BMW Group Innovation Days 2010.
Mobility of the future.
Contents.

1. Why electromobility?

In this day and age we see our society, and with it the sphere of individual mobility, confronted by growing challenges. More and more factors are influencing the implications of individual and corporate action. The world is in a state of environmental, economic and social upheaval. But which changes should we be focusing our attention on and how can we respond to them?

Climate change and global warming.

Climate change and the global warming that comes with it are facts. The decade from 2000 to 2009 was certainly the warmest ever recorded, yet the worldwide efforts to counteract this are greater than ever too. A further rise in the average temperature would bring with it a multitude of far-reaching consequences, including the faster melting of glaciers, a rise in sea level, changing precipitation patterns and greater extremes in weather. One cause of the steadily rising average temperature lies in the intensification of the natural greenhouse effect due to human action. The burning of fossil fuels, in particular, creates carbon dioxide gas (CO_2), which is harmful to the climate and further exacerbates the greenhouse effect, thus accelerating global warming. In order to slow down climate change and possibly even halt it, the most important challenge is therefore to reduce CO_2 emissions significantly and quickly. Possible ways of doing this include a switch from fossil fuels to renewable energy sources, as well as increasing the efficiency of all energy consumption.

Growing scarcity of resources.

In addition to the changes in our climate, the entire planet is affected most of all by the looming shortage of resources. Key raw materials such as petroleum and precious metals are not in unlimited supply, yet day-to-day demand is rising. One of the causes of dwindling resources lies in the increasing industrialisation of the emerging nations. But population growth, rising living standards and the irresponsible use of raw materials are also contributing to this trend. The upshot: prices are rising in almost every commodity sector. In the foreseeable future – the exact point in time is disputed – the maximum global limit of oil extraction (“peak oil”) will be reached. From that point onward the gulf between supply and demand will grow ever wider and it will not be possible to meet all needs. That is why the quest for alternatives to oil is already proceeding at full throttle.

Sustainability as a social trend.
Because of the dramatic escalation of climatic developments and dwindling resources, mankind is becoming ever more aware of its role in the ecological system. Many people have already got the message: they see themselves as part of a universal system and want to behave in a considered and responsible way – especially with future generations in mind – by adopting a sustainable lifestyle. However, "sustainable" means more than just "environmentally friendly". As generally understood, the term "sustainability" has three aspects: an environmental, an economic and a social one. Environmental sustainability describes the goal of preserving nature and the environment for future generations, that is to say, using resources responsibly. Economic sustainability requires economic behaviour that offers a robust and lasting foundation for commerce, employment and prosperity. Social sustainability means the development of society to ensure the involvement of every member of a community. As one of the first companies to do so, the BMW Group has already signed up for sustainability in all its three aspects with a view to creating added value for the company, for the environment and for society.

The fact that in business, too, sustainability is perceived as ever more important is reflected in tools like the Dow Jones Sustainability Index. Such share indices not only evaluate companies according to economic criteria, but also take account of ecological and social aspects. In this context the BMW Group has been the leader in its sector for the past five years.

Increasing urbanisation – cities require new solutions for mobility.
A further observable trend is increasing urbanisation. More and more people are moving from the country to the city, villages are evolving into towns, the boundaries between town and country are breaking down and large conurbations are being created. Since 2007, more than half the world's population has come to live in towns. According to UN forecasts, the proportion of the world population living in towns and cities will rise to 60% by 2030, and in 2050 it will reach 70%. Even today there are more than 130 cities throughout the world with over 3 million inhabitants.

One particular side effect of urbanisation is the emergence of so-called "megacities". Depending on the definition, the term "megacity" or "mega-urban area" is used to describe cities with at least 8 million inhabitants. Worldwide there are now more than 30 of these vast agglomerations, with a total population of some 280 million. While these cities are growing ever faster, so also are challenges such as overcrowding and pollution. Yet not all megacities are alike: Shanghai, London, Los Angeles and Tokyo are certainly megacities by definition, but they differ greatly in their transport infrastructure as well as in their citizens' demands for personal mobility. The influence of growth on the urban infrastructure varies from city to city.

Legislation reflects the changing environment.
The governments of various countries are also taking action as a consequence of climate change and declining resources. They are attempting to combat rising CO_2 emissions with the introduction of certification for zero-emission vehicles, restrictions on road access and ambitious fleet legislation. The USA, Europe, China and Japan, for example, are calling for a reduction in total vehicle emissions of up to 30% by 2020 as compared with 2008.

The response of the BMW Group.
Mobility of the future requires a new balance between global requirements and individual needs. What is needed are new solutions for personal mobility in urban areas. They should be recognisably sustainable and, as far as possible, unencumbered by restrictions, while at the same time offering the possibility of differentiation. In all this, the reduction of fuel consumption and emissions will become increasingly important. The BMW Group has recognised these needs and has set itself the goal of making zero-emission mobility possible. With that in mind, the BMW Group is developing a vehicle that opens up new possibilities in this area and can adapt to evolving customer needs.

"In the future there will still be a need for individual mobility. Customers will always want to decide for themselves when, where and how they will travel. But they will want to do this in the most environmentally friendly way possible. And the desire to be different from others will still be there – for instance, a wish to stand out from the crowd by owning premium products." (Peter Ratz)

E-mobility – sustainable solution and stable trend.

The BMW Group sees electromobility as one possible way of meeting future demand for personal mobility. Here, one great advantage lies in zero local emissions. Since e-mobility involves electric current rather than fuel being converted into propulsion, no climate-harming gases are created during the journey. If the energy to drive the vehicle is obtained from a renewable source, e.g. from wind or water power, e-mobility is climate-neutral and conserves natural resources, since even in generating the energy needed, no CO_2 reaches the environment. On the one hand, electric vehicles contribute in this way to reducing emissions and improving the quality of life in big cities. On the other hand, e-mobility thus meets the growing customer need to act in a holistic, ecologically sustainable and environmentally friendly manner.

"Electromobility allows people to be individually mobile without polluting the environment with harmful emissions." (Martin Arlt)

Power, torque and comfort – joy is e-mobility.

Yet electromobility is not just emission-free, it also offers a unique and exciting driving experience. It is not just that electric vehicles move almost noiselessly. In EVs, the entire torque of the electric motor is available from a standing start, which makes the car extremely agile and provides a high fun factor. Moreover, an EV accelerates right up to maximum speed without interruption.

"All our test customers assure us that electromobility is simply great fun." (Ulrich Kranz)

There is another unusual feature about driving with an electric engine. If you take your foot off the throttle, the car does not simply run on, but actively decelerates. The throttle pedal thus becomes a "driving pedal" and, especially at a moderate and slightly varying speed, makes for an extremely comfortable drive. This means that, in town traffic, some 75% of all deceleration manoeuvres can be handled without activating the brake pedal. The deceleration torque is also exploited as a means of generating energy, in a process called recuperation. As soon as the driver takes his foot off the throttle, the electric motor becomes a generator, the kinetic energy being converted into current and fed back into the vehicle's battery. In this way as much as 20% of the energy consumed can be recycled.

What are the limits of e-mobility?

Electromobility is just at the beginning of its development, and consequently further innovation work still needs to be done in certain areas. The greatest challenge is clearly the development of the energy storage system. Due to its specific properties with regard to energy density and weight, this is currently the limiting factor of e-mobility.

Energy density and weight of the energy storage system.

Up to now a battery has only been able to store a limited amount of energy as the energy density of the cell complex is comparatively low. Currently the energy storage device in an electric vehicle contains approximately the energy equivalent of two to three litres of fuel. However, the high efficiency of an electric motor partly compensates for this. For while a combustion engine can convert a maximum of 40% of the energy in the fuel, the electric motor uses as much as 96% of the available energy. Thus an electric motor can take you significantly further on less energy. Admittedly, the range of an electric vehicle today is still not comparable with that of a combustion engine; but the development of mobile energy storage systems for vehicles is only just beginning, which makes it likely that significantly expanded research efforts over the next few years will lead to further leaps in technology. In future, then, energy storage devices may not only become significantly cheaper, but also lighter and more compact, while at the same time delivering higher energy density.

