electronics enabling efficient energy usage

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Electronics enabling efficient energy usage

Results from the E4U project

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e4u

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Abbreviations

AC	alternate current
CIP	Competitiveness and Innovation Programme
CMOS	Complementary metal–oxide–semiconductor
CTE	coefficient of thermal expansion
DC	direct current
E4U	Electronics Enabling Efficient Energy Usage
ECPE	European Centre for Power Electronics
ELSA	European Large-Scale Actions
ETP	European Technology Platform
EV	electric vehicle
FACTS	Flexible AC transmission system
FC EV	fuel cell electric vehicle
FP7	Seventh European Framework Programme for Research and Technological Development
GaN	Gallium nitride
HEV	hybrid electric vehicle
HVAC	heating, ventilating and airconditioning
HVDC	high voltage direct current (electric power transmission system)
IC	integrated circuit
ICT	information and communication technology
IEA	International Energy Agency
IGBT	Insulated-Gate Bipolar Transistor
IPEM	integrated power electronic module
IPM	intelligent power module
LED	light-emitting diode
MOSFET	metal-oxide-semiconductor field-effect transistor
MPPT	maximum power point tracking
Mtoe	million tons of oil equivalent
MV	medium voltage (drives)
OLED	organic light-emitting diode
PE	power electronics
PHEV	plug-in hybrid electric vehicle
PPP	public-private partnership
PV	photovoltaic
PWM	pulse width modulation
RBS	radio base station
RF	radio-frequency
SiC	silicon carbide
V2G	vehicle-to-grid
VSD	variable speed drive
WBG	wide bandgap (semiconductors)
WEC	World Energy Council
WSN	wireless sensor network

1 Introduction

1.1 Energy Efficiency: Why we need to act

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.

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 (compared to the respective values in 1990).

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.

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. Figure 1 shows the forecasted electricity consumption growth and indicates that its growth rate is 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.[2]

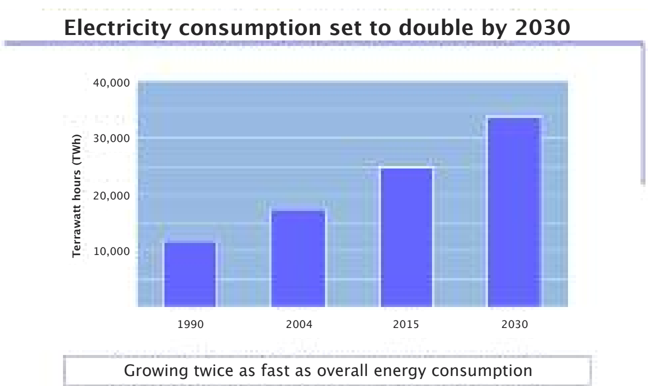

Figure 1: Electricity consumption forecast[1] (Source: International Energy Agency, IEA)

Power ! Electronics

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 efficient use, distribution and generation 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 mili 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.

1.2 Megatrends

Like any other technology, power electronics is striving to meet the needs of society. Table 1 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.

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.[3] 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%.[4] 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.[5] 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.[6] 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.[7] 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.[8] 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.[9]

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

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

Table 1: Societal megatrends

predicted to increase to 49 TWh in 2020. An important proportion of these losses is related to power supplies.[10]

It is estimated that European consumption of **broadband equipment** will be up to 50 TWh per year by 2015.[11] 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.[12]

„ ... "

I am convinced that ICT has a key role to play in enabling energy efficiency improvements across the whole economy, thus lowering emissions and fighting climate change.

Viviane Reading
European Commission

Energy supply – security, availability and reliability

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.[13] In the EC paper "Vision and Strategy for Europe's Electricity"[14] 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 inter-operable 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%.[15] 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.

One possible model for the electricity network of the future, virtual utility, would be analogous to the internet, in the sense that decision-making is distributed and that flows are bi-directional. This type of network would ease the participation of Distributed Generation (DG) and Renewable Energy Sources (RES), and it is enabled by modern ICT, advanced power electronics and energy storage.

Energy-positive ! buildings

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.

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[16] 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.

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.

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.

„ ... "

Energy efficiency is driving power electronics research. Developing research strategies is a must for universities and institutes nowadays. E4U has helped us in identifying future research topics and improving our vision and strategy.

Jose A. Cobos
Universidad Politécnica de Madrid

1.3 The E4U 2020 vision

Addressing the wide range of power electronics applications and looking into power electronics potential for energy efficiency and sustainability in these applications, the E4U project has come to the following vision for 2020:

I. The 'More Electric World': the share of green electricity in overall energy significantly increases.

II. Three technologies – information processing, power processing, and sensors & actuators – converge to enable smart, energy-efficient systems.

III. Industry in Europe takes global leadership in smart, energy-efficient systems and products based on these converging technologies.

IV. Universities and research centres in Europe take global leadership in research and innovation in electronics, enabling efficient energy usage.

V. Smart Grids in 2020 are able to handle a 20%-plus share of fluctuating renewable energy in an economical and efficient way.

VI. Zero-emission e-mobility in megacities.

VII. Halving lifecycle costs of buildings, including lighting and climate conditioning.

VIII. Energy on demand for ICT and wireless energy supply for mobile applications.

Introduction

I. The ´More Electric World´: The share of green electricity in overall energy significantly increases

The finiteness of fossil energy sources and the necessity to reduce our CO_2 emissions are pushing forward the electrification of our society. We are presently considering electric vehicles but also more-electric aircrafts and more-electric ships. 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 our vision of a 'More or All Electric World', electricity is produced in southern Europe and North Africa as well. In contrast to the previous decades' vision of a hydrogen society, where hydrogen was to be generated in the North Africa deserts and converted in fuel cells in Europe, in our vision the electrical energy is directly transported to the areas where it is consumed. This long-distance energy transmission is performed by a transcontinental super grid using low-loss HVDC (High Voltage Direct Current) technology. The peripheries in the South (for solar energy) and in the North (for wind energy) are connected to the European power transmission grid.

A solar thermal power plant covering the area of the Assuan reservoir would be sufficient to generate the amount of energy equivalent to the oil production of the whole Middle East region. Alternatively, 3% of the area of the Sahara desert would supply all the energy needed in Europe.

II. Three technologies – information processing, power processing, and sensors & actuators – 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. Further examples are load management, the use of decentralised energy storage systems for power quality function and grid stabilisation or smart remote control of decentralised PV converters for active power factor correction. Discrete solutions are possible today, but significant cost reduction and performance improvement is necessary for a considerable market penetration. This can be achieved by smart integrated power electronic modules. Furthermore, these advanced integrated modules, utilising high temperature power electronics and ultra-high power density mechatronics, will help to keep power electronics production in Europe.

III. Industry in Europe takes global leadership in smart, energy-efficient systems and products based on these converging technologies

European industry has an excellent starting position to take global leadership in smart energy systems as Europe has, on the one hand, a strong component and module industry (power semiconductors, driver and control ICs, integrated smart power, modules and IPEMs). On the other hand, Europe has 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).

IV. 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, and this has helped it to keep a strong industry in power semiconductors and devices, power conversion, industrial process, motor drives, consumer appliances, lighting, portable devices, space applications, renewable generation and connection to the grid. However, the fast development in research and innovation in emerging countries like China, India, Brazil and Russia, as well as the strong centres in the USA, Canada and Australia, can limit the capacity of our existing knowledge to keep the innovation and research pace needed to maintain the EU industry and universities in top position.

Skill shortage is a major concern for the engineering industry and academia, as they rely on highly skilled staff in research and innovation. 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.

Furthermore, long-term research will need to receive more investments. Most of today's research is short- to medium-term, and is project-oriented, resulting in incremental advances. For breakthroughs and paradigm shifts, long-term research and different shared innovation models will be needed.

V. Smart Grids in 2020 are able to handle a 20%-plus share of fluctuating renewable energy in an economical and efficient way

The change in the conception of the traditional grid to a situation in which more actors come into play will pose significant technological challenges that have to be faced. The smart grids have to fulfill customers' need for power where it is needed and when it is needed, while trying to provide most of the energy from renewable sources at high efficiency with low carbon emissions. The quality and the security of supply must also be assured, and all of this has to be provided in an economical and sustainable way.

In parallel with the development and penetration of renewable energy sources, the improvement in the efficiency of hybrid electric vehicles and electric vehicles, promoted by the advances in energy storage, electrical drives and power electronic technologies, will lead to a significant increase in the fleet of low-emissions electrical vehicles. The massive force of these small electric generators and storage systems, the electric vehicles, can help to support large-scale renewable energy sources and stabilise the grid. This situation will make possible the vehicle-to-grid (V2G) implementation, allowing for a more efficient use of energy. The power electronics-based systems will enable optimal energy flow.

The high complexity of future smart-grid and plug-in electric vehicles to support the grid will have to 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.

VI. Zero-emission e-mobility in megacities

Plug-in hybrid electric vehicles (PHEVs) which combine today's hybrid automotive technology with larger battery systems that can be recharged from the electrical grid are expected to enter the market in 2010. At the same time, full electric city cars (EVs) using lithium-ion energy storage technology enabling a driving range of 100–250 km will soon be widely available. Fleet tests are running in several European cities, e.g. in London and Berlin. Recently, four German Federal Ministries have launched a "National Development Plan on Electric Mobility", announcing a plan to put a million plug-in cars on the roads by 2020. 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.

This move to a more electric mobility will challenge the existing electric grids. An infrastructure is needed to charge the electric vehicles from the grid which has to supply the energy for this additional load. On the other side, it is possible to make the distributed energy storage capacity of these EVs available to the grid while increasing the share of fluctuating renewable energy sources.

Power electronics together with information and communication technologies is the key to meeting these challenges, providing the bidirectional flow of energy and information between the electric car and the grid.

VII. Halving lifecycle costs of buildings, including lighting and climate conditioning

The introduction of more energy-efficient technologies during construction can and will contribute to an increase in the initial cost of the building. However, 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.

The two main power consumers in tertiary buildings (and also large consumers in private dwellings) are lighting and HVAC. Therefore, energy-efficiency measures to reduce energy consumption in these areas are essential. Furthermore, buildings generating their own energy (PV, solar, micro-wind) will become energy-neutral or even energy generators. This will reduce the lifecycle cost of a building to just the construction and physical maintenance costs, with no energy cost. There might even be an energy revenue.

This vision can be achieved only if additional costs of including energy-efficiency measures and systems during construction are small compared with the overall construction costs. Therefore, power electronics must achieve the required efficiency, but within a limited budget.

Building developers and owners/occupiers are generally different entities with different interests. The first are responsible for (and will try to reduce) initial costs; the second are more interested in energy running costs. Therefore, this vision can be achieved only if both work in partnership. Furthermore, building regulations and energy rating of buildings will be necessary to encourage developers to include energy-efficiency measures during construction.

VIII. Energy on demand for ICT and wireless energy supply for mobile applications

The high penetration and growth of information and communication technologies is presenting significant challenges from the point of view of energy consumption, energy management, cooling and costs. According to some studies, the use of the internet is growing at 10% per year worldwide. This growth is supported by the increase of applications and uses of the net: information access, music and video on demand, online gaming, e-commerce, social networking interfaces and voice-over-internet. This increase in the use of the internet is also driving the increase of communications, personal digital devices, and processors and digital components.

The importance of energy efficiency of ICT equipment nowadays is highlighted by current data centres, in which the Energy Cost to Acquisition Cost ratio (EAC) is close to three, meaning that the cost of the equipment is exceeded by the electricity bill of the three first years of operation. In the case of communications, the efficiency of conventional radio base stations is around 1.2% (to transmit 120 W it is necessary to waste 10 kW). It is clear that this situation is no longer acceptable and new solutions must be provided to sustain the growth of ICT due to the tremendous social benefits of their evolution.

The use of intelligent load management, variation of the supply voltage according to the workload, and the integration of power electronics with the digital processors and devices can yield a tremendous improvement in the energy efficiency of all ICT systems. For example, the use of multi-core technologies to improve the performance per watt of current microprocessor can be improved even further if locally supplied cores can adapt their voltage according to their workload or even dynamically turn on and off their supply to follow the user demand. To make this happen, a significant research initiative into enabling technologies that will bring into being this supply-on-demand concept will have to be undertaken.

1.4 Electronics can make it happen

Table 2 shows the large 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

Application		Electricity consumption [% of EU consumption]	Electrical energy saving potential	Energy saving potential [% of EU consumption]	Enabling power electronics technologies
Motor control • industrial applications • appliances, HVAC, lifts • traction drives		~50%	30-40% (feasible in ~50% applications)	5-6%	IGBTs, SiC devices, Power modules
Lighting		21%	>70%	>14%	High-efficiency intelligent ballasts; Power semiconductors
ICT	Data centres and servers	2%	50%	1%	DC distribution networks ICT and power electronics integration
ICT	Radio base stations	1%	30%	0.3%	Efficient power amplifiers Low standby consumption technologies
ICT	Standby consumption	4%	80-90%	3.6%	Power semiconductors Intelligent control

Table 2: Power electronics applications and electrical energy-saving potential

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.

- Buildings (Commercial, Industrial and Residential)

    - Lighting – Currently 21% of total electrical energy is consumed by lighting. Savings of up to 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 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 advanced 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.[17] 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.[18]

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.

Given their large share of electricity consumption and the large savings potential shown above, the following four areas were chosen as the main focus of the E4U project:

- Buildings & Lighting;
- Power Supplies (with focus on ICT applications);
- Smart Electricity Grids (including vehicle to grid);
- Industrial Manufacturing (focus on industrial drives).

Even when very good power electronics-based technologies exist it does not mean that they will be implemented due to the complex interaction between the four drivers toward a future of sustainable energy: Technology, Economy, Policy and Public Acceptance.[19] The other three drivers are necessary for successful market penetration and thus exploitation of the significant energy-efficiency potential.

Although the technologies required for improving energy efficiency may already exist, the cost is a dominant issue both for purchase and installation, especially in the case of retrofitting. In spite of the short economic payback time of some applications, economic barriers are still present.

These include payback time being considered too long, lack of awareness, reluctance to change working process, split budgets, etc. Further reduction of power electronics cost through standardisation, integration and automated manufacturing is needed. Furthermore, new business models, often on the system level (i.e. buildings, factories) are needed.

The legal and regulatory framework is crucial to the adoption and exploitation of energy-efficient technologies. The importance of energy efficiency is well recognised within the framework of a sustainable energy future on national and EU level. A lot has already happened in Europe and will be presented in more detail in Chapter 4. The importance of power electronics has not yet been fully recognised. This is one of the goals of the E4U project.

„ ... "

Saving energy with advanced power electronics is possible using existing technologies – and we have to do everything to exploit its promise. But at the same time, research has barely scratched the surface of what is still to come.

Nicolas Cordero
The Tyndall Institute

Public acceptance is a powerful means of advancing technology take-up and development. In order for the general public to accept a technology and business model that radically changes their understanding and acceptance of a basic service, significant education must take place. Environmental awareness is already present, but the potential contribution of power electronics to a sustainable energy solution is not known to the general public. For example, photovoltaic systems are well known for their green energy epithet. Few know that the energy payback of power electronics systems through energy savings is a couple of months, while the PV systems energy payback is 1–1.5 years.

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2 The Electronic Efficiency Potential

2.1 Overview

Let us see how power electronics technologies can improve energy efficiency in the four areas of interest and how much energy savings can be expected if these technologies realise their full potential. To illustrate the benefits in the particular application, for each area one real-life case study will be presented.

2.2 Buildings and lighting

2.2.1 Energy consumption and savings potential

Buildings (commercial, industrial and residential) account for 40% of the overall EU energy consumption. In EU-27 tertiary / office buildings consume 130 Mtoe per year or 11% of the total energy consumption,[1] and the residential buildings consume around 285 Mtoe or around 25% of the total energy consumption. Of the total energy consumption in tertiary buildings 60% is electrical energy. In tertiary buildings, electrical energy costs (lighting, HVAC, lifts, etc.) during the life of the building are double the construction costs, and account for 40% of the total lifecycle costs.[2] HVAC uses more than 60% of the buildings' energy consumption, one-third of which is electrical. Lifts use about 10% of buildings' electricity consumption. It is clear that there is wide scope for the reduction of energy consumption.

Quantified savings for an average office building

The average energy consumption of an office building is estimated to be about 300 kWh / m^2 per year.[3] Therefore an average office building of 3,000 m^2 has an annual energy consumption of approximately 1 GWh. Of this, 60% (600 MWh) is electric and the rest is oil / gas mainly for heating. Ventilation and air conditioning account for 45% of electricity usage (i.e. approximately 270 MWh per year). Lighting accounts for 21% (~126 MWh). Lifts use around 10% of the total electricity (~120 MWh). The remaining 24% is used in other equipment (incl. IT), hot water, appliances, etc. which are not considered here (see power supplies and VSD for technological improvements and potential savings in these areas).

