

# Towards a Sustainable Energy Supply - The New Landscape of Energy Technologies

持続可能なエネルギー供給を目指して

- エネルギー技術の新たな展望 -

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## 1 Introduction

Awareness of global climate change due to overconsumption of fossil fuels and the inevitable cost increase of fossil fuel exploitation in the coming decades has stimulated worldwide research and innovation towards a sustainable and secure energy supply. Many nations consider renewable power sources, such as biomass, photovoltaic, wind and solar power, as the best alternatives for the next decades to minimize CO<sub>2</sub> emissions and reduce their dependency on fossil fuels. As a consequence, more distributed, but also more volatile power sources will mark the energy supply landscape. To cope with this volatility in the electrical grid, automated distribution systems will be needed, in combination with increased storage capacity and improved demand side management (DSM). In developed nations, approximately 40 % of all primary energy is consumed in buildings and homes. Hence, in this sector the highest potential exists to save energy. In addition, due to their large thermal mass, tuning the energy demand of buildings and homes to volatile energy sources offers a high potential to load level energy supply and demand and stabilize the electrical grid. Furthermore, the emissions (acoustic and particulates) of combustion engines has placed considerable strains not only on mobility but also on quality of life in an around large cities. These concerns spur use of electric and plug-in hybrid vehicles. Interestingly, electro-mobility is a concurrent development that enables increased use of volatile power sources as their batteries can provide an ultra large storage capacity for electrical networks.

## 2 Energy Market Liberalization - Prerequisite for a Sustainable Energy Supply

One can question the driving forces towards a more sustainable energy supply in which power sources are more distributed and entail more renewables. It is the author's

believe that market liberalization of the electrical energy supply has been a prerequisite for the current way of thinking to increase distributed and renewable power generation. This can be exemplified with what happened in Europe over the past decade and can be illustrated with statistics, comparing the European energy supply mix in the year 2000 and 2010, the latter is illustrated in Fig. 1 [1][2][3][4].

Market liberalization in Europe effectively started in the year 2000. Taking into account the EU27 member states and also Norway and Switzerland, i.e. the so-called EU29, the entire bulk electrical power (about 515 GW, 2900 TWh) was up to then provided by large scale central power plants, primarily based on coal, gas, lignite and nuclear. Hydro power plants (185 GW) are mostly situated in Norway and Switzerland and are mostly downstream. About 40 GW of hydropower plants are up-stream, i.e. can work as pumping stations. The technical "scaling laws" of (Carnot-type steam turbine) power plants, which state that bigger is more efficient, drove the size of power plants to extreme unit sizes (up to 1.3 GW). This view on electrical power generation had some major side effects. The need of cooling power often restricted the location of these power plants near major rivers or to coastal areas, often far away from end users. This fact, together with many other constraints, required not only long transmission distances but made district heating often economically unfeasible. Either the infrastructure cost for district heating or the negative impact on power plant efficiency was considered too high in relation to the cost of the primary energy. This centralistic design view led to an enormous waste of primary energy (55 to 65 % is converted in heat) in the production of electrical energy. Hence, most central power plants perform poorly from an exergy<sup>\*1</sup> viewpoint as few regions utilize the heat produced by central

\*1 "exergy" is the maximum available work or energy, that can be provided by a process from, for example, primary energy (coal, gas, nuclear, etc.).

