs) comes from the ability to control the motor speed to match the output with the system needs. The energy savings potential by introducing VSDs is estimated to be 30–40% for most applications. The technical potential for energy savings is for about 40–50% of all motors depending on the application, and given that VSDs have already been applied to about 15–20% of all motors the remaining potential is estimated to be about 30%. Combining all these figures, the total electrical energy-savings potential of VSDs is about 5–6% of the current electrical energy consumption. This translates into 150TWh, which eliminates the necessity of 100 fossil fuel power plants (the 350MW capacity) and a reduction of CO_2 emissions by 75 million tons (Figure 2).

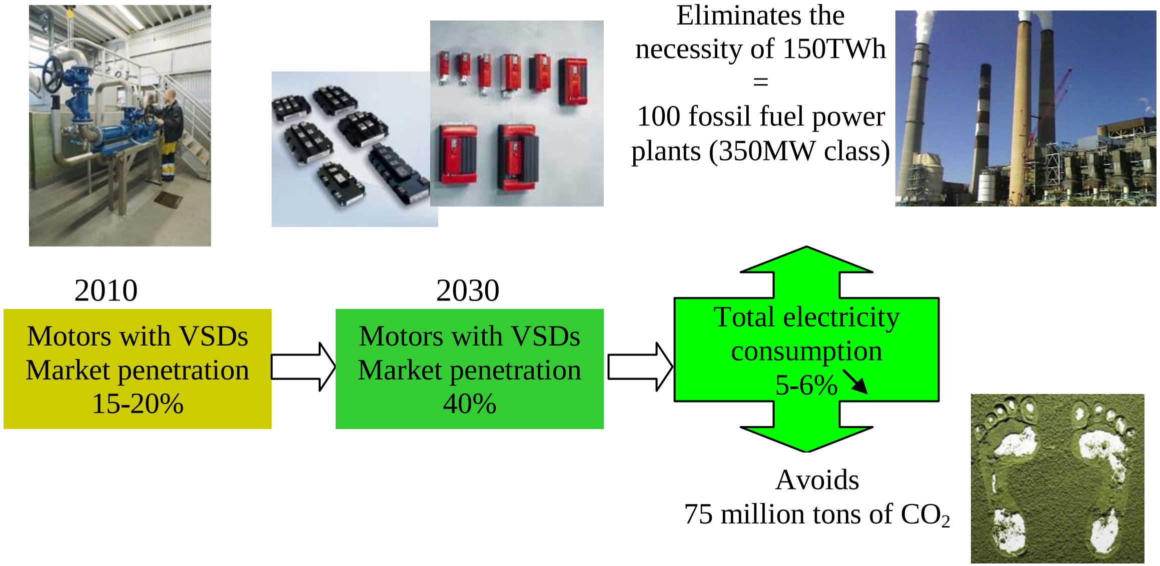


Figure 2 The impact of increased penetration of electronic speed control in motor driven systems

5.2 Power supplies for green ICT, industrial and medical applications

5.2.1 Field definition

This field includes the following categories of power supplies:

- Internal and external power supplies present in electronic equipment with special focus on ICT applications (data centres/servers, microprocessors, telecom power supplies (including RF amplifiers);
- Industrial applications: battery chargers (traction, forklift etc), induction heating, welding, plating;
- Medical applications: ultrasound and x-ray systems, laser power supplies, MRI scanners etc.

5.2.2 Objectives

The main objectives in the field of power supplies are:

- *Opening of new markets (techn. processes, applications) for high power SMPS applications*
- *Increase market penetration of high power SMPS by a factor of 2* - increase of the market share of electrical process heating, the market for hardening technologies (induction heating) etc.
- *Introduce/extend adaptive SMPS to applications in which a variable supply voltage as a function of the work load* can improve the overall efficiency of the system (microprocessors, memories, RF amplifiers,…);
- *Defend European's excellent market position*
- *Reduction of development and production costs (customer specific)*
- *Reduction of time for process analysis and time to market*
- *Reduction of costs of ownership* (efficiency, maintenance)
- *Increase of quality, reliability, redundancy, lifetime* (reduction of error rate by 50%)
- *Increase of flexibility* (fully digital, modularity)

5.2.3 Research priorities

In the case of data-centres, servers and telecom power supplies the main research priorities are:

- Improving energy efficiency of the whole energy chain through new DC power architectures;
- Tools and methodologies for the synthesis and analysis of these complex electronic power distribution systems
- Integrate system protection functions (over-temperature, voltage, current) in the power supplies to replace current fuses and breakers in distributed power systems. tolerant distributed architectures, auto-reconfigurable power distribution;
- Increasing reliability and utilization of data-centers and servers through fault tolerant distributed architectures, auto-reconfigurable power distribution;

- Optimizing energy efficiency and utilization of the data-center and infrastructure through developing communication protocols for power converters and adoption of power management strategies;
- Improving scalability of data-centers and servers through highly configurable power modules with current sharing capabilities;
- Reducing cost and improving deployment of new architectures through generation of standard interfaces, packages and communication protocols shared by manufacturers;
- Increasing power density through utilising high frequency and high temperature passives, high temp Wide Band Gap semiconductors and high frequency topologies.
- Developing standardized architectures, integration methodologies and tools for their synthesis

For power supplies for RF amplifiers, the main challenges are:
- New wide band gap (GaN) devices that will allow extending the switching frequency and so achieve high bandwidth converters;
- Improving energy efficiency through ultra-high bandwidth variable output voltage power converters;
- High level energy optimisation of RF systems through communication protocols for power converters, adoption of power management strategies for power converters and amplifiers;
- Modularity - improving scalability of RF amplifiers through modular power converters with variable output voltage and power sharing capabilities at ultra-high frequencies as well as fast digital control algorithms and devices.

In the field of micro-energy power supplies, the main research priorities are:
- High density integrated solid state capacitors, thin film integrated batteries;
- Integration of power converters in silicon through technologies for integrated magnetics and high density solid state capacitors;
- Reduction of stand-by losses by utilising ultra-low stand-by power semiconductors;
- Energy harvesting sources suitable for microfabrication and integration into standard CMOS technology for cost reduction.

For industrial applications power supplies the main research priorities are:
- Fully digital, self-learning converter-load / converter- grid-interfaces;
- Active-passive integration at very high power level / packaging / functional integration;
- High efficient system design platforms and virtual prototyping tools including process-physical /electrical / thermal / EMI / EMF / mechanical/economical issues;
- Intelligent and flexible interfaces (HMI) / remote control solutions /remote maintenance;
- Digital control of state-of-the-art and new converter topologies / control strategies;

- Process specification / process optimisation (heating, plasma, ...) / process understanding;
- Online system diagnostics for protection and EOL detection;
- System modularisation and simplification;
- Innovative cooling systems;
- Effects of electromagnetic fields on humans.

5.2.4 Impact

- Electrical energy demanded by *data centres and servers* in the Western Europe was 56 TWh in 2007 and is forecast to increase incrementally to 104 TWh in 2020. In a typical data centre, less than half of this power is delivered to the compute load, which includes microprocessors, memory and disk drives. The rest of the power is lost in power conversion, distribution, and cooling. The use of advanced power electronics techniques, like new DC distribution networks, can lead to a 10% reduction of the required energy. The integration of ICT technologies and power electronics, improving energy management, can save an additional 20%, and the implementation of best practices can lead to a 50% reduction, which translates into 1% savings of the total electricity consumption. Further research on reliability, implementation and cost reduction can further improve these numbers.
- Estimates indicate that the telecom industry consumed 1% of the global electricity consumption, and more than 90% is consumed by networks operators. Almost 30% of electrical energy savings can be achieved in *radio base stations* by employing efficient power electronics technologies such as efficient power amplifiers and techniques for low consumption in standby mode. If we take an annual electrical energy consumption of a 3G RBS of 20MWh and estimate the number of RBS in Europe to be 20000 per operator and ~30 large operators and predict the growth of 3X until 2010 this gives the total savings of 10TWh or ~0.4% of the total electricity consumption.
- The annual electricity consumption related to standby functionalities and off-mode losses in the Community was estimated to have been 47 TWh in 2005. It has been estimated that the total annual energy savings potential for standby consumption in the EU is 35TWh, and power semiconductor manufacturers claim that more than 90% standby consumption reduction is feasible.