Along with energy density, the weight of the energy storage component is the second factor that restricts range. In principle it is true that the lighter the vehicle, the greater the range for a given battery capacity. However, due to the low energy density, a battery to drive a road vehicle is approximately the size of a large suitcase as well as being very heavy. Although the range can be increased through higher battery capacity, that makes the battery even heavier, which would cancel out part of the extra range thus gained. The task, therefore, is to find the optimum relationship between the weight and thus the capacity of the energy storage system, and to further increase the range through such measures as systematic lightweight construction and intelligent strategies for battery charging and usage. Work is also being targeted at significantly slashing the recharging time through rapid charging. At the moment several hours, and thus idle time, are still needed to fully charge an EV.

“We are very aware of the limits of electromobility, but that doesn’t prevent us from pushing the envelope step by step, day by day.” (Martin Arlt)

The development engineers in the BMW Group have recognised the areas in electromobility that remain to be improved and are working intensively on optimal, customer-friendly solutions. In this context the BMW Group is running extensive pilot projects in Germany, the United Kingdom and the USA in order to obtain valuable information about the use and operation of e-vehicles and to make them even better suited to customer needs. As the first results of the MINI E trials show, the BMW Group is on the right track.

The BMW Group is pursuing a holistic, future-proof approach.
Electromobility is an integral component of EfficientDynamics. With this strategy, the BMW Group has for some time now been very successful in reducing consumption and emissions through new generations of highly efficient engines, aerodynamic measures, the use of innovative lightweight construction and intelligent energy management in the vehicle – while at the same time achieving better performance. That is what made it possible, between 1995 and 2009, to reduce the CO_2 emissions of the entire BMW vehicle fleet by almost one third. Even today, through EfficientDynamics, the BMW Group is achieving additional consumption benefits through further electrification of the powertrain, right up to hybridisation. Taking the long view, EfficientDynamics means the transition to emission-free mobility – through the use of battery power as well as renewably generated hydrogen.

“In the long term, mobility will be based on forms of energy derived exclusively from renewable sources. Resources are too valuable to be squandered.” (Peter Ratz)

Sustainability in the BMW Group.
Considering the product in isolation, however, is not enough for the BMW Group. Having affirmed its leadership claim with EfficentDynamics, the BMW Group intends to do the same in terms of sustainability across the entire value creation chain. That is why the BMW Group’s sustainability strategy not only commits the company to further development of efficient

drivetrain technologies and to the implementation of concepts for sustainable mobility in conurbations. In addition to that, under the Clean Production philosophy, consumption of resources and pressure on the environment must continue to be reduced in the production process as well. And as part of society, the company is committed to meeting social challenges – with the aim of actively collaborating in shaping the context for independent action inside and outside the company.

“Throughout the company we are convinced that, in future, premium mobility in particular will be defined to a far greater extent than before by its sustainability credentials. People who think ‘premium’ will in future naturally also mean sustainability.” (Martin Arlt)

BMW is systematically aligning its processes and structures to electromobility.

In order to pass on the company DNA to electric vehicles as well, the BMW Group places great value on the development and design of the defining attributes of an electric vehicle. When it comes to the energy storage system the development engineers are applying effective storage management, intelligent operating strategies and optimal temperature control in their attempt to extract the maximum performance and range from the cells. The highly efficient drivetrain is also an in-house development, as the BMW Group wants to lay claim to building the best automotive power units in the future as well, units which set themselves apart from the competition through efficiency and power delivery – even when current instead of fuel is converted into motion.

“The BMW Group embodies engine building competence in its name. And that will remain so in the future.” (Patrick Müller)

In other areas the BMW Group is developing its know-how with experienced partners. Whether it is with SB LiMotive in the field of power cell development or with SGL Automotive Carbon Fibers (SGL Group) in the development and production of carbon fibres and carbon fibre sheets, the engineers are jointly honing valuable skills with which to drive forward personal mobility in the future too. For example, as part of the joint venture with SGL Automotive Carbon Fibers (SGL Group), an ultra-modern, renewably powered carbon fibre production plant is being built at Moses Lake, USA, so that the material can be manufactured under the best possible conditions and processed economically.

The Megacity Vehicle – sustainable mobility in urban surroundings.
The Megacity Vehicle (MCV) demonstrates one way in which the BMW Group envisages future mobility in urban surroundings. As an example of "purpose design", the MCV is systematically designed with the needs and demands of e-mobility in mind. For as shown by the earlier development work on the MINI E and BMW ActiveE concept vehicle, the adaptation of a vehicle originally designed to be driven by a combustion engine (conversion vehicle) does not exploit the full potential of electric mobility. That is why the MCV integrates the newly developed drive components into a completely new vehicle architecture. The systematic application of lightweight construction and innovative use of CFRP (carbon fibre-reinforced plastics) complete the elaborately worked-out vehicle concept.

BMW took its first steps in the direction of electric drive as early as 1969 with an electrified BMW 1602. Over the last 40 years, with various prototypes and test set-ups, the BMW Group has been assembling valuable expertise on this alternative drive system and has repeatedly examined potential opportunities for putting it into practice. One such trial was with the BMW E1, an experimental vehicle which, as early as 1991, displayed many of the features of modern electric vehicles and which was used to explore the benefits and disadvantages of this form of power in practical operation. However, it was not until the advent of lithium-ion technology that real prospects of series development opened up, since this matched the requisite demands for cycle stability and load resistance and had already proved itself repeatedly in a variety of applications. The BMW Group acted swiftly and was able at an early stage to convert its know-how into a marketable product – the MINI E. This important milestone for the BMW Group in the development of e-mobility has already been on the road since mid-2009. And with more than 600 MINI E models, the BMW Group is today running one of the largest fleets of electric vehicles in customer hands. The first results of the trials clearly show that e-mobility is already fit for everyday use.

"The time is ripe for electric vehicles." (Patrick Müller)

BMW thinks beyond the product.

Electromobility also opens up completely new possibilities around the vehicle itself. Various services relating to the recharging of the EV are conceivable. For example, the BMW Group is already collaborating with energy suppliers to facilitate rapid and flexible access to “green” electricity. Intelligent charge control methods and remotely operated recharging are further possible ways of making e-mobility even more customer-friendly. That is why the BMW Group and its partners are trialling so-called “smart charging”. With this counter-cyclical recharging strategy the electric vehicle is only charged when overall demand for electricity is low or when renewable energy is available – for example overnight. To do this, the owner simply states the latest time by which the vehicle has to be recharged. Then, according to preference, the vehicle can be charged in a particularly environmentally friendly way or particularly fast. In the long term, ideas exist for making e-vehicles an element of energy supply and, for example, using them as storage buffers.

In future the BMW Group will encompass individual mobility in even wider terms. Since increasing urbanisation is progressively changing the ground rules for mobility, the BMW Group is also thinking about mobility services in which the intermodal links between different forms of transport play a key role.

2. project i

Based on its review of current social and environmental trends (ch. 1), in mid-2007 the BMW Group presented a new strategic roadmap for the company – the “Number One” strategy. This strategy makes a firm commitment to profitability, sustainable value creation and safeguarding the company’s independence. As well as growing the company’s core business, the aim is also to develop new profitable business lines across the entire automobile life cycle and value chain. At the same time, the BMW Group has resolved to invest substantial amounts in technologies of the future, new vehicle concepts and pioneering drive systems. The aim is clear: to maintain the BMW Group’s position as the leading supplier of premium products and premium services for personal mobility.

The new corporate strategy is based on a wide-ranging qualitative review of society’s aspirations in the field of mobility and also of the potential shape of future technologies, trends and challenges in this field – particularly in the context of climate and demographic trends. One of the company’s answers to these issues is project i.

“project i is the BMW Group’s response to the future challenges in the field of personal mobility.” (Martin Arlt)

project i: the mission.
project i, launched in late 2007, is an initiative to develop sustainable and pioneering mobility concepts. There must also be a collateral transfer of know-how from this project to the company as a whole and to future vehicle projects. The long-term goal of project i is to bring fresh thinking to the company’s technologies, processes and vehicle concepts, whether in production, development or sales. The concrete mission is to develop new, pioneering products geared closely to future challenges and customer requirements in the field of urban mobility.