HVAC – Replacing all the motors and pumps in the HVAC electric systems by higher-efficiency ones, including external continuous control (variable speed drives) and using intelligent control for HVAC and the environmental data gathered by wireless sensors, the energy efficiency of a complete system can be improved by 30–40%.[4] For electric ventilation and air conditioning, which consume 45% of electricity (270 MWh), this means a reduction of at least 13.5% of the total (81 MWh). Furthermore, implementing intelligent control will also help to reduce the energy consumption of the non-electric heating system (either gas or oil). Therefore this will contribute to a further reduction of at least 30% of the 400 MWh used for non-electric heating, a reduction of 120 MWh.

Lighting – 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 using electronic ballasts (>90% efficiency) (e.g. TL5) reduces the energy consumption by 61%,[5] which is a reduction of 77 MWh of the total consumption. 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 77.8% on current usage; this is 16.3% of the total (98 MWh). Further savings can be achieved by replacing fluorescent sources with LED luminaries fitted with highly efficient drivers (>90%) based on power electronics.

Lifts – Replacing hydraulic lifts with electric traction lifts with speed control and feedback and low consumption stand-by mode (which can represent up to 80% of a lift's annual energy consumption) can achieve savings of over 50%. The motors of the lifts can be further improved with speed control and feedback. These energy-efficiency measures reduce energy consumption by between 50 and 75%. Therefore a reduction of at least 5% of the total (30 MWh) is possible.

Intelligent control (incl. sensors) – Further improvement in efficiency can be achieved using continuous intelligent control. Self-powered wireless sensors can be placed over the building. The data gathered by the sensors (occupancy/presence, lighting levels, temperature, air quality, etc.), is processed together with known data (seasonal temperature variations, user behaviour, etc.) to provide continuous intelligent control of the lighting appliances (dimming) and of the HVAC systems (both electric and non-electric). Self-powered sensors (using either long-life batteries or energy harvesting) provide data for the intelligent control, and are easy and cheap to install, maintain and replace (no wiring or expert installers). Furthermore, they are suitable for both new buildings or the retrofitting of existing buildings.

	Energy Consumption (A)	PE Potential Savings (B)	Consumption Savings (A×B)
Non-electric	HVAC: 40%	30%	12%
Electric	HVAC: 27% Lighting: 12.5% Lifts: 6% Other: 14.5%vv	30% 78% 50% –	8.1% 9.8% 3%
Total	100%	–	**33%**

Table 1: Energy savings in an office building

The total energy savings from implementing these PE technologies as summarised in Table 1 would be 330MWh per year (electric and non-electric), which is 40% of the original consumption. This is a conservative estimate based on existing technologies. Using advanced technologies and including best possible scenarios and the savings for the other areas it could be possible to achieve a 50% reduction.

2.2.2 Energy contracting success

Energy performance contracting is a promising approach to realising energy savings in buildings by providing the required technical expertise, thorough lifecycle analysis, and guaranteed cost-effectiveness at the same time.

For the construction of the new Moevenpick Hotel in Frankfurt's new „Europa Quarter", real estate company Vivico and the Hochtief/Bilfinger Berger joint venture have opted for the „everything from one source" concept proposed by Siemens Building Technologies. This featured the abandonment of the conventional separation of electrical engineering and building automation systems in favour of a total solution package. The advantage for the owner of the building was that this bundling enabled Siemens Building Technologies to offer the functions being bid for at an economical all-in price. At the same time the owner of the building obtains a unified, overall concept based on the latest systems engineering and current design for switches, sockets and room automation. Furthermore, synergies within the high-voltage and low-voltage current systems and building automation make additional optimisation potential available, benefiting both the owner of the building (Vivico) and the hotel's tenant and operator (Moevenpick). The solution offered by Siemens Building Technologies therefore fulfills the investor's requirement for a lifecycle concept that takes into account the ecological and economic optimisation of the technical systems throughout the building's lifetime.

For this example, Siemens reports the savings shown in Table 2. In this case the resulting payback time is less than three years:[6]

	Savings €/a	Investment €
Optimized lighting (400 fluorescent tubes with electronic ballasts)	14.700,-	46.500,-
Variable speed drives and demand controlled ventilation (6 air-handling units)v	35.200,-	110.000,-
Heat recovery of kitchen exhaust air to room supply air	34.100,-	53.000,-
	84.000,-	***209.500,-***

Table 2: Energy savings

2.3 Power supplies

2.3.1 Energy consumption and savings potential

Data centres and servers

Electrical energy demanded by data centres and servers in Europe was 56 TWh in 2007 and is forecasted to have an increment to 104 TWh in 2020[7] or about 3% of the total predicted electricity consumption. 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 total 50% reduction, which translates into 1% savings of the total electricity consumption.

Telecom industry

Estimates indicate that the telecom industry consumed 1% of the global electricity consumption and 164 TWh in 2007 in the EU, and more than 90% of this is consumed by networks operators.
A typical Radio Base Station (RBS) with an output power of 120W has a power consumption of more than 10kW. This translates into a system efficiency of 1.2%.

Figure 1[8] illustrates the losses in the various subsystems:

- More than 4kW are consumed by the power amplifier and an additional 2.2kW by base band signal processing, resulting in only 6% combined efficiency.
- The power supply runs at only 85% efficiency, due to the low efficiency of the rectifiers.
- Climate equipment is responsible for additional losses of more than 2.5kW.

Efficiency of the power transmitter is barely 6%. The use of Envelope Elimination and Restoration techniques can significantly improve the efficiency of the transmitter since it can be based on a high efficiency non-linear RF amplifier, with a highly

„ ... “

We are excited by the huge potential role power electronics can play in improving energy efficiency but also frustrated by the lack of awareness of this potential and lack of structure currently in place to exploit this. The results from our E4U roadmap must be reviewed and acted upon, starting with an ETP.

Michael Hayes
The Tyndall Institute

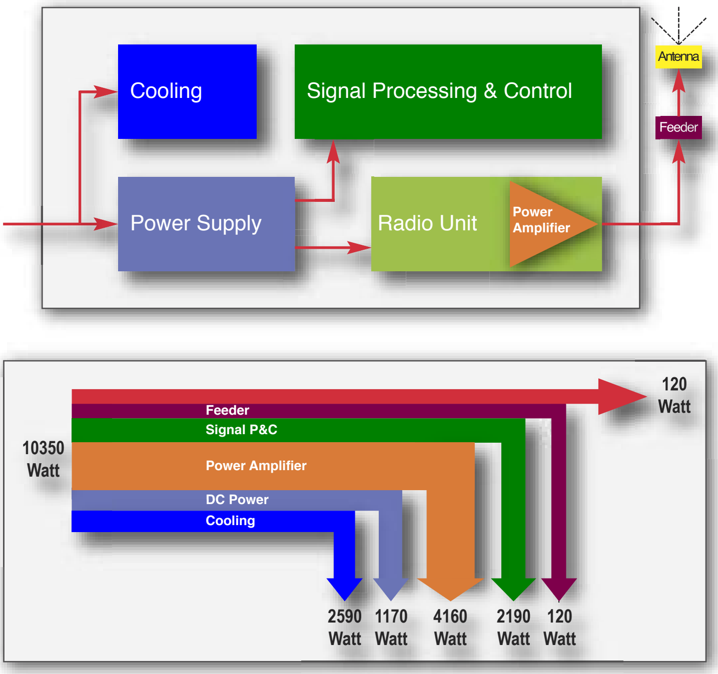

Figure 1: Power losses in a typical radio base station

efficient envelope power supply to implement a highly efficient linear RF amplifier. The use of conventional switched power converters for the envelope amplifier requires switching frequencies around five times the bandwidth of the envelope signal, penalising the efficiency of the converter. Innovative solutions like the use of multilevel converters and a linear regulator allow for the use of a switching frequency equal to the bandwidth of the envelope signal. Compared to an ideal linear amplifier, the efficiency can be increased from 29% to 43.7%, which means that the total energy required is reduced by 35%.

Almost 30% reduction of electrical energy consumption 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 20 000 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.

Stand-by consumption

It has been stated in the preparatory study for the Directive 2005/32/EC that standby functionalities and off-mode losses occur for the majority of electrical and electronic household and office equipment products sold in the Community, while the annual electricity consumption related to standby functionalities and off-mode losses in the Community was estimated to have been 47 TWh in 2005. Without the introduction of specific measures, the consumption is predicted to increase to 49 TWh in 2020 (an amount comparable to the total electricity consumption of Greece or Portugal). An important proportion of these losses is related to power supplies. It has been estimated that the total annual energy savings potential for standby consumption in the EU is 35TWh. Technologies for achieving 10mW standby power per appliance compared to the typical several watts are already available.

2.3.2 Successful initiatives for efficient power supplies

Massive penetration of mobile phones and portable devices with different connectors and chargers has led to a tremendous waste of material. Additionally, the efficiency of current chargers can be substantially improved and the energy consumed in standby, which is most of the time, can be significantly reduced. Initiatives like the one promoted by the GSMA and 17 leading mobile operators and manufacturers to implement a universal charger for new mobile phones will have a tremendous impact on the environment. On the one hand the adoption of a standard with energy-efficient chargers will result in an estimated 50% reduction in standby energy consumption.[9]

On the other hand, the standardisation of the chargers and connectors will lead to a reduction of 51,000 tonnes of duplicate chargers, with the additional benefit for the customer of finding a suitable charger for their mobile everywhere. The target of this group is to have a universal charging solution widely available in the market by 2012 based on the Micro-USB as the common charging interface. From the point of view of efficiency, universal chargers will also include a star labelling rating. The stand-by energy consumed by a five-star charger will be more than fifteen times less than an unrated charger (see Figure 2).

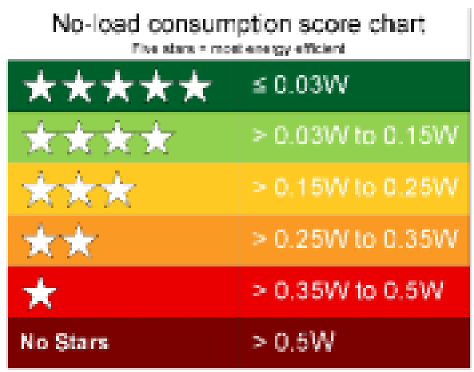

Figure 2: Rating system for energy-efficient chargers

Furthermore, with potentially 50% fewer chargers[9] being manufactured each year, the industry can expect to reduce greenhouse gases in manufacturing and transporting replacement chargers by 13.6 to 21.8 million tons a year.

2.4 Electric mobility

2.4.1 Energy consumption and savings potential

The transport sector plays a central role in the European economy and as such accounts for around 30% of total primary energy consumption. 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. Plug-in hybrid electric vehicles (PHEVs), which combine today's hybrid automotive technology with larger battery systems that can be recharged from the electrical grid, are expected to enter the market in 2010. At the same time, full electric city cars using lithium-ion energy storage technology enabling a driving range of 100–250 km will be available.

Power electronics is an enabling technology for the development of these cleaner and more fuel-efficient vehicles.[10, 11] They constitute a crucial part of the battery-charging system and drive train.
This move to a more electric mobility will challenge the electrical grids. An infrastructure is needed to charge the electric vehicles from the grid which has to supply the energy for this additional load. On the other side, it is proposed that the distributed energy storage capacity of these EVs will be made available for the grid while increasing the share of fluctuating renewable energy sources. Information and communication technologies including power electronics is the key technology for e-mobility, to meet the challenges on the vehicle side as well as on the grid side, providing a bidirectional flow of energy and information between the electric car and the grid.

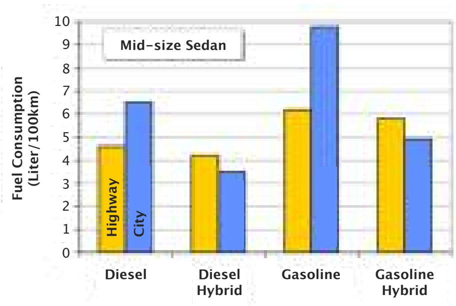

Figure 3: Fuel consumption: Conventional vs. hybrid vehicles (Source: M. Maerz, ECPE-HOPE Symposium Automotive Power Electronics, October 2008)

The key potentials of e-mobility are:

- Climate Protection: Reduction of CO_2 emissions in traffic;
- Guaranteed Energy Supply: Reduce dependency from oil;
- Improve Technology and Industry Position: Germany will become the driver market for Electrical Mobility, leading to an

innovation push in the European economy;

- Reduction of local emissions: Cities get rid of pollution, fine dust and noise, which improves quality of life;
- Vehicles-to-Grid: Improve efficiency and stability of grids and promote the further growth of renewable energies;
- New Mobility: Electric vehicles as key components of future intelligent mobility concepts.

Figure 3 shows the fuel consumption of a mid-size car for highway and city driving, comparing conventional cars with an internal combustion engine (diesel and gasoline) with the corresponding hybrid vehicles.[12] In a city driving mission profile, a 50% reduction in fuel consumption can be achieved.

Figure 4 shows a benchmark of efficiencies for different scenarios of future drive train concepts: conventional ICE vehicle, (plug-in) hybrid electric vehicle, battery electric vehicle and fuel cell electric vehicle. The calculation of efficiencies of electric vehicles in this comparison starts from the electricity and, therefore, does not include the efficiencies of the different power plants for electricity generation. Compared to the fuel cell option, with an overall efficiency of about 20%, the concept of e-vehicle using electrical energy storage has a three times better efficiency (65%) thanks to the high efficiency of an electrical drive.

Comparing the physical efficiencies of combustion engines and electrical drives is a tricky issue, because the result strongly depends on the energy mix used for electricity generation. The internal combustion engine has an efficiency of < 35% (under ideal conditions, in city driving < 20%), while an electrical drive has an efficiency of > 90%.

When comparing fuel consumption or CO_2 emissions one also has to consider the energy source for electricity generation: whether it is coal, gas, oil, nuclear power or renewable energies from wind, solar or water energy.

In a generic efficiency assessment of e-mobility, synergies when electrical vehicles are connected to the grid have to be taken into account, e.g. the use of surplus electricity during night hours to charge the battery. The EVs and PHEVs are a large load which is ready for demand-side management. In the next step, the batteries in the electrical vehicles can be used as distributed energy storage capacity to stabilise the grid, enabling a higher share of fluctuating renewable energies in the grid.

2.4.2 The success of efficient hybrid cars

The field of e-mobility and smart grids is a complex scene with many players (public, political and industrial) and a variety of technologies involved. Three success stories will be presented: the Toyota Prius hybrid as the world's first mass-pro-

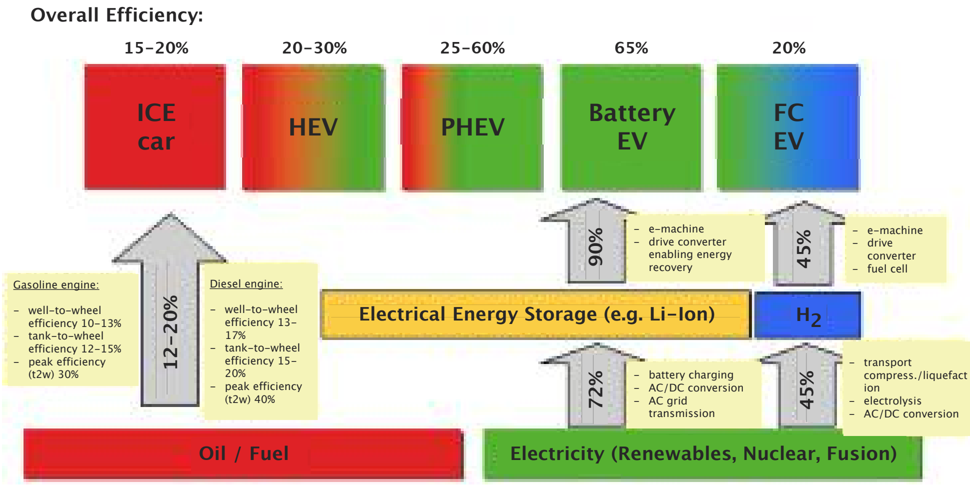

Figure 4: Vehicle efficiency comparison

duced hybrid and arguably the biggest success in the hybrid world so far; ultra-fast battery-charging infrastructure as an enabler for long driving range and reduction of total cost of ownership for professional vehicles; and HVDC as the enabling technology for efficient electricity transmission underground, under water or over long distances.

Toyota Prius hybrid electric vehicle

The first generation Toyota Prius entered the market in 1997 as the world's first mass-produced hybrid car. The company's Hybrid Synergy Drive System was introduced in 2004 on the second-generation Toyota Prius.

