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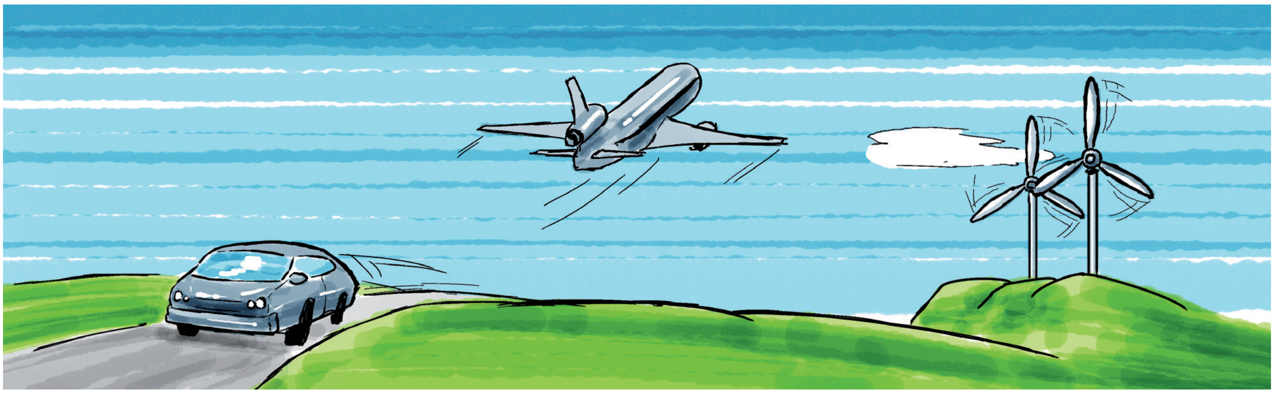

Lightweight, heavy impact

How carbon fiber and other lightweight materials will develop across industries and specifically in automotive

Table of contents

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Introduction and key messages

Lightweight materials and design have always been an important topic in product design across several industries. The concept has been most important in aviation but also in industries where large rotating parts (e.g., rotor blades of wind turbines) are key elements of product design and in automotive, where driving dynamics are a major consideration. Global trends toward CO_2 reduction and resource efficiency have significantly increased the importance of this topic over the last years.

Recent prominent examples lend evidence to this trend gaining momentum: the Boeing 787 Dreamliner is constructed largely of carbon-fiber-reinforced plastics (carbon fiber in the following) instead of the traditional aluminum body structure, and the BMW Project i is a new electric vehicle, whose support structure contains a significant amount of carbon fiber to reduce weight and to enhance driving dynamics. Besides these prominent examples, many other clever solutions have recently been introduced, e.g., the use of a one-piece carbon fiber car fender instead of a four-piece metal part, allowing for a 30 percent weight reduction and a 60 percent reduction in its tooling cost, and the use of carbon fiber bearings for an Airbus A340 horizontal tail, reducing its weight by 50 percent and cost by 30 percent.

McKinsey has investigated this topic and developed a fact-based perspective on the future development of the lightweight materials market

This document aims at answering crucial questions regarding the use of lightweight materials:

- How will the various material markets develop over time?
- Will carbon fiber become the "across all applications" material of the future?
- To what extent can industries learn from each other?
- What are the implications for the different players?

While the relevance of lightweight materials cuts across industries, the automotive industry is of particular importance in this discussion for two reasons. First, of the materials used by automotive, aviation, and wind combined, more than 90 percent is used by the automotive industry. Second, expected changes in materials use are likely to have the most significant impact on automotive. For these reasons, emphasis is placed on the development in that industry.

The main outcomes of the report are as follows:

The use of lightweight materials will significantly grow across industries – while the lightweight share is currently highest in aviation with almost 80 percent, automotive is massively increasing the lightweight share from 30 to 70 percent by 2030 (high-strength steel considered lightweight material).

All lightweight materials offer weight reduction potential at higher cost – carbon fiber therein with the highest weight reduction potential (50 percent lighter than steel) – but also by far the highest cost (570 percent the cost of steel today). The industrialization of carbon fiber may yield a cost decrease of up to 70 percent, thereby making it significantly more attractive (e.g., the delta from aluminum to carbon fiber could shrink from about 80 percent today to approximately 30 percent in 2030).

Focusing on automotive, the key driver for change is the CO_2 emissions regulation:

- The use of lightweight materials – with the exception of extreme lightweight concepts containing significant amounts of carbon fiber – is a cost-effective measure to reduce CO_2, but with limited abatement potential.
- Currently discussed CO_2 targets for 2025 in Europe cannot be achieved with engine efficiency measures and lightweight materials alone. Electrified powertrains will have to contribute to a certain extent to the fulfillment of the regulation.
- The increase in weight and system cost through required engine efficiency measures as well as electrification triggers additional need for lightweight to reduce the weight as well as the associated system and battery cost and to improve driving dynamics. OEMs will be willing to pay up to EUR 20 per kilogram saved depending on powertrain and vehicle segment.

To address the need for lighter cars, three different "lightweight packages" will emerge:

- A conventional package with a significant share of high-strength steel, which will be used by about two-thirds of cars produced – mainly small- and medium-sized cars with conventional or hybrid powertrains
- A moderate package with a higher share of lightweight materials, including aluminum, magnesium, high-strength steel, and (to a limited extent) carbon fiber, which will apply to approximately one-third of cars produced – mainly upper-medium-/executive-class vehicles and battery-electric vehicles
- An extreme package with a high carbon fiber share, which will remain limited to niche luxury and extreme premium BEV concepts.

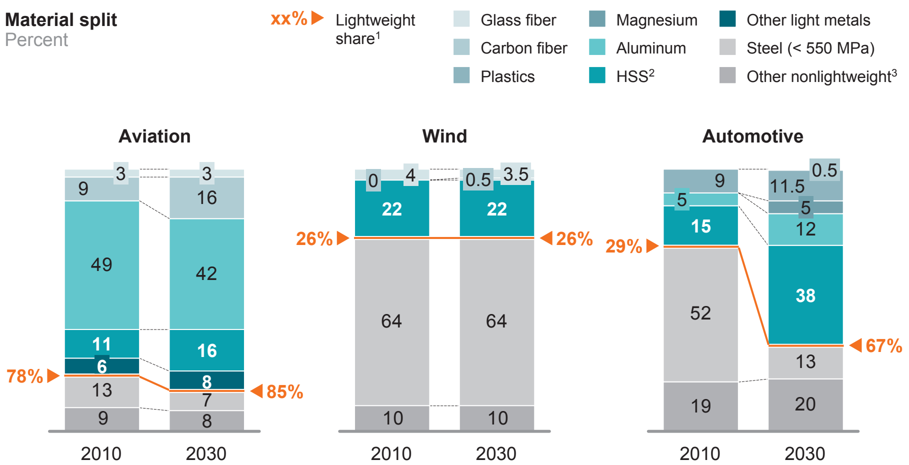
Since carbon fiber offers new degrees of freedom in car design as well as the opportunity for differentiation, the use of carbon will be particularly pushed by premium OEMs. This and potential developments, such as stricter CO_2 targets, an increase in required battery size or a decrease in battery cost, which is taking place more slowly than expected, might allow extreme lightweight packages to become even more relevant over time.