The approach.
But how best to implement this mission? Ultimately, what is required is

not just new processes and technologies but a complete critical reappraisal of automobile design as we know it. That is why project i transcends existing structures and brings together in a single unit experts and "outside-the-box" thinkers from throughout the company. This small but efficient and dynamic organisational unit is tasked with defining the aims and requirements for sustainable mobility solutions of tomorrow and aligning them with future customer requirements. To help this team shed all constraints and preconceptions, the project is not brand-specific. This allows the think tank to take an unconventional and independent approach, yet at the same time to work with the full support of experts drawn from the entire company. In a culture of open and transparent knowledge-sharing, project i leverages expertise from all parts of the company.

"It's a great experience for me to be able to work in a project like this, with colleagues who are all on a similar wavelength. From the start, we were given every freedom we needed. The result was a mood, an atmosphere you would normally only encounter in a start-up company." (Peter Ratz)

A new departure.

But the BMW Group development engineers who embarked on project i two and a half years ago were not starting completely from scratch. Their point of departure was the intensive research which the company had already undertaken into mobility issues and future customer requirements, with the aim of identifying new development potential for the BMW Group. And although the project i research work is carried out not just with reference to vehicles but in the wider context of integrated mobility solutions as a whole, it quickly became clear that the first milestone in the project would be a car, one that would combine maximum eco-friendliness – i.e. zero-emission operation – with a clear focus on modern urban mobility requirements. This vehicle has a name: the "Megacity Vehicle" (MCV).

The overall project goal is maximum sustainability. From the production process, starting with the first supplier, through to component recycling at the end of the vehicle life cycle, sustainability based on the three cornerstones of eco-friendliness, economic efficiency (profitability) and social compatibility must be the main process driver. First of all, therefore, the developers scrutinised all processes and components in the value chain. They verified whether existing processes were adequate to meet the project's high sustainability ambitions or whether some areas of the chain were in need of optimisation or redesign. The outcome of this assessment formed the starting point for developing the Megacity Vehicle.

“We wanted to get a clearer picture of what future mobility will look like and, based on that, to develop sustainable mobility concepts specifically for urban application. Also, we wanted this sustainability to extend to the entire process, from development of the product, through its useful life, to component recycling or reuse.” (Peter Ratz)

The result.
The project has made the most of all available freedoms and all scope for “pushing the envelope”. The result is an integrated and sustainable mobility concept – the Megacity Vehicle (MCV). The MCV represents the BMW Group’s vision of one possible concept for a sustainable city car. It is designed mainly for urban operation and combines dynamism with comfort and sustainability. With the newly developed electric drivetrain (ch. 3), the revolutionary “LifeDrive” body concept and the innovative use of CFRP in the passenger cell (ch. 4), it is a solution for confident, safe and convenient urban driving which is also completely emission-free.

The MCV was developed from an integrated, comprehensive perspective that necessitates certain fundamental process changes. Due to the new powertrain and vehicle architecture, and the use of innovative materials, certain production processes are entirely new. To meet these novel requirements, the BMW Group is lining up new, high-grade expertise, jointly developed with strong partners like SB LiMotive (battery cell development) and SGL Automotive Carbon Fibers (carbon fibre and carbon fibre fabrics manufacturing).

“The technologies developed by the BMW Group for project i offer enormous potential for ensuring ecological and economic sustainability.” (Martin Arlt)

But although the principle of sustainability underpins every stage in the process chain, the BMW Group never focuses solely on eco-friendliness and resource efficiency to the exclusion of all else. Its products must also be economically sustainable, as well as profitable.

MINI E – pioneering new ground in electric mobility.

The success story known as project i began to take more concrete shape in spring 2008 with the MINI E. It was also around this time that the project first came to the notice of a wider public. As the BMW Group's first e-mobility enabling project, the MINI E not only set new technical standards; with an average driving range of 150 kilometres in everyday operation and maximum power of 204 hp, it also pioneered new ground as part of the BMW Group's alternative drive development programme and as a step on the way to future CO_2-free mobility.

One of the first aims of the MINI E project was to release vehicles for customer trials as soon as possible in order to gain valuable feedback from users about the performance of electric vehicles in day-to-day operation. Since mid-2009, therefore, selected customers have been taking part in large-scale MINI E field trials in Germany, the USA and the United Kingdom. In two intensive testing phases, limited-production MINI E models are supplying important information about driving patterns and vehicle operating performance, all of which is being incorporated into the ongoing development and refinement of the MCV. Comprising more than 600 MINI E vehicles, the BMW Group's EV customer test fleet is one of the largest in the world.

The MINI E on the road.

In all three countries where trials are taking place, the BMW Group is working, often closely, with local energy companies, universities and governments. The MINI project is not just about giving users the opportunity to experience a completely new style of personal mobility, it is also about getting together with partners to shape some of the infrastructure. For example, the energy companies can enable users to run their vehicle on "green", renewable electricity, if the customer so wishes.

MINI E driving patterns study, Berlin – electric mobility is suitable for everyday use.

Although the trials are still in full flow, initial results from Berlin are extremely encouraging. In a pre-trial survey, the pilot users said they expected to find the vehicle's operating range and recharging times restricting. In practice, however, only in a few cases were these fears actually borne out. The Berlin study showed that more than 90% of participants did not find that the average 150-kilometre driving range restricted their customary mobility patterns in any way. Nor did they find the charging times a constraint.

Driving patterns for the MINI E users proved to be only marginally different from the driving patterns of comparable MINI Cooper and BMW 116i users. Average trip distance differed between BMW 116i, MINI Cooper and MINI E users by only two kilometres. Total daily mileage was also similar for all three vehicles, standing at 37.8 kilometres for the MINI E (slightly above the urban average for Germany as a whole), 42 kilometres for the BMW 116i and 43.5 kilometres for the MINI Cooper. The longest single trip to date by a MINI E customer was 158 kilometres. Nevertheless, a comparison with the typical driving patterns for the BMW 5 Series also shows that an electric vehicle is not equally suitable for all types of mobility needs. Nor has this ever been claimed. Nevertheless, 66% of Berlin users rate the MINI E as equal to a conventional vehicle on flexibility.

As far as recharging is concerned, it is becoming clear that, as regards public infrastructure, users' first preference is for charging points near to the workplace, in public parking garages, at major traffic hubs such as railway stations and airports, and in shopping centres. The most popular recharging option overall, however, is a home charging point, which is already sufficient to meet day-to-day driving needs. The option of recharging with renewable electricity provided by project partners Vattenfall Europe met with a great deal of interest. This indicates that users view the electric vehicle as part of a wider system which includes not only the vehicle, but also the recharging infrastructure and the origin of the energy used, and that they want to make responsible behaviour choices within that overall framework.

MINI E in the USA – more driving enjoyment, with zero emissions.
Customer field trials with the MINI E are under way in the USA too. Trials with the large 450-vehicle fleet in the USA were monitored by the BMW Group in a special research collaboration with the University of California (UC Davis). This study closely examined the MINI E's practicality for ordinary, everyday driving and again sought to shed more light on driving patterns.

The results confirm the positive feedback already obtained in Berlin. In the USA, too, the MINI E fully meets the mobility needs of pilot users. The range of 100 miles (approx. 160 km) is perfectly adequate for their daily driving needs. In the USA, the average total daily mileage quoted by the MINI E drivers was approximately 30 miles (48 km), which compares with average daily car use of 40 miles (approx. 64 km) for US drivers as a whole.

Home charging was not a problem for users in the USA either. Half of users routinely charged their vehicle on a daily basis, even if this was not actually necessary. As a result, they rarely needed to recharge the vehicle anywhere but in their own garage.

The MINI E also scored high on driving enjoyment. All drivers agreed that it demanded no concessions in this regard. The pilot users quickly got used to the new driving feel and many even went so far as to say that when they changed back to their own car, they found it a less satisfying drive. This is also reflected in the frequency of usage. A third of users said they actually clocked up a higher mileage in the MINI E than in the vehicle it replaced.

Conclusions from the studies.
The results from Berlin and California demonstrate that the BMW Group is on the right course. There were only a few trips that the pilot users could not perform with the MINI E. The reasons most frequently cited for this in the USA, as in Germany, were limited luggage and passenger capacity. The study data shows that, with a slightly longer driving range and more space, a Megacity Vehicle would meet virtually 100% of city dwellers' driving needs. The BMW Group is already pulling out all the stops to make the necessary changes.