In May 2008, Toyota announced that its worldwide cumulative sales of the Prius had passed the 1 million mark and by August 2009 this has risen to 1.43 million. In 2009, Toyota introduced the new 50-mile-per gallon third-generation Toyota Prius hybrid vehicle. The first-generation Toyota Prius was rated 41 miles per gallon combined city and highway driving, while the new Toyota Prius has increased the efficiency to an estimated 50 miles per gallon.

The Toyota Prius is a full hybrid, which means that it can run on combustion engine alone, electrically driven from the battery alone, or a combination of both. The system uses a combination of parallel hybrid and series hybrid designs to achieve the ability to operate on the electric mode alone, and to charge the batteries while the car is running.

Several power electronics-related aspects in the patented Hybrid Synergy Drive system in the third-generation Toyota Prius are responsible for the significant improvements over previous models:

- The inverter has a new direct cooling system to reduce size and weight.
- The inverter, motor and transaxle are smaller and 20% lighter.
- A newly developed electronically controlled regenerative braking system has been adopted, with control logic optimised to enhance regeneration.

According to Toyota, a Prius plug-in hybrid electric vehicle (PHEV) powered by lithium-ion batteries will become available for fleet buyers in 2010.[13]

Ultra-fast battery charging

Battery technology has played a crucial role in the rise of the electric vehicle. An important milestone in EV development is the second-generation lithium-ion batteries with high power density, leading to lower weight and smaller volumes. Furthermore, they can be charged fast, within minutes instead of hours, thus offering the potential to overcome one of the major obstacles to the wider penetration of EVs: long charge times of 4 to 12 hours. To facilitate ultra-fast charging, advanced power electronics solutions are required. Together with batteries and intelligent control systems, power electronics is an enabler of ultra-fast battery charging.

The NRGspot system[14] is part of a public ultra-fast charging infrastructure for electric vehicles, enabling clean transportation in cities across Europe. The NRGspot is an initiative of the utility company Eneco in cooperation with RCI (Rotterdam Climate Initiative) and TNT, and can be used to fast-charge electric vehicles, ranging from delivery scooters and electric bicycles to electric cars and delivery trucks. The charging systems are provided by Epyon, a spin-off company of the Delft University of Technology, and the only European company currently providing advanced ultra-fast charging solutions for electric vehicles used in critical business processes such as material handling, delivery of goods and transportation of people. The NRGspot system can be used by subscribers and is accessed through an intelligent interface. After a quick log-in the system can be used to charge the user's electric vehicle within 15-30 minutes. The fast charging functionality is compatible with a whole range of electric vehicles with special lithium-ion battery technology.

The charge points will exclusively supply green electricity. The systems will initially be placed in large cities at strategic places near shopping centres. The NRGspot can be used by fleet owners such as delivery services, taxi services and individual consumers. Two pilot NRGspots have already been placed in the city of Rotterdam, The Netherlands.

In the near future more charging points suitable for built-up areas will be deployed. Many municipalities and companies have already expressed their interest. Epyon develops and produces Ultra Fast Charging stations that are used to charge EVs in between 5 and 60 minutes, for example during coffee and lunch breaks, thus minimising the disruption to the business operation. They are specially designed to meet the needs of professional users of electric vehicles such as owners of forklift fleets, cleaning machines, delivery vehicles and taxi fleets, enabling a significant reduction of total cost of ownership in these industries.

IGBT based HVDC technology

IGBT based HVDC technology (such as HVDC Light[15], HVDC Plus[16] etc.) based on voltage source converters (VSCs) has the capability to rapidly control both active and reactive power independently of each other, to keep the voltage and frequency stable. This gives total flexibility regarding the location of the converters in the AC system. This is an alternative to conventional AC transmission or local generation in many situations. With extruded DC cables, power ratings from a few tens of megawatts up to several hundred of megawatts are available. Possible applications include:

- Connecting wind farms
- Underground power links
- Powering islands
- Oil and gas offshore platforms; power from shore
- Asynchronous grid connection
- City centre in-feed

This variant of HVDC technology offers numerous other environmental benefits, such as neutral electromagnetic fields, oil-free cables and compact converter stations, and is ideal for connecting remote wind farms to mainland networks without distance limitations or constraints on the grid.

One of the projects in which this technology has been employed is the world’s largest offshore wind farm cluster (Borkum 2) that is to be connected to the German grid by a 400 MW HVDC Light® transmission system. The German utility transpower stromübertragungs gmbh, formerly known as E.ON Netz GmbH, has awarded a contract to ABB to supply the power equipment that will integrate the world’s largest offshore wind farm into the German grid. Located more than 100 kilometres off the German coast in the North Sea, it will be the most remote wind farm in the world.

The Borkum 2 wind farm will consist of 80 wind generators of 5 MW located about 130km from the coast in the North Sea. The generators will feed power into a 36 kV AC cable system which will transformed to 154 kV for the HVDC Light® offshore station. The receiving station will be located at Diele, 75km from the coast, where the power will be injected into the German 380 kV grid.

Main data	
Commissioning year:	2009
Power rating:	400 MW
No of circuits:	1
AC Voltage:	170 kV (Platform BorWin Alpha), 380 kV (Diele)
DC Voltage:	±150 kV
Length of DC underground cable:	2 x 75km
Length of DC submarine cable:	2 x 125km
Main reason for choosing HVDC Light:	Length of land and sea cables.

The system concerned is a self-commutated HVDC, based on state-of-the-art power transistors (IGBT) and the use of lightweight, eco-friendly underwater and underground polymer cables. Compared to an AC link for the wind farm, this modern, ecocompatible technology, with its very low electromagnetic fields, oil-free cables and compactly dimensioned converter stations, cuts transmission losses by 25%.

This link, initially rated at 400 MW, constitutes the foundation for utilising offshore wind power, thus making an important contribution to the German federal government's goal of increasing the share of renewable energies in power generation from its present-day approx. 15% to 25–30% by 2030. Scheduled to be operational in September 2009, the wind farm is expected to avoid CO_2 emissions of 1.5 million tons per year by replacing fossil-fuel generation.

2.5 Industrial manufacturing and drives

2.5.1 Energy consumption and savings potential

Industrial motors and drive 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 the EU, motor-driven systems are among the largest consumers of industrial electrical energy, accounting for around 65% of the total EU industrial electricity consumption.[17] Given the fact that industry consumes around 41% of total electricity, this translates into 750 TWh.

The main applications of industrial drives are pumps, fans and compressors. Motor-driven systems consume 38% of the tertiary sector electricity consumption in the EU, which translates into more than 10% of the total electricity consumption.[18] In the US, motor systems in the residential sector use 13.1% of total US electricity consumption, in the commercial sector 11.3% and in the industrial sector around 25%, which adds up to around 50% of total electricity consumption.[19]

Energy-saving technologies

The majority of motors are still run at fixed speed regardless of the load. A throttling valve on a pump, for example, is used to regulate pump output. An analogy would be operating your car with the accelerator pedal pushed to the floor and regulating your speed by applying the brake. The energy-saving potential of installing Variable Speed Drives (VSDs) in motor systems comes from the ability to control the motor speed to match the output with the system needs. The main part of a VSD is a power electronic inverter that supplies 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 varies over time in pump and fan applications and the shaft power is proportional to the flow rate to the power of three. For example, if a rotodynamic pump is slowed by 10% the energy demand will be only around 70% of the energy at full speed and for the speed reduction of 50% the energy demand will go down to 12% of the energy demand at full load (see Figure 5[20]).

Variable-speed electric drives account for 15–20% of all motor drives in Europe (12% in Germany, 5% worldwide) within the industry field. Due to the additional cost of VSDs and the type of process it is not always feasible to implement them in all motor-driven systems. The feasibility measure is cost-effectiveness, translated into the total lifecycle cost. As regards the total lifecycle of motor-driven systems, energy costs during the operation of the drive are often greater than 90% of the total lifecycle costs. For pump-driven systems, the lifecycle cost breakdown is: energy 80%, purchase 8% and maintenance 12%.[21] It is estimated that it is feasible to have VSDs installed in 40–50% of all motor-driven systems. The total savings potential is then estimated to be 30–40% or even up to 70% depending on the application, operation and load cycle. Combining all these figures, the total electrical energy savings potential of VSDs is about 5–6% of current consumption.

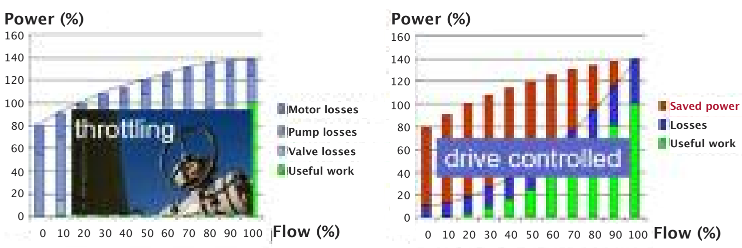

Figure 5: Energy savings potential of variable speed control in motor drive systems (Source: Position paper on Energy Efficiency – The Role of Power Electronics, ECPE European Center for Power Electronics, EPE European Power Electronics and Drives Association Brussels, March 2007)

2.5.2 Successfully saving energy and costs with speed controlled motors

Scenario

The following example illustrates the benefits of variable-speed motor control for the process industry.[22] In the production of the plastic material polyvinyl chloride (PVC), the Swedish company INEOS is the only one of its kind in Sweden. Production involves a chemical process consisting of several stages that ultimately produces a white powder. Pumps, fans, blowers, mixers, mills and centrifuges are all used as part of the process. INEOS is an energy-intensive industry that consumes as much energy as a medium-sized Swedish town.

Energy Savings

One of the big fans used for drying the PVC powder demonstrates clearly the excellent savings potential that results from streamlining electric motor drives. By replacing mechanical control with speed control, INEOS saves 25,000 euros per year in reduced electricity costs for this one fan alone. The efficiency of the drive motor increased by more than 25% when an Emotron variable-speed drive of 400kW was installed for control purposes. The difference is due to the energy that was lost when the airflow was controlled using dampers.

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3 Where We Stand in Europe

3.1 Power electronics in Europe

Before examining the four areas of focus under the framework of the E4U project, let us look at what the common status of the European power electronics scene is, both the internal strengths and challenges but also external factors leading to possible opportunities and threats.

Power electronics is a mature technology, especially as regards circuits, topologies and devices. The focus of future research and development will most likely be in better power semiconductors, packaging and interconnections and system integration. The power electronics market is estimated to be around 41 billion US dollars with an annual growth of around 7%.

Strengths

Looking at the strengths of the European power electronics scene, a few main aspects can be identified:

- Europe has a strong silicon power semiconductors and modules industry and is establishing a wide-band gap semiconductors technology base. For example, Infineon has the biggest market share in the power semiconductors market in the world and Semikron is the leading manufacturer of power modules.

„ ... "

The recent crisis has clearly shown the importance of energy efficiency and consequently of power electronics. It is an area of key importance and it is vital for our business that Europe remains a leader in this field.

Monika Kircher-Kohl
Infineon Technologies Austria AG

- Europe has high quality research groups at universities and research institutes. For example, the ECPE Network comprises more than 50 European Competence Centres in the field of power electronics. European research groups have achieved world records in high-efficiency power supplies (ETH Zurich, 99.2% efficiency rectifier for IT power supplies), high-efficiency inverters for photovoltaic systems (Fraunhofer ISE, 99.03% efficiency at 1.5kW), power density (TUDelft, 4kW/l power density in low-power industrial drives) etc.

- There are good networks and associations in Europe to provide the platform for discussion, cooperation and joint research (European Centre for Power Electronics (ECPE), The European Power Electronics and Drives Association (EPE), European Power Supply Manufacturers Association (EPSMA), European Photovoltaic Industry Association (EPIA), etc).

Challenges

On the other hand, the main weak challenges for the European power electronics community are:

- Technological: low integration level, large number of parts and processes and labour-intensive manufacturing and assembly of power electronics. This is especially striking in comparison to the level of integration and automation present in microelectronics.

- Cost (manufacturing and operating): with the cost reduction of power semiconductor devices (for given performance), a significant portion of manufacturing costs can be traced back to the labour-intensive manufacturing of assemblies and large number of parts (including mechanical parts such as housing and thermal management parts such as heat sinks) in the assembly. With high labour costs in the EU it is economically more effective to shift the production to lower-wage countries.

- The outside perception of power electronics as unreliable technology: The penetration of power electronics in new applications and the exploitation of the potential of replacing traditional mechanical, hydraulic or pneumatic systems with power electronics systems are sometimes hindered by the perception that power electronics is unreliable. The power electronics community has to work on changing this image.

- Lack of multidisciplinary simulation software and design tools for power electronics: This is especially critical giving the necessity of an integrated multidisciplinary (electromagnetic, thermal, mechanical) design of power electronics systems.

Opportunities

In today's world of awareness and actions related to the energy problem and climate situation as well as the continuing technology growth, the opportunities for power electronics are plentiful:

- Sustainable energy trend:

  - Energy efficiency enabled by power electronics (limited fossil fuels supply, rising energy costs, regulations);

  - Fast-growing world market for renewable energy technologies and grid infrastructure (e.g. high-efficiency HVDC lines for the Desertec project);

  - Climate changes related to CO_2 emissions and the awareness of power electronics potential in this regard;

- Other societal and economic megatrends where power electronics is an enabling technology:

  - The growth of industrial automation;

- Decentralised power generation;
- Information and communication: portable electronics, internet, PC, wireless sensor networks, etc.
- Mobility: hybrid/electric vehicles, more electric aircraft/ships, trains;
- Comfort & health: electrification, body implants.

Threats

Alongside the external factors that offer vast opportunities to power electronics, there are also factors that may be seen as potential threats to further technology advance and market penetration:

- Power electronics is perceived as a supporting technology instead of leading technology. Research funding in electronics has a strong focus on information and communication technologies. On the other hand, the key role of power electronics as a crucial and enabling technology for sustainable energy (use of renewables, energy efficiency, power quality) is not yet fully recognised and even less exploited.
- Power electronics is insufficiently represented in public research funding programmes. It is rarely explicitly mentioned as a research topic in both EU and national programmes.
- Next generation of engineers – shortage of students specialising in power electronics. In Europe power electronics is not perceived as an attractive direction for specialisation of young electrical engineering students in their final years of studies. One example is postgraduate programmes at European universities where a large majority of graduate students (master's and doctoral) come from outside of Europe (mainly Asia). With the expected growth of the power electronics market this shortage is going to become even more critical.
- Strong research increment in China, Taiwan, Korea, Japan, Brazil – emerging countries like China and India have identified power electronics as a key and enabling technology to develop their economies. These countries have the engineering capacity to enter the 'more-electric-world'.
- Outsourcing of research and technology to emerging countries (China and India);
- Key European industries could be taken over by competitors from Asia. This process has already started with some European power electronics components companies.

The above factors are common across all the applications of power electronics. Let us now look at the additional aspects specific to each of the four areas of focus: buildings and lighting, power supplies, smart grids and e-mobility, and industrial drives.

3.2 Buildings and lighting

As regards European strengths in power electronics-related topics in the buildings and lighting area, it is important to note that most of the required technologies for improved efficiency (solid-state lighting, energy harvesting, variable speed control) already exist, and European industry is a world leader. However, further improvement in the efficiency, cost reduction and integration of components and systems is required.

While the technologies are already available, their cost is the biggest barrier to market penetration. And this is not just the costs of the devices and sensors, but also those of installation (including retrofitting into existing buildings and lighting appliances) and maintenance costs, which contribute to the current low market penetration. Another challenge is the current lack of full building models incorporating both structural, HVAC and lighting data. In the lighting market, new regulations and shift in consumer preferences (due to energy costs and/or environmental concerns) open new market opportunities for solid-state lighting (both LED and OLED). To achieve high efficiency at the fixture level, there are also market opportunities for energy efficient power electronic drivers.

In the buildings market, the main opportunities are for:

- Sensors: wireless, suitable for retrofitting, miniaturised, self-powered with no maintenance (“deploy and forget”);
- Wireless Sensors Networks – energy management and conversion is one of the main bottlenecks to full autonomy of WSNs.
- Intelligent control;
- Power electronics for actuation (electrical or electromechanical) and control.

A lack of standardisation in the lighting market is an important bottleneck. Nowadays it is possible to find a wide range of solid-state light sources and fixtures, using different voltage levels (both AC and DC), physical sizes and connectors. Therefore it is necessary to produce light sources based on standards which can directly replace traditional sources (incandescent bulbs, fluorescent tubes, halogen bulbs, etc.) and also set up new standards.

In the building sector, there is also a lack of standardisation – in this case of sensors/actuators connectors, communication protocols and actuation protocols.

While the introduction of intelligent control can help reduce the overall energy consumption of HVAC systems, this can only be achieved by the usage of more energy-efficient appliances (heaters, fans, compressors and pumps).