5.3 Electronic lighting

5.3.1 Field definition

The field of electronic lighting as implied here includes the lighting technologies that rely on electronic circuits for proper starting and operating of the light source and that have long term application potential in the commercial, residential and exterior lighting market. This includes gas discharge lamps such as fluorescent and High Intensity Discharge (HID); and Solid State Lighting (SSL).

Because they have a negative incremental impedance, gas discharge lamps cannot be operated directly from the mains and must be operated in series with a current controlled ballast (a power electronic circuit). For fluorescent lamps, high-frequency operation at above 20 kHz is the most attractive approach, because the HF operation of fluorescent lamps provides higher discharge efficiency. For HID lamp operation, low-frequency-square-wave (LFSW) is the most used method. The square wave frequency is preferably chosen higher than the line frequency, and low enough to prevent those harmonic power components that excite acoustical resonances. A common compromise is 70–400 Hz. LED lamps also need a driver to regulate the current flowing through the LED during operation and protect it from voltage fluctuations. If the total power handled by the converter is higher than 25W, then the low-frequency harmonic content of the line current of these circuits must comply with specific regulations, which requires the use of an active Power Factor Corrector (PFC).

By including a combination of efficient sources and smart controls, there is great energy savings potential in commercial, residential and street lighting settings in both new construction and retrofit plans.

Fluorescent lamps use 25 to 35 percent of the energy used by incandescent lamps to provide the same amount of illumination (efficacy of 30 to 110 lumens per watt) and last about 10 times longer (7,000 to 24,000 hours). Improvements in technology have resulted in fluorescent lamps with light quality comparable to incandescent lamps. To improve the efficiency of fluorescent lighting, the magnetic ballasts can be replaced by high-efficiency electronic ballasts (class A). Replacing traditional fluorescent sources (e.g. T8) by high-efficiency ones (e.g. TL5) using electronic ballasts (>90% efficiency) reduces the energy consumption by 61%. Furthermore, using intelligent dimming based on data for occupancy and daylight (collected by wireless sensors) together with the use of dimmable efficient sources, gives an overall reduction of 78% on current usage.

High-intensity discharge (HID) and low-pressure sodium lamps are suitable for lighting purposes and where high levels of light over large areas are required. More recently, HID lamps have been used in small retail and residential environments. The most common types of HID lamps are mercury vapour, metal halide, and high-pressure sodium, all of which are much more efficient than incandescent lamps. Compared with fluorescent and incandescent lamps, HID lamps have higher luminous efficacy since a greater proportion of their radiation is in visible light as opposed to heat.

High-brightness light-emitting diode (LED) has been regarded as the next generation of “green” light source for its potential virtues of high efficiency, environmental friendliness, long lifetime, etc. With the significant improvement in the manufacturing process of high-brightness LEDs, LEDs will be applied in a wide range of applications, and may even be considered for common use in daily lighting application. The projections are that solid-state lighting will displace nearly all traditional lighting technologies in the future, with 2012 being the year that SSL is expected to surpass traditional fluorescent and HID lighting in terms of equivalent cost of light. There are also a growing number of higher power applications that are considering plasma technologies as an alternative to LED technologies.

5.3.2 Objectives

The main objectives for the field of power electronics in electronic lighting are:

- *Reduction of power consumption, improvement on reliability and availability, and overall system cost reduction* for broader market penetration of LED lighting.
- *Produce solid-state light sources (LED/OLED) suitable for direct replacement of existing ones* (incandescent lamps, fluorescent tubes, CFL bulbs, etc.) without the need of external cooling;
- *Replacing traditional fluorescent sources (T8, T12) by higher-efficiency ones with electronic ballasts* (e.g. T5);
- *Decrease cost of high power factor electronic ballasts* for off-line applications to compete with electromagnetic ballasts.
- *Penetration rate of LED light bulbs to be over 30% of total light bulb market by 2020.*

The following table summarises the strategic goals:

Year	**2010**	**2015**	**2020**	**2030**[*]
LED/OLED light fixture efficiency [lm/W]	80	120	150	160
Light source output (e.g. LED light bulb) [lm]	500	800	1000	>1000
Light source cost [lm/€]	50	200	500	2000
LED/OLED driver efficiency	>80%	>90%	95%	97%

[*] The technology is evolving quite rapidly and it is hard to predict where it will go after 2020. If the objectives for 2020 on amount of lumens per bulb/fixture and the efficiency (lumens/watt) are reached, the main thing left after that would be to reduce the cost, and/or to go for cheaper (and also more abundant and more environmentally-friendly) materials, like OLEDs. While OLED technologies will just be out of the lab and reaching the mass market in 2020 their evolution will mark the strategic objectives for 2030.

5.3.3 Research priorities

- Modelling of lamps and ballasts and their interaction to achieve robust closed-loop operating electronic ballasts;
- Efficiency improvement, especially in dimmable electronic ballasts;
- Development of reliable ignition circuits for discharge lamps;
- Techniques for acoustic resonance avoidance in high frequency electronic ballasts for HID lamps;
- Application of digital control to electronic ballasts;
- High efficiency (>90%) LED/OLED drivers;
- Development of dimming control methodologies where applicable, especially for retrofit applications;
- Modelling of the thermal interaction of power components with other ancillary components within high efficiency lighting devices to maximise device Lux operation levels and reliability (operation life);
- Examination of plasma and other alternative technologies.

5.3.4 Impact

Currently around 20% of total electrical energy is consumed by lighting. If this trend continues, energy consumption through lighting will rise worldwide by a third and in Asia by fifty percent. Savings of up to 50-70% of this that can be achieved using technology solutions which are already on the market, such as replacing traditional fluorescent sources by high-efficiency ones using electronic ballasts (>90% efficiency), and intelligent dimming based on data for occupancy and daylight (collected by wireless sensors). This translates into 10-15% of the total electricity consumption. The savings will be greater with new technologies based on solid-state lighting (i.e. LEDs).

Furthermore, new technologies will lead to new lighting experiences: scrolling electronic newspapers, adhesive films with integrated video, flexible instrument panel lighting, transparent lighting walls, etc.

5.4 Power grid infrastructure and renewable energy sources

5.4.1 Field definition

The trend of increasing electrification of society will continue in the future as the generation and consumption of electrical power is normally more efficient, cleaner and safer than the direct consumption of primary energy. Grids can integrate a large number of different renewables efficiently. Therefore, we will see a growing electricity energy demand in the next decades with an increase of > 70% until 2030. In the next 20 years, fossil fuels will continue to be the backbone for power generation while renewables are gaining in importance, see Figure 3a. Between 2030 and 2040, when the finiteness of oil and gas resources has dramatically increased the price of these fossil fuels, we can expect a substitution by a mix of renewable energy sources, see Figure 2b.