BMW ActiveE concept vehicle – the next step.
The BMW ActiveE concept vehicle is a logical continuation of the research and development work on electric mobility being carried out by the BMW Group under project i. Based on the BMW ActiveE concept, which was unveiled in December 2009, the BMW Group will release a second electric vehicle fleet for customer testing in 2011. The aim of this field trial will be to acquire further knowledge about how well electric vehicles can meet everyday driving needs, and to gain more feedback on what customers want from their vehicle.

Whereas in the MINI E interior space was relatively limited, the BMW ActiveE concept vehicle provides four full-sized seats and boot capacity of approximately 200 litres, thanks to improved integration of the electric drivetrain components. The electric motor specially developed for this all-electric BMW has a rated output of 125 kW/170 hp and a rated torque of 250 Newton metres. Energy is supplied from the likewise all-new lithium-ion batteries, which give a driving range of approximately 160 kilometres (100 miles) in everyday use. The electric powertrain components are a pre-production test version of a powertrain designed for the MCV.

The BMW ActiveE concept vehicle also presents new BMW ConnectedDrive services developed specially for electric vehicles. They include mobile phone-based functions such as battery status checking, charging station location and remote activation of the auxiliary heating and air conditioning.

The Megacity Vehicle – the BMW Group's first electrically powered production car.

With the Megacity Vehicle (MCV), the BMW Group will offer an innovative solution for sustainable urban mobility which will be brought onto the market by 2013 and sold under a BMW sub-brand. As the development work on the MINI E and BMW ActiveE concept vehicle confirms, any approach that simply converts an existing internal combustion-engined vehicle to run on electric drive (conversion car) cannot hope to harness the full potential of electric drive. The MCV is therefore designed uncompromisingly and specifically around the needs and requirements of electric mobility. The MCV has a newly developed drivetrain (ch. 3) and a revolutionary vehicle architecture (LifeDrive, ch. 4) that combines rigorous lightweight design with optimal space efficiency and maximum crash safety. Since the compact electric drivetrain creates opportunities for new interior configuration options and functionality, as well as greater design freedoms, the MCV will also appeal to a new clientele.

3. The electric drivetrain.

Up to now, driving a car has always meant having a combustion engine for company. However, changes in the environment and within society have shown that using fossil fuels across all areas of daily life comes at an ecological cost. And, of course, the fuels themselves will not be available indefinitely. The BMW Group views vigorously driving forward the technical development of electromobility as a way of combating these issues. But what does the term "e-mobility" actually represent? How does an electric drive system differ from a combustion engine? What is the potential of this technology? And what are the challenges the development engineers still need to overcome?

Emission-free and dynamic – the new generation of propulsion systems.

Powering vehicles solely using electric power opens up totally new avenues in mobility. As an electric motor emits no environmentally damaging gases, the use of electric energy offers a zero-local-emission and therefore eco-friendly route to mobility. The use of renewable energies, meanwhile, allows the energy generation process to be completely emission-free as well. Added to which, e-mobility also delivers a totally new and extremely agile driving experience. A new-generation BMW Group electric motor boasts impressive performance characteristics and quickly removes any associations with niche electric vehicles of the recent past. Only the absence of engine noise will remind you that you're driving an electrically powered vehicle.

"The power development of an electric vehicle is almost like that of a light switch: you get full power the moment you switch it on." (Hans-Jürgen Branz)

The BMW Group designs leading-edge electric drive systems, such as the unit for the Megacity Vehicle (MCV), that generate well over 100 kW. But their stand-out attribute is that the driver can already use the motor's full output when pulling away – rather than having to wait for the power to build up through the engine revs, as with combustion engines. The differentials, slip control systems and gear assembly ensure that every ounce of the motor's torque is transferred to the road. The ability to drum up peak torque from a standstill imbues electric vehicles with an exceptional level of agility and provides eye-catching acceleration. The rear-wheel drive of the Megacity Vehicle provides the perfect complement to the performance of the electric motor. Dynamic wheel load transfer allows more weight to be placed on the driven wheels when moving off, enabling better traction and power transfer. The electric motor's impressive torque and rear-wheel drive therefore combine to deliver the driving dynamics for which the BMW Group is renowned.

The BMW Group is also aiming to be the force behind the best drive systems over the years ahead – drive systems whose efficiency, performance and smoothness set them apart from the competition, even if it is electricity rather than fossil fuels that are converted into propulsion. To this end, the BMW Group is vigorously driving forward technical developments in the field of electromobility. The BMW Group's "electric power station", its centre of expertise for electric drive systems, brings together development, manufacturing and procurement specialists under one roof. All their efforts are focused on the development and implementation of the new generation of drive systems.

Accelerating without changing gear.
Electric motors operate over a far wider rev band than combustion engines, routinely exceeding the 12,000 rpm mark. This means that electric motors also take a different route to reaching their top speed. The impressive torque of an electric vehicle allows it to accelerate more quickly than a model of comparable output powered by a combustion engine, and the high usable rev band also enables uninterrupted torque delivery across the full rev range. The output of the motor is fed through just a single gear ratio directly to the wheels; there is no need for a multi-speed transmission. All of which means that an electric vehicle sprints from standstill to its top speed in just a single gear. This uninterrupted flow of forward propulsion with steadily increasing revs is a very special experience, one which a combustion engine has so far only been able to deliver through highly sophisticated engineering measures, such as dual-clutch gearboxes.

"Electromobility is by no means a disclaimer on wheels. Electric vehicles are genuinely enjoyable." (Patrick Müller)

Having said that, the engineers have chosen not to fully exploit the theoretical top speed of the Megacity Vehicle. Since the MCV will be used primarily in cities and surrounding areas, a maximum of 150 km/h is more than sufficient. Higher speeds would be possible, but not necessarily of discernible benefit. Driving at high speeds uses up very large quantities of energy and, as the vehicle's speed rises, so – exponentially – does aerodynamic drag, which also pushes up energy consumption. As the battery's storage capacity only delivers a restricted amount of energy, unnecessarily high speeds would eat into the vehicle's range significantly. Furthermore, a different gear ratio would be required to reach a higher end speed, and this would considerably reduce the vehicle's agility in urban traffic. Another way of increasing top speed would be to fit a multi-speed transmission, but that would entail a notably more complex construction, as well as a considerable increase in packaging space and weight.

Braking with the accelerator.

Another attribute of electric vehicles which adds to their very distinctive driving experience is the ability to brake using the accelerator pedal, making it effectively a "driving pedal". If the driver takes his foot off the accelerator, the vehicle does not continue to coast, but actively brakes. This deceleration force is harnessed for energy recuperation. Under braking the electric motor takes on the role of a generator, producing energy and charging the battery. The underlying principle is similar to that of the Brake Energy Regeneration technology in the EfficientDynamics package, although in the electric vehicle the recuperated energy can be converted directly into propulsion. Extensive use of the motor's energy recuperation function increases the range of the vehicle by as much as 20%. The "driving pedal" also allows relaxing driving with less frequent footwork. Moreover, it enables quick reactions and is therefore particularly well suited to "going with the flow" in city traffic. Here, up to 75% of deceleration manoeuvres can be carried out without bringing the brake pedal into play.

Powerful and compact – the drive components.

A vehicle powered by an electric drive system offers more than just a rewarding driving experience. The electric motor also boasts a greater power density than a combustion engine – i.e. it generates the same power but takes up less space. For example, the entire drive system in the BMW

ActiveE concept vehicle (and, in due course, the MCV) is – minus the energy storage system – the size of two crates of beer. The compact drive assembly can therefore be integrated neatly into the vehicle architecture, with the added benefit that there is no additional drivetrain or complex air intake system to be fitted in. The smaller dimensions and significantly lower mass of the electric drive system reduce the amount of installation space required by up to 50% compared to a combustion engine and transmission. Passengers will be the main beneficiaries of this extra room in future vehicle concepts, thanks to the increase in interior spaciousness.

An electric drive system as a whole consists of several components – the electric motor, the power electronics, a gear assembly and the electric energy storage system – which combine to provide the vehicle with propulsion.

Electric heartbeat – the motor.
The electric drive system is the heartbeat of the electric motor. In simplified terms, the latest-generation electric motor from the BMW Group consists of a tubular stator fixed to the casing and a rotating cylinder inside the stator (the rotor). The rotor is connected to the gear assembly and therefore – through the gear assembly – to the driven wheels. Inside the stator are coils in which a magnetic field is generated through current flow. On the rotor, meanwhile, are one or several magnets with fixed polarity. The electric motor is activated by generating calculated attraction and repulsion forces between the rotor and stator by means of a moving magnetic field (rotating field). To achieve this effect, the system uses the attraction of the opposite poles of a magnet and the repulsion of two identical poles (north and south poles attract each other, two south poles or two north poles repel each other).