„ … “

Lighting presently accounts for 19% of world energy consumption. The dramatic reductions in energy consumption of LED lighting when compared to other technologies providing the same lumens and light quality is compelling evidence of the huge opportunity for improved energy efficiency through use of LED solid state lighting. The primary potential improvement in energy efficiency comes from exploiting power electronics and control. This includes (i)new LED lighting technologies, (ii) higher efficiency power supplies to drive the lighting and (iii) intelligent sensor driven controls to supply sufficient lighting for users but with the minimum use of energy.

Gary Duffy
Excelsys Technologies Ltd.

3.3 Power supplies

Europe has a strong industrial and academic background in several power supplies-related aspects:

- Strong industry on Si-based power semiconductors for high-power applications;
- Global power supplies companies for telecom applications;
- Good position on micro-controllers;
- Higher level of integration and lower cost/kW in power supplies compared to other power electronics applications.

The challenges that the European power supply industry is facing are:

- Insufficient research on Wide Band Gap semiconductors;
- Little impact on power delivery for data-centres;
- Small market share for digital controllers for power supplies;
- Little research activity on high bandwidth converters for RF amplifiers.

The opportunities for high-efficiency power supplies are vast, ranging from the energy-efficiency labelling programmes, standards and regulations (Energy Star, Code of Conduct on External power supplies, EuP 2005/32/EC directive on eco-design requirements for energy-using products, etc.), new power architectures in existing applications such as data centres and radio base stations, through to emerging applications such as autonomous wireless sensor networks, e-mobility, etc.

Furthermore, it is important to note that conventional power supplies and power supplies for emerging applications have rather different requirements and application boundary conditions. For conventional power supplies, cost is the most dominant factor while for certain emerging applications criteria such as high power density, high efficiency or fast dynamic response may justify higher cost.

3.4 Smart electricity grids and e-mobility

Europe has a good starting position for the development of smart electricity grids and adoption of e-mobility:

- Good grid infrastructure in Europe with high quality / availability of power supply. The security of supply is very good: for example, in Germany the power grid availability is 99,99%, with only about 20 minutes outage in a year.

- Strong industry in Europe for high-power semiconductor devices e.g. ABB, Infineon, Dynex, Semikron, SiCED.

- Strong industry in Europe for grid infrastructure e.g. ABB, Areva, Converteam, Siemens.

- High quality research groups at universities and research institutes. For example, many of the 50 ECPE Competence Centres are active in the high-power area which is relevant for the smart grids.

The strength of a good grid infrastructure in Europe is at the same time also a weakness because it hinders the further development of the existing grid towards a smart grid integrating distributed power generation, intermittent renewables and a bidirectional power flow. Furthermore, Europe is facing a limited competition in grid operation. The status of grid ownership is not the same all over Europe. Often it is in a transition phase from public to private ownership without fully functional market mechanisms. This hinders the necessary investment in the grid infrastructure.

The largest push for the development of smart grids come from the global climate and energy situation, driving the investments and development of renewable energy sources, e-mobility and a greater use of electrical energy throughout the whole chain from generation to end-user. From this general trend, a number of opportunities can be identified:

- Urgent climate problems related to CO_2 emission will push the smart power grids. The pictures of the retreating Greenland glaciers and the polar bears sitting on the melting sheet of ice have been going around the world, leading to an increased awareness of the CO_2 problem on earth.

- Increasing energy costs will push the smart power grids. The increasing energy costs especially for the fossil fuels will facilitate the low-carbon economy.

- Fast-growing world market for power electronics components and systems. Power electronics is the key technology to feed renewable energy to the grid and to improve energy efficiency and power quality in the grid. This offers business opportunities of the strong European power electronics industry on the world market.

- Fast-growing world market for renewable energy technologies and grid infrastructure. The same holds for renewable energy technologies and grid infrastructure (market opportunity for European industry).

- E-mobility will push the smart grid, offering an additional controllable load. The forecast share of 20% EVs in 2020 in Germany corresponds to an additional load of 18 TWh. With a flexible load time during night the EVs help to balance the grid.

- Synergies between the use of intermittent renewables and e-mobility with distributed energy storage in the grid. In the next step, the batteries of the EVs can be used as distributed energy storage capacity, enabling a higher share of intermittent renewable energies in the grid.

- Smart metering and e-mobility will offer new grid-related business models. New business models are necessary to provide the benefits of demand-side management to customers.

- Supplying wind energy from northern Europe and solar energy from the south to the industrial areas in central Europe via the European super grid. A highly topical example is the Desertec Project, which is planning giant solar thermal power plants in the Sahara desert plus high-efficiency HVDC lines to transmit the electric power to central Europe. The goal of this €400bn Desertec project is to provide 15% of Europe's electricity.

Along with the large opportunities, there are factors that may threaten or slow down the development of smart grids – such as the high infrastructure costs to develop the grid. Grid infrastructure costs are extremely high. In Germany, the annual investment and operational cost of the power transmission and distribution grid is about €6bn. The costs of the planned Desertec HVDC lines are €50bn.

3.5 Industrial manufacturing and drives

The main strengths of the European industrial drives scene are:

- Variable speed drives are a mature technology;

- European industry has a leading market position. The main players such as ABB, Danfoss Drives, Siemens, Bosch, Schneider Electric, SEW Eurodrive etc are positioned in Europe.

- As a major energy-saving technology, VSDs have short economic payback time and very short energy payback time. Compared to for example solar panels, the energy payback time of VSDs is an order of magnitude smaller than that of solar panels.

Looking at the challenges:

- Cost (manufacturing and operating) – looking at the total lifecycle cost of motor-driven systems such as pumps, for example: 80% of the total lifecycle cost is energy costs, 12% maintenance and 8% is the purchase cost. Similar to other areas, the manufacturing costs can be traced back to the labour-intensive manufacturing of assemblies and the large number of electrical and mechanical parts. Energy costs are also higher in Europe compared to other parts of the world. Maintenance is also an issue, since in the case of VSDs the cause of a failure is often not so straightforward to identify.

- Technological: Robustness is an issue, since VSDs are designed to fulfill the design specifications and nothing more.

Given the energy-savings potential of VSDs the opportunities are plentiful:

- Fast-growing VSD market (~7% annual growth between 1991 and 2006), variable-speed drive penetration in motor-driven systems is only 20% in Europe, while the estimated economic potential is 50%.

- Energy efficiency: cost-reduction potential and regulations. One of the strong drivers of future adoption of VSDs in motor-driven systems is cost reduction through energy savings. Payback times are currently in the range of 1–2 years or even less depending on the application, while the typical lifetime of a VSD is in the range of 10 years. This translates into large monetary savings for the end user. EU and international legislation for energy efficiency in the field of industrial manufacturing and wider (such as EuP directive on eco-design requirements) will further encourage the adoption of VSDs.

- Increasing electricity and fuel prices – as electricity prices continue increasing the economic benefit of reduced energy consumption will become more and more important to the end user.

- The growth of industrial automation and addressing the challenge of producing more products with less material, less energy and less waste.

- New application fields for VSD or power electronics (decentralised power generation, more electric aircraft/ships).

The factors that may pose threats to the European VSD sector:

- Booming Asia Pacific VSD market – the Asia Pacific motor drives market experienced the largest amount of growth in 2007, and was the second-largest regional market. Valued at nearly $2.4 billion, the drives market in Asia Pacific is expected to continue growing at the fastest rate over the next five years. The Chinese market is expected to surpass the Western European market to become the largest in the world by 2012.

- India and China continue to exhibit a large demand for raw materials such as metals and chemicals, and the increasing spending power of their populations is driving the demand for construction and processed foods and beverages, all of which are industry segments that rely heavily on motor drives. In addition, as the region's economies continue to expand, there is a greater need to manage their limited energy resources, and motor drives will continue to be utilised to a great extent.

„ ... "

Power electronics is a foundational technology for several of our business units. Siemens does not develop or produce power electronics, but with our purchase volume we impact on innovation. For some business units, the turnover share of products and systems that build on power electronics is up to 40%.

Dr. Albert Wick
Siemens AG

- Economic crisis (short-term) – a decline in the motor drives market across all regions in 2008–2009 has been observed.

4 Current strategies

The efficient usage of energy has received considerable attention since the 1970s and is generally recognised as the most important means to address the issues of rising energy demand and climate change at the same time. Today, energy efficiency improvements – or so-called "negajoules" – are generally seen as the most important and cheapest energy resource, helping to curb the growing global demand for energy.

Moreover, greater energy efficiency offers the most cost-effective means of mitigating climate change while sustaining economic growth, and therefore constitutes an important pillar of global energy and environmental strategies all over the world. As a result of the pertinent policies defined at the global, European, national or regional level, a broad variety of instruments and measures have been developed and implemented in order to improve energy efficiency.

Within the E4U project, the focus has been on programmes and policies in the EU and elsewhere concerned with aspects of power electronics, electronics for energy efficiency, Green ICT etc. and in particular with research policies and programmes in these areas. Collecting information on such initiatives is a challenging task because many policies and programmes are currently under development.

The subject of electronics for energy efficiency or Green ICT is often not clearly defined and also often not made explicit as a part of more general energy-efficiency research programmes. Identifying the topic is also difficult due to the extremely broad field of energy efficiency, which often ranges from biogas to transportation. It was, therefore, necessary to include a large number of programmes and policies in the analysis, although their relevance is not always very clear.

But this fact already points to a first important conclusion: power electronics for energy efficiency would benefit from being made much more explicit in RTD initiatives and research programmes.

4.1 Research initiatives

4.1.1 Initiatives at European Union level

The European Commission has emphasised the massive potential for saving energy and addresses this topic in several RTD programmes.

„ ... "

The fragmentation of power electronics research groups all over Europe can only be overcome with more dedicated European funding. Otherwise we shall miss out on important European synergies that are necessary to successfully compete internationally.

Prof. Mattavielli
University of Padova

The EU **7th Framework Programme** is the main funding instrument for research and technological development at the European level. **Energy** constitutes one of the major funding research themes and is addressed by a specific programme within FP7's "Co-operation" theme. Naturally, this energy programme contains many references to energy efficiency, although power electronics topics are only rarely mentioned. Consequently, there is little power electronics-related research in the "Energy" part of FP7. An important exception is Activity Area 7: Smart Energy Networks, which explicitly mentions power electronics and other ICT topics as a priority area. This topic was, as an example, mentioned in a joint call with DG Information Society and Media's ICT programme.

In the "**ICT**" part of the Framework Programme, "ICT for energy efficiency" is now a focus of the activities. The programme targets innovative ICT-based energy-saving tools and techniques and smarter power grids using new ICT-based monitoring and control systems. However, power electronics is not yet an explicit topic in the ICT programme.

The **ICT Policy Support** Programme (or ICT PSP) aims at stimulating innovation and competitiveness through the wider uptake and best use of ICT by citizens, governments and businesses. ICT PSP is now a part of the Competitive and Innovation Programmes run by the European Commission. The project mostly uses so-called *pilots* that stimulate the uptake of innovative ICT-based services and products or builds on initiatives in the Member States or associated countries. In addition, it supports thematic networks as forums for stakeholders to exchange experience and build consensus. The ICT PSP does not support research activities, although technical adaptation and integration work can be funded.

The 2009 work programme includes ICT for energy efficiency and the environment. Pilot actions under this objective aim to demonstrate that advanced ICT components and systems (e.g. smart metering, smart lighting, power electronics for integration and management of locally generated renewable energy sources, etc.) can contribute directly to reducing both the peak-consumption and annual energy use by more than 15% under real conditions in European social housing.

As a part of its Economic Recovery Plan [ECREC 08], the European Commission has suggested the implementation of new **public-private partnerships** (PPPs) for the „Factories of the Future", „Energy-efficient Buildings" and „Green Cars". These initiatives should also include significant research efforts in three large industrial sectors – automotive, construction and manufacturing – which have been particularly affected by the economic downturn and where innovation can significantly contribute towards a more green and sustainable economy. The proposed investments by the EC and the industrial partners are significant:

1. „Factories of the Future" initiative for the manufacturing sector (€ 1,2 billion for R&D);

2. „Energy-efficient Buildings“ initiative for the construction sector (€ 1 billion for R&D); and

3. „Green Cars“ initiative for the automotive sector worth a total of € 5 billion, of which € 1 billion is for research activities.

The Commission foresees contributing 50% to the total R&D budget from the budget of the 7th Framework Programme, with matching investment coming from the private sector. The RTD priorities currently listed for the three initiatives include energy-efficiency topics and ICT and/or electronics for energy efficiency. The listed priorities are:

- energy efficiency in buildings and districts, coupled with improved quality of life (health, comfort and indoor environment) for citizens;

- development of information and communication technologies for 'smart' buildings and districts, and the integration of renewable energy systems;

- use of nanotechnologies, new materials, components, systems and construction processes, and their integration into energy-efficient buildings;

- large-scale demonstration actions highlighting innovative technologies in the final phase of their development;

- industrialisation of products and components – phase-change materials, insulation materials, smart windows and facades, etc. – contributing to energy efficiency, taking account of eco-design and Life Cycle Assessment;

- adaptation of processes, for building and product design, finding adequate financing, initiating new commissioning procedures, tackling behavioural issues, ensuring knowledge transfer.

Thus, the PPPs clearly would create further stimulus for research in power electronics – *if* this opportunity is taken up by the industry. The EC has launched appropriate calls in the NMP and ICT programmes of FP7.

With respect to industry-driven initiatives, our analysis of European Technology Platforms clearly shows that electronics for energy efficiency is a recurring issue in the strategic research agendas of several platforms. However, it is also evident that these platforms do not provide a strategy for research in the area of "electronics for energy efficiency" itself. The topic appears instead as a side-effect or an enabling technology in addressing other challenging research questions. Even in EPoSS, which certainly comes closest to the areas of Green ICT or Power Electronics, the energy-related aspects are only a small subset of the overall platform goals.

The industry on the other hand seems to have already recognised and reacted to the lack of a coherent strategy in this area. In the area of wind turbines, the VESTAS programme is an example of private efforts in this direction and the ECPE programme in power electronics is an even clearer signal that industry actors have recognised the need for strategic guidance and improved collaboration.

It is all the more surprising that these initiatives are not having a significant impact at the national levels and/or at the European level (with the notable exception of the German power electronics research programme). There still appears to be a significant shortcoming in the community concerning the clear communication with policy-makers, on the one hand, but also within the community about strategies and RTD priorities, on the other.

The community should thus evaluate the option of lifting existing platforms (such as the ECPE programme, the VESTAS initiative or even E4U) to EU level. This could either be achieved by means of a dedicated Technology Platform or by a stronger and more explicit presence in already existing platforms. In the latter case, however, it is clear that certain areas of economic potential would run the danger of being marginalised.

ETP for ! Power Electronics

A European Technology Platform specifically dedicated to power electronics for energy efficiency would certainly create new opportunities for substantial progress in this area by bringing together leading actors from various relevant fields.

4.1.2 National initiatives

Many member states in the European Union are currently preparing or have just started dedicated RTD programmes in the area of energy efficiency. However, only a few countries have dedicated power electronics research programmes or at least mention power electronics research in broader programmes. Examples are the cases of Austria, Germany and the Netherlands:

- Germany has a dedicated power electronics research programme, launched in the fall of 2008.
- Austria has included power electronics research topics in the calls of its energy-efficiency programme and continues to do so.
- In the Netherlands, the Innovative Research Programme for Electromagnetic Energy Technology (IOP-EMVT) covers power conversion as one of three main areas. Furthermore, power electronics is explicitly mentioned in one of the key areas within the Electric Vehicle Technology programme.

Descriptions in the programmes and policies suggest that in many countries research projects focusing on or including power electronics are eligible for funding. We expect that a significant number of power electronics projects are in fact funded as a part of energy-efficiency research initiatives.

However, finding out more about the extent to which this is the case would require an in-depth analysis at the level of individual research projects. Often, power electronics research may only appear as a smaller part in larger technical endeavours, e.g. in the control parts of a project developing improved wind turbines. This is clearly visible, for example, in the projects funded by the Austrian climate fund, where electronics is included in several RTD projects, but mostly as a relatively minor activity (also financially) in the whole project.

Some aspects in the design of the energy-efficiency programmes at national level are worth pointing out:

- In many cases the programmes are jointly owned by several ministries – or are managed collaboratively by several national ministries. This is interesting as it clearly points to the fact that energy efficiency / ICT is usually not clearly localised in just one ministry. Note that this is also true at EU level, where at least recently (with the PPP initiative) both DG TREN and DG INFSO co-operate. Interestingly, research in the field of power electronics for energy efficiency is only rarely associated with dedicated ICT research programmes (the EU's ICT programme being an exception).

- In many cases, the national programmes clearly target dedicated application fields such as buildings or transport or in particular e-mobility. The large economic and energy-saving potentials are certainly reasons for this. Also, the fact that these topics were identified at EU level relatively early and prominently may have helped these fields. On the other hand, this poses the key question whether other promising application areas such as power electronics for energy efficiency in industry (e.g. variable-speed drives) are receiving the attention they deserve.

