SCHAEFFLER

We pioneer motion

Sustainable construction machinery of the future

How a supplier is reducing greenhouse gas emissions with optimized and efficient products.

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About the authors

Patrick Scherr

Since 2017, Patrick has headed the Offroad Europe Business Unit. Following completion of his master's degree at the Technical University of Vienna, he joined Schaeffler in 2003, since when he has been gaining global experience in various roles in the industrial and automotive segments. He is currently focusing on the further development of friction-optimized bearings and on electrification.

Tobias Hofmann

After undertaking a work-study degree program with Schaeffler Technologies AG & Co. KG to qualify as an industrial mechanic and complete a Bachelor of Mechanical Engineering, Tobias Hofmann started working as an application engineer in the construction machinery segment in 2017. While completing his MBA in engineering management, he started in his current role as key account manager for a customer from the construction machinery segment. Alongside the ongoing development of the rolling bearing business, his main areas of interest are electrification and sensor systems.

Simon Wienröder

Simon has been a student of business and economics at the University of Bayreuth since 2018. He has been working in the business development section of the Offroad department at Schaeffler Technologies AG & Co. KG. Having become familiar with electric mobility and sustainability in the Offroad sector during his first work placement, he is now managing related projects as a student trainee.

Megatrends as drivers of technological change

Climate change and the latest scientific findings are forcing policymakers and companies to take direct action. In particular, the sixth IPCC Assessment Report on the physical science of climate change is once again spelling out the urgency of limiting CO_2 emissions to net zero (cf. IPPC, 2021, p. 36). Alongside this global and all-encompassing phenomenon of anthropogenic climate change, and the resulting political measures to achieve defined climate targets, factors like population growth, urbanization and demographic changes are also set tosignificantly change the structure of the construction machinery sector. The increasing need for housing and infrastructure, depleted resources and the labor shortages that will inevitably follow all have a direct impact on the needs of end customers. This white paper will discuss the foreseeable effects on the construction machinery industry and propose potential concepts as a response.

The challenges involved, and their implications for the construction machinery industry, including the potential contribution by Schaeffler, are summarized in Figure 1.

The focus of this paper is the trend of electrification. However, using friction optimized bearings, Schaeffler can also make a contribution to reducing CO_2 emissions in conventional drivetrains with either fossil or synthetic fuels.

For a long time now, the catastrophic consequences of climate change have no longer been mere theoretical models by scientists. They are here. Now.

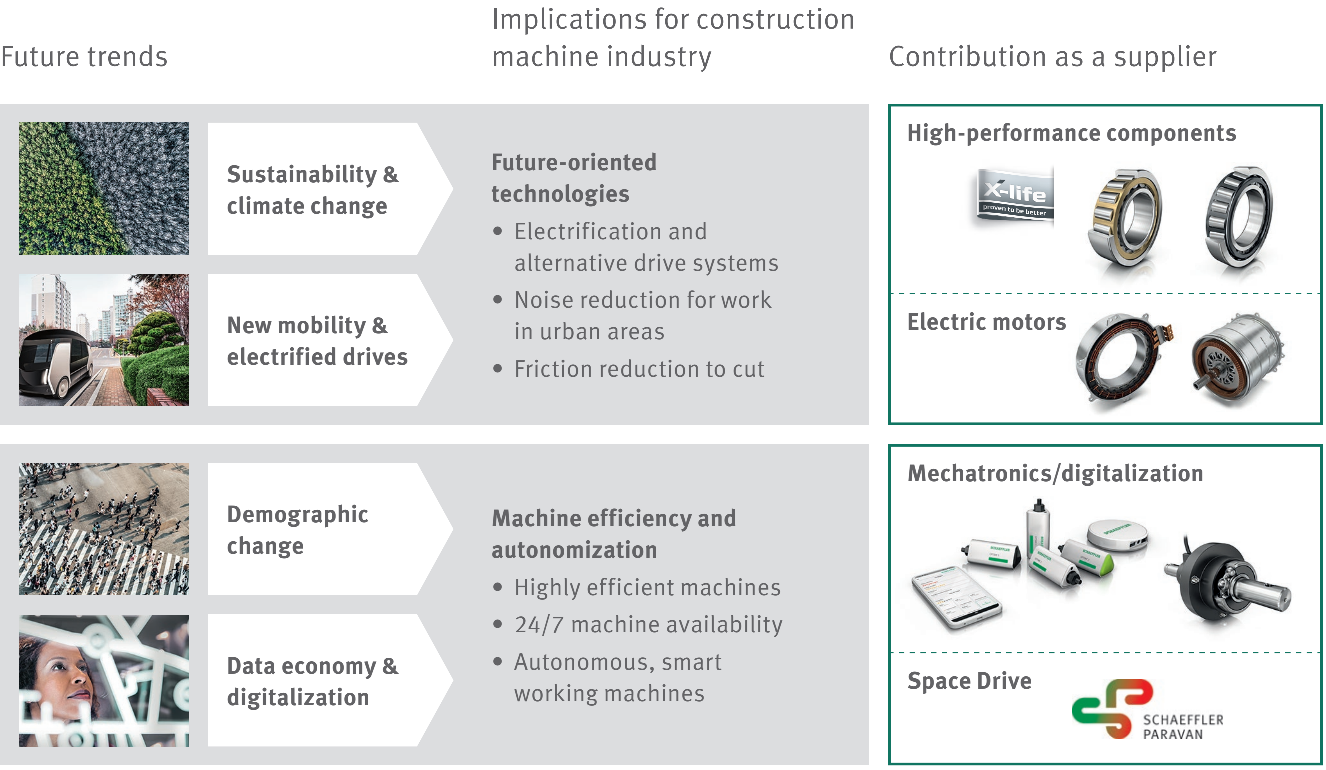

Figure 1: Future trends and solutions from Schaeffler

Electrification in construction machinery

Nowadays, machines in the Offroad segment continue to be dominated by the conventional diesel engine, not least due to its cost efficiency. However, alternative drive systems are seen as an important step towards achieving net zero CO_2 emissions. For example, PORSCHE Consulting determined that 90% of all companies in the construction machine industry currently assume that CO_2 regulations will have a substantial impact on their future business (cf. Porsche Consulting, 2021, p. 7). Cities, municipalities and regional authorities will prescribe the emission requirements to be met for public sector building projects. The city of Oslo, for example, has stipulated that from 2025, all government building sites, and from 2030 all other building sites, need to be operating emission-free (cf. Bellona Europa, 2021).

Whereas it is still possible to meet the existing emission limits, like those defined for example in the EU Stage V regulation or in similar standards like Tier 4 in the USA, by means of exhaust gas after-treatment in conventional combustion engines, innovative alternatives will need to be developed and/or implemented to achieve net zero emissions. In this context, it is clear that for the time being, it cannot and will not be possible to have just one, optimal drive technology of the future in the construction industry, owing to its extensive diversity and the low numbers of machines involved.

The common denominator with a majority of the alternative drive concepts are the electric motors used, whereby it does not matter whether it is a hybrid vehicle, or the construction machine is powered by a battery, an external source or a fuel cell. Most of the resulting technological changes will not represent an evolution of the conventional drive concept but will offer revolutionary and innovative system solutions.

In this conjunction, it is not just up to the OEMs to identify the suitable concepts and key technologies. Tier 1 and Tier 2 suppliers like Schaeffler that have suitable core competencies and system knowledge will show which concepts are feasible and practical.

To make progress as quickly as possible with reducing CO_2 emissions, it is advisable to first investigate which construction machines are responsible for the highest amount of emissions in the sector.

According to McKinsey, the entire construction supply chain produces 13.7 Gt CO_2 equivalents (CO_2e). In addition to the actual CO_2 emissions, the global warming potential of other greenhouse gases is also converted into CO_2 units and included in the analysis. Of the 13.7 Gt, 2%, i.e. around 280 Mt CO_2e, comes from all construction machinery in operation. This means that at a total annual emission volume of 54.2 Gt Co_2e, construction machinery is responsible for 0.5% of global CO_2e emissions (Figure 2) (cf. McKinsey, 2021).