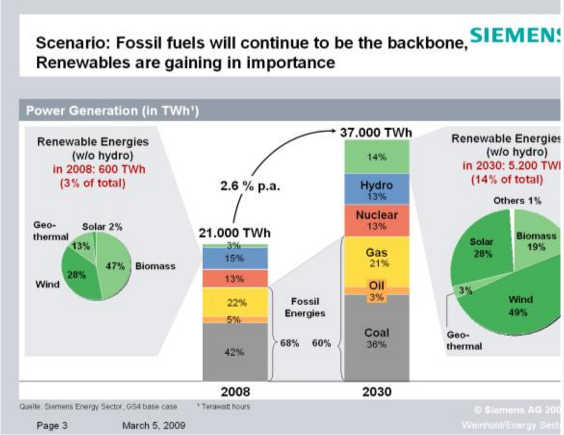


Figure 3a Power generation 2008 and forecast 2030

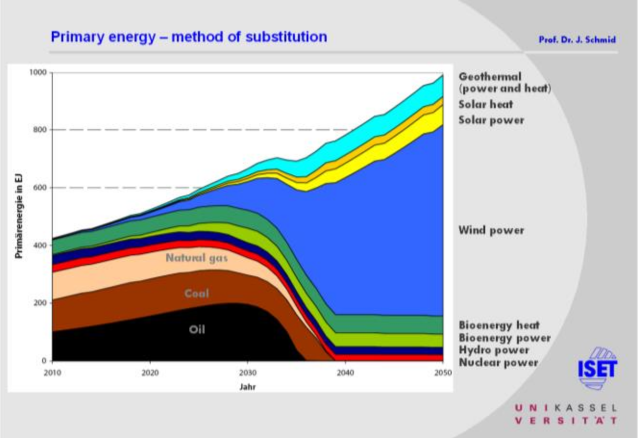


Figure 4b: Primary energy: future energy mix

This increasing share of renewables is pushing an evolution of grid design from the traditional unidirectional grid with centralised power generation towards a future smart grid integrating distributed power generation, fluctuating renewables and a bidirectional power flow, as shown in the table:

Traditional Grids	Future "Smart" Grids
- Centralised power generation - One-directional power flow - Generation follows load - Operation based on historical experience - Limited grid accessibility for new producers	- Centralised and distributed power generation - Intermittent renewable power generation - Consumers become also producers - Multi-directional power flow - Load adapted to production - Operation based more on real-time data

The key elements of smart grids are:

- Integration of Renewables;
- Efficiency and Reliability;
- Demand Response
- Integration of Electric Vehicles

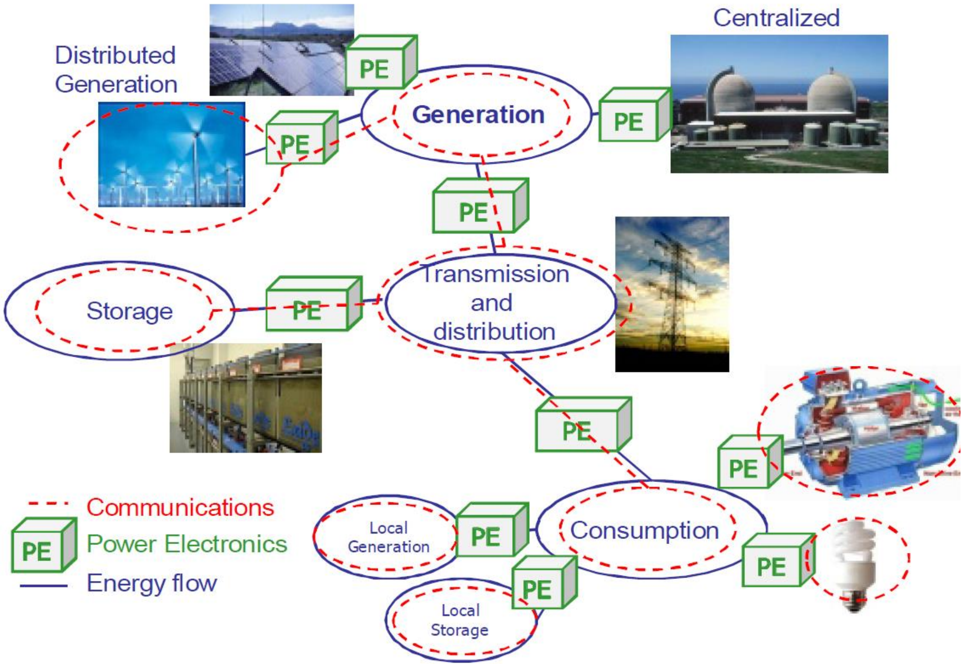


Figure 4 Power electronics along the whole chain of energy supply

Power electronics is needed at all levels to increase controllability in transmission and distribution grids, and to adapt new generation and storage to the grid (Figure 4). Power electronics is also necessary to interface renewable energy sources to the existing and future grid. Critical factors to accelerate the implementation of power electronics for smart grids are losses, reliability, lifetime, and cost. Use of power electronics, communication and automation is the key to innovative solutions for operating modern power systems with improved reliability and power quality.

5.4.2 Objectives

The main high level objectives for the field of power electronics in the field of power grid infrastructure and renewable energy sources are:

- *Increased share of renewables* (>30% by 2030);
- *Distributed power generation (micro grids);*
- *Balanced load to supply, demand response;*
- *Efficiency and reliability of the grid, power quality;*
- *Cost reduction of PV panels and power converter stage (*40% by 2015, x% by 2030);
- *Increased PV converter efficiency;*
- *Increased reliability of PV systems;*
- *Increase in the power production of wind turbines (>5MW);*
- *Increase in penetration of small wind-turbine systems (tens to few hundreds of kW);*
- *Integration of wired and wireless sensors and actuators into the grid* to interpret the data gathered and convert to energy efficient actions as well as perform conditional monitoring operations.

5.4.3 Research priorities

In order to reach the objectives shown above, more research in the following technology areas needs to be done:

- Low-loss, long distance HVDC power transmission, meshed HVDC overlay grids;
- MV DC grids with high power DC/DC converters;
- EV charging load management and intelligent bidirectional power interface between EV and grid;
- High power semiconductors enabling high voltage (10kV), high currents and high temperature based on Si devices or wide band gap devices (SiC, GaN);
- Packaging challenges associated with high power (thermal expansion, insulation clearances etc), thermal management;
- Solid state transformers - advanced (soft switching) topologies for high efficiency power solid state transformers (SST) for distribution purposes;
- Next generation of multi-level power conversion to interface with conventional AC power systems;
- New design environments and real time digital simulators for power electronics control;
- Highly intelligent and self-sensing integrated module as a building block for new distribution system architecture, wireless or fiber optics control interface;
- Control of micro- and super- grids (island mode and normal grid mode);
- Remote monitoring and control of solar and wind farms;
- Bi-directional flow of power and information;

- Power and ICT interface between the grid and the appliances;
- Increasing efficiency of PV power converters by means of transformeless topologies and converters based on SiC devices;
- Maximum power extraction topologies;
- Integration of the power converter in the panel to reduce the problem of minor energy production due to panel mismatch;
- Advanced islanding detection algorithms that help monitor grid condition and compliance with grid standards and codes;
- High power converters for wind turbines based on modular technology;
- Design of wired and wireless sensors and actuators and their integration into the grid for both conditional monitoring and energy efficiency optimisation operations

5.4.4 Impact

Reaching the objectives listed for this field will have major impact on the European energy and climate picture:

- Reduction of dependence on fossil fuels – towards sustainable energy supply in Europe;
- Reduction in CO_2 emissions by increased penetration of renewable energy sources;
- Improved European technology and industry position in grid and renewable technologies.