Switching on the current causes the south pole of the magnetic field generated in the stator to attract the north pole of the rotor magnet. However, before the north pole of the rotor reaches the south pole of the stator, the south pole is switched onto the next phase. As a result, the rotor also continues to turn and “chases” the alternating magnetic fields produced by the stator. Through its rotational movement the rotor transfers the mechanical energy required for propulsion. The speed with which the rotating field moves around the stator dictates the speed of the vehicle. Torque levels, meanwhile, are controlled by the number of magnets and the current strength: the greater the number of magnets on the rotor and the stronger the current, the more torque the electric drive system is able to generate.

The operating principle described here is for the type of permanently excited, three-phase synchronous motor to be used in the ActiveE concept and the MCV. In this type of synchronous unit, the rotor follows the rotating exciter field on the stator synchronously. In addition, magnets ensure that the magnetic field of the rotor is permanently excited and does not first have to be induced (externally generated). External generation would be significantly more complex, as it would require a second intervention to generate the magnetic field in the rotor. Permanently excited motors currently offer the optimum balance of complexity, function and the ability to meet driver requirements.

Electronics boost performance – the power electronics.
The fundamental ingredient in a functioning electric motor when it comes to providing optimum performance is the correct rotation of the magnetic field around the stator. In order to achieve revs of over 12,000 rpm, the magnetic fields in each phase have to be switched extremely quickly and precisely. This important task is carried out by a special power electronics control unit, which ensures the rotating field is switched at the desired speed and with the necessary field strength. In this way it ensures that the rotor spins at the required speed and delivers the desired torque.

The battery – the electric vehicle's "fuel tank".
An extremely strong electric current is required to drive the motor of an electric vehicle. Currents of up to 400 amperes are activated for each phase, which equates to roughly 25 times that of a domestic power outlet. At up to 400 volts, voltages are also almost double those of the conventional power supply of everyday devices. A package of newly developed lithium-ion storage cells is used to store this energy and make it available as required. This lithium-ion technology has already demonstrated its exceptionally high storage capacity and cycle life in a large number of applications – e.g. mobile phones and laptops. A single lithium-ion cell for automotive usage is roughly the size of a notebook and has a rated voltage of approximately 3.7 volts. The usable voltage range of a cell lies between 2.7 and 4.1 volts, so in order to create a high-voltage battery meeting the 400 volt requirement, around 100 of these cells are connected in series.

There are, though, one or two specific factors to bear in mind in the use of battery cells. For example, lithium-ion cells do not work in the same way in different temperatures. Indeed, only their optimum operating temperature of around 20 degrees Celsius will ensure that the car's maximum range is achievable. With this in mind, the temperature of the energy storage system is adjusted as required using additional heating elements and active cooling. Having said that, there is substantially greater scope in the usage temperature range of the cells for vehicles than might be familiar from other battery cells. Some laptop cells, for example, should not be charged at temperatures below zero, where the machine's performance would also be greatly diminished. While the cells used by the BMW Group do suffer from a drop-off in performance at low temperatures, a different composition of chemicals inside the battery means that this is much less pronounced. Preconditioning of the battery – during charging and as part of the need-based temperature control process while on the move – eliminates this potential drawback.

Safety is paramount.

The other main consideration in the development and design of the energy storage system concerned passenger safety. There is a certain risk potential inherent in the energy storage system, given the strong electric currents involved and the chemicals used (which react on contact with one other, possibly causing them to ignite). However, a host of measures are in place to eliminate the possibility of electric shock or the system catching fire. To start with, the compositions of chemicals used in battery cells for vehicles are much more "forgiving" than those in laptop batteries, for example. Plus, the vehicle body offers reliable protection for the battery modules to guard against damage in a crash. Meanwhile, coolant, sophisticated monitoring algorithms and on-board sensors ensure that the battery does not overheat when in use or during charging. Cut-off mechanisms secure the energy storage system against excessive discharge or overcharge, and measures have even been taken to ensure that there are no critical consequences should the energy storage system be pierced by metal objects.

The lifespan of a vehicle.

The BMW Group development engineers are currently working on ensuring that the capacity of the energy storage systems is maintained for as long as possible. Here, various factors need to be taken into consideration which can impact on the system's service life. A battery ages in two dimensions: in calendar terms – i.e. as it gets older its performance and maximum usable energy content declines – and in response to a range of other factors which affect the service life of a cell. For example, the depth of discharge or temperature at which the battery is used are important criteria which influence how long it can continue to operate. The validation tests conducted by the BMW Group ensure that the cells meet customer requirements in terms of both service life and what is known as "cycling potential" over the vehicle's entire lifespan. And, as far as sustainability is concerned, batteries which are no longer usable for a vehicle can be reused elsewhere. For example, although the battery capacity may no longer suffice to power a vehicle, it will still have enough left in it to serve as a stationary energy storage system for numerous other applications.

Challenges for the future.

The future of e-mobility lies in the ongoing development of energy storage systems. For this reason, the BMW development engineers are working intensively on ways of making them more compact and lighter, and at lower cost. However, the primary focus is on carrying as much energy as possible on board to give the vehicle a long range. The energy density of the energy storage system in the electric vehicle has not yet reached levels comparable with that of a full tank of fossil fuel. A high-voltage battery with 22 kWh contains energy equivalent to approximately 2.5 litres of premium unleaded petrol – and the distances possible in electric cars are currently much less as a result. Having said that, an electric motor has an efficiency level of up to 96%, much higher than a combustion engine, which is capable of 40% at best. So an electric vehicle with only this small amount of energy on board will take you much further than a similarly powered vehicle fitted with a combustion engine. This extraordinarily high level of efficiency means that the distances possible in an electric vehicle are already sufficient for many people in day-to-day use. The first wave of results from the usage studies with the MINI E show that 90% of the test users have been able to maintain full mobility with the range currently possible.

Range-extending measures.

But the central question remains: how can range be further extended? One possibility would be to increase battery capacity. The problem is that a larger battery would make the vehicle heavier, and that would limit range once again. Simply enlarging the battery on an open-ended basis is therefore not an option because from a certain point on, the extra weight of the battery cancels out the increase in range. Consequently, the BMW Group engineers are looking at ways of exploiting the available battery capacity as effectively as possible. The key here is to minimise the vehicle weight through the application of lightweight design principles wherever possible and the intelligent use of materials (see also ch. 4). In addition to this, the batteries are discharged as far as possible. The usage range of the BMW Group's battery cells is between 400 and 250 volts, which equates to around 85% of the available energy in the battery. Further discharge is not possible, as excessive discharge triggers chemical-physical processes which would damage the battery cells irreparably.

"We're using every kilowatt-hour produced by the battery extremely carefully. Our aim is to ensure that the system works as efficiently as possible." (Patrick Müller)

As well as the drive system of the vehicle, functions such as the lights, climate control and infotainment systems also need energy to work. While these auxiliary consumers barely register in a vehicle powered by a combustion engine, they have a very noticeable impact on the range of an electric vehicle. For example, in city driving a vehicle requires only about 2.5 kW on average for propulsion, whereas the air conditioning can use up to 5 kW under full loads. For this reason, the engineers are exploring ways of using intelligent charge control techniques and efficient operating strategies to reduce energy consumption as far as possible. This means that the temperature inside the vehicle can be adjusted while it is charging and the full capacity of the battery is therefore available almost exclusively for propulsion during the journey. A pleasant side-effect of this intelligent charging strategy is the comfort value of being able to get into a pleasantly cooled or heated vehicle, as the summer or winter weather demands. Two ways of increasing the range of the vehicle during a journey might be the deactivation of functions which are not required and the option of being able to let the vehicle "glide" at the right times (using the vehicle's own momentum to coast along without requiring the motor for propulsion). However, the development engineers see the longer-term future in the further development of energy storage systems to increase energy density.

Range extender – small engine, long range.