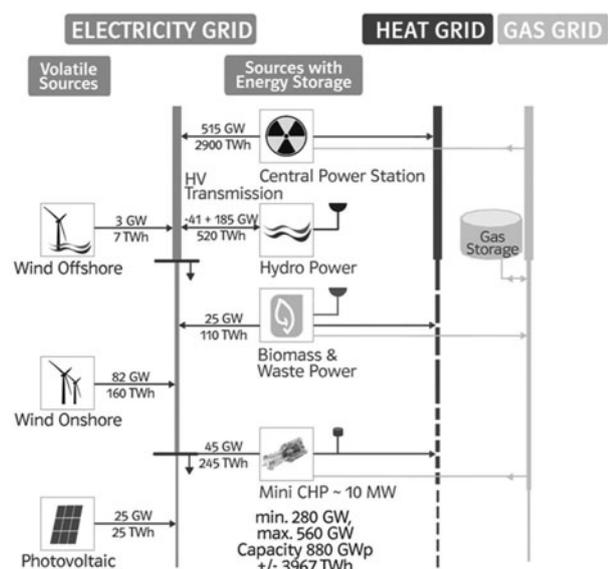


Fig. 1 Simple line diagram representation of the EU27+2 energy grids (electricity, heat and gas) in year 2010, ten years after market liberalization. The dramatic change towards more decentralized and renewable power sources is visible, totaling an installed 70 GW of CHP and biomass & waste power systems, 85 GW<sup>peak</sup> of wind power and 25 GW<sup>peak</sup> of PV systems. Also shown is the increased linkage between the electrical grid and heat storage systems, as well as the gas grid. The total system exerts a higher exergy level because less heat is wasted in decentralized power units. Extra transmission lines based on high-voltage DC (HVDC) technology have been installed. Lowest electrical demand is around 280 GW and highest peak is at 560 GW.

power plants for district heating. Obviously, in this centralized, mostly nationalized energy market, local medium- or small-scale combined heat and power (CHP) generation in the industrial and the commercial sectors was often not economical or even restricted by regulations. Furthermore, little linkage exists between the electrical grid and the heat and the gas grid.

Hence, it is not possible to use the large storage capacity of the heat grid or the gas grid as a storage medium for the electrical system. Consequently, as the electrical grid by itself has no significant storage capacity, power plants have to follow power demand. In case of large-scale base load power plants this would cause thermal cycling, which can dramatically limit life of such power plants (and increases operating maintenance costs). To avoid this, sufficient loads at all times have to be ensured. Several countries, in particular those that have a high level of (nuclear and coal) base load power plants offer at certain times of day the end-users incentives in the form of lower tariffs to consume electrical power in off-peak hours. Furthermore, utility providers

installed equipment to manage, for example heat storage systems or boilers in buildings and private houses. Hence, several demand side energy management systems were already in place prior to the market liberalization to cope with the fluctuating nature of the electrical loads. Of course, these measures did not create any incentive to save energy or to improve the exergy of the entire supply system.

Looking at Fig. 1, which shows the situation of EU29 in 2010, one can see the remarkable change that took place in less than ten years. Clearly, the energy market, once liberalized, is not so conservative as one often believes it is! Over this relatively short period, about 70 GW of medium scale or so-called “mini-power” plants (ranging from 0,1 to 30 MW) with CHP technology have been installed. These plants produce electricity and heat based on biomass, waste and gas. Not only possess these units a high exergy level but they also can respond fast to load and supply variations. Furthermore, their primary feedstock can be stored in form of solids, liquids or gas, providing additional storage capacity and, if automation is provided, fast response for secondary power support. In addition, due to policies in various countries, renewable power sources have been installed at a high rate. Whereas photovoltaic systems reached by end of 2010 a peak installed capacity of 26 GW, wind power plants (both on- and off-shore) reached a peak installed rating of 85 GW. Statistics show that despite a 20 % reduction of CO<sub>2</sub> emissions, due to higher efficiencies in the industrial and commercial sector, as well as energy savings in buildings, the total electrical power consumption increased. This can only be interpreted that more processes have moved to electrical systems exactly because they are more efficient or provide additional functionality. Heat pumps that reach seasonal performance factors above 3.75 are on the market [5]. Next to lower heating costs, they also provide cooling power, which has become necessary in new energy efficient buildings and in several regions due to higher ambient temperatures. Consequently, in future efficient buildings and homes, less gas consumption will be needed for heating, while electricity consumption will increase for heating and cooling.

Of course, the increased use of volatile renewable power sources has posed questions with respect to power quality and stability of the electrical grid. However, even without coordination of the approximately 70 GW distributed mini-power plants, the grid operators and the main power generation units have been able to keep the approximately 100 GW of total installed peak generation capacity of volatile sources (wind and PV) under control.