5.5 Automotive and avionics

5.5.1 Field definition

Ever increasing fuel prices and the global energy and climate situation have triggered worldwide investment in electric and hybrid vehicles and increasing penetration of these vehicles into the market. Recent advances in battery technologies, raising public interest for greener, energy efficient electric and plug-in hybrid-electric vehicles and policy incentives have resulted in plug-in hybrids and all-electric vehicles being on the threshold of serious market introduction. The US government has committed to a goal of one million plug-in EVs in the next five years. In Europe, the German government announced a national platform on electric mobility to put a million plug-in cars on the roads by 2020, France intends to have one hundred thousand electric vehicles on the road by 2012 and The Netherlands is aiming at having one million electric cars on the roads by 2020. Since battery vehicles driving range and charging times are still a bottleneck, for medium/large vehicles and longer ranges the hydrogen fuel cell electric vehicle (FCEV) may offer the lowest carbon solution. Since this category of cars accounts for 50% of all cars and 75% of CO_2 emissions FCEVs are expected to be one of the important market segments in the long run. The automotive field as assumed in this SRA includes the power electronic technologies involved in the development and implementation of (plug-in) hybrid electric, electric and fuel cell electric vehicles, as well as the power electronics technologies involved in electrification of previously mechanical and hydraulic vehicle functions, such as x-by-wire applications like steer-by-wire or brake-by-wire, electric active suspension, electromagnetic valves etc.

The avionics field includes power electronic technologies involved in replacing bleed air and hydraulic power sources with electrical equivalents thus enabling a significant improvement in efficiency, system flexibility, aircraft reliability and specific fuel consumption. Examples are electrical wing ice protection, electrical flight control actuator, full electrical APU, electrical braking etc. In these *more electric aircrafts*, power electronics systems are crucial for the aircraft's distributed power system and the total power electronic load is 1MW compared to several kW in conventional aircrafts. As demonstrated with Boeing's More-Electric-Aircraft 787 Dreamliner a significant reduction in fuel of 20% and CO_2 compared to its conventional counterpart 767 is achieved to its efficient no-bleed engines and the composite airframe.

5.5.2 Objectives

- *The share of Electric Vehicles (EVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Fuel Cell Electric Vehicles (FCEVs) in Europe will exceed 50% in 2025 and 75% in 2030, 90% by 2050 (of new passenger cars)* enabling emission-free individual mobility in cities.
- *Reduced* CO_2 *by 50% per passenger per km for aircrafts, reduce* NO_x *emissions by 80% by 2020, reduce noise to one half of the current levels.*

5.5.3 Research priorities

The power switching devices and power electronic circuits, electric motors, and associated control systems and components play a key role in bringing hybrid, electric and fuel-cell vehicles to market with reliability and affordability. The available power electronic components are based on components optimized for industrial applications and hence have many disadvantages for application in commercial electrical vehicles. Some examples of such components/sub-systems are:

- Low-cost drive inverters with standardized dc input voltages – this will enable to get the necessary large quantities.
- High-power high-voltage dc/dc converter to control the energy exchange between the high voltage battery or the fuel cell and the drive inverter and match the fuel-cell voltage with the battery pack. The dc/dc converters currently available on the market are heavy and expensive.
- High temperature converters to simplify the cooling equipment of hybrid and fuel cell drives using one cooling system for both ICE and electric drive in case of hybrid or for fuel cell and electric drive in case of fuel cell vehicles.
- High efficiency LED drivers and converters in auxiliary systems (climate control, lighting etc).

To make the development of such subsystems possible, more research on the following topics is needed:

- Fault tolerant systems for safety critical systems;
- Diagnostic capabilities of power semiconductors;
- Smart power semiconductors;
- SoC and SiP integration;

- Standardised high power density power electronics building blocks for modular systems;
- High power high temperature SiC and GaN switching devices;
- High temperature packaging technologies (200°C);
- High temperature mechatronic integration;
- High temperature PCBs;
- Double sided cooling technologies;
- Improved dielectric materials for high frequency, high voltage and high temperature capacitors;
- Topologies with integrated functions (inverter, charger, dc/dc converter);
- Topologies for smart charging for long battery life time and efficiency;
- Multilevel converter topologies;
- Fault-tolerant topologies and control techniques;
- Integrated EMI filters;
- Low cost manufacturing technologies for power electronic converters.

5.5.4 Impact

The foreseen implications of the more electric automotive and avionic sector will be:

- The reduction in fuel usage reducing dependence on foreign oil through increased efficiency of (hybrid) electric vehicles (a hybrid vehicle with a 65km range could eliminate the need for 7.5 out of 11l of petrol needed by traditional petrol vehicle).
- Lower CO_2 emissions and tailpipe emissions (NO_x, dust, etc) – emission free mobility in cities;
- Aid to the shift to renewable energy sources making the transport sector more sustainable;
- Increased passenger safety and comfort;
- Improved vehicle performance (better acceleration and very fast response).

Figure 5 shows the difference in vehicle efficiency for petrol and electric vehicles. Figure 6 shows the impact of the scenario from the first objective where 75% of new passenger vehicles are electric vehicles. In the calculations it is assumed that all the electricity for the electric vehicles comes from the fossil fuel generation, if the actual electricity mix is taken into account the savings will be even larger.