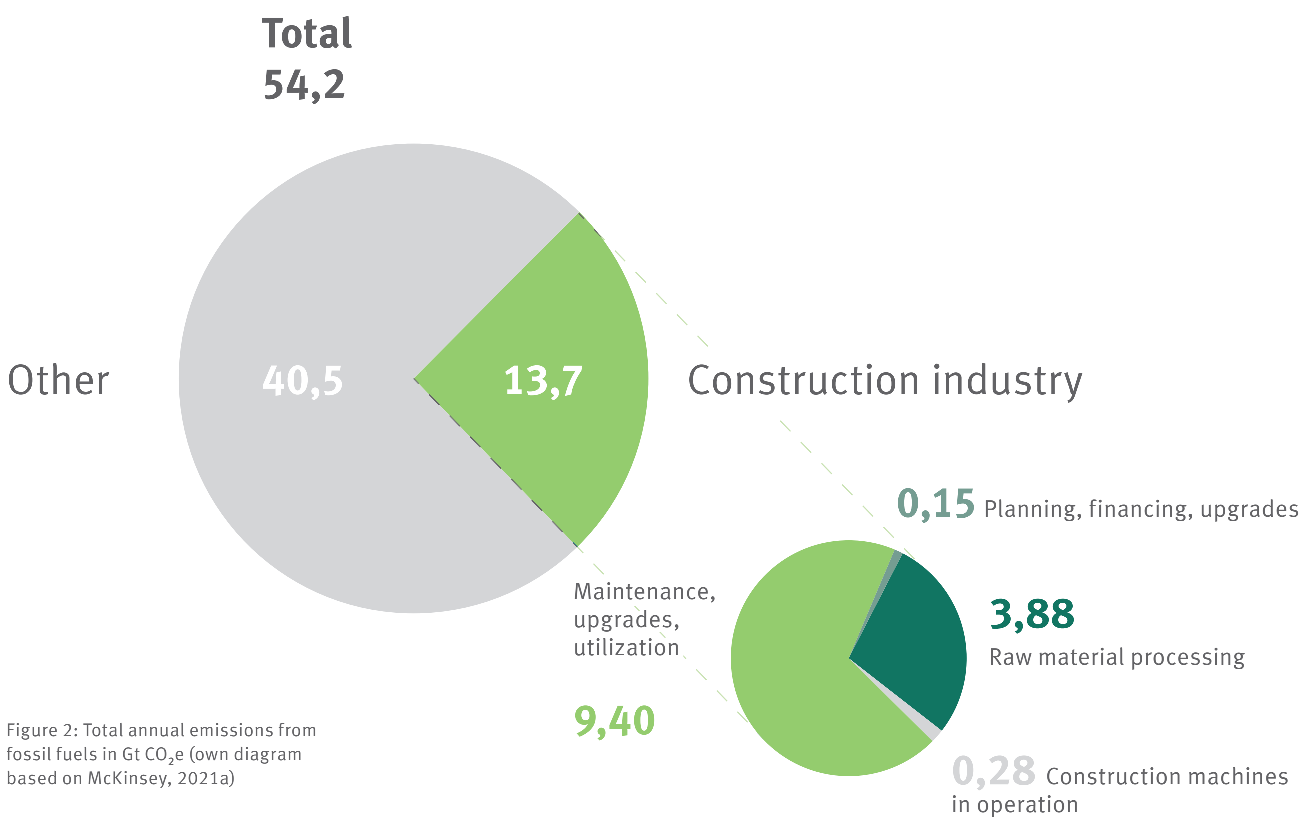

Figure 2: Total annual emissions from fossil fuels in Gt CO_2e (own diagram based on McKinsey, 2021a)

When considering the CO_2 emissions from construction machinery, excavators and wheel loaders account for the largest proportion, at 45% and 18% respectively (see Figure 3).

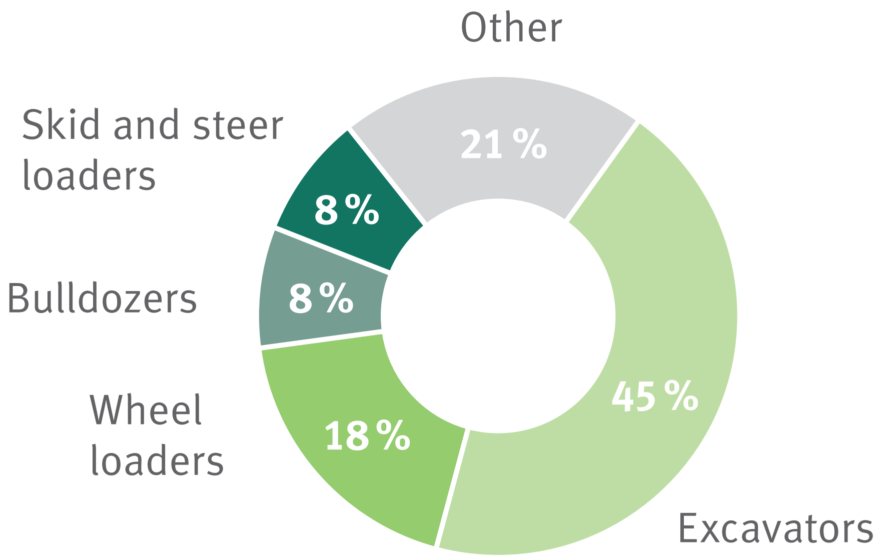

Figure 3: Global CO_2 emissions from construction machinery (own diagram based on Danfoss, 2021)

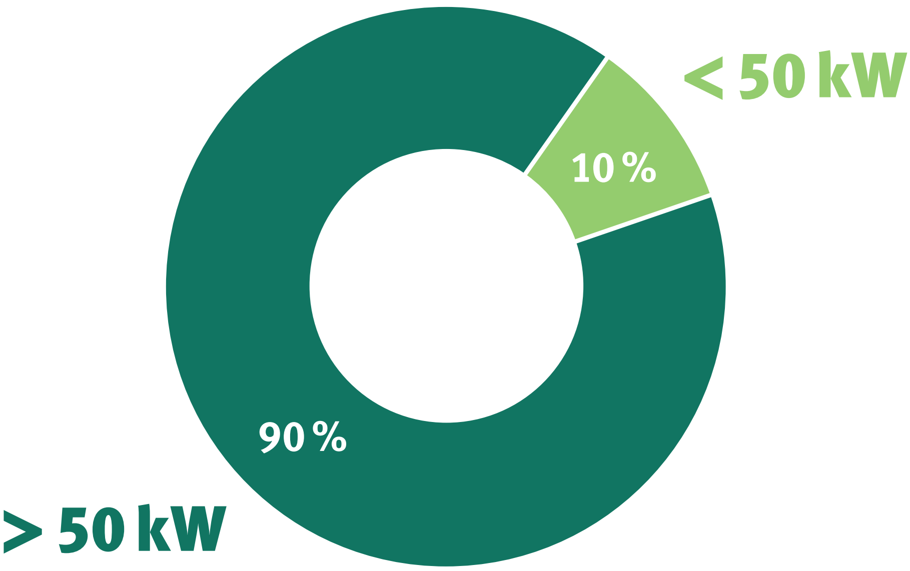

Figure 4: CO_2 emissions by machine size (own diagram based on Danfoss, 2021)

A closer look at the CO_2 emission by machine size shows a 90% share for vehicles with outputs greater than 50 kW (see Figure 4).
At 430,000 units, the proportion of construction machines with outputs of less than 50 kW is around 37% of all construction machines registered every year (cf. KGP, 2021).
However, these only cause 10% of the emissions.

It is surprising that alternative drive systems are currently being offered in the compact construction machinery segment in particular, given that it accounts for a very low percentage of the total CO_2 emissions from the construction machinery industry.

Wacker Neuson, for example, already has a fully electric mini excavator (cf. WackerNeuson, 2021a), two dump trucks (cf. WackerNeuson, 2021b; cf. WackerNeuson, 2021c) and a wheel loader (cf. WackerNeuson, 2021d) in its product range. In addition to its existing fully electric machines – the ECR25 compact excavator and L25 compact wheel loader – Volvo CE has introduced another wheel loader and two compact excavators (cf. Volvo CE, 2021a).