One particular approach to increasing a vehicle's range comes in the form of a "range extender" strategy. Here, a combustion engine produces electricity via a generator in order to charge the battery during a journey or maintain it at a constant charge. This could add a considerable distance to the vehicle's range. With a full-size electric motor already fitted, this combustion engine only needs to be relatively small. Studies show that, on average, output of 20 to 30 kW is ample for normal driving. A range extender of this size would therefore supply enough energy to fulfil the customer's driving requirements without burning unnecessary quantities of fossil fuels. The compact electric drive system components and new vehicle architectures would make the range extender easy to integrate.

Although a thoroughly conceivable short-term answer to the issue of increasing vehicle range, the range extender remains a compromise solution for the BMW Group. Looking further ahead, the BMW Group development engineers are focusing firmly on the further development of battery technology. The low energy density of the energy storage system – and, therefore, its lower range – combined with its relatively high weight remain limiting factors in e-mobility. However, with energy storage technology for vehicles gaining in momentum we can look forward to further significant advances in development.

"Over the next few years we can expect further leaps forward in development. Soon, smaller and lighter batteries will be capable of taking vehicles greater distances. We are currently midway through a process of development which still has much potential left to exploit." (Patrick Müller)

4. Lightweight design and the LifeDrive concept.

New body concepts to meet the challenges of a new mobility.
Powering a vehicle electrically means more than just replacing the combustion engine with an electric drive system. The electrification of a vehicle involves far-reaching revisions to the entire body, as the electric drive system components place very different demands on the packaging space in a vehicle. The development work on the MINI E and BMW ActiveE concept projects quickly showed that "conversion cars" – i.e. vehicles designed to be powered by combustion engines and subsequently converted to run on electric power – do not represent an optimum long-term solution when it comes to meeting the demands of e-mobility. As important as these vehicles have been in amassing knowledge on the usage and operation of EVs, the integration of an electric drive system into a "foreign" vehicle environment is not the best way of exploiting the potential of e-mobility. Conversion cars are comparatively heavy. Added to which, accommodating the big and heavy battery modules and special drive electronics is a complex job, as the structural underpinnings of the vehicles are based on a very different set of requirements.

A new body concept therefore had to be developed which carefully addressed the full gamut of technical peculiarities of an electric drive system and provided the ideal response to all safety-related considerations. So how does a functional and effective body construction for an electric vehicle shape up?

Lightweight design for electric vehicles.
A modern vehicle body has to be not only strong but, above all, light as well. When you're dealing with a vehicle powered by an electric drive system, lightweight design is particularly important because, alongside battery capacity, weight is the key limiting factor when it comes to the vehicle's range. The lighter a vehicle, the longer the distance it will be able to travel – simply because the electric drive system will have less mass to move. Under acceleration, in particular, every kilogram of extra weight makes itself clearly felt in the form of reduced range. And in the city – the main

hunting ground for an electric vehicle – the driver has to accelerate frequently due to the volume of traffic.

As well as a longer range, lower vehicle weight also makes for noticeably better performance. After all, a lightweight vehicle accelerates faster, is more nimble through corners and brakes to a standstill more quickly. Lightweight design therefore paves the way for greater driving pleasure, agility and safety. In addition, lower accelerated mass means that energy-absorbing crash structures can be scaled back, which in turn saves weight.

And so the task for the engineers is to keep the overall weight of an electric vehicle as low as possible from the outset. However, the fundamental aspects of an electric car's construction are anything but helpful in this regard. The drivetrain of an EV is far heavier than that of a vehicle with a combustion engine, full tank of fuel included; an electric drive system (including battery) weighs around 100 kg more. The battery is the chief culprit here. To cancel out the extra weight it brings to the vehicle, the BMW Group is working rigorously on the application of lightweight design principles and the use of innovative materials. By using the optimum material for each component, depending on the requirements and area of usage, the BMW Group engineers have succeeded in ensuring that the heavy battery barely carries any weight, so to speak.

"Lightweight materials are an important enabler in the drive towards electromobility, as they can even out the extra weight added by the energy storage system." (Bernhard Dressler)

Purpose design – the LifeDrive concept.
Lightweight design, however, is just one facet, albeit a very important one, of the development work which goes into modern body construction. The full electrification of a vehicle gave the BMW Group engineers the opportunity to completely rethink the vehicle architecture and to adapt it to the demands and realities of future mobility. With the LifeDrive concept they used purpose design to create a revolutionary body concept which is geared squarely to the vehicle's purpose and area of usage in the future and offers an innovative use of materials.

Similarly to vehicles built around a frame, the LifeDrive concept consists of two horizontally separated, independent modules. The Drive module –

the aluminium chassis – forms the solid foundation of the vehicle and integrates the battery, drive system and structural and basic crash functions into a single construction. Its partner, the Life module, consists primarily of a high-strength and extremely lightweight passenger cell made from carbon fibre-reinforced plastic, or CFRP for short. With this innovative concept the BMW Group adds a totally new dimension to the areas of lightweight design, vehicle architecture and crash safety.

“The LifeDrive concept links all the systems required to drive the vehicle with the realities and requirements of electromobility, and puts them into practice with a new approach – yet still in trademark BMW Group style.” (Uwe Gaedicke)

Drive module – the basis and solid foundation.

The Drive module brings together several functions within a lightweight and high-strength aluminium structure. This is the basic body, complete with the suspension, crash element, energy storage device and drive unit. Weighing around 250 kg and with dimensions similar to those of a child’s mattress, the energy storage system is the driving element of the integrative and functional design of the Drive module. The initial priority in the conception of the Drive module was therefore to integrate the battery – the largest and heaviest factor in the electric vehicle in terms of construction – into the vehicle structure so that it would be operationally reliable and safe in a crash.

The Drive module is divided into three areas. The central section houses the battery and surrounds it securely with powerful aluminium profiles. The two crash-active structures in the front and rear end provide the necessary crumple zone in the event of a front or rear-end impact. The Drive module is also where you will find the components of the electric drive unit and numerous suspension components. The electric drive system is, as a whole, much more compact than a comparable combustion engine, cleverly accommodating the electric motor, gear assembly, power electronics and axles within a small space.

Life module – CFRP enters a new dimension.

The LifeDrive concept is rounded off by the Life module, a passenger cell mounted on the load-bearing structure of the Drive module. The stand-out characteristic of the Life module is its construction mainly out of carbon fibre-reinforced plastic (CFRP). The selection of this high-tech material – on this scale – for a volume-produced vehicle is unprecedented, as the extensive use of CFRP has previously been thought of as too expensive and still not sufficiently flexible to work with and produce. However, with more than ten years of intensive research work and a programme of process optimisation under its belt, the BMW Group is the only carmaker with the manufacturing experience necessary to use CFRP in volume production. CFRP offers many advantages over steel; it is extremely strong, yet at the same time very light. Indeed, while it is at least as strong as steel, it is also around 50% lighter. Aluminium, by contrast, would save “only” 30% in weight terms over steel. This makes CFRP the lightest material that can be used in body construction without compromising safety.

The extensive use of this high-tech material makes the Life module extremely light and gives the car both a longer range and improved performance. Added to which, it also has clear benefits in terms of the car’s handling; the stiffness of the material makes the driving experience more direct, with even rapid steering movements executed with flawless precision. At the same time, CFRP enables a higher level of ride comfort, as the stiff body dampens energy inputs extremely effectively. As a result, unwanted vibrations on the move are eliminated: there are no rattles or shakes.

As well as being extremely lightweight, the Life module also opens up a whole new perspective on how a vehicle interior can be perceived and designed. The integration of all the drive components into the Drive module allows the removal of the transmission tunnel – through which the engine’s power was previously channelled to the rear wheels but which took up a lot of room in the interior. The Megacity Vehicle (MCV) therefore offers significantly more room for its occupants within the same wheelbase. This new structure also enables the integration of new functionalities, allows a new degree of freedom in the design of the vehicle architecture and therefore clears the way for the interior to be optimally adapted to the demands of urban mobility.

CFRP in body construction.
CFRP has a wealth of benefits as a material for a vehicle body. It is extremely corrosion-resistant and does not rust, giving it a far longer lifespan than metal. Complex corrosion protection measures are unnecessary and CFRP retains its integrity under all climatic conditions.

The secret of this extremely high-strength material lies in the carbon fibres. They are exceptionally tear-resistant longitudinally. The fibres are woven into lattice structures and embedded in a plastic matrix to create the carbon fibre/plastic composite material CFRP. In its dry, resin-free state CFRP can be worked almost like a textile, and as such allows a high degree of flexibility in how it is shaped. The composite only gains its rigid, final form after the resin injected into the lattice has hardened. This makes it at least as durable as steel, but it is much more lightweight.