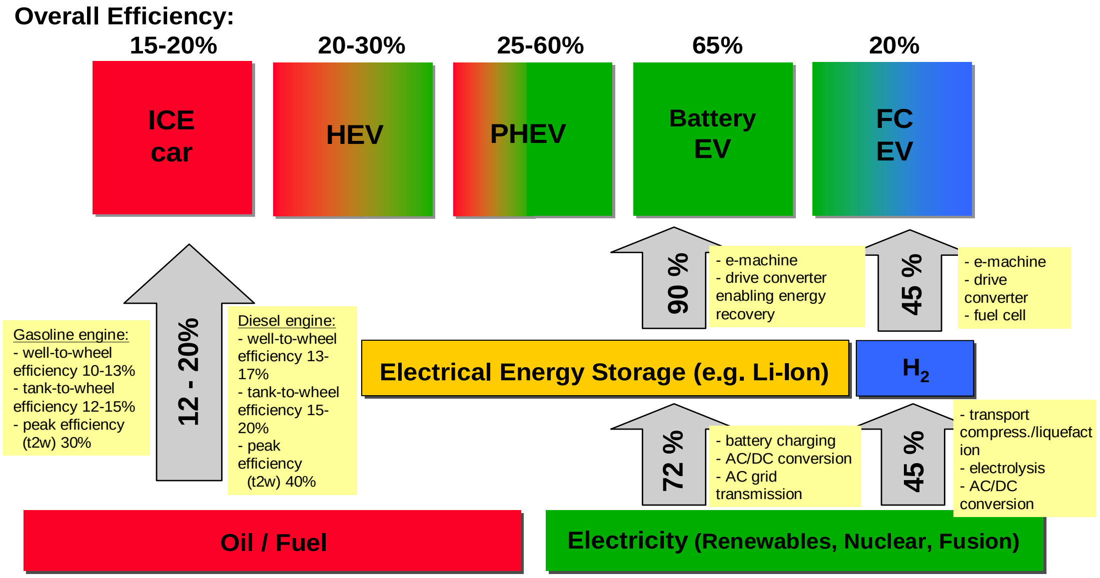


Figure 5 Vehicle efficiency comparison

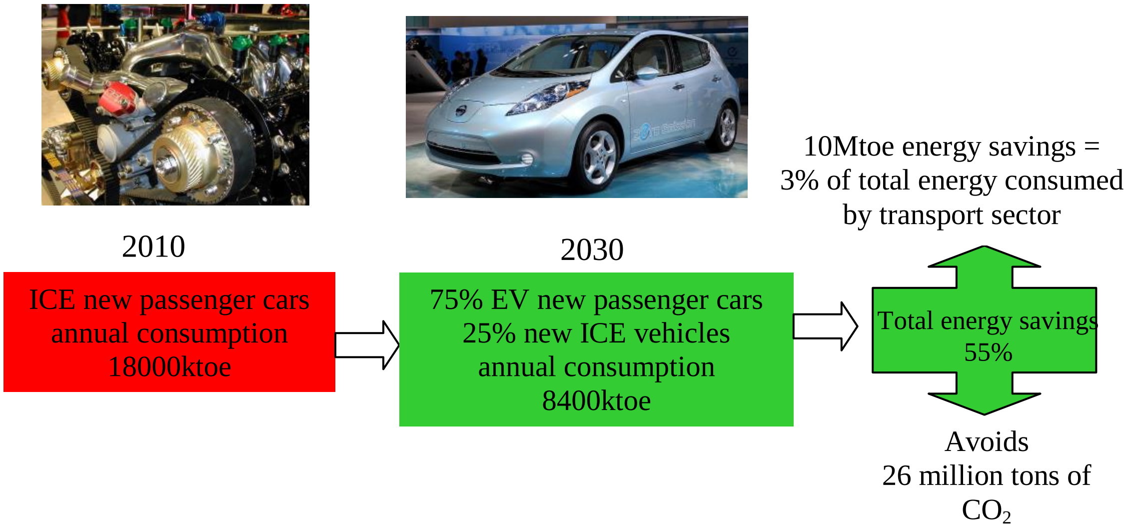


Figure 6 The impact of large market penetration of electric vehicles

Technology challenges

In the previous sections, the main research priorities for each area have been identified. This section will identify general technological challenges that power electronics will face in the next decades on the road to fully exploiting its potential. Power electronics is a multidisciplinary technology and advancements in the following key technologies are crucial for further progress of power electronics:

- Power semiconductors;
- Passives;
- Packaging and interconnections;

- Cooling;
- Reliability.

5.6 Power semiconductors

Power semiconductors are experiencing ever increasing demands in terms of dynamic characteristics, overload capability, device ruggedness and built-in reliability. In the automotive segment, the main requirements are high operating temperature while the industry applications demand high blocking voltage capabilities. Furthermore, while the key technology has primarily been power semiconductor devices, this is now shifting towards system integration.

Wide band gap power semiconductor technologies such as SiC, GaN are opening up vast possibilities for power electronics circuits. The superior electrical and thermal properties of these semiconductors such low loss, high operating temperature, high breakdown voltage offer a significant potential for better performance, minaturisation and cost reduction of power electronics systems in automotive, aircraft, marine, power supplies, renewable energy applications. The driving force is the benefit to realise low loss and very fast unipolar diodes and switches with blocking voltages from 600V up to 4000V. High power rating Schottky diodes (up to 50A, 1200V) are the state-of-the-art today; high voltage (1200V, 1500V) unipolar VJFET switches are in the development phase. The understanding and improving of the manufacturing process to improve the reliability and yield has been the main focus of research in the past years. The main future challenges for SiC are foreseen to be:

- Increasing power rating of SiC power Schottky rectifiers;
- Exploring SiC MOS-gated power transistors, maintaining/improving reliability for larger wafer diameters;
- Move to larger diameters for cost reduction;
- Understanding and reducing certain defects (Killer epitaxy defect density, bipolar degradation etc.), the epitaxial growth process etc;
- Development of high-voltage (>10kV) SiC IGBTs for high power applications.

To make SiC competitive in standard drive applications it is necessary to reduce the chip area costs to less than about four times the area costs of a Si- IGBT or to increase the maximum possible junction temperature swing through reducing the thermal resistance (e.g. by heat spreading, chip-on-diamond etc.).The key success factor for future device developments is foreseen to be a tight cross-functional cooperation between device physicists, packaging experts and system engineers.

GaN power devices seem to be very promising as silicon power MOSFET replacements. They can withstand higher voltages, have far superior switching performance and offer good cost-effectiveness potential of the wide band gap performance at the price of silicon. The typical on-resistance*gate charge figure-of-merit of these devices is in the range of order of magnitude superior to that of silicon power MOSFETs. These characteristics open up many possibilities for end products using GaN transistors with greater battery life, less power consumption, smaller size, and lower costs. It is expected that in 3-5 years 1-2% of all applications will be with GaN devices. Consequently all major power semiconductor companies are doing their share of technology development in the field of

GaN devices. The main future challenges and opportunities for GaN to make these devices effective replacements for power MOSFETs are foreseen to be:

- Exploiting possibilities for monolithic integration of multiple power (and control) devices on a single chip;
- Exploiting GaN in existing applications and identifying new applications enabled by GaN ((H)EV automotive, lighting, PV inverters, very high frequency POL converters etc);
- Exploiting GaN devices properties for improved performance of existing and introducing new topologies;
- Vertical GaN devices for high voltage operation (avoiding current collapse);
- Technology issues: yield, stability, leakage current, gate dielectric strength etc;
- Optimal driving of these fast devices;
- Further improvements in reliability;
- Normally-off operation challenge.

Even when the technology issues surrounding the wide-band gap SiC and GaN power devices are solved it will only be possible to fully exploit their superior performance if the surrounding issues, such as packaging, layout, passive components, thermal management etc. are adequately addressed.

Despite the large interest for and potential of wide band gap semiconductors, silicon power devices have certainly not come to their evolutionary end. The roll out of modern chip technology for very high voltage traction IGBTs (up to 6.5kW) is in progress, the lower voltage rage IGBTs are being replaced with new generation devices. New device concepts such as Reverse Conducting IGBT (RC-IGBT), Reverse Blocking IGBT (RB-IGBT) also promise performance improvements in certain applications. It is foreseen that there is still enough innovation potential for at least two further IGBT and diode generations with lower losses at lower costs before the next switch for inverters (SiC or other Si based switching concept) arises for mass application and production.

5.7 Passives

In the past the main focus of power electronics research has been on active devices, both on power semiconductors and the integration of control, protection and driving circuits with power semiconductors. Significant progress has been made in this field, in terms of performance, miniaturisation and cost. This has resulted in the situation where the size and cost of power semiconductors have been reduced to the level where it is not the main limiting factor in achieving high power densities and low cost. In a commercial off-line laptop power supply the power semiconductors occupy the minor part of the total volume (less than 5%) while the most volume is occupied by air, passive components and thermal management. The situation is similar in other power electronics products. We have reached a point where passive components are becoming a limiting factor for the further progress in the power electronics technology development. It has become clear that more research effort needs to be put in passive components and their subassemblies, in order to improve their performance, size and cost.

Improvements in the design of inductive and capacitive components are expected from new materials and technologies, better understanding and improved analysis of the underlying loss mechanisms and innovative cooling concepts. High temperature magnetics and capacitors are a must if they are to be implemented in high temperature environments together with high temperature semiconductors (such as SiC and GaN).

Magnetic materials

Ferrites are preferred magnetic material for high-frequency applications due to their high electrical resistivity resulting in that they do not need to be laminated to minimize eddy current loss. The application spectrum of ferrites is very wide: automotive, lighting ballasts, industrial, consumer, telecom etc. The important market driver for ferrites is low energy consumption in low power applications such as chargers, standby functions of electronic devices etc. Another important driver is miniaturisation that has been a steady trend for over 5 decades. This can be achieved by means of low loss materials, higher switching frequencies and integration of several functions into one component. Ferrites are limited by their temperature sensitivity, low Curie temperature, and low saturation flux density. Recent improvement in ferrite technology has been driven by improved process control rather than fundamental breakthroughs. The emerging technologies such as nanocrystalline ferrite materials will be explored for power electronics applications. Concerning ferrite magnetic materials, the main improvements to be expected are in:

- Further loss reduction of materials for specific operating conditions (frequency, flux density and temperature);
- Increasing stability of material properties such as $\mu(f)$, $\mu(T)$, losses (T);
- Operating temperatures of materials (>160°C).