In addition, a positive side effect of the more distributed generation can clearly be seen in Fig. 1. The (local) heat and gas grids become more and more linked to the electrical grid. This coupling already provides lots of opportunity to buffer for instance excess, i.e. low cost, electrical energy of PV and wind, for example in the form of heat. For instance, heat can be stored in the thermal mass of buildings, in earth soil, hot water boilers, etc. to be used on demand by the consumer. Apparently, low temperature heat storage systems with time constants up to days are cost effective as several new buildings use these storage systems in conjunction with heat pumps. Although studies show that compressed gas (biogas, natural gas) provides the most cost effective large-scale energy storage system, liquefied gas storage provides the greatest potential for long-term storage of very large energy reserves (in the form of chemical energy). At present, efficient (up to 60 %) and fast starting combined cycle (gas and steam) power (CCP) plants in conjunction with gas storage is the most economical option to load level volatile power over longer periods of time and provide security in the energy supply.

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### 3 Innovation to Increase Use of Renewable Sources

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Industry and utility companies are just learning the technical and business opportunities that open up with this new situation. As energy companies are considering installing large-scale renewable power plants themselves, it becomes imperative that a more coordinated electrical supply system is needed. In this respect, automated dispatching of more distributed power generators, a concept known as the virtual power plant, may become necessary to keep the AC grid stable. Furthermore, automation of energy transmission and distribution, also known as the “smart grid”, and automation of energy demand, for example in city quarters, buildings and homes, may allow further increased use of renewable power sources. All these measures, which require monitoring, control and communication are innovation steps that are being implemented step by step in new-build infrastructure. Of course, the most critical issue is the reliability and security of such highly automated systems. It is a well-known fact that in the classical alternating current (AC) grid, all power stations “communicate” with each other via two electrical quantities, namely the voltage level and frequency signal of the AC grid. Based on the inductive nature of the grid, operators have learned that voltage control (specified by e.g. IEC standards to remain with +/- 5 % of nominal voltage) can be realized by

reactive power injection in the grid, while frequency control relates to the active power that is delivered by the power plant. These simple control principles have led to an extremely robust and reliable supply system, which is an amazing feat, when one realizes that the electrical power grid is by far the largest and most expensive infrastructure so far built by mankind. Also, providing safety and preventing faults to propagate to the entire grid was relatively easy as transformers limit short-circuit currents, thereby allowing circuit breakers to separate faulty apparatus from the network. Coordination of protective gear was straight forward as the power flow was typically “top-down”.

However, the increased use of decentralized power systems, in particular micro-CHP systems and PV systems enforces new safety rules and pushes the limits of the current AC technology. Over the past decades, many solutions to control power quality (STATCON, DVR, UPFC, etc) and improve reliability of the AC grid (e.g. current limiters, hybrid switches, solid state transfer switches, etc.) have been investigated to cope with situations where power flow can be reversed [6][7][8][9]. Indeed, since market liberalization took place many consumers became “active”, i.e. they deliver power to the grid. Although most solutions mentioned above have proven to be working well when solving specific problems, a general solution to operate AC grids with very large-scale use of renewables is not available. Hence, most compensation and protection equipment is not standard and remains very expensive. Yet, the global production capacity of wind turbines (estimated in 2010 about 40 GW per annum) and PV (estimated in 2010 about 15 GW per annum) outperforms already the production capacity of new large central power plants. Furthermore, the production of these renewable power sources has created lots of new job opportunities, so that this development seems politically and socially unstoppable for years to come. Hence, new technologies are required to transport and distribute electrical power, to provide storage capacity and improve the balance between supply and demand. On top of this, large-scale wind farms and PV systems are constructed on locations where their production is more optimal. For example, onshore wind turbines produces on average annually about 25 % of their peak installed power rating, while offshore turbines can reach 30 %. Hence, the power has to be transported over longer distances. At the same time, engineers have to cope with ever higher expectation levels of the public with respect to quality of life, environmental conditions, air quality, sight pollution (no overhead lines), noise, etc. Basically, the public wants

clean and sustainable power. However, except for roof-top PV systems, no-one wants it in his back-yard. It is the author's believe that, in effect, these constraints make electrical power engineering a much more exciting field than it has ever been before.