The high tear resistance along the length of the fibres also allows CFRP components to be given a high-strength design by following their direction of loading. To this end, the fibres are arranged within the component according to their load characteristics. By overlaying the fibre alignment, components can also be strengthened against load in several different directions. In this way, the components can be given a significantly more efficient and effective design than is possible with any other material that is equally durable in all directions – such as metal. This, in turn, allows further reductions in terms of both material use and weight, leading to another new wave of savings potential. The lower accelerated mass in the event of a crash means that energy-absorbing structures can be scaled back, cutting the weight of the vehicle.

“CFRP allows you to build an extremely lightweight plastic body without having to make compromises in comfort and safety.” (Bernhard Dressler)

Lightweight design and safety – with CFRP, lighter also means safer.
In addition to lightweight design, passenger safety also played a major role in the development of the LifeDrive concept. The current impact stipulations for a vehicle body are extremely stringent and a wide range of different crash scenarios have to be taken into account. Generally speaking, this presents development engineers with serious challenges, especially as far as the use of new materials is concerned. However, the combination of aluminium in the Drive module and the CFRP passenger cell in the Life module exceeded all expectations – even in the initial testing phase – and clearly showed that lightweight design and safety are not a contradiction in terms.

"Lightweight design does not automatically mean 'unsafe' – quite the contrary, in fact: in some respects, the LifeDrive concept outperformed existing constructions in crash testing." (Nils Borchers)

Impressive rigidity, combined with its ability to absorb an enormous amount of energy, makes CFRP extremely damage-tolerant. Even at high impact speeds it displays barely any deformation. As in a Formula One cockpit, this exceptionally stiff material provides an extremely strong survival space. Furthermore, the body remains intact in a front or rear-on impact, and the doors still open without a problem after a crash.

Unbeatable protection in a side-on impact.
The ability of CFRP to absorb energy is truly extraordinary. Pole impacts and side-on collisions both highlight the impressive safety-enhancing properties of CFRP. Despite the heavy, in some cases concentrated forces, the material barely sustains a dent, and passengers enjoy unbeatable protection. All of which makes CFRP perfectly suited for use in a vehicle's flanks, where every centimetre of undamaged interior is invaluable.

"To demolish CFRP you need to apply extremely heavy forces and/or extremely heavy acceleration – significantly more than you'd think at first glance." (Bernhard Dressler)

However, there are limits to what CFRP can endure. If the forces applied go beyond the limits of the material's strength, the composite of fibres breaks up into its individual components in a controlled process.

The best of both worlds – combining aluminium and CFRP.
The new Drive module has also been carefully designed and structured with these exacting crash requirements in mind. Crash-active aluminium structures in the front and rear sections of the vehicle provide additional safety. In a front or rear-on collision, these absorb a large proportion of the energy generated. The battery, meanwhile, is mounted in the underbody section of the car to give it the best possible degree of protection. Statistically, this is the area that absorbs the least energy in the event of a crash, and the vehicle shows barely any deformation here as a result. Moreover, positioning the battery in the underbody allows the BMW Group development engineers to give the vehicle an ideal low centre of gravity, which makes it extremely agile and unlikely to roll over.

In a side-on collision the battery also benefits from the crash properties of the Life module, as it absorbs all the impact energy and stops it from reaching the energy storage system. The mixture of aluminium in the Drive module and CFRP in the Life module ensures that the battery also enjoys the best possible protection through the body sills.

“The Drive module is the safest form a battery can take.” (Hans-Jürgen Branz)

All in all, the high-strength CFRP passenger cell teams up with the intelligent distribution of forces in the LifeDrive module to lay the foundations for optimum occupant protection. And this allows the combination of materials in the LifeDrive module to provide better safety levels than a steel monocoque. Testing has shown how much potential there still is in CFRP and its use in combination with other materials. Indeed, in what are still only relatively early days, CFRP already outperforms other materials at a much more advanced stage of development.

Advantages of LifeDrive.
Purpose design allows the LifeDrive concept to integrate all the key features of e-mobility – such as the large and bulky battery and compact drive elements – into an impact-resistant structure. However, the advantages of the LifeDrive concept lie not only in the weight savings it allows, the longer range and improved performance characteristics this results in, and enhanced safety. It becomes evident how much more lies behind the LifeDrive concept when you consider not only the product itself but also the production processes associated with it. The LifeDrive principle allows it to meet all the demands placed on a sustainable product within a sustainable production chain.

The vehicle’s frame construction is extremely practicable when it comes to the production of moderate unit figures, while the use of parallel working processes ensures a high level of flexibility. The vehicle’s new architecture opens the door to totally new production processes which are both simpler and use less energy. For example, the horizontal separation of the modules allows the two elements to be manufactured separately before being put together virtually anywhere in the world in a straightforward assembly process.

“Development work over recent years has made it clear to me that the LifeDrive concept is currently the solution when it comes to meeting the full spectrum of requirements presented by electromobility, while at the same time making the best possible use of its inherent potential.” (Uwe Gaedicke)

5. CFRP – a material for the future.

The aerospace industry and the world of motorsport already rely heavily on carbon fibre-reinforced plastic (CFRP). This material has many advantages, which automotive engineers are increasingly exploiting wherever components need to combine high stress resistance with light weight, high stiffness and high strength. The experts at the Landshut Innovation and Technology Centre (LITZ) have been intensively investigating this high-tech material for over ten years. This long-running development work, and a successful transition into volume production, means the BMW Group now has know-how which is unrivalled in the motoring industry about processes, tools and manufacturing techniques. It has also achieved high levels of mass production. But what is so special about this material?

Incredibly light and as strong as steel.
Carbon fibre-reinforced plastic (CFRP) is a composite material consisting of carbon fibres surrounded by a plastic matrix (resin). Very few other materials can compare with CFRP, which exhibits a unique combination of positive properties. First and foremost, CFRP is extremely rigid and strong – yet at the same time extremely lightweight. For equivalent or even better functionality, CFRP is approximately 50% lighter than steel and 30% lighter than aluminium. It is also resistant to corrosion, acid and organic solvents, giving it a much longer useful life than metal. In addition, CFRP remains stable under all climatic conditions, showing very little change in shape even when exposed to large temperature fluctuations.

Light weight involves no compromises on safety.
The high rigidity of this material is also accompanied by excellent damping qualities and high impact strength. CFRP has remarkably good energy-absorbing capabilities, making it very damage-tolerant. As a result, body components made of CFRP are not only very light, they also demonstrate outstanding crash performance. In fact, CFRP is the lightest material that can be used in vehicle body manufacturing without concessions on safety.
That said, CFRP's stress tolerance is not unlimited. When its load

capabilities are exceeded, the fibre composite structure breaks down, in a controlled manner, into its individual components.

“The forces (or accelerations) needed to destroy CFRP are far higher than might be assumed.” (Bernhard Dressler)

The right strength in the right places.

The secret of this high-strength material lies in the carbon fibres. In contrast to quasi-isotropic metals like aluminium or steel, which have equal strength in all directions, CFRP is anisotropic. This gives it very high strength, like a rod, in one direction, namely along the tensile/compression axis. This is its key advantage. Since an individual component is never simultaneously exposed at all points to loads in all directions, this special quality means that the stress resistance of components can be optimally matched to the loads they will actually encounter in practice. As in nature, where bones or plants use thicker structures only where really necessary, so the BMW Group engineers likewise tailor the thickness and fibre alignment of CFRP components to meet actual requirements, varying the quantity of fibres used and aligning them in the direction or directions along which loads will be exerted in the future product. These precisely gauged component parameters also help to minimise weight.

“CFRP allows material to be used efficiently, combining optimal strength and functionality with minimal weight.” (Bernhard Dressler)

Using CFRP is more than simply a straight substitution, like using aluminium in place of steel. With its special properties, this high-tech material also opens the door to completely new approaches and design concepts. Electric mobility is a case in point, where CFRP offers great potential as a material for vehicle body components since its lightweight properties result in a higher power-to-weight ratio, and therefore an extended driving range. Provided that this material is properly understood, it can be strategically deployed to achieve vast improvements in a wide range of lightweight products.