The fact that at present, it is mostly machines with outputs of less than 50 kW that are being electrified is not attributable solely to the requirement to reduce CO_2 emissions but is also due to pragmatic time-to-market considerations.

- Compact machines are ideal for purely battery-electric operation, as they do not need a lot of power and are not normally in operation for more than four hours a day.
- In addition, it is relatively easy to replace the combustion engine in a compact machine by an electric motor. Due to the relatively low daily operating times, the corresponding battery can be sized accordingly and easily integrated into the vehicle. No changes are necessary to the remaining drivetrain, which can be used as is.
- Moreover, in the compact machine segment there are already some successfully commercialized electric motors that can be taken over from other applications like counterbalance forklifts, allowing economies of scale to be exploited.
- Apart from the commercial aspects, the area of use also plays a crucial role for the electrification of compact machines, which are used above all indoors or in inner city areas, where improving air quality and reducing local CO_2 emissions and noise load are especially important.

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Figure 5 provides an overview of electrified excavators with outputs of less than 50 kW, including their respective stage of development.

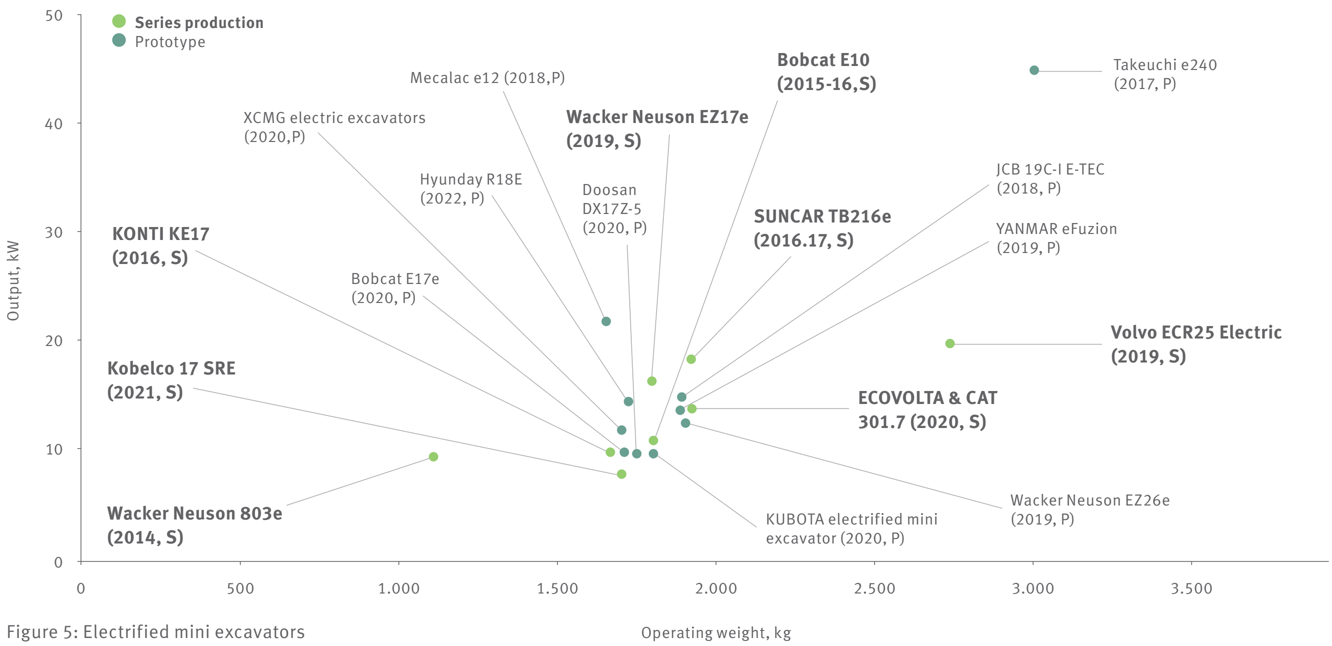


Figure 5: Electrified mini excavators

In a 2020 study, McKinsey predicts the share of purely battery-electric powered construction machines in the compact segment to be around 15% – 30% in the next 10 years, while larger, more power-hungry machines up to outputs of 150 kW and 10 operating hours will only account for 5% – 15% (cf. McKinsey, 2020).

However, the fuel cell is better suited to more powerful machines with outputs higher than 150 kW and more than 10 operating hours. Compared with the charging cycle of a battery, hydrogen for the fuel cell can be refilled more quickly. In addition, the power density of a fuel cell is currently higher than that of a battery (cf. McKinsey, 2021b).

STM Stieler also envisages similar growth in battery-electric construction machinery in the next few years. Moreover, growth of the same magnitude is also forecast for hybrid vehicles (cf. STM Stieler, 2018).

On the other hand, British consultancy Knibb, Gormezano and Partners (KGP), which focuses on the Offroad sector, thinks that fully electric drives in construction machinery make sense for niche applications. For outputs greater than 50 kW, hybrid solutions will predominate. KGP considers the fuel cell to be rather unsuitable (cf. KGP, 2021).

Conversely, JCB sees the fuel cell and hydrogen combustion as the drive solutions of the future. JCB Chairman Lord Bamford announced that the company will continue to invest in the fuel cell, as it believes that battery-electric drives do not offer an all-round solution and will only become established in the lower output class (cf. Stone, 2021).

Following a thorough analysis of these studies, Schaeffler is assuming a future spread of 70% combustion engines, 15% hybrids and 15% battery-electric drives in 2030 (Figure 6).

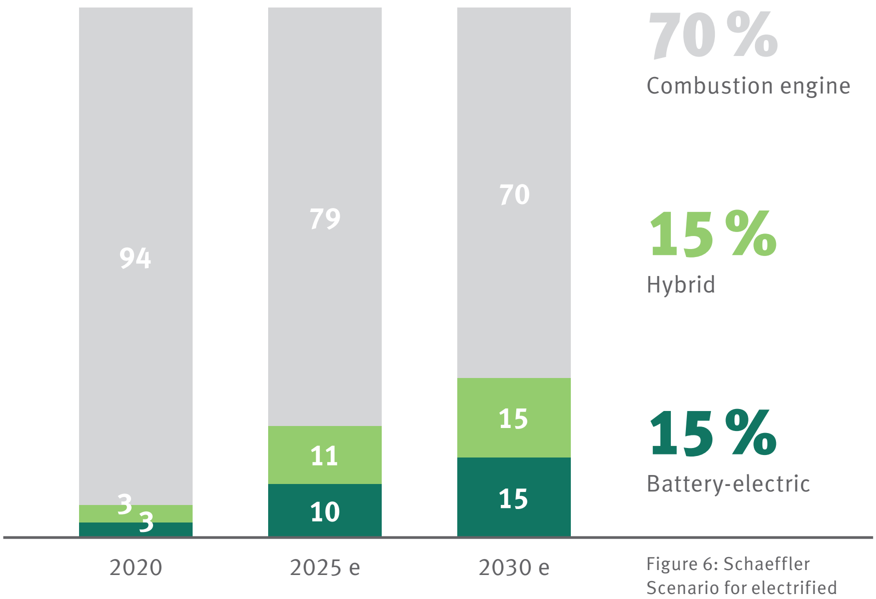


Figure 6: Schaeffler Scenario for electrified construction machinery

According to Schaeffler, even higher-powered construction machines (greater than 50 kW) will assume an important role in the electrification process.

Some construction machine manufacturers, for example, do not just have electrified compact machines in their product range but for several years now have also been developing larger electrified vehicles.

At the Bauma 2020 exhibition in China, Volvo Construction Equipment, for example, showcased two battery-electric crawler excavators, a 5.5 t and a 22 t. Both developments are currently undergoing field tests at selected customers (cf. Volvo CE, 2021b).

Komatsu has also signed a collaboration agreement with battery supplier Proterra Inc. with a view to bringing powerful battery-electric excavators into commercial production from 2023 (cf. Proterra, 2021).

As a Tier 1 supplier in the electric mobility segment, Schaeffler has also been conducting in-depth development talks with some OEMs for several years now. The projects under discussion include small to large wheel loaders with a well-known German manufacturer of construction machinery, large wheel loaders and haulers with a US manufacturer, and electric drive solutions for shovel loaders with a UK company.