Overall, the use of lightweight materials in all three industries in scope – automotive, aviation, and wind – will increase significantly in volume over the next two decades, creating a market of more than EUR 300 billion for high-strength steel, aluminum, and carbon fiber. Traditional steel will be substituted to a large extent by high-strength steel, and carbon fiber will reach the highest growth with almost 20 percent per year. Through the enormous changes in the material mix, significant challenges and opportunities will emerge – automotive suppliers and the machinery industry are expected to be the key beneficiaries.

Lightweight materials across industries

Lightweight materials and design are becoming increasingly important in many industries. There are three industries, however, where lightweight has played an important role in product design almost from their inceptions: aviation, wind energy, and automotive. In these industries, the use of lightweight materials and design is expected to grow even more in the coming decades. For the automotive industry, the importance of lightweight will grow at the speed of light and the share of the lightweight materials used in production will more than double in the next 20 years (Exhibit 1).

Aviation currently uses the most lightweight materials in terms of share, but automotive will catch up



1 HSS, aluminum, magnesium, plastics (beyond current use), glass/carbon fiber
2 High-strength steel (> 550 MPa)
3 Mainly other metals, glass, fluids, interior parts for automotive, etc.

SOURCE: McKinsey

Exhibit 1

Lightweight pioneers in aviation and wind energy

In **aviation,** lightweight materials (such as light metals, aluminum, plastics, and composites) already make up roughly 80 percent of all materials – significantly ahead of all other industries. The use of lightweight materials in aviation has two main drivers: the need to reduce fuel consumption and related costs and the wish to increase passenger/cargo load per flight. While steel played a very prominent role in the early years of aviation, it has been rapidly replaced by lighter materials. Aluminum is currently the most important lightweight material in aviation (about 50 percent) – mainly used in structural parts.

New aircraft models, such as the Boeing 787 Dreamliner and the Airbus 350 XWB, will have a significant share of carbon fiber (about 50 percent of their structural weight) to reduce weight even further. Boeing delivered its first 787s in 2011 and Airbus is scheduled to follow with its new lightweight planes in 2014/15. With the planned ramp-up in production for these models, the share of carbon fiber in the aviation industry will increase and the need for some traditional materials will decline. This effect as well as the expected growth of the industry overall (double the annual aircraft deliveries in 2030 as compared to 2011) will lead to strong growth in the carbon fiber market (from 8,000 to almost 40,000 tons).

In the **wind industry,** extreme lightweight materials are applied in the long rotating blades, which transform the wind energy into rotating energy that is then transformed into electricity. Due to the high wind speeds and the size (length and mass) of the blades, the blade material has to bear high stress, which can be reduced by using extremely light materials. The majority of wind turbine manufacturers currently use glass fiber as structural material for their blades.

Despite its high cost, two of the industry's big players are already using carbon fiber for stabilization, because it is stiffer than glass fiber. The stiffness factor of carbon fiber may allow for a further increase in blade length that cannot be achieved with glass fiber, resulting in greater output per wind turbine. This will become increasingly important as off-shore wind energy increases.

Since wind turbine installation in 2030 is expected to be four times that of 2011, the market for lightweight materials will grow at a rate that (at the very least) keeps pace.

Ramp-up of lightweight in automotive

The automotive industry has been paying attention to vehicle weight for decades since it has a direct impact on driving dynamics, agility, and fuel consumption. Due to the high cost of potential lightweight solutions and consumers' limited willingness to pay for weight reduction in automotive, the use of costly lightweight materials has so far been limited.

The introduction of CO_2 emissions targets and correlated penalties, however, has reignited the conversation with an even stronger focus on weight reduction as a lever to minimize fuel consumption. The trend of ever-increasing weight for cars has been curtailed in recent years through the increased use of plastics (e.g., for fenders and recently doors in the new smart) and improved steel alloys (e.g., for the chassis).

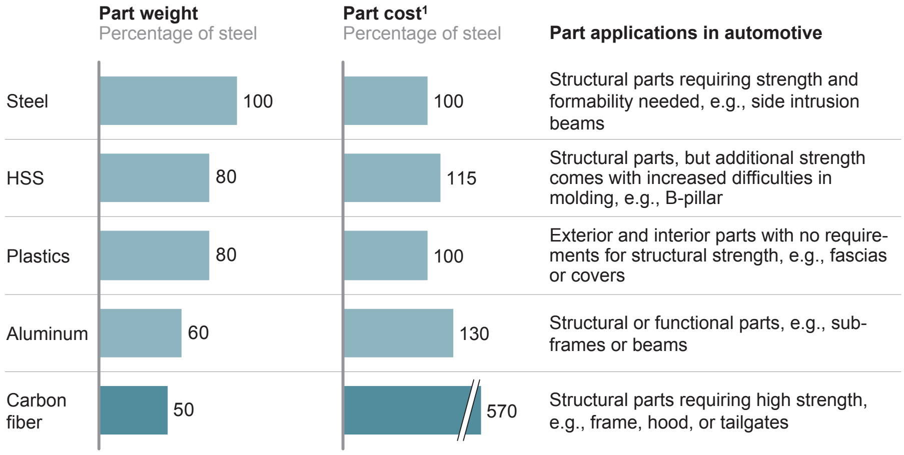
As regulators call for even higher emissions standards in the coming years, the importance of lightweight materials will increase. Lightweight measures can help reduce CO_2 emissions to a certain extent (approximately 0.08 g CO_2 reduction per kilogram saved). However, the overall impact of lightweight measures in combination with further optimized internal combustion engines (further called ICEs) will not be sufficient to reach currently discussed CO_2 targets for 2025. Therefore, OEMs will push for electric cars with a resulting increase in system weight and cost (e.g., the cost for bigger batteries, breaking, and damping systems). Lightweight here again is needed to reduce the impact of additional system costs for electrification but also for CO_2-optimized ICEs.