The programmes are usually very much development- and / or application-oriented. Some programmes also include more fundamental or longer-term research, but this is the exception rather than the rule.

4.2 Other policies

4.2.1 Global energy policies

At the Gleneagles Summit in 2005, the G8 leaders addressed the challenges of climate change and energy supply and agreed a comprehensive *Plan of Action on climate change, clean energy and sustainable development*, known as the *Gleneagles Plan of Action*. At the request of this Summit, the International Energy Agency (IEA) initiated a three-year programme of work, known as the *G8 Gleneagles Programme*.[1] At the G8 2008 Summit, the IEA presented the resulting report, *Towards a Sustainable Energy Future* [IEA 08a]. The IAE considers improving energy efficiency to be the crucial first step towards addressing the global climate and energy challenges in a cost-effective manner and calls for immediate action: "*Improving energy efficiency in all sectors of the economy is fundamental and urgent. It has the greatest potential for CO_2 savings and the lowest cost (in most cases negative costs). Energy efficiency can deliver results quickly. But our analysis of recent efficiency trends shows that the past ten years' performance in IEA member countries has declined to about half the rate of improvement in previous decades. A fundamental turn-around is needed*" ([IEA 08a], p. 4).

In the framework of the G8 Gleneagles Programme, the IEA also developed a package of energy efficiency policy recommendations [IEA 08b], covering 25 fields of action in seven priority areas. "*The IEA estimates that if implemented globally without delay, the proposed actions could save around 8.2 $GtCO_2$/yr by 2030. This is equivalent to one fifth of global reference scenario energy-related CO_2 emissions in 2030*" ([IEA 08b], p. 4). Moreover, the IAE has also compiled and continuously updates the *World Energy Outlook Policy Database*[2] and, more specifically, a database of *Energy Efficiency Policies and Measures*.[3] This online service provides an excellent source of information on energy-efficiency policy developments.

Following a similar mission "*to promote the sustainable supply and use of energy for the greatest benefit of all people*", the World Energy Council (WEC)[4] has put an emphasis on energy-efficiency policies. Since 1992, WEC has been collaborating with the French Environment and Energy Management Agency (ADEME)[5] on a project on *Energy Efficiency Policies and Indicators*. Its 2008 report [WEC 08] identifies and analyses recent energy-efficiency trends in selected countries and regions. Moreover, it presents and evaluates energy-efficiency policies, based on a survey carried out in more than 70 countries around the world. The project aims to share experiences and draw conclusions on advantages and drawbacks of different policies, and to give recommendations based on the identification of policy measures proven to be most effective.

4.2.2 Policies at European Union level

Increasing energy efficiency is an important pillar of European energy policy. The strategies, guidelines, and action plans developed at the European level over the past two decades aim to serve two major objectives at the same time, namely to develop a common European energy policy and to fight against climate change.

In recent years, additional objectives have been integrated into the development of energy policies, in particular increasing supply security, strengthening the competitiveness of European economies, and promoting sustainable development. Improving energy efficiency is seen as a key factor to simultaneously achieve these goals. This is reflected in the Green Paper on *Energy Efficiency – or Doing More with Less* [DOING 05], published by the European Commission in June 2005, as well as in the subsequent Green Paper of 8 March 2006, A *European strategy for sustainable, competitive and secure energy* [ENERGY 06].

The *Energy Efficiency Green Paper* [DOING 05] particularly advocates cost-effective energy-saving measures. It points out that energy costs amounting to € 60 bn could be saved in the EU, which results in savings of € 200 to € 1000 per year for an average household – depending on energy consumption. The paper mainly addresses policy-makers in Europe. It suggests a number of key actions ranging from annual energy-efficiency action plans, information campaigns and tax incentives, to the use of public procurement, state aid and financing instruments. It also targets a new EU directive for buildings and fuel-efficient vehicles. The Green Paper mentions electronics only in the context of research in FP7, namely for "power management for computer systems and energy 'scavenging' techniques".

4.2.3 European Union action plans and instruments in support of efficient energy usage

In response to the 2006 Spring European Council, the Commission put forward, in October 2006, its *Action Plan for Energy Efficiency* [EEAP 06]. Fig. 1, taken from this plan ([EEAP 06], p. 5), illustrates the growing importance of energy efficiency, which was triggered, in 1973, by the first oil crisis. The resulting savings (or so-called "negajoules") were almost able to compensate for the increasing energy demand and have become, by 2005, the "*single most important energy resource*".

The Action Plan aims at further intensifying these improvements, based on the assumption that "*it is still technically and economically feasible to save at least 20% of total primary energy by 2020 on top of what would be achieved by price effects and structural changes in the economy, natural replacement of technology and measures already in place*" (cf. [EEAP 06], p. 5). Consequently, the Action Plan provides a framework of policies and measures aiming to mobilise the general public and policy-makers at all levels of government, but also market actors. It makes an effort to give precise figures for savings. It particularly identifies residential and commercial buildings as a target area for improving energy efficiency. Other application areas include motors in the manufacturing industry, street lighting, and the transport sector.

Development of the primary energy demand and of „negajoules“
(„negajoules“: energy savings calculated on the basis of 1971 energy intensity)

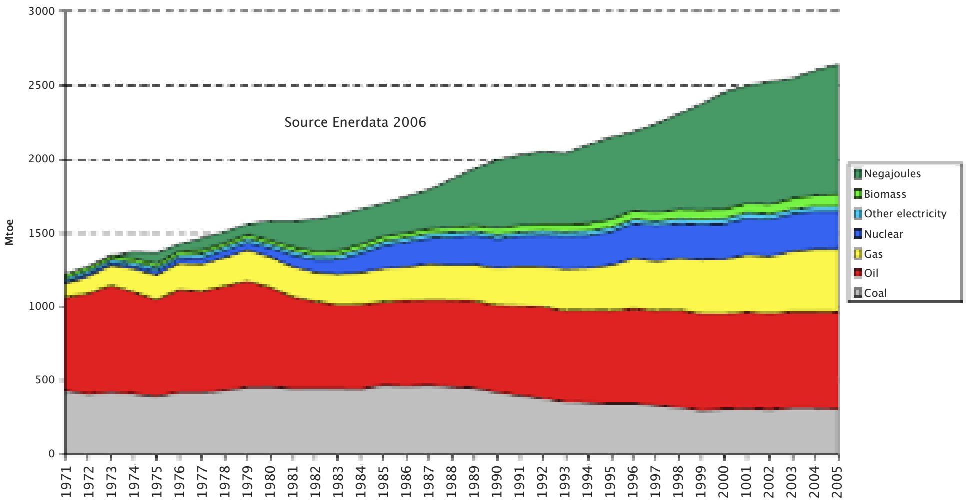

Figure 1: Negajoules have become the single most important energy resource (Source: [EEAP 06], p. 5).

The Action Plan lists several areas that are of particular concern for the area of power electronics:

- Priority Action 1 – Appliance and equipment labelling and minimum energy performance standards: This comprises 14 different product groups from boilers to washing and the definition of eco-design requirements to adopt minimum energy performance standards.
- Priority Action 3 – Making power generation and distribution more efficient: This targets energy production and distribution, but also transformation losses.

The list of proposed measures annexed to the Action Plan includes several more concrete areas of concern for power electronics such as the implementation of the Eco-Design Directive, developing eco-design requirements for additional products, implementation and amendment of the Labelling Framework Directive and the Energy Star Agreement for office equipment or measures to improve energy transformation.

Although most actions target policy issues, the plan also emphasises the role of innovation and technology and points forward to the Strategic Energy Technology Plan [SET 07] for a long-term energy technology outlook and the opportunities offered by information and communication technologies.[6]

In parallel, the European Commission, DG Environment, presented, in July 2008, an *Action Plan on Sustainable Consumption and Production and Sustainable Industrial Policy* [SUST 08] in order to "*improve the energy and environmental performance of products and foster their uptake by consumers*" ([SUST 08], p. 2). As part of this plan, the Commission has proposed to extend the scope of the ecodesign Directive[7] and, subsequently, to revise energy labelling.[8] According to these proposals, not only household appliances, but also commercial and industrial applications (e.g. motors in water pumps, elevators) shall be covered. Moreover, the scope of both instruments shall be broadened from energy-*using* products to energy-*related* products (e.g. windows).

In a recent communication [ENEFF 08], the European Commission pointed to the risk of falling short of the 20% saving objective and stressed, once again, the importance of energy efficiency as the "*most cost-effective way of reducing energy consumption while maintaining an equivalent level of economic activity*" ([ENEFF 08], p. 2). This communication starts from the observation that "*main obstacles to energy efficiency improvements are the poor implementation of existing legislation, the lack of consumer awareness and the absence of adequate structures to trigger essential investments in and market uptake of energy efficient buildings, products and services.*" The Commission therefore re-emphasises the importance of non-RTD policies and instruments, as laid down in the 2006 Energy Efficiency Action Plan.

The Energy Efficiency Action Plan will be evaluated in 2009 with a view to its revision. In the meantime, the European Commission has tabled, as part of the 2008 *Second Strategic Energy Review* [ENREV 08] an Energy Efficiency Package, proposing initiatives such as:

- A revision of the energy performance of buildings Directive;
- A revised energy labelling Directive;
- The implementation and extension of the ecodesign Directive (stipulating minimum requirements for light bulbs, electrical equipment in standby and off-mode functions of devices, etc.);
- The development of benchmarking and networking mechanisms to disseminate best practice; and
- A Green Tax Package.

Furthermore, in view of the difficult situation in financial markets, the Commission is preparing specific funding instruments jointly with the European Investment Bank and other financial organisations to mobilise large-scale funding from capital markets for investments in energy efficiency.

The **Intelligent Energy – Europe** (IEE) Programme is a part of the EU's Competitiveness and Innovation Framework Programme (CIP) and seeks to bridge the gap between EU policies and how they impact on the ground. This programme has become the main Community instrument to tackle non-technological barriers to the spread of efficient use of energy and greater use of new and renewable energy sources.

The objective of the Intelligent Energy – Europe II Programme (IEE II) is to contribute to secure, sustainable and competitively priced energy for Europe. The programme covers actions in the field of new and renewable energy resources, energy in transport, and energy efficiency and rational use of energy. The latter explicitly includes aspects related to energy efficiency in buildings and is thus most related to power electronics issues and ICT for energy efficiency; but these issues can be found throughout the programme.

„ ... "

Our new (European Energy) policy must include: greater investment in new capacity and technology, more interconnections between Member States, higher energy efficiency, more diverse energy sources and a truly common European voice on international energy supply issues.

Neelie Kroes
European Commission

4.2.4 Framework conditions with respect to the potential of power electronics in major application sectors

Improving energy efficiency is, in the first instance, a matter of individual behaviour. In most cases the decisions made by energy consumers are based on some economic rationale. However, clear price signals alone are not sufficient to guarantee the take-up of the most efficient technology. A broad range of obstacles stand in the way of desirable investments and the energy savings they could generate, including market imperfections, information gaps, lack of appropriate financing mechanisms, and the split incentives problem. Public intervention is necessary to overcome these barriers.

Recent research and development has already made available a wide spectrum of technologies to improve energy efficiency. However, there is a huge yet untapped potential for energy-efficiency improvements which are both technically feasible and cost-effective, based on today's technologies, energy prices, and required investments. An extensive study carried out by the European Center for Power Electronics (ECPE) [Petri 07] confirms the high potential for efficiency gains enabled by power electronics. ECPE estimates that electric energy consumption could be reduced by up to 30% with modern technology, corresponding to savings of up to 660.000GWh for the European Union (EU-15). ECPE furthermore assumes that approximately 50% of these savings (327.000GWh) will be achieved by the application of power electronics ([Petri 07], p. 7).

Within the E4U project, the focus has been set on potential improvements enabled by power electronics in four areas of application:[9]

- Many solutions already exist to improve energy efficiency for **lighting and buildings**. Buildings account for more than 40% of energy use in developed countries and hold great potential for cost-effective energy savings. Between 50 and 60% of this energy consumption is electrical. Data gathering and intelligent processing are the two main areas for further technology improvement. In office buildings, energy costs (lighting, HVAC, lifts, etc.) during the building lifecycle are double the construction costs, and account for 40% of the total lifecycle costs. However, barriers such as split incentives between owners and tenants, lack of awareness of energy-efficient options, and high initial investments hamper the implementation of energy savings measures. Lighting represents around 20% of electricity consumption. Fluorescent lamps use smart electronics to convert and then regulate the flow of electricity and consume approximately one-fourth of the energy of equivalent incandescent bulbs. Even higher efficiency can be achieved with recent solid-state lighting technology. Furthermore, it has been shown that an additional reduction of 43% in energy consumption can be realised if intelligent dimming and automatic lighting controls are used. Cost continues to be the main barrier to improve the market penetration of energy-efficient technologies into buildings and lighting. Therefore the most successful non-RTD policies are those which improve uptake through encouragement and enforcement.

- **Power supplies** process all the energy that is required to operate almost all electronic equipment, both externally and internally. According to the International Energy Agency, residential appliances account for over 30% of electricity consumption in most countries and represent one of the fastest-growing energy loads. It is estimated that at least one-third of this could be saved cost-effectively by 2030. External power supplies alone represent around 6% to 10% of the electrical energy consumption. Replacing most of the inefficient linear external power supplies by switched power supplies would reduce the energy requirements of such equipment by 2 to 4 times. Most of the barriers that prevent users from adopting changes that offer very reasonable paybacks are typically not technological but organisational.

- The **smart grid** is a combination of information, communications and power electronics enhancing all the elements of the electricity chain from generation, transmission, and distribution to consumption in order to improve the efficiency, reliability, security of supply and cost. The main benefits of the smart grid from an energy efficiency point of view are the inclusion of distributed and renewable energy resources; a higher transmission capacity and lower transmission losses; the ability to reduce power consumption at the consumer side during peak hours; and the efficient integration of plug-in electric vehicles. In future, smart electricity networks power electronics will play a key role since it is *the* enabling technology to efficiently use, distribute and generate electrical energy. The combination of power electronics, communication and information processing is the answer for the deployment of the smart grid.

- In the industrial manufacturing area, regulatory and other supporting measures are expected to foster a wider penetration of power electronics-enabled variable-speed drives into the market of motor-driven systems. Electric motors and drive systems are widely present, their applications ranging from the low-power area (e.g. in home appliances) over medium power in industrial and automotive applications up to the large MW power in the field of generation. Over half of all electricity is consumed by electric motors. In the EU, electric drives account for around 65% of industrial electricity consumption. The market for industrial drives has been experiencing a continuous growth all over the world. Currently, the vast majority of these motors do not have electronic controls. By converting all such simple electric motors to variable speed, it is possible to cut power consumption by almost half. Energy saving and improved energy efficiency is a major driver for drives and generator systems development, and power electronics provides the key for energy-efficient variable-speed drives.

A great portion of current efficiency gains in these and other areas of application have been enabled by the deployment of semiconductors and power electronics. Using today's technology and assuming cost-effective investments alone, the growth rate of energy demand can be significantly slowed down. However, our analyses as well as numerous studies from the literature clearly demonstrate that the technological advances and ongoing research in power electronics offer vast opportunities for additional savings. In fact, a recent study[10] suggests that by putting in place public policy measures which drive greater investments in semiconductor-enabled efficiency technologies, it would be possible to even reduce total electricity consumption in the US to a level below today's.

Hence, carefully designed non-RTD policies and a comprehensive set of measures are needed to complement RTD in power electronics in order to exploit its full potential. Conversely, such accompanying measures will help create new market opportunities and thus stimulate new research directions.

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[3] Cf. *www.iea.org/textbase/pm/index_effi.asp*

[4] Cf. *www.worldenergy.org/*

[5] Cf. *www.ademe.fr*

[6] For more details, cf. [E4U 09a], p. 5f

[7] COM(2008) 399 final

[8] COM(2008) 778 final

[9] For more details, cf. [E4U 09b], p. 37ff.

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5 Challenges for Europe

5.1 Key issues

Making the E4U Vision 2020 come true and harvesting the potential of electronics for energy efficiency clearly demands going beyond technical challenges in power electronics and energy-efficient technologies. The E4U strategic action plan thus addresses the more technical research strategy but also RTD policies and the non-RTD framework including such important topics as education and standardisation issues.

Strategic ! Objectives

The following set of five high-level strategic objectives has been identified:

- *Achieve awareness and acceptance of electronics as a key technology to solve energy-related challenges.*
- *Exploit power electronics for growth in Europe.*
- *Secure future human resources in Europe for power electronics engineering.*
- *Clear positioning of electronics for energy efficiency as a key enabler within energy and ICT fields and programmes.*
- *Develop a pan-European research agenda and strategy.*

5.1.1 Power electronics: The key to efficiency

Achieve awareness and acceptance of electronics as a key technology to solve energy-related challenges.