#### 4 New Technologies enable Ultra Large-Scale Use of Renewables

One could ask which technologies are required to implement an electrical energy supply solely based on renewable power. Simple calculations based on the production capacities stated above, show that this feat could be accomplished for the entire electrical power consumption needs of Europe in about 15 years! Several concepts along these lines have been proposed, for example DESERTEC [10][11]. In these concepts, solar base-load power plants with high temperature heat storage (at 525 °C) would be built in desert areas (South of Europe or even in Africa). Wind turbines would be installed offshore or along coastlines, i.e. places with favorable wind conditions. Small-scale (0.1 to 30 MW) biomass and waste processing power plants would provide heat and power. Most electrical engineering companies are convinced that such large-scale concepts would require a multi-terminal DC high-voltage grid to transmit the electrical energy in large quantities to urban areas. This multi-terminal DC technology is based on high-voltage power electronic converters and uses mostly DC cross-linked polyethylene (XLPE) cable technology. The latter has reached voltage levels up to  $\pm 300$  kV [12]. Due to substantial technology developments over the past decade, the costs of both DC cables and high-voltage power electronic converters have decreased substantially. A multi-terminal DC system has more flexibility to absorb fluctuating power because the power electronic converters at each terminal control output terminal voltage independently. Furthermore, compared to AC systems, such DC systems can be operated at higher efficiency, especially at partial load, not only because of the lower losses (no skin-effect in DC cables), but also because the power flow in the cables can be fully controlled by the conversion stations.

Having such multi-terminal HVDC transmission system in place, it becomes apparent that medium voltage distribution systems in cities and buildings would offer higher efficiency and lower costs. As shown in Fig. 2, electronic transformers are key enabling technologies for such systems to link distribution grids together and to tap power from the high-voltage DC transmission system. Electronic transformers

consist of two back-to-back DC to AC inverters that are coupled to each other via medium frequency transformers [13]. The advantage of such DC system is that most converters are concentrated in the substations (not in the power generators). Furthermore, detailed studies show that the transformers at higher frequencies become not only smaller and lighter, but also more efficient [14].

To provide storage capacities the electrical grid should become more linked with heat storage systems (and local heat distribution) and the gas grid for example, by heat pumps and electrolyzers, respectively. To keep costs of storage down, dual-use storage systems will be required. Dual use means that the storage capacity is already available in existing infrastructure. Clearly, as mentioned above, low temperature heat storage systems can be found in buildings and the building infrastructure. Using heat pumps to provide heating (and cooling) provides a link between the electrical grid and the heat storage. In Germany alone it is estimated that the building infrastructure provides for 8 hours a storage capacity of over 330 TWh, without losing comfort even in wintertime [15]. Hence, massive amounts of excess wind or PV energy can be stored over periods measured in days.

Excess wind and PV energy should also be stored in gas storage systems using electrolyzers that produce hydrogen and oxygen. These systems are under development but already conversion efficiencies have been reported up to 77 %. Both gases (H<sub>2</sub> and O<sub>2</sub>) could be stored to cope with long periods of no wind (in Europe periods of no wind over 12 days have been recorded). Fuel cells (using oxygen and

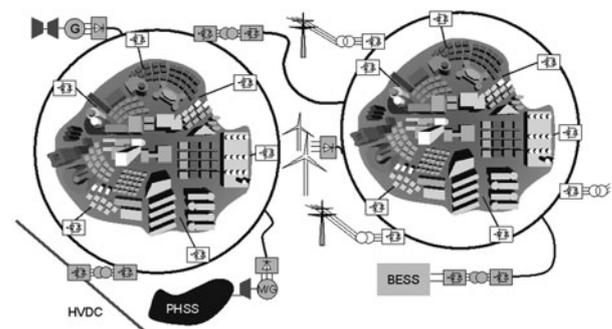


Fig. 2 The future energy transmission grid will comprise multi-terminal high-voltage DC (HVDC) networks to feed power via DC-to-DC converters (electronic transformers) in a medium-voltage DC ring bus cable network. These DC-to-DC converters can also link medium voltage (MVDC) buses to provide redundancy and provide an interface to DC power sources such as PV and battery energy storage systems (BESS). Windturbines, CHP units and pumped hydro storage systems (PHSS) are linked to the MVDC bus via simple rectifiers or inverters.

hydrogen) with over 75 % efficiency have been demonstrated [16]. Of course, hydrogen can be mixed in existing gas pipelines or can be stored. Ultimately, by liquefying the gas, large strategic reserves can be built for entire seasons to provide security of supply. These gas mixes can drive combined cycle gas and steam turbines to produce heat and power on demand (electrical efficiency up to 60 %) compensating the fluctuating power supply of wind and PV.