Carbon fiber vs. other materials: biggest weight advantage, new design opportunities, but highest cost

Various lightweight materials are in use, but the particular material used depends on its characteristics and the requirements of the application. For example, one lightweight material may offer superior stiffness while another is more malleable. The materials under consideration all offer a significant weight advantage but come at higher costs (Exhibit 2). High-strength steel, for example, offers a weight advantage of 20 percent over steel at an additional cost of 15 percent per part, and aluminum is 40 percent lighter but 30 percent more expensive. Cost considerations have so far often prohibited the use of lightweight materials. Since the introduction of CO_2 targets and resulting penalties, the use of lightweight materials now delivers a monetary benefit, which will justify an increased use of lightweight materials in the future.

Today lightweight materials are costly but offer significant weight advantages

EXAMPLE AUTOMOTIVE FENDER



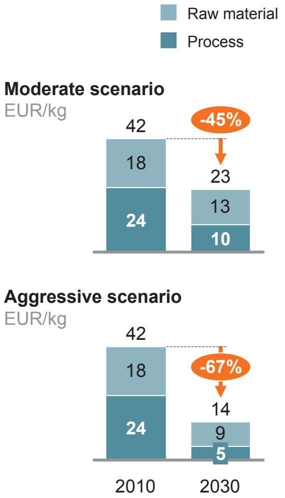
1 On a 60,000 pieces-per-year assumption

SOURCE: McKinsey

Exhibit 2

Carbon fiber may decrease its huge cost disadvantage over time

EXAMPLE AUTOMOTIVE CHASSIS COMPONENT



Expected improvements in scenario

	Process	Raw material
Moderate scenario	▪ **Tact-time reduction** from currently 5 down to 3 minutes ▪ Resulting in **~ 33 percentage points** of **improvement**	▪ **Textile PAN precursor** available ▪ **Economies of scale** due to bigger raw material production plants ▪ Resulting in **~ 12 percentage points** of **improvement**
Aggressive scenario	▪ **Tact-time reduction** down to 1 - 2 minutes through **technology changes** and changes in **raw material** (e.g., introduction of fast-curing resins) ▪ Resulting in **~ 45 percentage points** of **improvement**	▪ **Lignin-based precursor** available ▪ Resulting in **~ 22 percentage points** of **improvement**

SOURCE: McKinsey

Exhibit 3

Carbon fiber is currently the most discussed lightweight material due to its high potential for weight reduction in certain applications. But current costs are enormous (five to six times as high as steel, already assuming a mass production of 60,000 units per year) and prohibit high penetration. Over the next two decades, however, we will observe a significant cost decline for automotive carbon fiber applications, from about EUR 42 per kilogram today down to EUR 23 in a conservative cost scenario and EUR 14 in an optimistic cost scenario by 2030 (Exhibit 3).

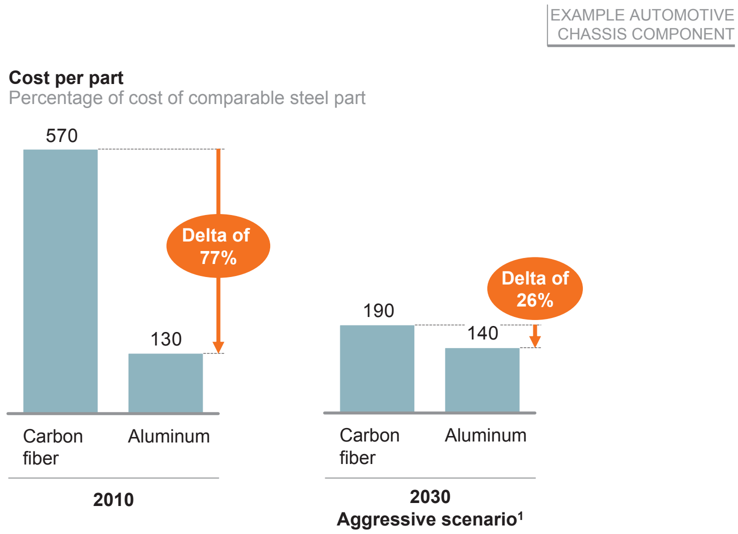
The projected carbon fiber cost decrease will be mainly driven by

1. The development of a less expensive precursor material to produce the carbon fibers (textile PAN precursors or even lignin-based precursors instead of oil-/gas-based precursors to decouple the material price from oil price developments), resulting in a 30 to 50 percent cost decrease for the raw material

2. A reduction in the processing cost for pre- and part forming of 60 to 80 percent due to radical reductions in cycle times driven by, for example, the development of fast-curing resins and the resulting reduction of investment and labor costs per part.

This fall in cost will bring carbon fiber significantly nearer to comparable aluminum parts though a difference of 20 to 30 percent will remain (Exhibit 4). Since carbon fiber has the biggest weight advantage, offers a greater degree of freedom in car design and performance, and has positive effects on the brand positioning, it will gain a significant share in selected applications despite the remaining cost gap.

The cost gap between aluminum and carbon fiber will shrink over time



1 Assuming increase in energy cost for both carbon fiber and aluminum

SOURCE: McKinsey

Exhibit 4

CO_2 reduction as fundamental driver for lightweight in automotive

Especially in Europe, but also globally, regulations are forcing OEMs to significantly reduce the CO_2 emissions of their cars. In Europe, for example, the average emissions of all models sold by an OEM in one year need to drop from about 140 g CO_2 per kilometer to 95 g in 2020 and to 75 g (possibly less) in 2025 and beyond (with some exceptions/adaptations regarding the vehicle class).

Cornerstones of European CO_2 regulation

The European legislation defines a value curve that limits CO_2 emissions for new vehicles according to the mass of the vehicle. The curve is set in such a way that the target for all new cars sold in one year (an average of 130 g of CO_2 per kilometer in 2012) is achieved. Through the correction factor for the vehicle mass, each OEM has to fulfill a slightly different target for its yearly sales compared to the aspired average (e.g., targets of premium OEMs are slightly higher). Starting in 2012, a manufacturer will be required to ensure that the average emissions of all new cars it produces and which are registered in the European Community are at or below the permitted level of emissions as indicated by the curve.