Information and communication technologies as well as power electronics technologies have not yet received the attention they deserve when it comes to saving electrical energy. Although there is now more information available in this field – for example, because of the European Commission's actions on ICT for energy efficiency – there is still a long way to go. It is an important long-

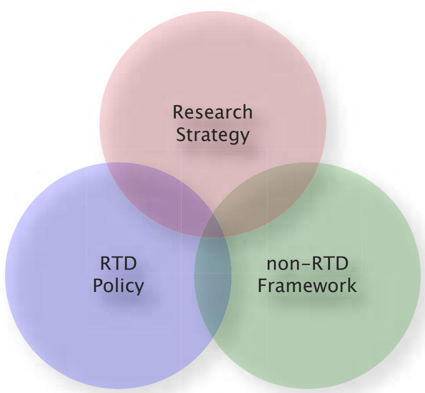

Figure 1: The E4U strategic action plan domains

term objective to improve the awareness of power electronics as a key technology for energy efficiency. This strategy targets experts as well as policy-makers and a broad public.

5.1.2 Creating jobs and growth

Exploit power electronics for growth in Europe.

There is an enormous economic potential of power electronics. This can be seen, for example, in the figures for the power electronics industry. It is a sizeable sector with a turnover of US$41bn world-wide and annual growth rates of 7%. Europe plays a significant role in this market: Infineon Technologies was the largest supplier for the global power semiconductor discrete and module market in 2008, for the sixth consecutive year. Moreover, power electronics technology helps in focusing products on existing European industrial strengths, for example in the areas of communication or the automotive industry. This potential needs to be better exploited in the future.

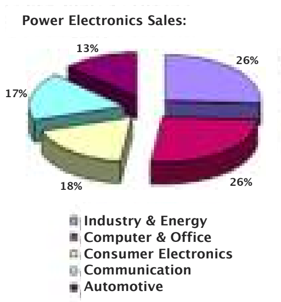

Figure 2: Power Electronics Sales

5.1.3 Investing in people

Secure future human resources in Europe for power electronics engineering.

Research and technical developments but also innovation and exploitation of novel techniques for saving energy with electronics require educated researchers and technicians capable of high-quality engineering in power electronics. Not only is there today in Europe a shortage of engineers in general, but this shortage is particularly severe in the area of electronics. And there is evidence in several EU member states that the figures of students interested in careers in electronics are even decreasing further. Reversing this trend will be vital for securing sufficient human resources as will be the growing interest of young women in careers in green jobs.

5.1.4 Positioning the field

Clear positioning of electronics for energy efficiency as a key enabler within energy and ICT fields and programmes.

Presently, electronics for energy efficiency in general, and power electronics in particular, is not clearly positioned as belonging completely in either the energy or the ICT domain.

This is true at the level of faculties in universities, but more importantly also concerning research programmes and public administrations. For example, in the European Commission, RTD activities for power electronics mostly lie with DG Information Society today, although it can well be argued that the topics addressed should be in many cases at the heart of the topics that DG Transport and Energy deals with.

The area exhibits characteristics of energy technologies, since it deals with the control of flow of energy from the source to the load. But in being semiconductor-based and dealing with control, it also exhibits features of information technologies.

The area of electronics for energy efficiency needs a better positioning in both fields so that synergies with both areas – and between the areas – can be optimised. In the future, the area of electronics for energy efficiency may even become a new scientific field in its own right.

It is also necessary to clearly inform about the fact that electronics, and in particular power electronics, is a key technology enabling energy efficiency.

5.1.5 Pan-European strategies

Develop a pan-European research agenda and strategy.

In the last decade, we have witnessed dramatic improvements in electrical energy efficiency based on new developments in ICT, semiconductors and power electronics. However, we have still barely scratched the surface of what will be possible in the future. Scientists are actively working on new materials, have started to investigate zero-power standby solutions, and target a broad range of application domains at the system level. Yet, we need to strengthen research in electronics for energy efficiency.

Europe is home to research groups in power electronics, ICT and semiconductor technologies for energy efficiency that are recognised worldwide today. Such groups can be found in industry, from small technology-based companies to large global players in power semiconductor technology. Furthermore, there are excellent researchers and groups in Europe's universities and research organisations. However, most of these groups are small and they are spread out all over Europe. In order to harvest the full potential of these groups, we need to overcome their fragmentation.

One way of achieving this is to develop and maintain a pan-European research agenda and strategy. Such a strategy should be driven by the industry and the opportunities for new technologies that help save energy. Researchers from universities and other research organisations will contribute not only approaches and solutions, but also new ideas for such an agenda.

5.2 What should Europe do?

The E4U strategic action plan identifies strategies and actions within these strategies to achieve the top-level goals.

5.2.1 Improving coherence at European level

Exploiting electronics for saving energy presents a massive opportunity for Europe. With our excellent university research teams and world-class engineers in the industry Europe has important prerequisites in place.

However, the research scene is often fragmented into too many small groups. What we need today is cooperation of teams across national boundaries and more effective collaboration amongst the actors in different sectors – industry and academia.

5.2.1.1 European Technology Platform

Action: Initiate a European Technology Platform "Electronics for Energy Efficiency and Sustainability"

European Technology Platforms bring together companies, research institutions, and other organisations, with a view to defining, at European level, a common strategic research agenda which should mobilise a critical mass of national and European public and private resources. They also address technological and non-technological issues for implementing this agenda.

Several Technology Platforms have developed into public-private partnerships set up at European level to support large-scale multinational research activities. They bring together private and public partners to define common objectives of wide societal relevance and to combine funding and knowledge in order to fulfil these objectives.

Although the topic of energy efficiency cuts across different technological fields and application domains, existing technology platforms only include isolated aspects of this important topic. Also, power electronics is sometimes mentioned in the strategic research agendas of different platforms. However, a European Technology Platform focusing on Power Electronics is clearly missing as the core topics, are only insufficiently and inadequately addressed today. Most importantly, there is no platform that brings together the European key players from industry and research with a shared vision of the future.

The European Centre for Power Electronics (ECPE) forms an excellent nucleus for a future European Technology Platform on Power Electronics. The platform shall be open to new players in order to maximise its pan-European and even global impact. Most importantly, the new platform shall be

„ ... "

E4U helped to clarify that the power electronics industry in Europe will greatly benefit from a Technology Platform in this field. Now is the time for strategic thinking and action at European level.

Thomas Harder
European Center for Power Electronics

positioned to overcome the extraordinary fragmentation of power electronics research, support an improved pooling of resources with the aim of strengthening the European power electronics industry and making better use of existing European strengths.

5.2.1.2 Establish power electronics as a topic in the EU Framework Programme

Action: Include power electronics as a research topic in future EC framework programmes

The European Framework Programme for Research and Technological Development (FP7 until 2013) is a €50bn initiative to respond to Europe's needs in terms of jobs and competitiveness, and to maintain leadership in the global knowledge economy. It complements national research activities in areas identified as priorities for Europe with a clear European added value. There can be little doubt, however, that power electronics as a cross-functional discipline of enormous economic potential is a topic that should be included in the Framework Programme.

This fact has already been partially recognised by the European Commission and the Member States in including joint calls on relevant power electronics topics in the Energy and ICT programmes. However, the power electronics field requires a much more explicit and long-term presence in the Framework Programme in the future. The fact that challenging research in the area of energy efficiency often lies at the system and interface level also means that power electronics solutions address both – the energy and ICT fields.

Systematically including power electronics for energy efficiency in the Framework Programme would immediately mean improved visibility of the topic and clear opportunities for collaboration in a way that overcomes national boundaries. This is an opportunity to exploit the existing potential for synergies between smaller research teams and leverage their excellence to a truly global level.

5.2.2 Improving the visibility of power electronics research

Power electronics usually remains invisible as a technology although it is present in a broad range of products that we use every day such as cars or mobile phones. The situation is even worse for power electronics research that is hardly ever visible even to ICT or energy experts. Improving the awareness of power electronics research successes and the many research questions still open is an important prerequisite for improving the situation of research related to electronics for energy efficiency.

5.2.2.1 Promoting power electronics as a European industrial opportunity

Action: Promote power electronics for energy efficiency, renewable energy, e-mobility, smart grids etc. as an opportunity for European industry.

The European power electronics industry is strong and globally active. The power electronics market is estimated to be around 41 billion US dollars with an annual growth of around 7%. The success of the European power electronic industry is based on technical excellence but also on adequate exploitation of economic opportunities. This success is based on technical excellence but also on adequate exploitation of economic opportunities. However, the success of the power electronics industry is not widely known. Policy-makers, even top-level managers and in particular the non-power electronics industry, are not sufficiently aware of past success and the many opportunities that still exist.

There is a clear need today to promote power electronics for energy efficiency in areas such as renewable energy, e-mobility or smart grids – to name just the most prominent examples of today. ECPE has recently produced an image film in an effort to better explain – even within larger corporations – what the achievements of power electronics are.

Much more of this kind of promotional activity is needed to inform also the non-power electronics industry of the economic potential that still lies dormant. Making best use of these opportunities will also be a task for young engineers, start-up entrepreneurs and spin-offs from academic institutions.

But this will require much more awareness of the potential of power electronics through advertising, discussions, training, and exchange of views on market trends and opportunities. Lastly, such awareness will lead to new and improved products through additional research and technological development in the area of electronics for energy efficiency.

5.2.2.2 Ensure explicit references to power electronics in public research programs

Action: Encourage explicit reference to power electronics in RTD programmes.

Power electronics research today suffers from a paradoxical situation. Energy efficiency and information technologies in general rank highly on the research policy-makers agendas in many European member states and at the European level. Microelectronics, smart grids, e-mobility and other areas closely related to power electronics also often feature prominently in thematic research programmes that have been designed and implemented recently.

However, with very few exceptions there is usually no reference to power electronics in research programmes targeting either technologies or applications. This is all the more disturbing since power electronics can indeed sometimes be funded under such thematic programmes. What will be required in the future are more explicit references to power electronics as a key technology in public research programmes.

This explicit reference is important to improve the visibility of the area, to increase the awareness of all actors about the technical benefits of power electronics and also to facilitate the funding of leading-edge power electronics research and innovation.

5.2.2.3 Large-scale demonstration

Action: Implement large-scale demonstrators for power electronics

Power electronics research and innovation today usually happens in small projects or as a small part of larger endeavours. While this is partially rooted in the cross-domain nature of the field and in the fact that energy efficiency is mostly a system property, it significantly impairs visibility and recognition as a key technology. It is thus proposed that a few large-scale demonstrators with clear reference to the role of power electronics for saving energy be implemented.

Such large-scale demonstrators can be implemented using public–private partnership models such as the recently launched initiative on European Large-Scale Actions (ELSA). For example, it will already be important to make sure that power electronics topics are adequately taken into account in energy-related ELSAs.

„ ... “

I have very rarely seen a technology with such a huge potential to save energy and cost whilst at the same time improving technical functionality. I am confident that we can meet the challenges for power electronics research at EU level if all the actors work together closely.

Dr. Erich Prem
eutema Technology Management

Although power electronics may still often be a relatively minor part of such large-scale actions in terms of costs, they can significantly improve the situation of power electronics research and technological development in Europe. Large-scale demonstrators not only improve visibility but also demonstrate the maturity of the technology, further public recognition and understanding and have the potential to boost self-awareness in the power electronics research community and industry.

5.2.3 Improving the visibility of power electronics for energy efficiency

Power electronics research is not only hindered by an insufficient recognition of the research progress, challenges, and opportunities at the technological level. It is also not often clearly visible just how important power electronics is for energy efficiency – using already existing technical solutions. This is why we in Europe also need initiatives to improve the visibility of existing power electronics solutions for improving energy efficiency.

5.2.3.1 Revise labelling and extend its scope

Action: Revise labelling, extend its scope, keep it simple and comprehensible

There is clear evidence that labelling schemes have the power to overcome market failures including lack of information of customers about the true costs of energy-consuming products. Such labelling schemes are increasingly important also to accelerate the take-up of new technologies and to overcome economic and business hurdles to successfully marketing energy-efficient solutions.

Further revising labelling schemes and extending their scope is thus an important tool for improving the take-up of existing power electronics technologies. Such labels should be simple, easy to understand and implemented at a pan-European or even global level. They provide an opportunity for the take-up of power electronics technologies that have already been developed but are not yet commercially viable. Naturally, such labelling schemes also further push power electronics research, for example on cost-effective solutions.

Existing labelling schemes in the area of chargers for mobile phones can be considered an example with direct impact in the area of power electronics. Initiatives like the one promoted by the GSMA and 17 leading mobile operators and manufacturers to implement a universal charger for new mobile phones will have a tremendous impact on the environment. The target of this group is to have a universal charging solution widely available in the market by 2012 based on the Micro-USB as the common charging interface. On the one hand, the adoption of a standard with energy-efficient chargers will result in an estimated 50% reduction in standby energy consumption. On the other hand, the standardisation of the chargers and connectors will provide a reduction of 51,000 tonnes of duplicate chargers, with the additional benefit for the customer of finding a suitable charger for his or her mobile everywhere.

5.2.3.2 Include energy efficiency in education programmes

Action: Include energy efficiency in education programmes

For many technical areas such as computing, microelectronics, or even biotechnology it has become commonplace to include them in the curricula at universities, technical colleges or even schools. However, this is not true for the area of electronics for energy efficiency. Despite the fact that the technology has been developed for decades and despite the fact that it is functioning in a large number of products people use every day, there is nearly no reference to it in the educational programmes in Europe today.

Power electronics for energy efficiency should be included in the training schemes at schools and technical colleges and become a topic in the courses for engineers and other university curricula. The educational programmes may include training content on basic technologies and applications but can also be in the form of student contests or industry-academia outreach programmes.

For example, programmes for donating experimental electronics kits to schools should be extended by power electronics component manufacturers. The topic lends itself neatly to a slight but significant expansion of curricula that presently already often include renewable energies or microelectronics topics.

5.2.3.3 Raise public awareness

Action: Improve public awareness of power electronics for saving electrical energy

Public acceptance is a powerful means of advancing technology take-up and development. In order for the general public to accept a technology and business model that radically changes its understanding and acceptance of a basic service, significant education must take place.

Environmental awareness is already present but the potential contribution of power electronics to a sustainable energy solution is not known to the general public. For example, photovoltaic systems are well known for their green energy epithet. Few know that the energy payback of power electronics systems through energy savings is a couple of months, while the energy payback of photovoltaic systems is 1–1.5 years or more.

Although targeting the broad public is always challenging, it will be important to also raise public awareness of the topic of electronics for energy efficiency. Such information needs to be provided in a suitable format. An example includes an image film on power electronics (as recently produced by ECPE) or the E4U success stories brochure. This and other material suited for a broad audience should be widely distributed and made available, for example exploiting electronic communication channels, online newsletters and website or social software networks.

5.2.4 Focus on key industry challenges

Research and technological development of novel power electronics solutions for energy efficiency needs to be better focused on key challenges for the European industry. The fragmentation of research in Europe and a lack of trans-national or larger-scale projects can easily lead to a lack of guidance, insufficient joint efforts and only weak emphasis on priority research and development topics. Roadmaps and research agendas are important tools for providing guidance at European level.

5.2.4.1 Create and update technology and system roadmaps

Action: Create technology and system roadmaps for power electronics for energy efficiency and provide regular updates

In order to better align the research agendas of industry and research institutes, a joint view of technological and application system trajectories is a prerequisite. Technology and system roadmaps are a tool to ensure a shared view of development and research trends.

Creating and maintaining up-to-date technology and systems roadmaps for power electronics for energy efficiency will help in providing the required guidance for engineers and researchers. Such roadmaps also support the joint definition of challenges and provide the foundation for strategic decisions. They also deliver important inputs into research policies.

Academic and industrial researchers should cooperate in the creation of technology and research roadmaps and regularly update them, for example in two-year intervals. This will also facilitate a better identification of European successes and allow for a clearer global positioning of European research and technology excellence.

5.2.4.2 Create and maintain a pan-European research agenda

Action: Create a Strategic Research Agenda

Based on identified technology trajectories including the systems level, it is necessary to develop a European research agenda for power electronics in energy efficiency that is widely accepted at European level. Such a research agenda will provide guidance for European industry and identify opportunities for European research collaboration.

A pan-European research agenda driven by industry needs can be best maintained in the framework of a European Technology Platform for power electronics. It is important that key power electronics manufacturers collaborate with colleagues from other industries including system manufacturers. Experience from other platforms also shows that universities need to be included to ensure that synergies with top-level academic groups are adequately considered.