Electrical sub-systems and components

When considering electrified sub-systems and components, the experts from Interact Analysis determined that the global market in 2020 amounted to €9 billion, and that it will rise to more than €21 billion by 2030 at a CAGR of 8%.

Interact Analysis believes that in this context, the greatest challenges are (source: Interact):

- low economies of scale due to widely varying vehicle sizes,
- different electricity demands,
- wide range of work cycles,
- lack of charging infrastructure and
- long downtimes during charging periods.

When considering the individual sub-systems in a mobile work machine, the greatest sales potential is offered by batteries, inverters and motors, says Interact Analysis (Figure 7).

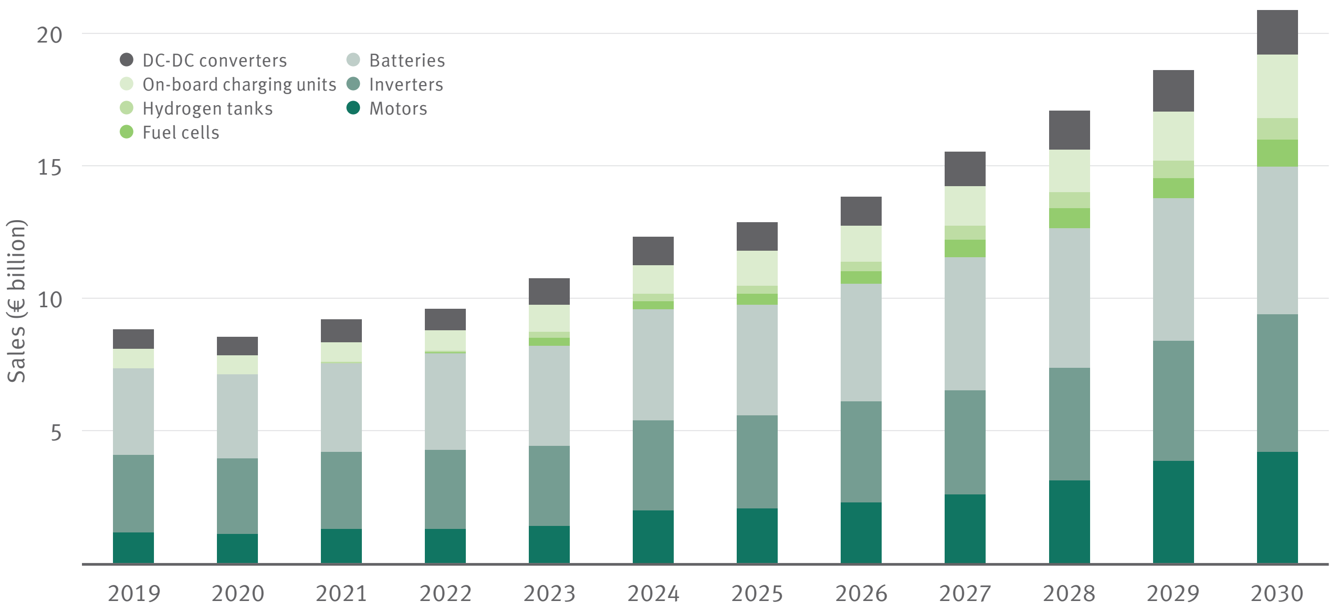


Figure 7: Global market for electrified Offroad equipment by component (own diagram based on Hayfield, 2021)

According to this analysis, forklifts will continue to take the lead when it comes to electrification. It is assumed that in 2030, 50% of the components for electrified Offroad machines will continue to be used in forklifts. In addition, the proportion of electrical solutions specifically for excavators, tractors and wheel loaders will increase to more than 30%. This means that in 2030, these four types of Offroad vehicles will account for more than 80% of the component market for electric mobility (Figure 8).

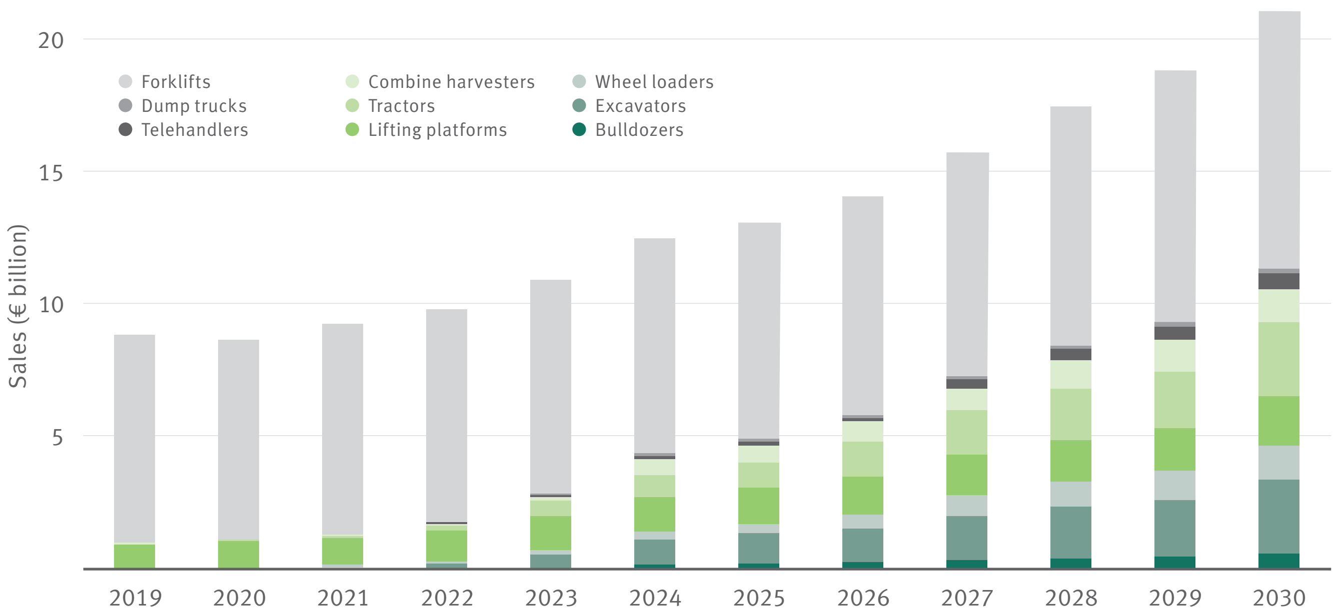


Figure 8: Global market for electrified Offroad equipment by vehicle application (own diagram based on Hayfield, 2021)

Regionally, the focus of electrification will shift from Europe and America to Asia-Pacific and China. China in particular will be a driver of electric mobility with a significant increase in electrified Offroad vehicles (cf. Hayfield, 2021).

Based on its experience from various projects and initiatives in recent months, Schaeffler believes that the electrification of construction machinery in the coming years will enjoy accelerated growth in both the compact and larger machine segments. This view is also supported by the expected gradual tightening up of the legislative frameworks.

Other groundbreaking initiatives are expected to emerge from the 26th UN World Climate Conference in Glasgow from Oct. 31, 2021 to Nov. 12, 2021 (cf. UN Climate Change Conference UK 2021, 2021).

Electrical drive concepts

The development of drive concepts is currently experiencing great momentum. Various approaches are being presented on the market at increasingly shorter intervals. Technological progress, the necessary infrastructure and government subsidies, which affect cost-benefit analyses, will determine which solutions will ultimately prevail as 'best practice'.

Regardless of whether battery-electric drives or fuel cells are used, various architectures can be identified.

As with the compact construction machines, the combustion engine can be replaced by an equivalent electric motor, as shown in the example of a wheel loader in Figure 9. The advantage of this is that it is easy to implement without a lot of extra design modifications. A second electric motor is used for the operating functions.

Another possible concept is to replace the diesel engine with two smaller electric motors for the drive plus a third electric motor for the operating functions. Two motors work together to drive the transmission and thus provide the total output necessary for the drive. The benefits are lower heat generation and better scalability. Limiting factors are the robustness of the transmission and rising costs, because an extra converter is needed for each additional motor and the control software gets more complex.