If the average emissions level is above the limit defined in the value curve, an "excess emissions premium" of EUR 95 per gram of CO_2 beyond the limit (after 3 g over the limit) is imposed. The precise formula for the value curve is:

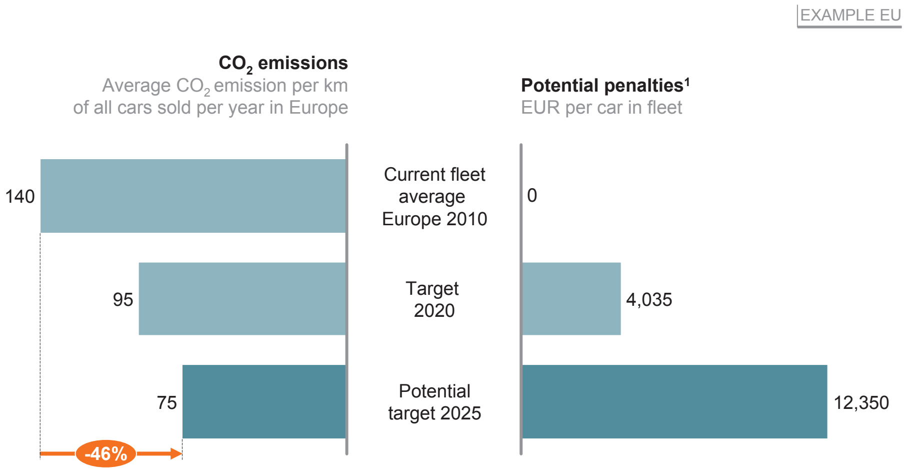
Permitted specific emissions of CO_2 = 130 + a × (M – M0)

Where: M = mass in kg, M0 = 1,289 kg, a = 0.0457 g CO_2/kg

However, this slope does not reflect the physical correlation between weight and CO_2 emissions, which is at about 0.08 g CO_2 reduction per kilogram saved. Therefore, reducing weight does help reach CO_2 targets, but more than half of the physical reduction is eaten up by the amended CO_2 target – if an OEM manages to reduce the vehicle weight by 100 kg, it saves approximately 8.5 g CO_2 per 100 km, but its CO_2 target gets raised by 5 g CO_2 per 100 km. This regulation therefore leads to a de facto doubling of cost of reaching European CO_2 targets via lightweight measures and by that discriminates the weight reduction compared to other CO_2 reduction measures, such as electrification. We have focused our calculations on the real cost and CO_2 abatement effects of lightweight measures, not taking into consideration this discrimination.

Due to the extremely high penalties (EUR 95 per gram deviation and per car sold from the fourth gram onwards today, potentially to increase up to EUR 190 per gram and car sold in the next decades), failing to meet the CO_2 targets is not an option for OEMs at all since the penalty per car sold could amount to more than EUR 12,000 (Exhibit 5).

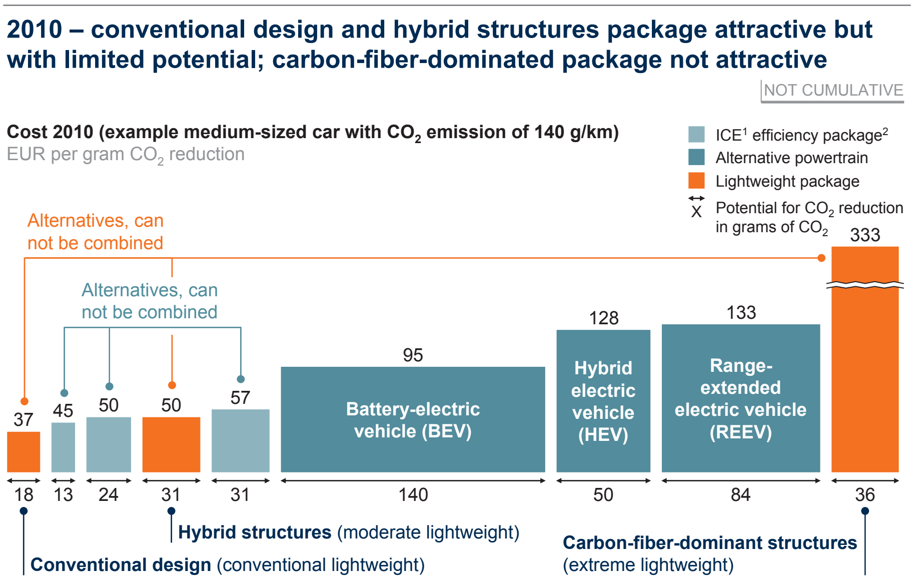
Regulations in Europe force OEMs to significantly reduce CO_2 emissions



1 Assumption: in comparison to today's average European CO_2 emission of 140 g CO_2 per km per car; penalties for exceeding CO_2 emissions from 2015 onwards: for 1st gram EUR 5, 2nd gram EUR 15, 3rd gram EUR 25, 4th gram and beyond EUR 95; penalties from 2030 onwards: EUR 190 for each gram

SOURCE: McKinsey

Exhibit 5



1 Internal combustion engine
2 Efficiency measures clustered into packages depending on ease of implementation and cost; cheapest package contains, e.g., moderate downsizing of engine, optimized gear translations; 2nd-best package additionally includes high downsizing and variable value control; most expensive package additionally implements direct injection, reduced friction, duplex clutch

SOURCE: McKinsey

Exhibit 6

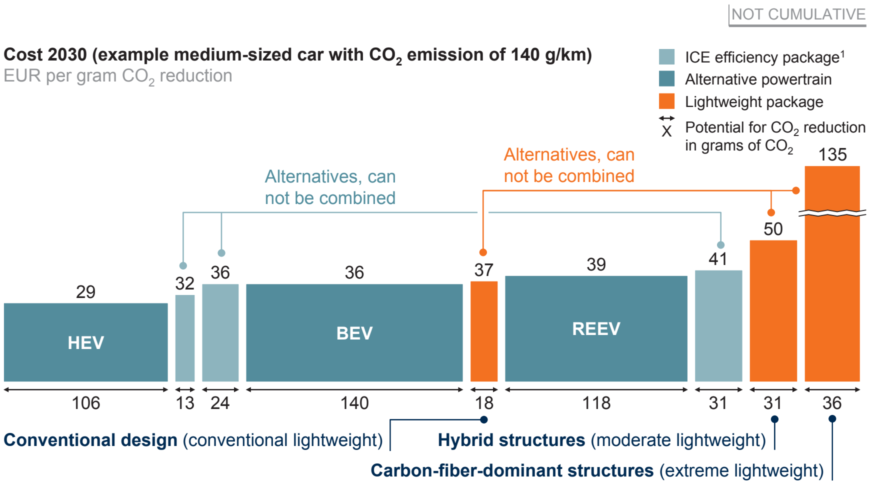
To reach their CO_2 targets, OEMs can choose between different alternatives, starting with measures to improve the efficiency of the powertrain (e.g., through improved start-stop-systems or downsizing), usage of lightweight materials, or electrification (not necessarily meaning pure battery-electric vehicles, but also hybrids and range extenders). Exhibit 6 shows the different options with their cost per gram of CO_2 avoided and their maximum CO_2 reduction potential.

Today the conventional and moderate lightweight packages can compete in cost against powertrain efficiency measures (EUR 37 to 50 per gram CO_2 reduction). The extreme lightweight package (high share of carbon fiber) comes at a cost of more than EUR 300 per gram CO_2 reduction. The current cost of this option exceeds that of other CO_2 reduction options, such as full-battery electrification, hybrid, or range-extended electric vehicles, by far. (For the detailed definition of the three lightweight packages, see the next chapter).