This pan-European research agenda is particularly important in power electronics-related research because collaboration between competing companies is far less prevalent than in other areas of electronics engineering. Joint pre-competitive research efforts of industry supported by universities are a key element for developing the required collaborative medium-term perspectives and for strengthening European industry in a sustainable fashion.

5.2.5 Improve reputation of power electronics in engineering

Power electronics solutions for energy efficiency are stable and mature: they are based on a decade-long history and wide application in a large number of solutions. However, they sometimes still suffer from a reputation of not being as reliable as other, more conventional solutions. It also remains a challenge to improve the knowledge of engineers in other fields about the advantages of power electronics solutions for energy efficiency while also maintaining reliability and robustness.

Actions should involve mechanical and systems engineers, and civil and environmental engineers, but also software developers and designers such as architects and urbanists or even other related groups such as material scientists. Again, this shows the interdisciplinary nature of electronics for energy efficiency.

5.2.5.1 Focused research on the robustness and reliability of power electronics

Action: Perform targeted research on the robustness and reliability of power electronics for energy efficiency

There is currently little doubt that power electronics solutions for energy efficiency are technically superior to many alternative approaches. But power electronics is still a relatively young field compared to mechanical engineering. This has sometimes led to a certain reluctance among systems engineers with a more mechanical background to fully trust power electronics, in particular concerning their long-term reliability or the robustness of the solutions.

In order to improve our knowledge about long-term effects, targeted research on the robustness and reliability of power electronics solutions for energy efficiency is required. Such research should address the long-term stability of power electronics materials as well as the robustness of systems solutions and systematically compare them to other existing approaches. Results of such research can help to further support the uptake of power electronics for energy efficiency and may provide important pointers for future research.

5.2.5.2 Foster exchange with mechanical and systems engineers

Action: Create discussion platforms for a systematic exchange of views with a broad range of engineers

Power electronics solutions today often replace more traditional mechanical, hydraulic or similar approaches that may have been around for more than a century. Sometimes such systems are perceived as being more reliable, in particular by systems engineers from a more traditional, mechanics background.

In order to better inform mechanical systems engineers about the potential of power electronics, a more focused exchange of views is required. It is highly desirable to create platforms for a systematic exchange of knowledge between power electronics and mechanical engineers. Such platforms can provide important factual information about the benefits of power electronics for energy efficiency, but also concerning additional functionalities.

It can be expected that such platforms will also provide important insights from the views of mechanical systems engineers for further improving the acceptance of power electronics solutions. Actions should also involve civil and environmental engineers, software developers and designers such as architects and urbanists (e.g. concerning lighting and HVAC applications) or even other related groups such as material scientists. Suitable platforms include online discussion forums, best-practice exchange and workshops or conferences in the vicinity of more traditional mechanical engineering events.

5.2.6 Attract more young researchers to the field

The field of power electronics is, unfortunately, no exception in experiencing a lack of engineers, students and young people interested in careers in research and technology.

The enormous potential of power electronics for energy efficiency and the general increase in awareness about saving natural resources, however, provide an excellent basis for attracting more young people to the field. Targeted actions should be taken now to exploit the generally positive attitude to the benefits of the area.

„ ... "

We have now put more emphasis on power electronics for energy efficiency in our courses at TU Delft and the students just love it.

Jelena Popovic
Delft University of Technology

5.2.6.1 Better advertise careers in "green jobs"

Action: Advertise careers opportunities in power electronics for energy efficiency as "green jobs"

Industry and also academia in Europe are threatened by decreasing numbers of students, a lack of engineers and also researchers in many fields of science and technology and the area of power electronics is, unfortunately, no exception. It is thus necessary to attract more young people to the field by better advertising the many career options in the industry and also in research.

The general policy environment and also the many business opportunities provide rather positive support for careers in "green jobs". But today's young generation has the attitude that power electronics is a hard-core technology area rather than a solution to current societal challenges. The many career options and diverse applications of power electronics need to be better advertised. It is recommended that the targeted advertising of jobs in the field of power electronics for energy efficiency as "green jobs" on dedicated websites be improved. Such actions should include information about current job opportunities and open positions as well as trends and future directions in the job market.

5.2.6.2 Devise new curricula and job titles

Action: Attract more students through new curricula and job titles for power electronics for energy efficiency

The current lack of interest among young people in power electronics research and engineering careers is often caused by a lack of knowledge about the potential application areas and the impact that the technology can have. The field is perceived as purely technological or without direct impact on energy efficiency, sustainability, environmental and societal aspects.

Industry and academia should join forces in making the references to topics such as sustainability or ecological aspects more explicit in power electronics course curricula and even in course titles. The aim of such a rebranding of the field is to attract more students, including larger numbers of young women, to the area of power electronics for energy efficiency. Experience shows that changing the course titles, but also including more societal and environmental topics in curricula, can significantly attract more students in search of a promising professional career that also provides a purpose beyond a purely economic perspective.

It is also necessary to include new subjects in the existing electrical engineering curricula that explicitly inform about power electronics and ICT technologies for improved energy efficiency. This is particularly important for the education of energy engineers, but is also of concern for a broad range of engineers, including such relatively distant areas as architecture and urban planning.

5.2.7 Improve innovation in power electronics for energy efficiency

Innovations in the area of power electronics for energy efficiency are often hindered by rather specific economic hurdles such as a lack of awareness about the true life-time costs of systems or the fact that system users and system investors are different legal entities etc.

However, novel power electronics solutions for energy efficiency still have a broad economic potential and efforts need to be stepped up to exploit this potential also for economic well-being of Europe.

5.2.7.1 Make better use of existing instruments at EU level

Action: Increase the awareness of existing European instruments for innovation in the power electronics community and better exploit these opportunities

Compared to many other fields of science and technology, the power electronics research and technology community has not been very active in the past in taking sufficient advantage of instruments devised to foster innovation. Examples range from technology take-up actions to dedicated initiatives (including the energy-related CIP programme) and actions targeting people (e.g. Marie Curie). The power electronics community should take better advantage of these existing opportunities based on targeted information and joint action. Also, the power electronics RTD community should clearly communicate its interest in these fields and better inform about existing projects and successful applications of the available instruments.

5.2.7.2 Increase public funding for innovation in power electronics

Action: Improve innovation in power electronics for energy efficiency through targeted public funding

The large potential for innovation in the extremely dynamic markets related to energy and improving energy efficiency still remains untapped today. The exploitation of novel technologies in the field of power electronics for energy efficiency cannot be left to large corporations alone. On the contrary, small and medium-sized enterprises play an important role in this field. Successful European examples include support for young entrepreneurs from universities such as YES!Delft, an initiative of Delft University of Technology that provides coaching and support to start-up high-tech companies such as the TUDelft spin-off Epyon.

But Europe needs more innovation of this type and should step up public funding where private sources are not sufficient. Areas such as e-mobility, smart grids etc. all provide playgrounds for start-ups or spin-offs. Also, these areas are often already open to public intervention so that the additional effort required to consider targeted actions for innovation in this domain is small. Increased public funding for innovation in power electronics can also contribute to further improving the field and delivering important success stories for European research and technological development in the field.

5.2.8 Advertise short- and long-term benefits

The area of electronics for energy efficiency in general is characterised by a tendency to focus solely on the short-term benefits of already existing technology. While it is true that underused technologies exist in this field, the medium- to long-term potential must not be overlooked. Also, it is important not to constrain the views of the field purely on a single dimension, be it technical, economic or environmental. We need to emphasise the short- and long-term potential and inform about the broad benefits in different dimensions at the same time.

5.2.8.1 Emphasise current and long-term potential

Action: Clearly inform about the existing short-term and medium- to long-term potential of research and technological development in power electronics for energy efficiency

We are presently in the fortunate situation that many promising technologies already exist for further improving energy efficiency using power electronics. Such technologies are often not adequately utilised due to the specific economic boundary conditions. This is a field where regulation, labelling etc. but also research on cost reduction and improved system technologies can help. Such actions are already being implemented and policy-makers have acknowledged the need to act in this respect.

However, such a focus on the more short-term benefits of exploiting and deploying existing technologies often means that the medium- to long-term benefits of research are overlooked. Despite existing and underused technologies there is an enormous potential for further energy savings, new materials, novel system solutions and much more.
For example, a burning research question from the perspective of industry will remain to reduce cost. From a more academic perspective zero power solutions will remain an important driver of research (such as zero power stand-by of electronic equipment). Addressing such challenges will provide the basis for tomorrow's success of European industry to deploy highly reliable, cost-efficient solutions for power electronics to improve energy efficiency.

5.2.8.2 Advertise technical, economic, and environmental benefits

Action: Improve the advertising of the many dimensions in which power electronics solutions for energy efficiency are advantageous

Using electronics for saving electrical energy will in many cases mean that system-level designs of technical systems undergo significant improvements. Also, the use of power electronics to achieve the desired savings often equips the systems with additional benefits which may be technical, economic or environmental – but often are also functional.

It is important to avoid a single-dimensional perspective on the benefits of power electronics as being solely about improved energy efficiency. Often it is the combination of additional functions, different system features and cost and energy reductions that provide convincing arguments for changing from traditional systems to those using power electronics.
Advertising the many dimensions where power electronics can be beneficial simultaneously is a challenge, as marketing requires simple and clear messages often reduced to a single feature. We thus need to emphasise that focusing on just a single dimension runs the risk of missing out on the combined advantages from many dimensions when using power electronics.

5.2.9 Create the new area of "electronics for energy efficiency and sustainability"

Power electronics as a scientific field is rooted in the materials and methods of microelectronics. It is thus often associated with information and communication technologies. The field is also closely related to research in the area of energy as well as mechanical and control engineering. Power electronics in general is a cross-domain technology with applications in a large number of different fields from the automotive industry to renewable energy. Positioned at the intersection of disciplines and application areas, the field experiences constant creative impulses from many different directions. On the downside, the area also suffers from this lack of clear positioning – for example, when research funding is not clearly accessible at this intersection of fields. Creating a new, clearly positioned area "electronics for energy efficiency and sustainability" can help in overcoming such obstacles.

5.2.9.1 Stimulate discussions about the field, describe its aims and methods

Action: Stimulate the creation of a new scientific discipline "electronics for energy efficiency and sustainability"

A young discipline such as computer science will naturally evolve into a collection of different disciplines as it matures. The last decades witnessed the advent of areas such as health informatics or computer graphics. In many universities, the more mature energy field has also developed into areas such as high-voltage technology or renewables. It is likely that the area of ICT and electronics for energy efficiency will mature into its own scientific field with contributions from energy, physics, electronics, and computer science.

Such a development will help to better position the area as important for energy while heavily drawing on methods and materials from information and communication technology. The creation of new journals and conferences starting with workshops and discussions are a means to accelerate the ripening of the area into a discipline in its own right.

5.2.9.2 Create dedicated university courses and chairs

Action: Create dedicated university courses for the new field "electronics for energy efficiency and sustainability"

In order to fully exploit the potential of power electronics for energy efficiency the interaction between power conversion systems and their sources and loads have to be thoroughly understood and taken into account when designing both the power electronics circuit and the load circuit. This is especially critical now given that power electronics is getting increasingly closer to the loads or even integrated with the load. Today's university courses and curricula are not sufficient to equip future engineers with the necessary knowledge.

One example is power management for systems-on-chip (SoC), where the knowledge of both analogue and digital circuit design and power electronics is necessary for the design of both power circuits and SoCs. In most European and worldwide universities, students specialise either in power engineering or microelectronics, and do not gain sufficient knowledge of both fields. New, dedicated university courses would bridge this and similar gaps.

5.3 Roadmaps

Creating and developing technology and system roadmaps was identified as one action in the strategic plan. Technology and system roadmaps are a tool to ensure a shared view of development and research trends. Such roadmaps also support the joint definition of challenges and provide the foundation for strategic decisions.

Creating and maintaining up-to-date technology and systems roadmaps for power electronics for energy efficiency will help in providing the required guidance for engineers and researchers. E4U has taken the first step and in synergy with the ECPE roadmap activities created draft roadmaps for the four application areas.

In this section, several challenges and gaps as well as strategic goals for two areas, power supplies and industrial drives, are presented. Furthermore, a bottom-up approach technology roadmap in the area of power modules from the ECPE roadmap activities is presented.

5.3.1 E4U application areas

5.3.1.1 Power supplies

Limiting challenges and technology gaps

The field of power supplies is a very broad one and different applications have considerably different requirements and boundary conditions.

The tables below show the limiting challenges, technology gaps and strategic goals for power supplies in the areas of micro-energy technology, data-centres and servers, telecom power supplies and power supplies for RF amplifiers.

MicroEnergy Technology

Issue	Challenge	Technology Gap
Energy storage	Integrated micro-energy storage components	High-density integrated solid-state capacitors, thin film integrated batteries
Energy generation	Energy harvesting sources	Advanced materials suitable to micro-fabrication and integration into standard CMOS technology for cost reduction
Reduction of standby losses	Ultra-low standby power semiconductors	Die design for low leakage currents
Power supplies on chip	Integration of the power converters on silicon	Integrated magnetic materials on silicon. High-density solid-state capacitors.

Data-centres and servers

Issue	Challenge	Technology Gap
Energy efficiency	Improve energy efficiency of the whole energy chain	New distributed architectures. New simulation tools and models to optimise the power architecture.
Reliability	Increase the reliability and utilisation of data-centres and servers while keeping the cost down	Fault-tolerant distributed architectures, auto-reconfigurable power distribution.
Power management	Optimise energy efficiency and utilisation of the data-centre and infrastructure	Communication protocols for power converters, adoption of power management strategies
Modularity	Improve scalability of data-centres and servers	Highly configurable power modules with current sharing capabilities
Standardisation	Reduce cost and improve deployment of new architectures	Generation of standard interfaces, packages and communication protocols shared by manufacturers
Power density	Improve space utilisation	High-frequency and high-temperature passives. High-temp Wide Band Gap semiconductors. High-frequency topologies.

Telecom power supplies

Issue	Challenge	Technology Gap
Energy efficiency at system level	Improve energy efficiency while keeping the cost down	New distributed architectures. New simulation tools and models to optimise the power architecture.
Energy efficiency at load level	Improve the efficiency of telecom processors and digital devices	Power Supply on Chip. Integration of passives into CMOS processes. Dynamic voltage supply on chip.
Reliability	Increase reliability and utilisation while keeping the cost down	Fault-tolerant distributed architectures, auto-reconfigurable power distribution.
Power management	Optimise energy efficiency and utilisation of telecom infrastructure	Communication protocols for power converters, adoption of power management strategies
Modularity	Improve scalability of telecom infrastructure	Highly configurable power modules with current sharing capabilities
Standardisation	Reduce cost and improve deployment of new technologies	Generation of standard interfaces, packages and communication protocols shared by manufacturers
Power density	Improve space utilisation	High-frequency and high-temperature passives. High-temp Wide Band Gap semiconductors. High-frequency topologies.

Power supplies for RF amplifiers

Issue	Challenge	Technology Gap
Energy efficiency	Improve the efficiency of RF amplifiers	Ultra-High bandwidth variable-output voltage power converters. High-frequency power semiconductors (Wide Band Gap). High-frequency topologies.
Power management	High-level energy optimisation of RF systems	Communication protocols for power converters, adoption of power management strategies for power converters and amplifiers
Modularity	Improve scalability of RF amplifiers	Modular power converters with variable output voltage and power-sharing capabilities at ultra-high frequencies. Fast digital control algorithms and devices.

Goals and strategies

MicroEnergy Technology

Technology	Status	2015	2020	Strategy
Energy storage	Discrete components: capacitors, super-caps and thin film batteries	Integrated micro-energy storage components. Thin film batteries and solid-state capacitors		Increase research on basic technologies for integrated energy storage
Stand-by losses	Low-leakage current control circuits integrated with CMOS power switches	Ultra low-leakage control circuits integrated with power semiconductors	Multiple supply voltages with on/off power management	Combination of low-leakage current semiconductor design, multiple rail voltage circuit design and power management according to the workload and activity.
Active current	Constant switching frequency or hysteretic control	Switching frequency control to optimise power consumption	Variable switching frequency and intelligent on/off control	Integrated design of power stage/control circuitry according to the type of load. Adoption of low-power digital control circuits to drive the power
Power Management	Discrete step-up converters with low consumption	Discrete Maximum Power Point Trackers (MPPT) for the source	Ultra-low consumption Silicon integrated MPPT converters	Tight communication of the load and the converter. Combined design of the converter according to the source. Adaptive digital control circuits. Multiple and/or multi-output converter on chip.