## 5 The New Energy Landscape – how it affects mobility

This brings us to the question of how mobility of people and goods in large urban areas should be powered when renewable power sources are available at an ultra-large scale. Clearly, the ever-increasing health problems in large cities, due to emissions (noise and particulates) of combustion engines, have reached proportions that concern many and are no longer tolerable. In addition, the ever increasing oil prices on the one hand and the improvements of battery and propulsion technology on the other hand have convinced politicians and industry leaders that electric propelled vehicles (trams, busses, delivery vans, passenger cars, scooters and bikes) will be necessary in large urban areas. The synergy between these electric vehicles (EVs) and renewable power sources cannot be underestimated. The batteries of all EVs (typical passenger car EV has 10 kWh battery) can be used as an electric storage buffer for primary energy control of the electrical grid. Primary energy control is needed to stabilize the electrical grid when sudden disturbances, such as short circuits, or load dumps, take place. Normally, these disturbances are compensated within few minutes. This primary energy control could be provided by controlling the charging instances of the electric vehicles that are connected to the grid. Of course, utilities have to find ways to motivate drivers to plug in their cars. However, next to price incentives, one major motivator could be the fact that battery life can be extended when the battery is discharged during parking and re-charged just prior to driving. Statistics show that typically 80 % of all EVs will have discharged their battery less than 40 % upon arriving in the evening at home (100 km range battery, 10 kWh battery). Recent studies show that it is important to discharge the battery first and recharge the battery to be ready just in time for driving in the morning [17]. The lifetime of the battery could be improved three-fold with such charging scheme. This approach would require bi-directional battery chargers to be implemented in all EVs [18]. As most cars are parked in garages or near private

homes, such chargers would be part of a “smart building or home” energy managing system, to minimize energy costs. Hence, dual use of EV batteries provides a very large electrical storage capacity for primary energy control of the electrical grid. If 25 % of the 220 million passenger cars in Europe would be electric and half of them would be plugged-in, a virtual battery storage of 275 GWh would be available with a power capacity of at least 100 GW (assuming a 16 A, i.e. 3,7 kW single-phase charger). Fig. 3 illustrates the ultimate new landscape as described in this paper. Note, that this new landscape can, from a technical viewpoint, be realized with today’s technologies. Furthermore, based on current production technologies, this vision can be realized in a time frame of about 15 years. Studies show that the end-user kWh price would be same as today’s prices [19].

## 6 The New Energy Landscape – how it affects homes

Clearly, with these technology developments in the energy and mobility sector, the entire house design, energy and climate control becomes a challenging but rewarding engineering task that could support a more sustainable energy supply system while improving comfort level and quality of life. Most energy consumed in homes is still related to heating and cooling (air conditioning). Studies show that heat pumps with seasonal performance factors around four are available

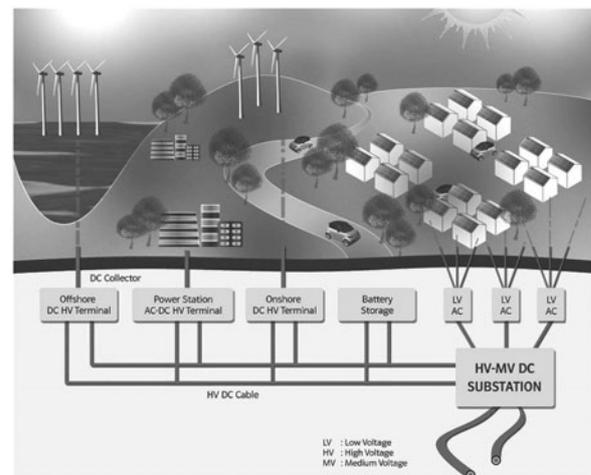


Fig. 3 The future energy and mobility landscape in urban and sub-urban areas. Electrical power will be distributed via underground DC cables. Substations will convert this to AC or DC power. Most passenger vehicles will be electric. Dual use of the EV batteries provides a very large electrical storage for primary energy control. Charging of vehicles will be integrated in the energy management systems of homes and buildings.

today, making heat pumps economic alternatives against gas furnaces. Furthermore, most electrical energy in homes is consumed by refrigerators and laundry machines (i.e. dryers and washing machines).