Until 2030, the cost of the different lightweight packages will change significantly. We assume that the cost for electrification (mainly driven by the cost of batteries) will decrease dramatically due to technological advances. The same holds true for the extreme lightweight package, mainly due to the already-mentioned decrease in carbon fiber cost. However, this does not apply for the quite cost-stable other two lightweight packages, where already well-known materials and processes will be used, leading to limited continuous improvement while raw material costs are expected to increase slightly rather than decrease (Exhibit 7).

Thus, considering today's cost, powertrain efficiency and lightweight measures will be significantly pushed to fulfill CO_2 regulation. But looking on a potential future cost development of the different options, the introduction of electrified powertrains will

2030 – despite significant cost reductions, carbon-fiber-dominated package still not attractive due to expected cost reductions for alternatives



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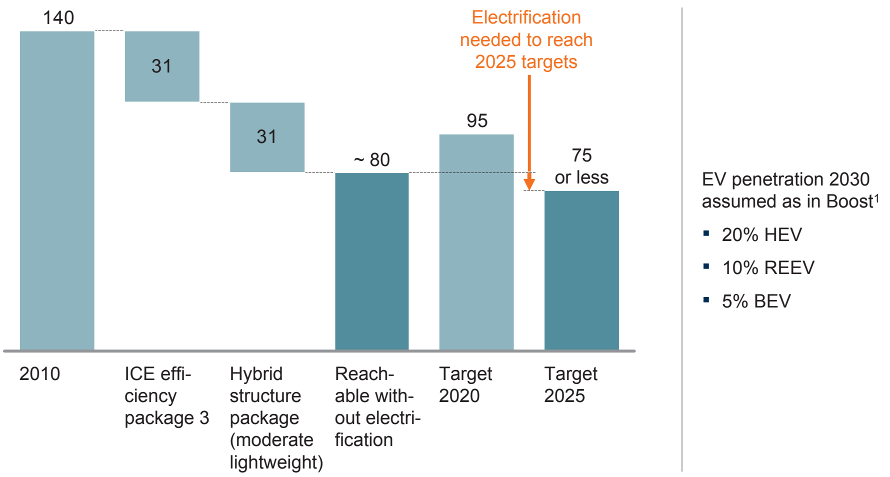
SOURCE: McKinsey

Exhibit 7

ultimately be needed to reach the expected CO_2 targets beyond 2025 due to limitations in abatement potential of the other alternatives: By introducing the ICE efficiency package with the highest potential and the moderate lightweight package with hybrid structures from metal and plastics, CO_2 emissions of an average car could be reduced to about 80 g per kilometer. This would be enough to satisfy the announced targets for 2020 but will not be sufficient to fulfill expected targets in 2025 or beyond (Exhibit 8). What is more, not even the currently very expensive extreme lightweight package with carbon fiber structures would be able to meet the CO_2 targets in the future. Therefore, hybrids, which further reduce fuel consumption, and full-electric vehicles, which are considered zero-emissons vehicles (even though a well-to-wheel perspective shows significant CO_2 emissions, depending on the energy mix used, e.g., roughly 100 g per kilometer for the current German electricity mix) will play an increasingly important role in the future.

Lightweight measures are urgently needed as the ICE and electric vehicle emissions reduction measures automatically result in additional weight (e.g., roughly 50 kg for ICE efficiency measures, about 250 kg for a BEV). As the increase in weight causes additional system (e.g., bigger batteries, breaking, and damping systems are needed) and battery cost along with diminished driving dynamics and range, lightweight materials and design become highly desirable as a counterbalance to reduce system cost and improve driving performance rather than a measure of its own to reduce CO_2. Depending on the weight increase and the related performance and system/battery cost changes, different ranges of accepted cost for weight reduction exist for the various powertrains and vehicle segments, ranging from EUR 3 per kilogram saved for a small/medium-sized ICE vehicle up to EUR 20 per kilogram for a BEV at today's cost (Exhibit 9). The penetration of lightweight materials is therefore strongly dependent on actual cost and accepted cost for certain measures. The next chapter examines the usage of lightweight measures depending on the vehicle segment and powertrain type.

OEMs need to electrify the fleet and improve the ICE powertrain to reach increasingly ambitious CO_2 emission targets



1 Boost! Transforming the powertrain value chain – a portfolio challenge (McKinsey brochure)

SOURCE: McKinsey

Exhibit 8

Powertrain and vehicle segment: the formula for choosing the right lightweight package

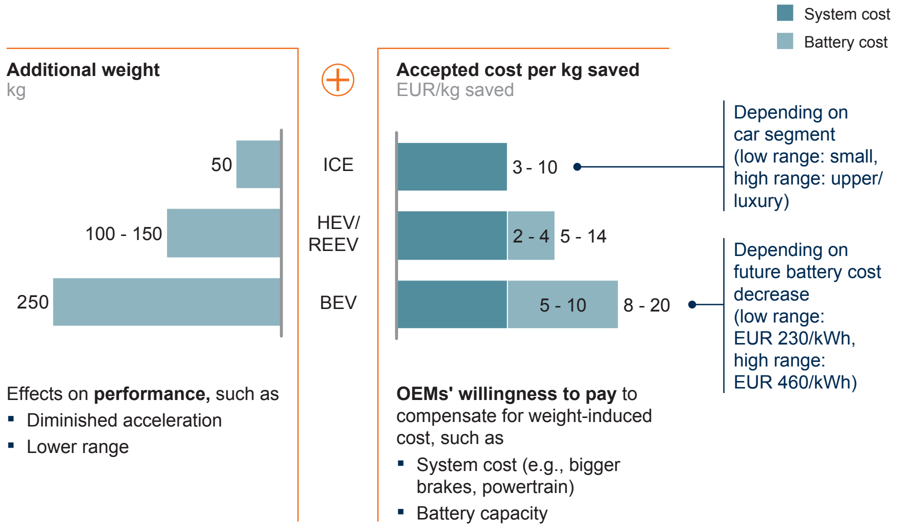
Ultimately, a part-specific materials strategy needs to be developed by the OEMs since each part has different requirements regarding formability, strength, temperature resistance, etc., and the cost of each material is different. For example, a fender can easily be made of plastics or carbon fiber instead of steel while a rail for diesel common rail applications will always be made of high-strength steel due to the high requirements for pressure and corrosion. In this study, we investigated the main materials that account for more than 90 percent of the vehicle weight. The basis of our analysis was a typical mass-market vehicle – necessary adaptations for different car segments were made, especially for analyzing the impact on overall material markets.