“Lightweight design requires a proper understanding of the properties of CFRP.” (Jochen Töpker)

Technological expertise in the BMW Group.

There are a number of reasons why, in the past, use of CFRP was confined to small-batch or prototype production. For the most part, components using this still relatively new material were built by means of a manual, highly time-consuming production process. This resulted in high costs and lengthy cycle times, which posed a major obstacle to mass production. Then, in 2003, the BMW Group took the plunge and began volume production of CFRP components. It has been ramping up output ever since. Today the Landshut plant is even mass-producing roofs (for the BMW M3 and M6 models) and bumper supports (for the M6) in CFRP.

Thanks to intensive material and process engineering efforts over the past ten years, the BMW Group has built up a high level of expertise in CFRP-specific production processes, efficient tooling solutions and optimised cycle times. The BMW Group's CFRP specialists have steadily refined and automated the CFRP production process at the Landshut plant so that, for the first time, it is now possible to mass-produce CFRP body components cost-efficiently and to a high quality standard. The process engineers at the Landshut Innovation and Technology Centre (LITZ) have thereby removed one of the main hurdles to increased use of carbon fibre components in vehicle body manufacture. With these pioneering advances, the BMW Group is helping to ensure that CFRP's potential is even better utilised in the future.

State-of-the-art production in the BMW Group.
The still widespread production technique whereby prepregs – fibres pre-impregnated with resin – are processed and then cured in an autoclave (a kind of giant oven) is not compatible with mass production of automobiles. As early as 2003, the BMW Group therefore introduced a next-generation production system geared to high-quality volume production of CFRP parts. This state-of-the-art process has very short cycle times. What's more, it is not tied exclusively to the Landshut plant but could theoretically be used at any BMW plant in the world, subject to certain basic requirements. So how exactly does this BMW production process for CFRP components work?

From fibre to fabric.
The starting point for CFRP production is the so-called precursor. This thermoplastic polyacrylonitrile fibre is the raw material for carbon fibre manufacture. In a complex multi-stage process, conducted under varying temperature and pressure conditions, the various constituent elements of the fibre are removed one by one, by gasification, eventually leaving a fibre that consists of virtually pure carbon, with a stable graphite structure. The

resulting carbon fibres are just seven microns (0.007 millimetres) thick. A human hair, by comparison, has a diameter of 50 microns. For automotive application, approximately 50,000 of these individual filaments are bundled into so-called rovings or heavy tows and wound, prior to further processing. In addition to automotive applications, fibre bundles of this thickness are also used, for example, in large rotor blades for wind turbines.

In the next stage in the process, the fibre bundles are processed into non-woven fabrics. In contrast to a woven fabric, in these fabrics the fibres are not placed at right angles to one another and interwoven, but are all aligned in the same plane. Weaving would kink the fibres and detract from their special properties. The alignment of the fibres in the fabric is crucial to achieving optimal quality in a CFRP component.

Preforming and preform joining – a component takes shape.
At the so-called "preforming" stage, the cut but still flat fabric begins to acquire a shape. During this process a heat source is used to give a fabric stack a stable, three-dimensional contour. The final shape of the component is already clearly visible. Several of these preformed stacks can then be joined to form a larger component. In this way CFRP can be used, for example, to produce highly integrated components with a large surface area, which would be extremely cumbersome to manufacture from aluminium or sheet steel. This has major benefits for vehicle body design and manufacture. For example, mounting parts or other features can be integrated directly into the component. Also, complex structural components and entire body modules with varying wall thicknesses can be produced in a single moulding tool.

At both process stages – preforming and preform joining – the big challenge lies in ensuring good production processability of the flexible fabric so that the preforms will maintain a stable shape and can be joined with maximum precision. Here, too, the BMW Group has acquired valuable expertise over the years.

High-pressure resin injection with Resin Transfer Moulding (RTM).
The joined preforms are now ready for the next stage in the process: resin injection. This second major component in the composite structure – the resin – ensures that the preformed stacks permanently maintain their preconfigured shape. The resin transfer moulding (RTM) process

involves high-pressure injection of resin into the preforms. Firm bonding between the fibres and resin, and the subsequent hardening process, give the material the rigidity which is key to its outstanding qualities.

The impregnation of the fibres by the resin is a highly complex process full of conflicting requirements. For example, on the one hand the resin must reach every area of the material with minimal delay, impregnating every fibre right down to microscopic level. This means the resin must have as low a viscosity as possible, so that it can flow freely enough to be dispersed quickly throughout the fabric. On the other hand, as soon as it has impregnated all the material, the resin needs to harden as quickly as possible. Thirdly, a release agent is required that will allow the resinated components to be parted from the moulding tools without the components being damaged – yet without affecting the bonding between the fibre and the resin. Resolving all these conflicting requirements simultaneously is a highly complex task. The BMW Group has developed its own process, moulding tools and production equipment to resolve these conflicts and to ensure high productivity combined with very high quality.

During resin impregnation of the fibres, some ten different substances and materials must be bonded together, but under no circumstances must they react with one another. It is also important to ensure full bonding throughout the composite structure – between the carbon fibre fabric, the resin, the hardening agent, the binder, the yarn, the release agent and other materials – both at macroscopic and at microscopic level. This is a major challenge when working with fibre composites, because the material is always only as good as the bond between resin and fibre.

Final processing – a water jet cutter applies the finishing touches.
After resin injection and hardening, the production process is almost complete. All that remains is the finishing work such as precise contour cutting and the insertion of any further openings that may still be required. At BMW Group plants this finishing work is performed by a water jet cutting machine. Since the finished CFRP component is already, following resination, very stiff and robust, ordinary milling heads would quickly run into wear and tear problems and would require frequent replacement. Water jet cutting and drilling on the other hand are wear-free. For CFRP applications, this technique does require certain modifications – which the BMW Group

has already introduced.

“Our matured production processes enable us to produce components precisely in line with the engineers’ specifications and in accordance with the product’s function.” (Andreas Reinhardt)

Recycling – offcuts make a comeback as new structural components.

The BMW Group’s CFRP strategy extends throughout and beyond the life cycle of the product. Over the course of time, a variety of concepts have been developed and evaluated for recycling this high-grade material, but it was not until recently that a solution was found for optimal recycling of production waste. Now the BMW Group has developed a concept for recycling segregated production waste into commercial-quality raw material. This system, the first of its kind in the world, allows a substantial proportion of carbon fibre waste to be returned to the production process. Thanks to a special refining procedure, the resulting material can even be used as a substitute for primary fabric. After all, the benefits of recycling are twofold: cutting waste reduces not only environmental impacts but consumption of new material as well.

“Our aim was to reuse offcuts from the production processes in high-grade applications for our own products.” (Andreas Reinhardt)

Of course, BMW’s CFRP strategy is ecologically sustainable not just with regard to recycling but also in terms of production. For example, the Group is committed to ensuring that the new plant in Moses Lake, USA, operated by the joint venture with SGL ACF (Automotive Carbon Fibers), obtains its energy exclusively from renewable sources. The plant will also set standards for energy efficiency.

Cradle-to-grave approach for optimal results.

The developers and CFRP experts have continuously improved all processes, materials, production equipment and tools over the past ten years, thereby ensuring a successful ramp-up to mass production. Throughout, the improvements were focused on the complete process and value chain. The BMW Group is currently in a unique position in that it is able to influence all processes in this chain, from fibre production to recycling. That means it can ensure that progress at particular points in the chain quickly feeds through to the system as a whole.

Mass production was always the aim.

With the steady ramping up of output, and the development of innovative processes, the BMW Group has now accumulated a vast amount of in-house expertise and experience. This know-how is spread across its workforce, its production equipment and its processes. It was only possible to achieve such a high level of expertise thanks to the unwavering focus on one overriding goal: mass production of CFRP components. That's because the BMW Group sees CFRP not simply as a niche application for specific vehicles, but as a pioneering technology for automotive design in general. That is why, from the outset, the company has invested heavily in acquiring and continuously developing in-house competences – whether process capabilities or employee skills. This high level of self-sufficiency and in-house expertise throughout the production process has also served to make the BMW Group largely independent of and free from external constraints. The result is a production process whose maturity is reflected above all in high component quality.

"The key to successful mass production of CFRP components is a focus on creating quality in-process rather than through end-of-process checking." (Jochen Töpker)

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