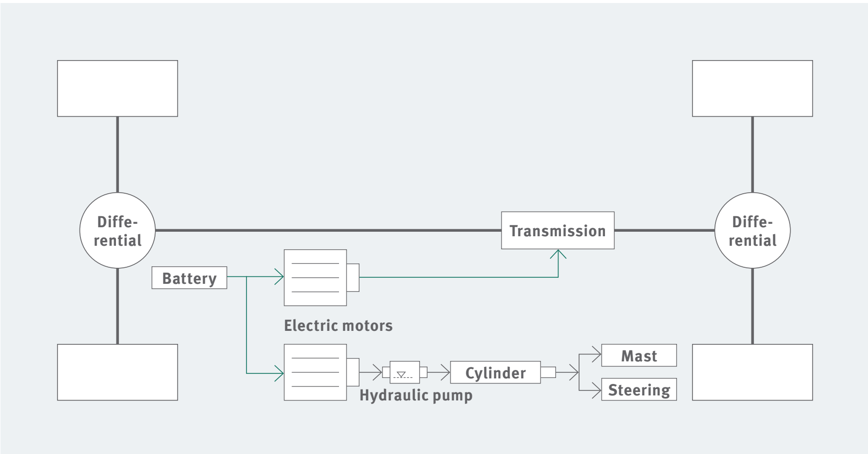


Figure 9: Electrification of a wheel loader with conventional drivetrain retained

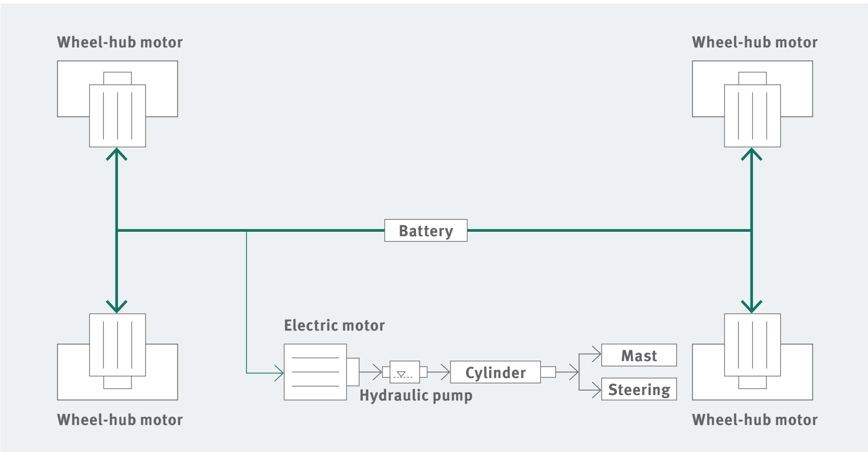


Figure 10: Electrification of a wheel loader with wheel-hub motors

Another concept to separate operating and driving functions is the use of wheel-hub motors. In this case, four separate motors are inserted into the wheel hubs. Accordingly, the electric motor for the operating functions is designed small, see Figure 10.

Figure 11: Power wheel

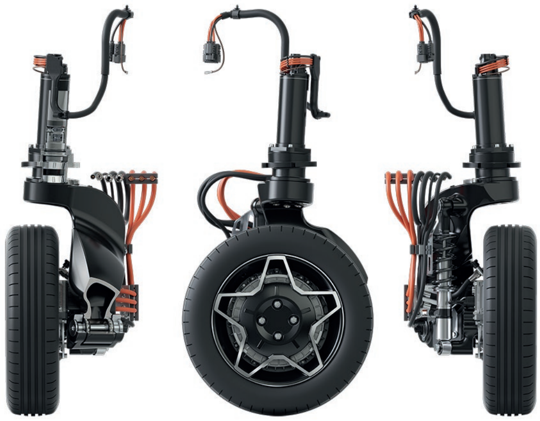


Figure 12: Wheel module from Schaeffler

These wheel-hub drives are being developed at Schaeffler under the name ‘Power wheel’ (Figure 11). Moreover, an additional integration of the steering into the wheels allows completely new approaches in mobility.

Schaeffler’s wheel module (Figure 12) offers both drive and steering in the individual wheels and allows the vehicle to turn on the spot thanks to a steering angle of 90°, offering a crucial advantage on narrow construction sites.

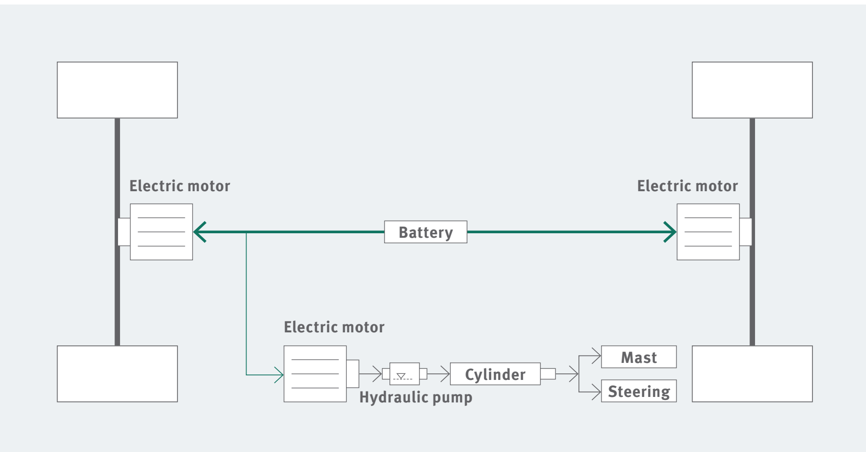


Figure 13: Electrification of a wheel loader with electric axle drives.

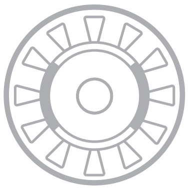
The fourth concept, see Figure 13, consists of what are called ‘electric axles’. In this case, as with the concept described above, the drivetrain is largely dispensed with. The electric motors are integrated directly into the front and rear axles. In this concept too, a conventional engine can be replaced by two smaller and more efficient electric motors. An additional third motor is used for the operating functions.

Due to the different requirements on the output of the construction machines, Schaeffler assumes that there will be use cases for all concepts.

Electric motors

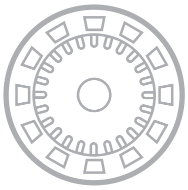
Regardless of which electrification concept takes hold, at least one electric motor will always be needed. Using the example of the electrified wheel loader with conventional drivetrain, the chart below looks at the necessary characteristics of the electric motor for mobile machines (cf. Lajunen et al., 2018, p.10 f).

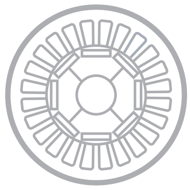
- Efficient cooling
- Compactness (torque-to-weight ratio)
- High torque
- High energy efficiency over wide operating range
- Low costs



	Permanent magnet synchronous motor (PSM)	**Synchronous reluctance motor (SRM)**
Field excitation, rotor	Permanent magnet	Reluctance
Torque density in basic setting range	Very high	Low
Power drop in field shunting range	High	Very low
Maximum efficiency	Very high	Medium
Cycle efficiency	Medium	Medium
Advantages	High efficiency, high torque density	Simple structure, low power drop in field shunting range
Disadvantages	Magnet protection required against centrifugal force, risk of demagnetization, short circuits, drag torque due to induced voltage	Low torque density, noise, torque ripple

Table 1: Characteristics of common types of electric motors





Externally excited synchronous motor (EESM)	Asynchronous motor (ASM)	PSM with buried (interior) magnets (IPM)
Excitation coils + reluctance	Short circuit squirrel cage winding	Permanent magnet + reluctance
High, provided transformer is possible in same installation space	Medium	High
Very low	High	Medium
Medium	Low	High
Very high	High	High
High efficiency in field shunting range, flexible control of rotor flux, no drag torque, safe condition when de-energized (isolation), not dependent on price of magnets	No drag torque, safe condition when de-energized, not dependent on price of magnets	Balanced characteristics, ideal compromise
Transformer (installation space, service life), heat dissipation rotor, imbalance, additional circuit in inverter necessary for rotor excitation	Low efficiency, complex controllability, heat dissipation rotor	Short-circuit behavior, drag torques due to induced voltage

For construction machinery, the use of permanent magnet synchronous motors (PSM), synchronous reluctance motors (SRM), externally excited synchronous motors (EESM), asynchronous motors (ASM) and permanent magnet synchronous motors with buried magnets (IPM – interior permanent magnet synchronous motor) is conceivable. The respective modes of operation, characteristics and associated advantages and disadvantages are shown in Table 1.