We defined three different lightweight packages that OEMs may consider in the future, depending on the vehicle segment and the powertrain used. The three packages are defined as follows (Exhibit 10):

- **Conventional lightweight.** Currently used "normal" steel is replaced by high-strength steel – as already implemented, e.g., in cars of many premium manufacturers. The use of even lighter materials (especially carbon fiber but also aluminum) is prevented by cost considerations. Maximum weight savings for a medium-sized car is around 18 percent at an additional cost of EUR 3 per kilogram saved.

- **Moderate lightweight.** Currently used steel is replaced by aluminum, magnesium (mainly in casting parts), or high-strength steel – use of carbon fiber is only considered for selected parts that have to be extremely stiff or where weight reduction really pays off (e.g., roof). Maximum weight savings for a medium-sized car is around 30 percent at an additional cost of EUR 4 per kilogram saved.

ICE improvements and alternative drivetrains will drive up weight and vehicle system/battery cost



SOURCE: McKinsey

Exhibit 9

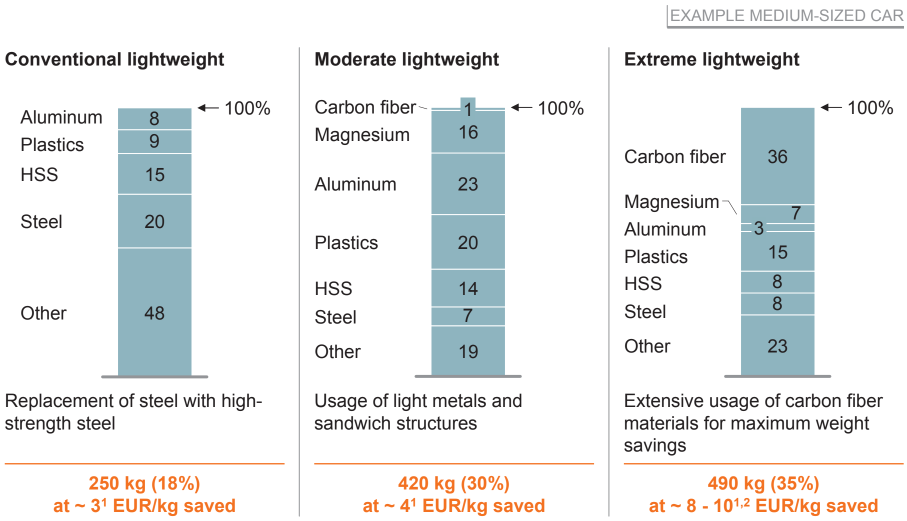
- **Extreme lightweight.** This package is the lightest solution that can technically be applied – cost considerations do not limit the use of any material. Maximum weight savings for a medium-sized car is around 35 percent at an additional cost of EUR 8 to 10 per kilogram saved.

As discussed in the last chapter, OEMs' willingness to pay for weight reduction depends on the type of powertrain and on the vehicle class. Exhibit 11 illustrates which lightweight package OEMs might apply with respect to those two dimensions. Two-thirds of the market, namely small and medium-sized cars with ICEs (e.g., the Toyota Corolla), or hybrids/range-extended electric vehicles will focus on the conventional lightweight package since the accepted cost per kilogram saved is met only by this package.

One-third of the market, namely upper- and large-class cars (e.g., the Mercedes E-Class) across all powertrain types as well as BEVs for small and medium-sized cars, might apply the moderate lightweight package. Most of these cars already use high-strength steel and in some cases aluminum. Light metals, such as aluminum and magnesium, as well as sandwich structures will be heavily used. The implementation of this package goes along with a slightly higher but still moderate cost of approximately EUR 4 per kilogram saved – which is below the willingness-to-pay level of EUR 5 to 14 per kilogram saved.

Finally, the extreme lightweight package – extensively applying carbon fiber in structural parts to reach maximum weight savings – in the next one to two car generations will most probably be applied only in luxury class vehicles and also in selected (premium) electric vehicles (in total about 1 percent of cars) due to the high additional cost of roughly EUR 8 to 10 per kilogram saved.

Lightweight packages apply different lightweight material mixes with different weight and cost impact



1 Numbers in 2030   2 Low range: aggressive scenario, high range: moderate scenario

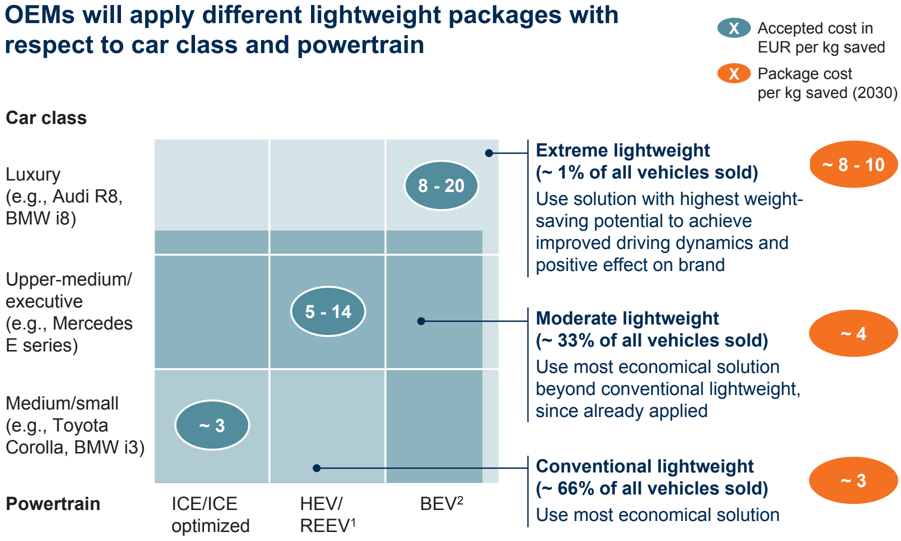
SOURCE: McKinsey

Exhibit 10

The amount of change in materials will depend on the package used, but for all cars, many components will change significantly in material within the coming decades. We foresee that lightweight competence will be a key differentiator especially for premium OEMs in the coming years. The intelligent use and marketing of lightweight design can have a significant effect on the brand and the overall attractiveness of premium OEMs itself.

Key materials we expect to play an increasingly important role in the future are high-strength steels, aluminum, plastics, sandwich materials (various combinations of these three), magnesium, and to some extent carbon fiber. Structural parts (e.g., frame or seat structure) will often consist of high-strength steel or aluminum or (in more radical niche applications) even carbon fiber. Functional parts, where strength is the key requirement (e.g., steering or transmission), might be built out of high-strength steel or carbon fiber. Interior parts, where plastics is the predominant element today, will remain plastic, and plastics will become even more important, e.g., as a substitution for windshields/screens but also for nonstructural body parts, due to its cost-weight ratio.