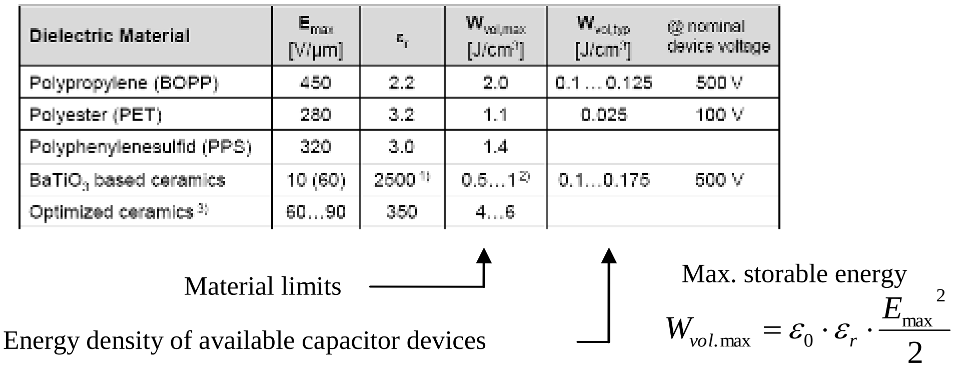
Concerning the loss reduction, it appears that understanding the nanoscale phenomena is the current road towards systematic improvements on ferrites.

Nanocrystalline magnetic materials are made by annealing of iron based amorphous tapes to nanocrystalline phases (~10nm grain size). These materials have high initial permeabilities, high saturation flux densities, smaller temperature dependency of permeability and low core losses compared to other magnetic materials. Nanocrystalline materials are competitive with polycrystalline alloys at low frequencies, despite higher cost, because of their equivalent saturation flux density and low eddy current loss. They can also compete with ferrites at higher frequencies because of their higher saturation flux density and Curie temperature. Furthermore, a significant volume reduction potential (as high as 60%) for the implementation of EMI inductive filtering components in nanocrystalline compared to ferrite needs to be investigated. Improvements on manufacturing process are needed to alleviate the affects of increased losses due to using cut cores instead of wound cores.

Dielectric materials

Looking at the maximum achievable energy density limited by material properties, and that found in available capacitor devices (Figure 7) it can be seen the ratio of the maximum and available energy density is more than an order of magnitude for both metal film (polyester and polypropylene) and ceramic capacitors. This shows that there is significant room for improvement.

Metal film capacitors have a large application potential in power electronics (hybrid vehicles, industrial drives, traction, renewable energy etc.) due to their characteristics such as: ease of integration (available in various customised shapes due to different winding technologies), low parasitic inductance, high operating temperature rating, high current handling capability, self-healing properties etc. Furthermore, there is a potential for metal film capacitors to replace short life time, high loss electrolytic capacitors in high volume applications such as motor drives provided that the control is properly designed. As can be seen from the table, ceramic capacitors have greater potential in terms of energy density than metal films capacitors. 5 J/cm3 would open up great opportunities in power electronics, for e.g. in high voltage DC links in hybrid electric, electric and fuel cell vehicles.



Dielectric Material	E_{max} [V/µm]	ε_r	$W_{vol,max}$ [J/cm^3]	$W_{vol,typ}$ [J/cm^3]	@ nominal device voltage
Polypropylene (BOPP)	450	2.2	2.0	0.1 … 0.125	500 V
Polyester (PET)	280	3.2	1.1	0.025	100 V
Polyphenylenesulfid (PPS)	320	3.0	1.4		
BaTiO$_3$ based ceramics	10 (60)	2500 $^{1)}$	0.5…1 $^{2)}$	0.1…0.175	500 V
Optimized ceramics $^{3)}$	60…90	350	4…6		

$$W_{vol.\max} = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{E_{\max}{}^2}{2}$$

Figure 7 Energy Storage Density of various dielectrics

Concerning the potential of nanodielectrics, by embedding barium titanate nanoparticles into the polycarbonate's matrix of polycarbonate (polymer that is already used in metal film capacitors) the permittivity can be raised from 3-4 to 20). This is a promising direction for realizing capacitors with a very high energy density with a high dielectric constant (coming from the barium titanate particles), but also with a high breakdown voltage (due to the polymer).

Integration of passives

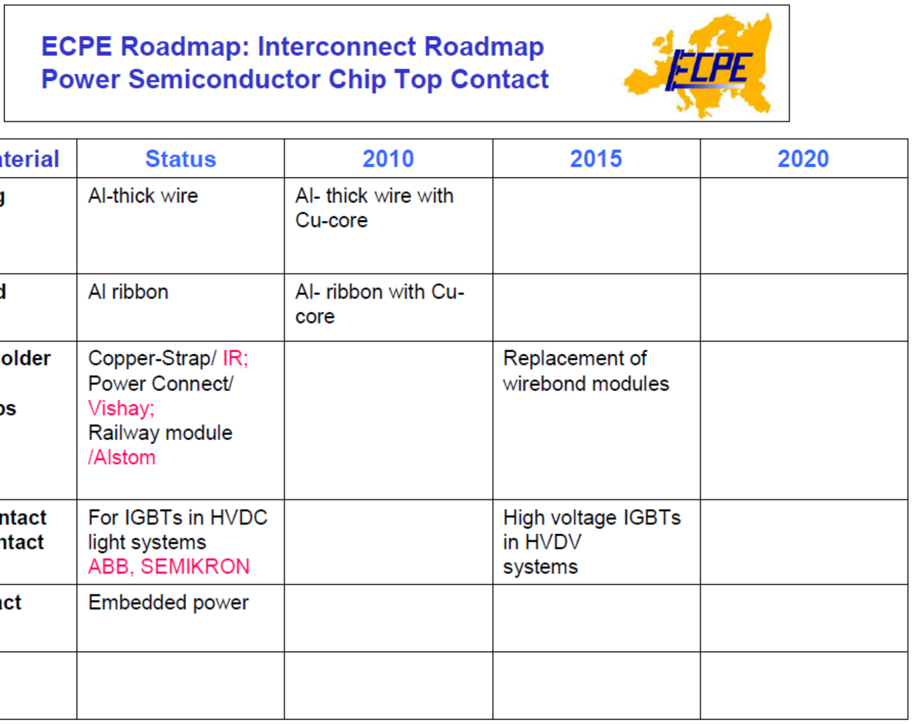
In comparison to power semiconductors and control electronics, the level of integration in passive components is very low. Another challenging research area is integration of passives, including electromagnetic integration of functions, higher power density assemblies and advanced cooling concepts. The possibilities for progress in this area are numerous, e.g. by utilising parasitic components as part of the needed functionality or by integration of the components in substrate materials such as PCB or ceramic.

5.8 Packaging and interconnections

Chip-level interconnections and packaging

Ultrasonic wire bonding has been the dominant die-level interconnect technology in power electronic applications. Wire bonding technology is a mature technology making wire bonding well suited to automation and consequently mass production. Ultrasonic wire bonding has the advantage of low cost, flexibility and reasonably good reliability. The main disadvantages are: large resistive and inductive parasitics which are especially critical in applications that require fast delivery of large currents in small time intervals such as high-speed microprocessors, detaching from the semiconductor die due to electrical and thermal fatigue, wirebonds occupy one of the two die surfaces making only single sided cooling possible, etc.