According to Interact Analysis, the majority of electric motors used in the future will be PSMs (cf. Hayfield, 2021). The PSM meets the requirements for electric motors for construction machinery mentioned above, since among other things it offers high efficiency and very high torque density in the basic setting range. The drawbacks are the need to secure the permanent magnets against centrifugal force, the risk of demagnetization, short-circuit behaviors, and drag torque due to induced voltages.

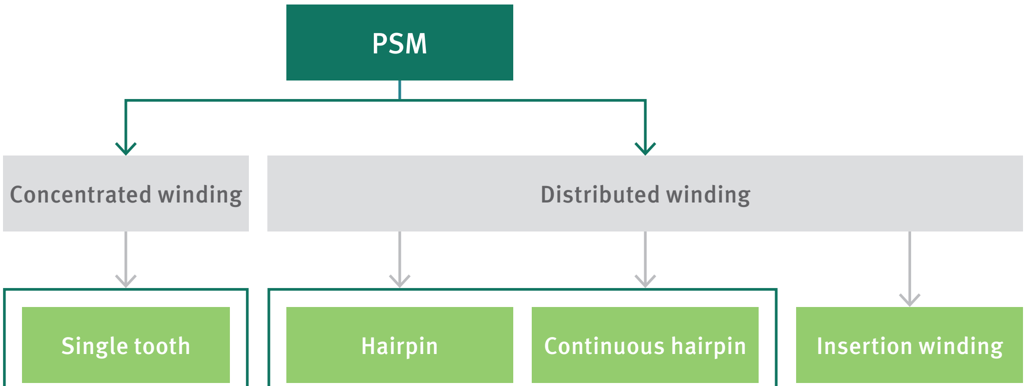
The SRM has a simple structure and the power drop in the field shunting range is very low compared with the PSM. The negatives are the low torque density in the basic setting range and poor performance in respect of noise development and torque ripple. The maximum efficiency is fairly average, by comparison.

With the FSM, the torque density in the basic setting range is high, provided the installation space can accommodate the transformer. The power drop in the field shunting range is very low. However, the transformer needs a relatively large installation space and only has a limited service life. The rotor also needs an additional circuit in the inverter for control purposes. The FSM only has a medium total efficiency.

The ASM only has a medium torque density in the basic setting range, the power drop in the field shunting range is high, and the maximum efficiency is low. Although there is no torque drag, and the motor is not dependent on the price of magnets, the negative characteristics predominate.

Schaeffler is therefore concentrating on the IPM for its motor development. The IPM combines the strengths of the PSM with the advantages of the reluctance effect. This reduces the power drop in the field shunting range, resulting in a motor with balanced characteristics. The permanent magnets no longer need to be secured as they are buried in the motor.

In this context, Schaeffler uses various winding methods. These technologies, and their associated characteristics, are shown in Figure 14.



	Single tooth	Hairpin	Continuous hairpin	Insertion winding
Winding overhangs	+ good	0 medium	0 medium	– poor
Torque ripple	– poor	+ good	+ good	+ good
Space factor	0 medium	+ good	+ good	– poor

Figure 14:
Winding technologies for permanent magnet synchronous motors

Rolling bearing technology

Apart from the use of alternative drive systems, a large proportion of greenhouse gases and GHG emissions can still be reduced in conventionally powered, mobile work machines.

In this context, measures to mitigate against climate change are taken along the complete supply chain. Therefore a circular approach, in which waste products and the use of raw materials can be minimized, makes sense.

A change in production and consumption models is essential to achieve sustainability goals. A raw material must no longer just be processed in the production chain and then disposed of after use. Rather, it is important to bring these products and materials back into circulation. The goal is produce machines that use renewable energy efficiently, are built without waste, have maximum operating times and an optimal lifespan

(cf. Wordsworth, S., 2021. Keys to a carbon neutral future (and it's not just electromobility). Ivtinternational.com).

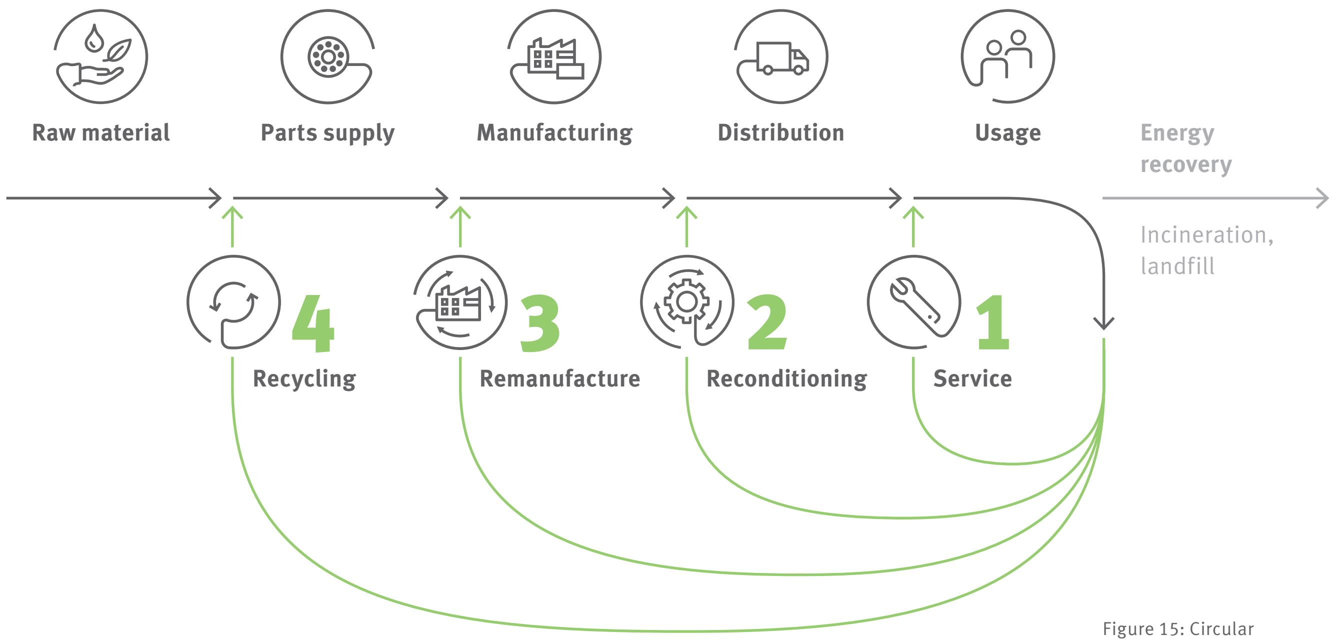
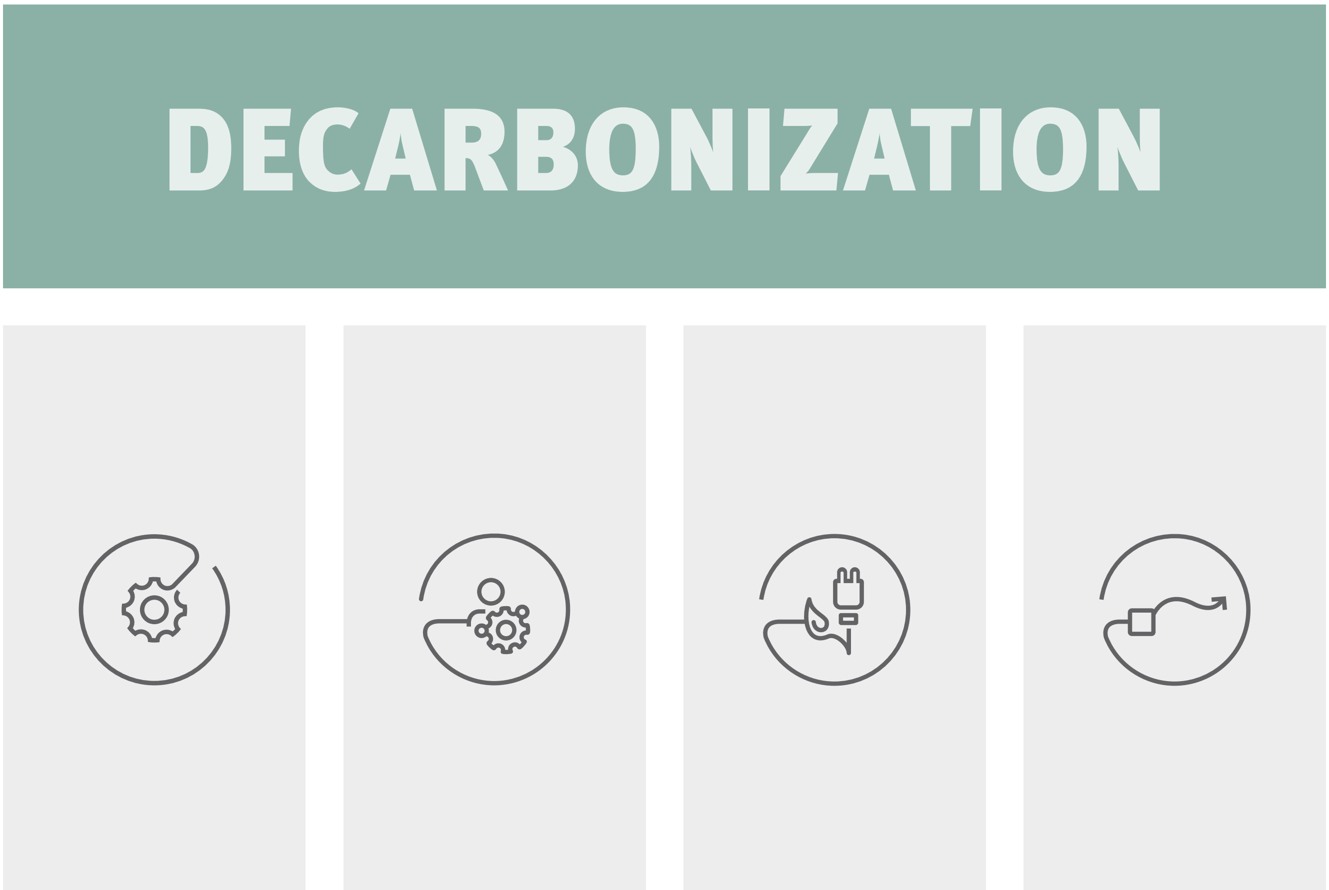