OEMs will apply different lightweight packages with respect to car class and powertrain



1 Range HEV/REEV 30 - 100 km
2 Range BEV 200 km

SOURCE: McKinsey

Exhibit 11

Carbon fiber's unique but surmountable industrialization hurdles

Despite the significant weight reductions it promises, the high cost of carbon fiber is the key obstacle to broad use of this material in the automotive industry. In addition to the high cost, several other challenges are often cited, which will, from our point of view, be overcome in time (Exhibit 12).

The three main challenges beyond carbon fiber's cost are maintenance and repair, sustainability/recycling, and crash simulation:

- Maintenance of carbon fiber parts is difficult since damage can often not be seen through a visual inspection, and detection requires acoustic emission detection or thermal, ultrasonic, or x-ray imaging. All of these technologies impose potential investment cost on dealerships and workshops but can, through the development of smart concepts, probably be made affordable – manual tap testing of one trained mechanist per dealership and the pooling of detection equipment across dealers and workshops are possible solutions. In terms of repair, many methods already exist in the aviation industry, such as bolted or bonded repair. Depending on the damage, these methods can also be applied to the automotive industry. Additionally, internal delamination can be repaired by injecting resin if the damage affects a nonstructural, only-local part. Of course, in the case of very severe damage or really critical components, a replacement will remain the only option, but these instances will be limited.

- Since EU legislation sets a target of 85 percent recyclability for vehicles, carbon fiber's recyclability is core to its potential for success. Many efforts are under way to address this challenge and promising results have begun to surface. It is already possible to reuse cutting waste from pre- and part forming (which is currently up to 30 percent of the used carbon fiber) for applications with lower requirements on stiffness or size. Also for already-produced carbon fiber, which was long seen as completely nonrecyclable, two methods (crushing and thermal/chemical cracking) have been developed to ensure recyclability. Recycled carbon fiber will be of inferior quality to the new material, but uses for it exist.

With carbon fiber, several surmountable industrialization hurdles exist across industries

Reliability	**Maintenance and repair** ▪ Damages invisible ⇨ higher maintenance effort ▪ Aging effects unknown ▪ Corrosion
Environment	**Sustainability** ▪ So far only partially recyclable ▪ High energy consumption for fiber production, risk for negative CO_2 impact
Physical parameters	**Development** ▪ Challenges to install Faraday cage, steer by wire, etc. **Simulation** ▪ Limited crash simulation available
Production	**Workforce** ▪ Little experienced workforce available ▪ Little experience with production technologies **Tooling and assembly** ▪ Low tolerance, hard to reach (787 disaster) ▪ Low turnover rate due to long curing times (e.g., 4 min. with RTM[1]) ▪ Expensive to tool/hard to form – high scrap rate (about 30%) ▪ Expensive material (e.g., EUR 16/kg for automotive grade fiber)

Solutions for hurdles are currently being invented – hurdles will be overcome in time

1 Resin transfer molding
SOURCE: McKinsey

Exhibit 12

- For crash simulations, the automotive industry can profit from the existing knowledge of the aviation industry. Selected automotive manufacturers are already teaming up with aviation companies to benefit from their simulation experience (e.g., Boeing-Lamborghini). But limitations in crash simulations still exist today due to the anisotropic behavior of the material. Simulation programs allowing for the prediction of this material will be developed over the coming years.

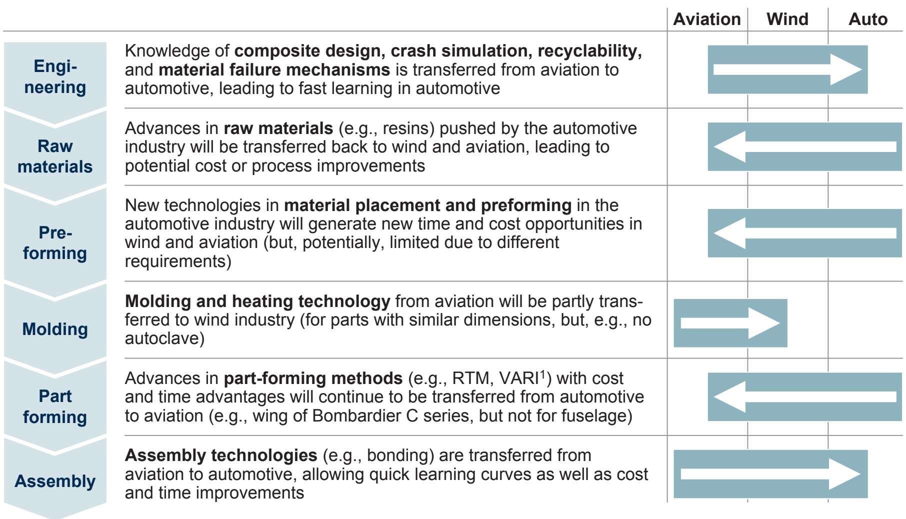
- Overall, there are still many different hurdles (including the extremely high energy consumption involved in carbon fiber production, bearing the risk of an overall negative CO_2 impact depending on the energy mix used). All of these are challenging, but with further research and innovation, they will be solved. Cross-industry learning may play an important role here.

Also in other areas, cross-industrial learning between the aviation, wind energy, and automotive industries will occur and help increase the speed of industrialization (despite significant differences in the applied materials and processes). The aviation and wind industries will contribute mainly in composite engineering and assembly knowledge towards the automotive industry. Conversely, process and raw materials advances (such as new technologies in material placement or advances in resin curing) will be initiated by the automotive industry to reduce cost and will then be transferred to the aviation and wind industries (Exhibit 13).

Not only will industry players be able to overcome carbon fiber's challenges in ways that increase the feasibility of conventional and moderate lightweight packages, it is also quite possible that extreme lightweight packages may gain prevalence. A significantly higher penetration of the extreme lightweight package in the automotive industry may be pushed by two potential developments:

- Demand for longer-range HEVs/REEVs or a slower-than-expected cost reduction for electrification may increase the willingness to pay for the extreme lightweight package.
- Further tightening of CO_2 regulations may lead to a further increase in the penetration of this package since thereby a higher share of even lighter vehicles and/or electrified vehicles with compensating lightweight measures will be required.