As the demands for increased power density grow, power converters are moving to higher operating frequencies with higher dI/dt and dV/dt, double sided cooling and more compact design. All these requirements ask for alternative die-level interconnection technologies that allow for metallization of all interconnects at the same time, 3D layout and improved reliability. These technologies range from those that use solder joint instead of bond wires to produce chip scale packages such as solder bump flip chip technology and direct-chip mounted double sided Direct FET, to planar metallization technologies that allow not only for chip-level interconnection but also metallising multiple chips, implementing layers for dielectrics and magnetic components and stacking these layers in a quasi-3D manner such as Embedded Power etc. Reliability, thermal behaviour and manufacturing cost of these and emerging wirebondless technologies are the crucial steps in introducing them into the market. Figure 8 shows the ECPE technology roadmap for the chip-top interconnect technologies, anticipating the development of the above mentioned interconnect technologies.

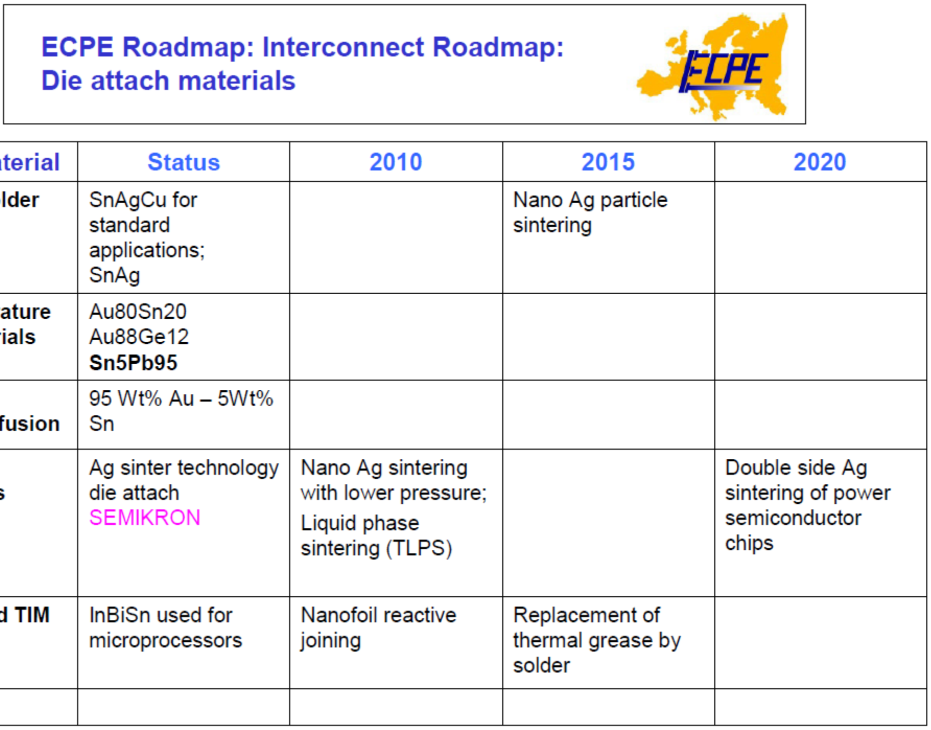


ECPE Roadmap: Interconnect Roadmap
Power Semiconductor Chip Top Contact

Joining Material	Status	2010	2015	2020
Wirebonding Al on Al	Al-thick wire	Al- thick wire with Cu-core		
Ribbon bond	Al ribbon	Al- ribbon with Cu-core		
Large area solder contact; Solder bumps	Copper-Strap/ IR; Power Connect/ Vishay; Railway module /Alstom		Replacement of wirebond modules	
Pressure contact & Spring contact	For IGBTs in HVDC light systems ABB, SEMIKRON		High voltage IGBTs in HVDV systems	
Planar contact	Embedded power			

Figure 8 Power semiconductor chip top interconnect technologies roadmap (ECPE)

With the significant progresses made in crystal growth and device fabrication of SiC and GaN power devices, in order to take full advantage of their superior characteristics such as thermal conductivity, high breakdown voltage, high operating temperature capability etc. new interconnecting and packaging technologies need to be developed. The state-of-the-art die-attachment technologies where the die is attached to a substrate with a solder alloy or an electrically conductive adhesive are not suitable for high-temperature operation because these alloys/adhesives have low melting and degradation temperatures. A few alternative approaches are being explored to provide the high-temperature die-attachment, including silver-indium joining technique, sintering of microsilver or gold pastes using external pressure and low temperature silver sintering. Figure 9 shows the technology roadmap for the die attachment developments over the next decade.



ECPE Roadmap: Interconnect Roadmap:
Die attach materials

Joining Material	Status	2010	2015	2020
Lead-free solder	SnAgCu for standard applications; SnAg		Nano Ag particle sintering	
High-temperature attach materials	Au80Sn20 Au88Ge12 **Sn5Pb95**			
Solid Liquid Interface Diffusion	95 Wt% Au – 5Wt% Sn			
Sinter technologies	Ag sinter technology die attach SEMIKRON	Nano Ag sintering with lower pressure; Liquid phase sintering (TLPS)		Double side Ag sintering of power semiconductor chips
Solder based TIM	InBiSn used for microprocessors	Nanofoil reactive joining	Replacement of thermal grease by solder	

Figure 9 Power semiconductor die attach interconnect technologies roadmap (ECPE)

Power modules

Power modules as an integrated assembly of power semiconductors are basic building blocks for many power electronics assemblies. In a conventional power module several power semiconductors (MOSFET or IGBT chips and diode chips) which are electrically isolated from the mounting surface (heatsink) are integrated into a case on a common base plate.

The development in new packaging technologies in power modules are focused on the following:

- improvement of heat dissipation/advanced cooling technologies;
- highly flexible assembly and connection technology;
- higher level of integration;
- improved reliability.

Figure 10 shows a roadmap for the level of integration of power modules until 2020. The state-of-the-art power modules have already come far compared to several years ago, in terms of having higher thermal conductivity and better CTE ceramic substrates and improved interconnections including large area soldering and advanced wire bonding/thick wire technologies. Modules are mainly forced air or water cooled. There are some highly integrated modules on the market but the majority has power semiconductors and some additional electronics.

The current trends are towards developing and applying interconnection technologies alternative to soldering, such as sintering, and wirebondless interconnection technologies. It is expected that the modules in 2015 will feature these technologies as well as a higher level of integration with integration of drivers and sensoring circuitry.

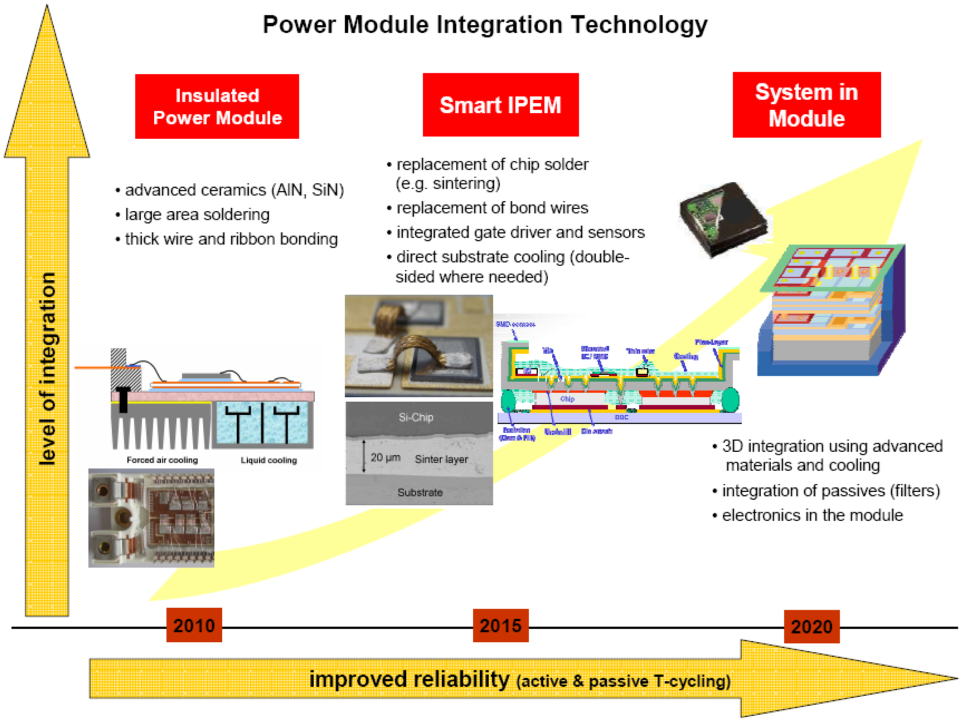


Figure 10 Power module roadmap

Further increasing the level of integration would include integrated passive components (such as for filtering) into the module, which would require three-dimensional packaging approaches to accommodate the volumetric requirements of passive components. Adding other necessary control, protection and auxiliary electronics will result in having the full system integrated in the module. This is expected to happen by 2020.