Centralized control (automation) of these large energy consumers and recuperating heat (and water) would allow better control of power quality of the supply system and allow more renewable power to be integrated in the system. Several manufacturers are anticipating this by providing communication functions in their appliances to coordinate energy consumption in conjunction with so-called smart meters. The concept of dynamic tariffs is just one way to stimulate end-users to become active participants in the energy supply system of the future.

Energy efficiency of appliances and home entertainment equipment is of utmost importance to minimize energy consumption. Lighting is already efficient and moves further to more efficient LED and OLED lighting systems. Even when lighting consumes merely 3-4% of the primary energy supply, it is beneficial to improve its efficiency in buildings and homes because less cooling power is required during summer seasons. Also, architects are experimenting with light conduits that guide light into houses and buildings during daytime so that energy consumption by electrical lighting systems can be reduced.

Energy efficient homes that are active, i.e. produce energy using PV, solar thermal systems or micro-CHP units, often become net producers of electrical energy. On top of this, they consume little or no gas for heating (use electrical heat pumps instead). Already in many city quarters, the cost of the infrastructure for gas distribution (mostly designed for heating purposes) cannot be recuperated. This poses serious questions on how the energy will be provided to single-family homes in the future. It may well be that only one energy carrier will be available in the future. In new-build houses, which need less heating and more cooling power, it may make sense to install only the electrical energy supply. Furthermore, hot water boilers with electrical heaters are cheap heat storage systems, which can be controlled to provide load leveling of PV systems and wind turbines.

Unfortunately, to benefit from grid feed-in tariffs, which are offered in several countries, it is necessary to feed all excess renewable energy in the AC grid first, often via expensive DC-to-AC inverters, rather than using low-cost DC-to-DC MPP tracker devices that feed the PV energy in a local DC bus or storage system. It is clear that further optimization of power electronic costs can be realized when no such feed-in

guidelines are provided. In Germany, new regulations with respect to feed-in tariffs have been implemented to remunerate also the PV electrical energy that is stored intermediately in batteries. This measure was taken to prevent peak overload conditions of the distribution grid during noontime, when most inhabitants are not at home and sun irradiation is maximal. In suburban areas this led to over-voltages in the distribution grid, which could damage electrical equipment. To overcome this problem, a more flexible medium voltage distribution system will be required. Medium voltage DC cable networks may be the only viable and acceptable way to accomplish this voltage control. Furthermore, dual use of the battery (for driving and for energy storage) makes the PV system and the electric vehicle companions in the struggle for a more sustainable energy supply and a clean environment. Also, the synergies in these mass markets would drive cost down and offer great business opportunities, both for car and PV manufacturers alike.

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Rik W. De Doncker received his Ph.D. degree in electrical engineering from the K.U.Leuven, Belgium in 1986.

In 1987, he was appointed Visiting Assoc. Professor at the Univ. of Wisconsin, Madison, where he lectured and conducted research on induction motor drives, soft-switching converters and DC-to-DC converters for the NASA space station. In 1988, he was a General Electric Company Fellow at IMEC, Leuven, Belgium. Dec. 1988, he joined the General Electric Company Corporate R&D Center, Schenectady, NY, where he led research on drives and high-power soft-switching converters for aerospace, industrial, and traction applications. In Nov. 1994, he joined Silicon Power Corporation as Vice President, Technology. He worked on high-power converter systems and MTO devices and was responsible for the development and production of a 15-kV medium-voltage static transfer switch.

Since October 1996, he has been a professor at Aachen University of Technology, Aachen, Germany, where he leads the Institute for Power Electronics and Electrical Drives. In Oct. 2006 he was appointed director of the E.ON Energy Research Center at RWTH Aachen University, where he leads the Institute for Power Generation and Storage Systems.

He has published over 200 technical papers and is holder of 25 patents. He is member of the Board of the German engineering Society VDE-ETG. He is an IEEE Fellow and is past president of the IEEE Power Electronics Society (PELS). He is member of the EPE Executive Council. He was founding Chairman of the German IEEE IAS-PELS Joint Chapter. Dr. De Doncker is recipient of the IEEE IAS Outstanding Achievements Award and the IEEE Power Engineering Custom Power Award (2008). In 2009, he led a VDE/ETG Task Force on Electric Vehicles. In 2010, he received a Doctor Honoris Causa Degree of the Technical University of Riga, Latvia. Currently, he is active member of the German National Platform for Electro-mobility.