Cross-industry exchange may increase the speed of industrialization



1 Vacuum-assisted resin injection

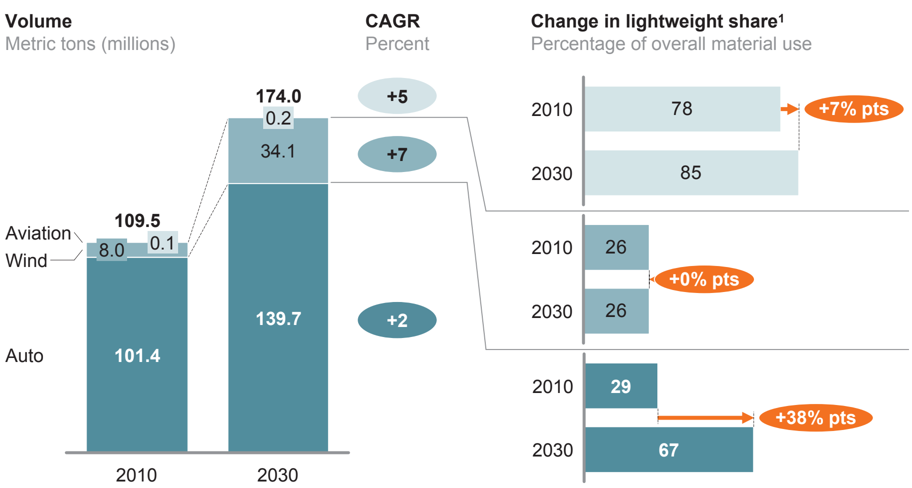
SOURCE: McKinsey

Exhibit 13

Overall impact on material markets and implications for relevant industries

Volumes will grow significantly over the next two decades, resulting in a related increase in use of materials across all three industries in scope. Despite higher growth rates for aviation and wind, the automotive industry will remain the dominant market due to the high current material use in automotive. The automotive industry will also face the most significant changes in terms of material mix – its lightweight share may increase from roughly 30 to about 70 percent (Exhibit 14) resulting from the developments described in the previous chapters.

The largest industry (in terms of material use) is facing the most significant changes in material mix in the coming years



1 HSS, aluminum, magnesium, plastics (beyond current use), carbon fiber, glass fiber

SOURCE: McKinsey

Exhibit 14

As a consequence, the overall lightweight market in automotive will increase from EUR 70 to 300 billion, reflecting an annual growth rate of 8 percent. Looking into the different materials (Exhibit 15), this means the following:

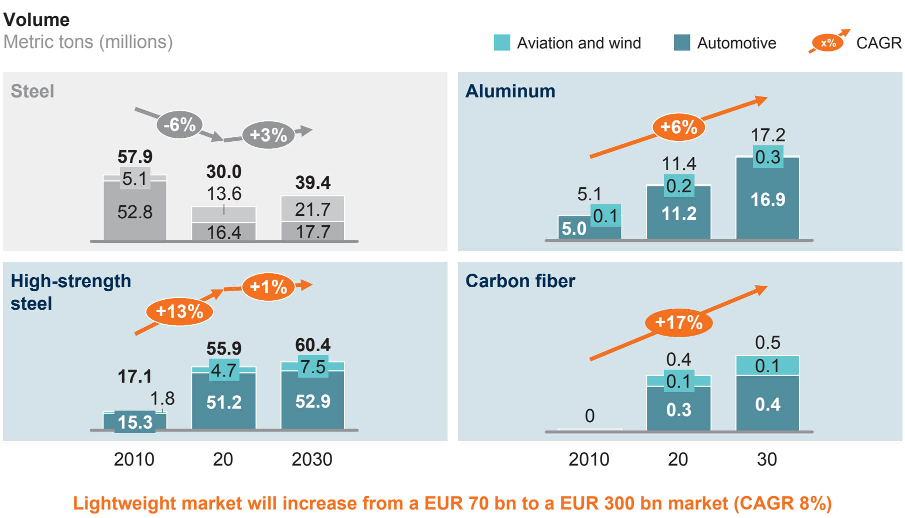
Production of "normal" steel will dip by almost 50 percent in the next decade, mainly due to the replacement trend of "normal" steel by high-strength steel in the automotive industry, and then slightly recover with the help of expected car/wind turbine volume increases until 2030.

Production of all lightweight materials will increase significantly within the next two decades:

- High-strength steel will see strong growth in the next decade due to its comparatively low cost resulting in already significant weight reductions. The penetration of high-strength steel will then slow down significantly since the replacement of steel will be mostly complete and high-strength steel may be replaced by other, even lighter materials.

- Aluminum and carbon fiber, which we have seen as essential components of the moderate and the extreme lightweight packages, will experience two decades of strong growth, with carbon fiber reaching a CAGR of almost 20 percent – an impressive number though starting from a low base. This conservative prediction considers carbon fiber's niche use, but this number could even increase dramatically if certain conditions occur, such as greater CO_2 reduction pressure or further cost decreases of carbon fiber.

Automotive's shift towards lightweight will result in significant changes in the base materials industry



SOURCE: McKinsey

Exhibit 15

Having recognized the significant changes in the material mix, with an overall decrease in "normal" steel and a steep increase in lightweight materials, a number of challenges and opportunities exist for different players. Overall, we assume dynamic changes along the value chain, which might result in significant opportunities but also threats for the affected players. To name just some of them:

- **Suppliers.** Opportunities will arise for suppliers with lightweight competencies to enlarge their product portfolio towards new materials, such as carbon fiber.

- **Machinery industry.** The machinery industry will profit from the expected market changes since new production technologies and new tools for lightweight materials (e.g., carbon fiber) will be required to reduce current cycle times, thereby creating a high demand in the industry.

- **Base materials.** The materials industry will profit due to increasing volumes and prices (e.g., high-strength steel and aluminum), and new materials suppliers may emerge, mainly in the carbon fiber area, while traditional steel suppliers may experience shrinking revenues if they can not also deliver high-strength steel.

- **OEMs.** The effects for the OEMs will be twofold: on the one hand, opportunities will arise for OEMs through the possibility of creating new designs and concepts based on the new material, achieving a positive effect on the brand. On the other hand, due to the more expensive material, the OEMs will be directly confronted with a threat to their margins and may have to deal with the additional cost of challenges that cannot be fully anticipated at the moment, such as repair and maintenance. Competence in lightweight thus will be key in future cost competitiveness.

Beyond those concrete examples, interesting questions for the future will evolve: What is the optimum material use in hybrid structures for each component? How can OEMs and suppliers early on secure their access to the required human capital and potentially scarce resources regarding carbon design and production? How can suppliers prepare to become part of the new carbon fiber business? Should OEMs integrate vertically to secure core competencies and supplies as it has already been observed in the aviation industry (e.g., Boeing buying a factory and a 50 percent stake in a joint venture that makes parts for the Dreamliner)? How will the new carbon fiber material affect car insurances? What aftermarket opportunities (particularly recycling) might arise for carbon fiber?

We are convinced that the journey towards lightweight has significant potential to change the industry and are excited to be part of this important discussion.

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