Figure 15: Circular approach to sustainability (own diagram based on Wordsworth, S., 2021. Keys to a carbon neutral future (and it's not just electromobility). Ivtinternational.com)

In this context, significant reductions in CO_2 emissions result from innovations.

The decarbonization of the construction industry is based on four pillars:



Machine efficiency
Integration of optimized machine components and sub-systems (e.g. motor, transmission, hydraulics, rolling bearings etc.)

Efficient operation
Professional machine operators for efficient and effective use of the machines

Alternative energy sources
Use of synthetic or biological fuels, electrical drives, hydrogen etc.

Process efficiency
Optimal workflow – including choice of most suitable machines and their combination

Figure 16: Four pillars of sustainable energy efficiency for the construction industry (own diagram based on CECE, CEMA, 2018, p. 4)

Modern machines can be made more environmentally friendly through alternative drive systems and ‘smart’ technologies, but other components like rolling bearings can also reduce greenhouse gas emissions when optimized (cf. CECE, CEMA, 2018, p. 4).

In this context, suppliers can make a major contribution to machine efficiency, because emissions occur among other reasons due to power loss (friction) in the entire drivetrain.

According to a 2017 study by Prof. Dr. Kenneth Holmberg and Dr. Ali Erdemir, about 1/3 of all energy produced worldwide is lost due to friction. As a result, not only does friction add 8.1 Gt CO_2 to total global emissions, it also gives rise to costs amounting to €250 billion (cf. Hollmberg, Erdemir, 2017, p. 271).

More efficient work machines that optimally exploit the power of diesel engines can cut fuel consumption and as a result, significantly reduce GHG emissions.

With this in mind, Schaeffler conducted an analysis based on a tractor in the medium power range (83 kW engine power at a nominal speed of 2,200 rpm to ECE R120). The complete drivetrain of the tractor was considered, including the various load cases and operating cycles with and without power takeoff.

The calculation of the mean system friction of the bearings in the tractor produced a striking result: the average friction loss of all bearing positions per tractor was more than 3%. A consistent optimization of the rolling bearing points would save 252 liters of diesel and/or 670 kg CO_2 after just the first 1,000 operating hours.

We know that in Offroad applications, various hydraulic units are responsible for the power transmission. Variable axial piston pumps and motors are specifically designed for the use of electrical machine control systems.

In this conjunction, friction-optimized rolling bearing solutions have a very substantial influence on the reduction of power loss, installation space and weight.

In close collaboration with a renowned hydraulic pump manufacturer, Schaeffler has optimized numerous bearing points for the development of new axial piston pumps and motors and is using highly efficient bearing solutions.

A key role is played by X-life cylindrical roller bearings with optimized rib contact. X-life stands for eXtended life or maximum service life. These bearings feature an optimized internal design and improved raceway topography. Depending on model, the dynamic load rating is at least 30% higher than for conventional rolling bearings.

The improved contact geometry between end face and rib minimizes the maximum contact pressure, allowing a load-bearing lubricant film to form. The rollers now slide on the lubricant film under axial load. This means it is possible to operate the cylindrical roller bearings with a Fa/Fr ratio of 0.6. The admissible axial load can therefore be 60 percent of the radial load. In conventional cylindrical roller bearings this value is just 40%. At the same time, the frictional torque reduces by up to 50% depending on axial load. This also has a positive effect on the bearing temperature during operation, increases efficiency and saves energy.

In the case of tapered roller bearings as well, the optimization of the rib contact is particularly important. Especially in the event of increasing axial load, the frictional torque of conventional tapered roller bearings increases significantly. In the case of the X-life tapered roller bearings, Schaeffler has therefore modified the geometry, surface topography, material, and dimensional and running accuracy. The result is an increase in dynamic load ratings by up to 20%, which is associated with an increase in service life of up to 70%. At the same time, the greater dimensional and running accuracy, in combination with the improved surface topography, reduces the frictional torque by up to 75% compared with conventional products. Thanks to the optimized friction, there is less strain on the lubricant, extending lubricant service life and consequently, maintenance intervals. All adjustments to the internal design lead overall to a significant reduction in noise in the X-life tapered roller bearings.

Ultimately, the overall efficiency of pumps and motors could be increased by around 2% in each case, and the systems could therefore be designed to be much more energy efficient.

In total, around 9 kW can be saved in the case of a wheel loader with a new hydraulic pump and two hydraulic motors with a drive power of 140 kW. Extrapolated to 1,000 wheel loaders working for eight hours, this results in an annual savings potential of around 26,000 MWh. This is equivalent to the average annual energy consumption of more than 6,500 three-person households and translates to savings of around €7.5 million (0.30€/kWh) or about 16,000 tons of CO_2. This in turn is equivalent to the annual emissions from 4,200 compact cars with an annual mileage of 25,000 km each.

As well as the hydraulic units, substantial efficiency improvements can also be realized through application-specific optimizations in the transmission systems. Building on the above-mentioned X-life design, and using our own simulation software Bearinx, the design of the rolling bearings is precisely adapted to the load spectrum and conditions of the respective transmission. In addition, the roller profile, rib contact and micro-geometry of the raceways could be optimized thanks to advances in manufacturing technology and as a result, the tapered roller bearing could be made even more smooth-running.