Data-centres and servers

Technology	Status	2015	2020	Strategy
Energy efficiency	AC distributed architectures. Medium-efficiency power supplies (60% to 80%)	DC distributed architectures. High-efficiency power supplies (90%)	Highly configurable DC distributed architectures. Ultra high-efficiency power supplies (>95%)	Develop simulation models and tools to evaluate different architectures in different scenarios. Research on low-loss semiconductor devices and highly configurable solid-state circuit-breakers.
Reliability	99,99%[1] (four nines reliability)	99,999% (five nines reliability)	99,9999% (six nines reliability)	High reliability packaging and soldering technologies. Redundant power architectures. Reconfigurable power architectures.
Power management	No power management implemented	Optimise energy efficiency and utilisation of the data-centre and infrastructure	Communication protocols for power converters, adoption of power management strategies	Develop communication protocols for power converters, research on hierarchical power management strategies for energy optimisation
Modularity	Some modules with parallel operation	Improve scalability of data-centres and servers	Highly configurable power modules with current-sharing capabilities	Research on topologies and control strategies for parallel/series connection of modules to increase scalability of data-centres. Communication between modules and high-level controllers.
Standardisation	Ad hoc solutions. No power supplies standards.	Addition of standard communication protocols to power supplies	Standard interfaces and packages and communication protocols shared by manufacturers	Develop standards for communications, converter packages, pinouts, and interfaces to be shared by manufacturers.
Power density	1kW/liter	3kW/liter	10kW/liter	Research on high-frequency/high-temp semiconductors and passive devices. New thermal material and packages. Low parasitic interconnections. Multi-physics simulation tools for the design.

Telecom power supplies

Power supplies for RF amplifiers

Technology	Status	2015	2020	Strategy
High Bandwidth dc-dc converters	200 kHz bandwidth with constant output voltage	2 MHz bandwidth with variable output voltage	10 MHz bandwidth with variable output voltage	Research on new topologies/architectures to boost bandwidth limitations. Research low parasitic interconnections. Simulation models and tools for components, layout and interconnections.
High-Frequency power semiconductors	LVDMOS	WBG devices: GaN power semiconductors	Improved GaN power semiconductors	Research on current and new Wide Band Gap materials. Research on new semiconductor structures to improve high switching frequency behaviour
Power Management	No power management	Selective ON/OFF of power supplies as a function of long-term traffic demand	Fast ON/OFF of power supplies as a function of current traffic demand	Research control strategies and power structures to provide fast turn on and off. Development of communication protocols and digital control techniques.
Modularity	Parallel converters with constant output voltage and current sharing	Parallel converters with variable output voltage and current sharing	SW configurable parallel converters with variable output voltage and current sharing	Research on topologies and control strategies for current sharing at very high frequency. Development of adaptive control strategies to selectively turn on modules as a function of the workload.

5.3.1.2 Industrial drives

Limiting challenges and technology gaps

The critical gaps for increasing the market penetration of VSDs in motor-driven systems are cost (both equipment costs and running costs) and legislation. The main challenges from the user side are cost (economic factor), reliability (critical in existing and emerging applications) and power density (important for successful integration of VSDs in systems). Efficiency is also important, but since VSDs are already very efficient (97%-98%), more attention has to be paid to the rest of the system (motor, end load).

Major technology gaps to be closed to meet the challenges are:

- New semiconductor materials with broad applications (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. High-performance cooling technologies allow for small volumes and high power densities but are expensive.

- 3D-integration – including passive components, necessary for achieving high power densities.

- Sophisticated control platforms and integration of self-powered sensors with wireless communication – by 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.

- New converter topologies or configurations – in MV drives minimisation 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 the reliability challenge.

Goals and strategies

Goal 1: Increase market penetration of inverter drives to 40% by 2020. (percentage of inverter drives related to sum of drives).

This goal supports the megatrends "clean power" and "energy savings" by avoiding local emissions and increasing the efficiency of motor-driven systems. Hence, the task of the electric drive industry is to produce economical electric drives. This task is supported by the technology goals. 1/3 of all the

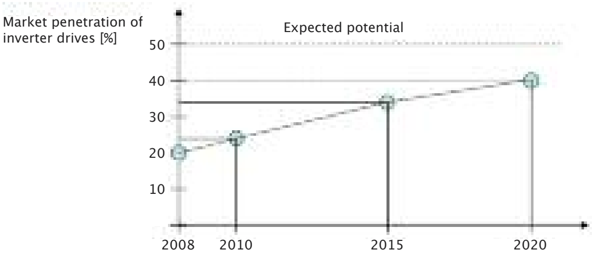

Figure 3: Expected market penetration of inverter drives by 2020

electricity consumed is used to power electric motors and drives (2/3s of the electricity in industry is consumed by electric motors). Today, in Europe, 15–20% of motor drives use VSDs (5% worldwide). The estimated potential is that 50% of motor drives in EU could be driven by inverters in the future (estimates vary but this is the most widely accepted figure). The market penetration goal presented above can be achieved by supporting technology goals. Furthermore, the achievement of the technology goals will ensure the competitiveness of the European drives industry compared to the US and Asia.

Goal 2: Efficiency goal – increasing efficiency of drives to >99% by 2020 (>98% by 2010)

The efficiency of the 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 has to be paid to increasing the efficiency of the other system components. However, increasing the efficiency of drives does have its merits. By reducing the losses in the converter the cooling requirements are reduced, which reduces the total volume of the converter, which in turn reduces the energy required for manufacturing of the converter. Furthermore, the energy consumption of the cooling system is reduced.

The following technology developments and challenges are needed to achieve this goal:

- Devices: SiC and GaN device development;
- Converter control: topologies for reducing converter losses (including soft switching and multilevel topologies);
- System level: Power grid control issues with increasing the efficiencies (the dampening resistances disappear and the risk of resonances increases).

Goal 3: Power density goal – Increase the power density of drives to 400% of 2007 level.

The potential to realise this goal lies in system integration, high-temperature technologies and passive components. The absolute value of power density depends strongly on the cooling system.

The following technology developments are needed to achieve this goal:

- Devices: SiC and GaN further development and cost reduction
- Packaging: double-sided, high-temperature interconnection technologies
- Cooling technology: active (forced/spray) cooling, phase change/heat pump technologies, conductive thermal transfer, new materials etc.
- System integration aspects: passive components suitable for high density integration, integrated electrical, thermal and electromagnetic design tools, topologies suitable for high power density

Goal 4: Enhanced performance, intelligence and communication goal

The 2020 drives will have:

- automatic initialisation;
- power management;
- optimised operation with respect to application requirements – e.g. maximum efficiency tracking by changing flux level;
- diagnosis functions;
- (wireless) sensors;
- communication between multi motor drives.

The main energy efficiency potential under this goal is to optimise the process to consume minimum drive energy (e.g. reduce pump speed if less liquid flow is necessary for process). This requires intelligent process planning. Plant monitoring of drive and process energy consumption is enabled through (self-powered) sensors and wireless communication.

The following technology developments are needed to achieve this goal:

- Enhanced functionality and ease of use: minimise user parameter entry/maximised auto-commissioning using AI techniques,

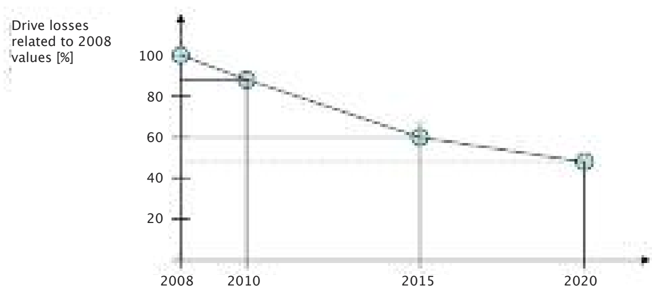

Figure 4: Expected drive loss reduction by 2020

increased parameter tracking for enhanced performance;

- Communications: standardisation of protocols, wireless sensors and communication.

Goal 5: Increased reliability and fault tolerance goal – "Reduce failure rate to 10% at same hardware functionality"

The 2020 drives will have:

- reduced number of components
- minimum sensor count
- ability to reconfigure system in case of a fault
- diagnostics and prognostics functions

The following technology developments are needed to achieve this goal:

- Reduced number of components – increasing the level of integration;
- 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.

5.3.2 Technology roadmaps

Contrary to the top-down application driven system roadmaps such as the two examples presented above, in the bottom-up roadmap approach the focus is on the development of basic enabling technologies in power electronics, such as power semiconductors, power modules, advanced cooling, passive components etc. As an example of this approach the power modules roadmap is presented below.

5.3.2.1 Power modules roadmap

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 classic function of a power module is to separate the heat flow from the current flow.

When these systems first came into use, the common type of circuitry used was the half-bridge configuration, in which two semiconductor components are connected in series. Recently, systems with increasingly complex configurations have become more and more prevalent – modules with an integrated input rectifier, a three-phase inverter and other integrated functions (shunts for current measurements etc.) The additional integration of driver circuits enhances the module to an IPM (Intelligent Power Module). By adding sensors, a complete DC link and an auxiliary power supply, an intelligent sub-system is created. This is extended to a power electronics system by adding a controller and the appropriate software.

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.

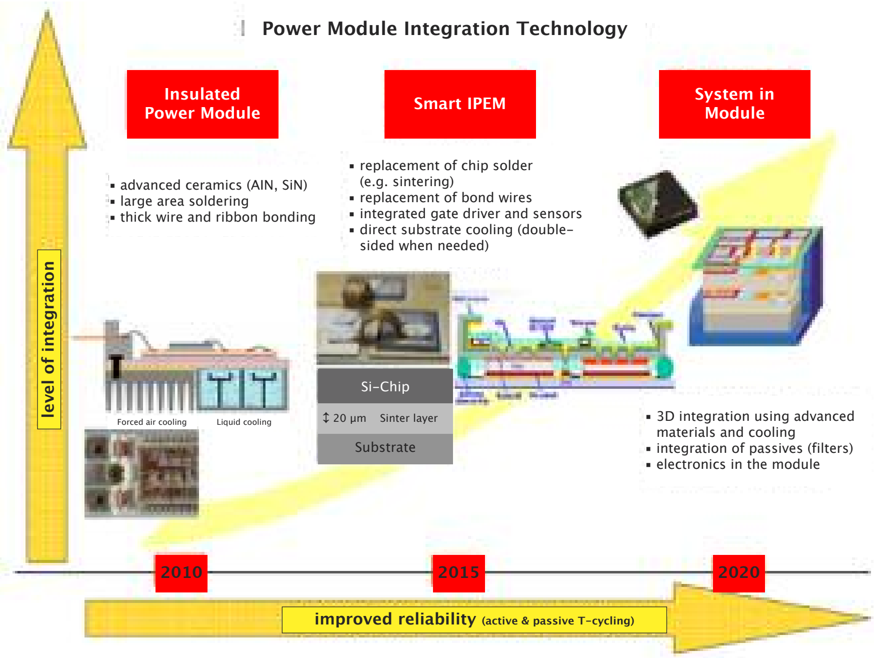

Figure 5: Power Module Integration Technology

Figure 5 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 have 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. 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.

5.4 Conclusions

The overview presented in this publication ranges from assessing the potential and impact of power electronics for energy efficiency in the four areas of interest, to analysing the current position of the European power electronics scene. We have done this from a technological point of view but also looking at external factors such as worldwide, EU and national measures and policies, research programmes etc., and on to the development of a strategic plan of actions and technology roadmaps to help power electronics realise its potential and make a significant contribution to our sustainable energy future. Most importantly, we have emphasized the need to strengthen European research in electronics enabling efficient energy usage as an opportunity that we should not miss for us – and for generations still to come.

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[1] Bill Brown, P. E. „Data Center Power System Reliability Beyond the 9's: A Practical Approach" *www.data-centerdynamics.de*

6 Acknowledgment

6.1 Methodology

This strategic action plan is based on a series of discussions with experts, on several analyses performed by the E4U project team and includes the results of expert workshops and dedicated conference sessions. Experts contributing to the discussions came from the power electronics industry, from application and system manufacturers, as well as representatives from companies in the area of renewable or large utilities.

At several stages over period of 18 months, officials from European member states and the European Commission contributed their views and kindly offered guidance on directions for the project and the strategy.

This strategy was first presented to the research community in a dedicated conference session at the European Power Electronics Conference 2009 in Barcelona. A large group of top experts from academia and industry contributed many details and provided ample support for the strategy as a whole.

As an important element of the strategy, the decision to initiative a dedicate European Technology Platform was scrutinized by the Board members of the European Centre for Power Electronics and also presented in dedicated policy workshops in Brussels and Vienna.

6.2 The E4U project

The E4U initiative was a project supported by the European Commission in the Information and Communication Technologies programme of the 7th Framework Programme. The project started in May 2008 and finished in November 2009. E4U was initiated and completed by a team of four European partner organisations:

eutema Technology Management GmbH, Austria (coordinator)

eutema is a strategic research and technology consultancy based in Vienna, Austria. eutema designs and implements research strategies for EU member states and manages RTD projects and programs. Its customers and partners include the European Commission, Austrian ministries, research councils, funding agencies, universities as well as global industry players, small companies and private research organisations.

www.eutema.com

The European Center for Power Electronics e.V., Germany

Leading power electronics industries have founded the European Center for Power Electronics (ECPE) in 2003 in order to promote research, education and technology transfer in this field. ECPE aims at promoting the importance of power electronics to the public. For an efficient realisation two legal bodies have been founded, the registered association ECPE e.V. and the limited company ECPE GmbH. Today ECPE is an industrial and research network for power electronics in Europe with about 40 industrial members and more than 50 European Competence Centres

www.ecpe.org

Universidad Politécnica de Madrid, Spain

The Universidad Politécnica de Madrid is the oldest and largest of the Spanish Technical Universities. The Centro de Electrónica Industrial (UPM-CEI) is mainly devoted to power conversion systems, Embedded systems design, and power quality. All these research lines have horizontal activities in common, such as design and integration of electronic systems and advanced techniques for modelling and simulation.

www.upm.es

University College Cork (Tyndall Institute), Ireland

The Tyndall National Institute was created in 2004 at the initiative of the Department of Enterprise Trade and Employment and University College. The strengths of the institute at the present time lie in the area of photonics, electronics, materials and nanotechnologies and their applications for life sciences, communications, power electronics and other industries.

www.tyndall.ie

6.3 About the authors

José A. Cobos, UPM, is a Professor at UPM since 2001. His contributions are focused in the field of power supply systems for telecom, aerospace, automotive and medical applications. His research interests include low output voltage, magnetic components, piezoelectric transformers, transcutaneous energy transfer and dynamic power management. He has published over 200 technical papers and holds 3 patents. He has been actively involved in 22 R&D projects awarded with public funding in competitive programs, and 42 direct contracts for research and development for different companies worldwide.

Nicolas Cordero, Tyndall, Nicolas Cordero graduated in 1990 from the Technical University of Madrid (UPM). In 1990 he joined the Tyndall National Institute (formerly NMRC) in Cork as a Research Engineer. At Tyndall he carried out research on numerical modelling of electronic and optoelectronic devices based on compound semiconductors; he has also worked on modelling of photo-voltaic systems. Since 2000 his research has focused on thermal management of electronic/photonic devices and systems and modeling and simulation of micro and nanosystems. He has been Tyndall's technical leader for several European Projects on thermal and energy-efficiency issues in the aerospace and automotive industries.

Thomas Harder, ECPE, has received his diploma in semiconductor physics from the University of Kiel (Germany). As a researcher he has 15 years experience in microelectronics packaging and interconnection technology, working e.g. in the Fraunhofer Institute for Silicon Technology (ISIT) in Itzehoe responsible for microsystems packaging. He was the coordinator of several EC IST Projects e.g. FLEX-SI, FLIBUSI and VABOND. Since 2003, Thomas Harder is the general manager of ECPE, the European Center for Power Electronics .

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eutema is a strategic research and technology consultancy based in Vienna, Austria. eutema designs and implements research strategies for EU member states and manages RTD projects and programs. Its customers and partners include the European Commission, Austrian ministries, research councils, funding agencies, universities as well as global industry players, small companies and private research organisations.

European Center for Power Electronics e.V., Germany

Leading power electronics industries have founded the European Center for Power Electronics (ECPE) in 2003 in order to promote research, education and technology transfer in this field. ECPE aims at promoting the importance of power electronics to the public. For an efficient realisation two legal bodies have been founded, the registered association ECPE e.V. and the limited company ECPE GmbH.

Universidad Politécnica de Madrid, Spain

Universidad Politécnica de Madrid is the oldest and largest of the Spanish Technical Universities. The Centro de Electrónica Industrial (UPM-CEI) is mainly devoted to power conversion systems, Embedded systems design, and power quality. All these research lines have horizontal activities in common, such as design and integration of electronic systems and advanced techniques for modelling and simulation.

University College Cork (Tyndall Institute), Ireland

The Tyndall National Institute was created in 2004 at the initiative of the Department of Enterprise Trade and Employment and University College . The strengths of the institute at the present time lie in the area of photonics, electronics, materials and nanotechnologies and their applications for life sciences, communications, power electronics and other industries.

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