Converter-level interconnections and packaging

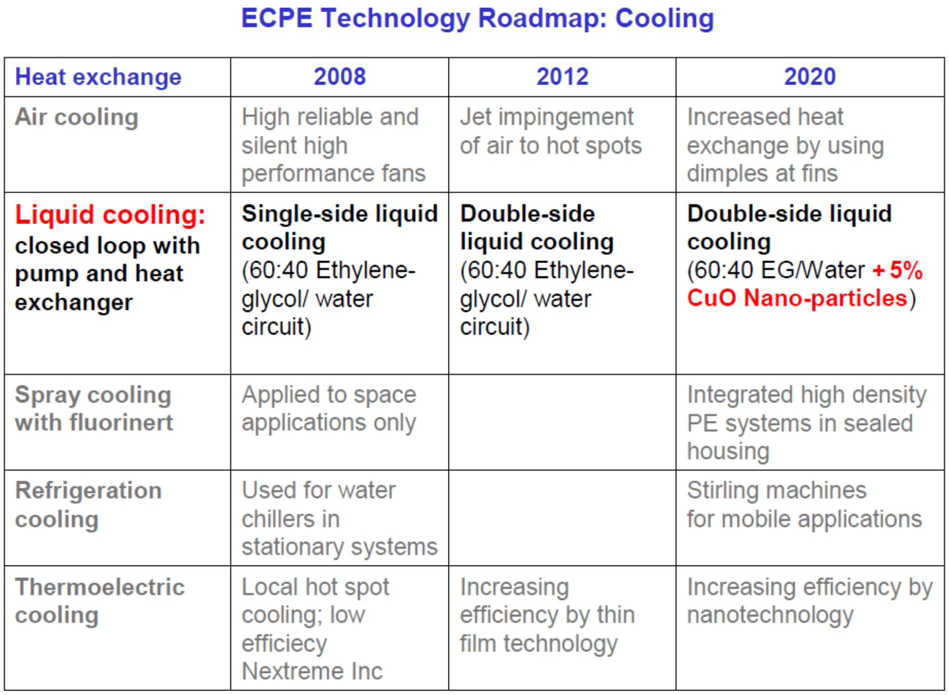
Printed circuit boards (PCBs) are traditionally associated with low power electronic circuits. In power electronics, PCBs are mostly used as the main carrier for low power converters. In the higher power range, PCBs are used as carriers for passives, driver and control circuits and interconnected to power modules or discrete power devices by means of busbars. An ongoing industry trend is to push the power capability of PCBs towards higher power, reaching as high as 100kW. From the system integration point of view, this is expected to bring cost benefits together with achieving more compact design and higher performance. Technologies allowing high currents PCBs are thick copper PCB technologies, miniature heat pipes for PCBs etc. Furthermore, there is significant research effort to increase the functionality of PCBs by integrating passive and active components in PCB layers by means of PCB-compatible dielectric and magnetic materials and special processes for embedding active devices in the PCB.

Packaging materials (isolating, thermal interface)
Hybrid integration of power electronic converters in the form of integrated modules or cells brings along constructions that combine many layers of materials, including solid dielectric materials. The coupled electromagnetic-thermal-mechanical nature of the constructions will pose unconventional and challenging requirements to all the materials, including the dielectrics in terms of interface, thermal and mechanical considerations. Insulating materials in integrated modules perform various functions: substrates, passivation, encapsulation etc. Close coupling of these materials in the highly integrated structures will require detailed analysis of electromagnetic, thermal and mechanical behaviour of these materials. Improvements in metallisation of ceramic substrates including stresses at the metal/ceramic interface, investigation of new substrate materials like diamond (Si_3N_4), polymerization process of silicone gels, materials for passivation of high voltage, high temperature SiC devices are some of the research focuses in this field. High temperature silicone encapsulants are necessary for the assembly of power modules for high temperature applications.

Due to its low thermal conductivity, thermal interface materials are becoming ever more dominant layer of the heat flow path as the thermal resistance of the other parts (DCBs, base plates, solder) are decreasing. In the past decade, significant progress has been made in the development of thermal greases, phase change materials, solders and carbon nanotubes. Greases, followed by gels and phase change materials are the most widely used and their bulk thermal conductivity has reached $10mm^2K/W$ (for thin bond-line thicknesses). While the thermal conductivity of thermal interface materials has experienced significant improvements, the reliability issues of these materials including phenomena such as dry-out, pump-out, non-uniform application and complex underlying physical phenomena thereof are coming into the research focus.

5.9 Cooling

Thermal management is, together with reliability and costs, one of the most challenging issues in power electronics. Depending on the heat density and application, various types of cooling are used, going from natural convection to pool boiling as the most efficient cooling technique. The advanced cooling techniques, like two phase cooling and double-sided liquid cooling, novel liquid cooling concepts like Danfoss ShowerPower, highly integrated concepts including heat pipes for heat conduction, nano-particle enriched double sided liquid cooling etc. are currently in the research focus. Figure 11 shows the cooling roadmap created by the ECPE technology roadmap team.



ECPE Technology Roadmap: Cooling

Heat exchange	**2008**	**2012**	**2020**
Air cooling	High reliable and silent high performance fans	Jet impingement of air to hot spots	Increased heat exchange by using dimples at fins
Liquid cooling: closed loop with pump and heat exchanger	**Single-side liquid cooling** (60:40 Ethylene-glycol/ water circuit)	**Double-side liquid cooling** (60:40 Ethylene-glycol/ water circuit)	**Double-side liquid cooling** (60:40 EG/Water **+ 5% CuO Nano-particles**)
Spray cooling with fluorinert	Applied to space applications only		Integrated high density PE systems in sealed housing
Refrigeration cooling	Used for water chillers in stationary systems		Stirling machines for mobile applications
Thermoelectric cooling	Local hot spot cooling; low efficiecy Nextreme Inc	Increasing efficiency by thin film technology	Increasing efficiency by nanotechnology

Figure 11 Cooling roadmap (ECPE)

5.10 Reliability

With the ever increasing demands for miniaturisation, system integration and high temperature operation, reliability is becoming an increasingly important and challenging aspect of power electronics systems. The operating temperature of the components and temperature cycling are of vital importance for the reliability of power electronics. Significant research effort has been put into identifying and understanding main failure mechanisms in power electronics modules and systems such as bond wire fatigue, bond wire heel cracking, solder fatigue and voids etc. Various multidomain simulation concepts aimed at analysing the reliability of high temperature electronics in particular for automotive applications have been developed and reported. Design for reliability and fault-tolerant systems are receiving more and more attention in the power electronics research community.

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