We have therefore managed to reduce the friction of the 6-gear dual clutch transmission of a SUV with an unladen weight of 1,370 kg and a 120 kW diesel engine by 71% compared with the standard solution. Specifically, this means a reduction of CO_2 emissions by 3.8 g per kilometer traveled.
Converted to the total emissions of the vehicle this corresponds to a reduction of 2.5%. The relationship between friction and the various development stages of the tapered roller bearings is shown in Figure 17:

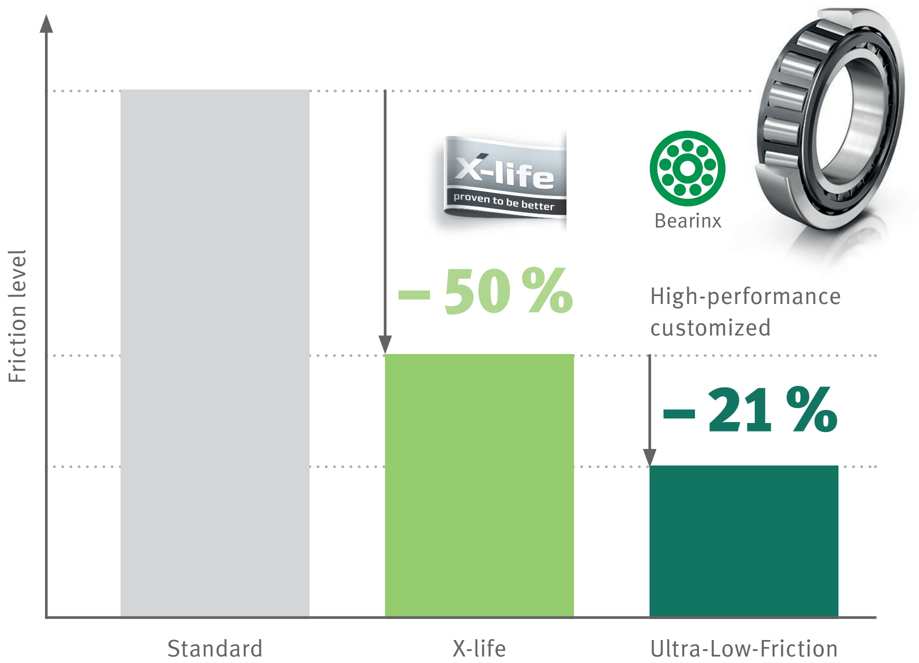


Figure 17: Friction level of tapered roller bearings

References

Holmberg, K. und Erdemir, A. (2017): Influence of tribology on global energy consumption, costs and emissions. In: Friction. Vol. 5 (3). S. 263 – 284.

McKinsey (2021a): Call for action: Seizing the decarbonization opportunity in construction.
Online unter URL: https://www.mckinsey.de/industries/engineering-construction-and-building-materials/our-insights/call-for-action-seizing-the-decarbonization-opportunity-in-construction (Abruf 19.10.2021)

United Nations (2018): The World's Cities in 2018.
Online unter URL: https://www.un.org/en/events/citiesday/assets/pdf/the_worlds_cities_in_2018_data_booklet.pdf (Abruf 12.02.2021).

United Nations (2019): Population Facts.
Online unter URL: https://www.un.org/en/development/desa/population/publications/pdf/popfacts/PopFacts_2019-6.pdf (Abruf 12.02.2021).

VDMA (2017): Emissionsgesetzgebung für Mobile Maschinen: EU Stufe V – Fact Sheet.
Online unter URL: https://bub.vdma.org/documents/266753/15008694/1494833760690_2017-05-15_VDMA_EU%20Stufe%20V_Fact%20Sheet_DE.pdf/562d8124-cc59-4cfd-9249-17d7c10ad012 (Abruf 18.06.2021).

United Nations (2021): The Paris Agreement.
Online unter URL: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (Abruf 24.06.2021).

Wordsworth, S. (2021): OPINION: Keys to a carbon neutral future (and it's not just electromobility).
Online unter URL: https://www.ivtinternational.com/opinion/opinion-keys-to-a-carbon-neutral-future-and-its-not-just-electromobility.html (Abruf 14.10.2021)

Schröder, Dr. Marit (2021): Weltklimarat: Doppelter Weckruf durch den IPCC-Bericht.
Online unter: https://www.topagrar.com/energie/news/weltklimarat-doppelter-weckruf-durch-ipcc-bericht-12660605.html (Abruf 05.10.2021).

IPCC (2021): Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [MassonDelmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Bellona Europa (2021): Norwegian cities lead the way in reaching zero-emissions in construction sites.
Online unter: https://bellona.org/news/climate-change/2021-03-norwegian-cities-lead-the-way-in-reaching-zero-emissions-in-construction-sites (Abruf 05.10.2021).

Danfoss (2021): Leading toward zero-emission construction. (PowerPoint)

KGP (2021): Options for low-carbon mobile machinery. (PowerPoint)

WackerNeuson (2021a): EZ17e – Der erste elektrische Minibagger von Wacker Neuson.
Online unter: https://www.wackerneuson.ch/de/produkte/zero-emission/ez17e/model/ez17e/ (Abruf 07.10.2021).

WackerNeuson (2021b): DW15e – Der Elektro-Raddumper mit Allrad Antrieb.
Online unter: https://www.wackerneuson.ch/de/produkte/zero-emission/dw15e/model/dw15e/ (Abruf 07.10.2021).

WackerNeuson (2021c): DT10e – Elektro Dumper.
Online unter: https://www.wackerneuson.ch/de/produkte/zero-emission/dt10e/model/dt10e/ (Abruf 07.10.2021).

WackerNeuson (2021d): WL20e – Innovativ, elektrisch, emissionsfrei – der Radlader mit Elektroantrieb.
Online unter: https://www.wackerneuson.de/de/produkte/zero-emission/wl20e/model/wl20e/ (Abruf 07.10.2021).

Volvo CE (2021a): MEHR POWER FÜR IHR BUSINESS.
Online unter: https://www.volvoce.com/deutschland/de-de/products/electric-machines/add-silence/ (Abruf 07.10.2021).

McKinsey (2020): Offroad follow up. (PowerPoint),

McKinsey (2021b): Offroad (PowerPoint),

STM-Stieler (2018): Future drive technologies for mobile working machines 2020/2025 Construction equipment.

Volvo CE (2021b): VOLVO CE PRESENTS CONNECTIVITY, AUTOMATION AND ELECTROMOBILITY INNOVATIONS AT BAUMA CHINA 2020.
Online unter: https://www.volvoce.com/global/en/news-and-events/press-releases/2020/bauma-china-2020-press-kit/volvo-ce-presents-connectivity-automation-and-electromobility-innovations-at-bauma-china-2020/ (Abruf 08.10.2021).

Proterra (2021): Komatsu and Proterra Announce New Collaboration to Develop All-Electric Construction Equipment.
Online unter: https://www.proterra.com/press-release/komatsu-electric-construction-equipment/ (Abruf 08.10.2021).

Hayfield, Alastair (2021): Interact Analysis Projects 150% Growth By 2030 for Off-Highway Electrified Components Market.
Online unter: https://www.oemoffhighway.com/market-analysis/news/21735164/interact-analysis-projects-150-growth-by-2030-for-offhighway-electrified-components-market?utm_source=OOH+Equipment+Market+Outlook+eNL&utm_medium=email&utm_campaign=HCL210923007&o_eid=1651F0081734E6V&rdx.ident%5Bpull%5D=omeda%7C1651F0081734E6V&om_id=1024748005&oly_enc_id=1651F0081734E6V (Abruf 08.10.2021).

Stone, Tom (2021): Boris Johnson attends JCB unveiling as firm announces £100m hydrogen-engine investment.
Online unter: https://www.ivtinternational.com/news/engines/boris-johnson-attends-jcb-unveiling-as-firm-announces-100m-hydrogen-engine-investment.html. (Abruf 25.10.2021).

UN Climate Change Conference UK 2021 (2021): COP26.
Online unter: https://ukcop26.org/. (Abruf 25.10.2021).

Lajunen, Antti; Sainio, Panu; Laurila, Lasse; Pippuri-Mäkeläinen, Jenni; Tammi, Kari (2018): Overview of Powertrain Electrification and Future Scenarios for Non-Road Mobile Machinery. In: Energies, 2018, 11, 1184.

Porsche Consulting (2021): The Future of Construction Machinery Manufacturers. Ecosystem with a new perspective.

CECE, CEMA (2018): CECE and CEMA Optimising our industry 2 reduce emissions.
Online unter https://www.cece.eu/stream/cececo2booklet-1.3.pdf (Abruf 25.10.2021).

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