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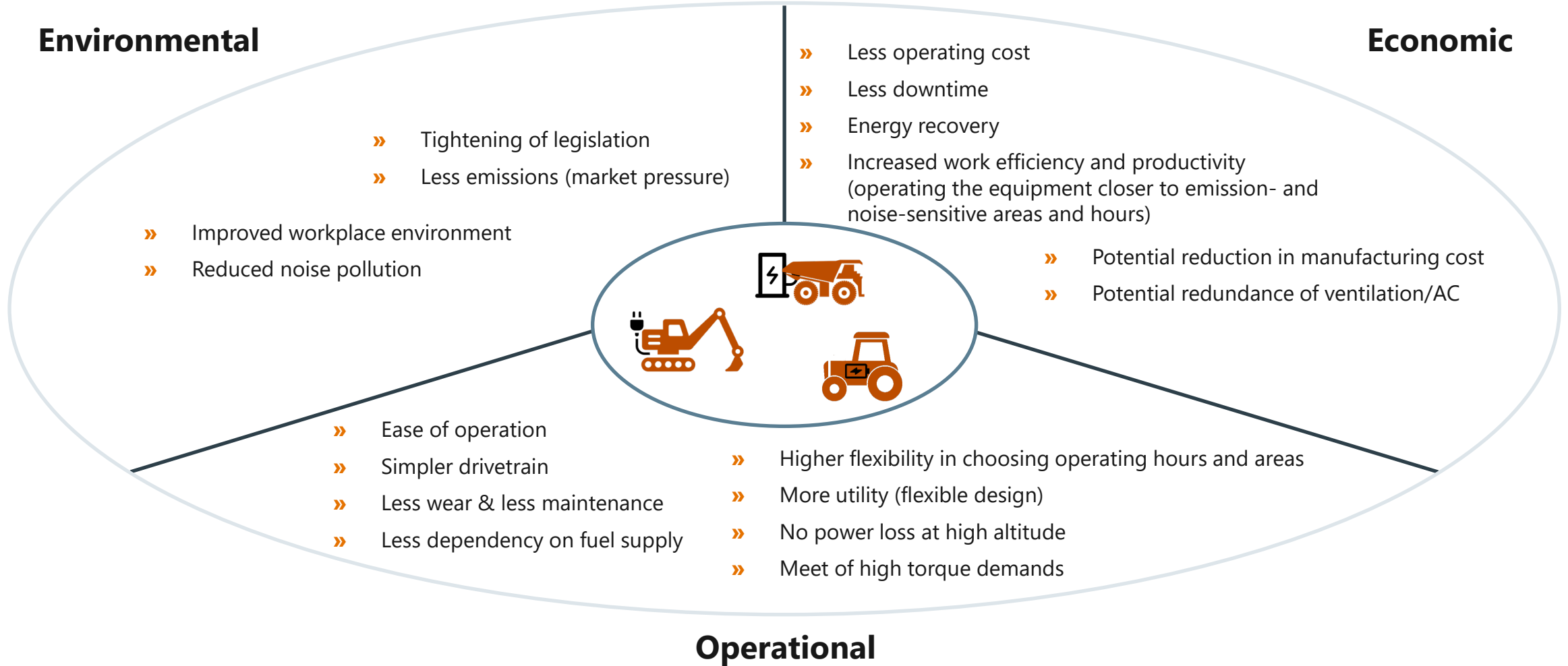
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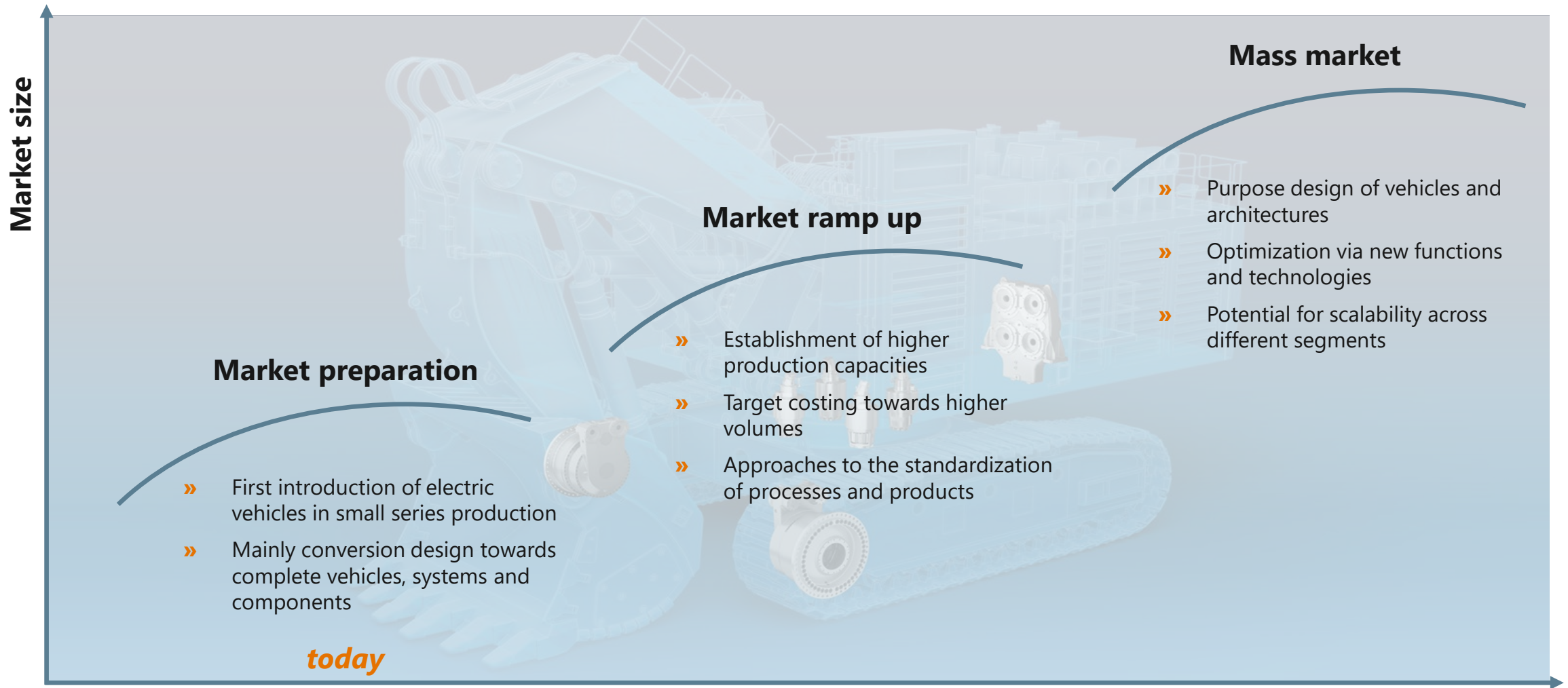
# ACTIVATE TECHNOLOGY AND BUSINESS POTENTIALS IN THE ELECTRIFICATION OF OFF-HIGHWAY VEHICLES

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# In the off-highway industry, reduction of emissions and pollution is a major driver – however not the only important force for electrification



# Relevant off-highway OEMs have already started their xEV activities with potential for suppliers to cooperate in an early market preparation phase



# On the path to mass market, the diversified industry requires different strategies and electrification architectures according to power supply

## Industry needs



### Agriculture

- » Precise timing requirements
- » Requires robust equipment for harsh environments like high heat, moisture, dust
- » Unique infrastructure challenges: Sites often located in rural areas lacking grid connection

**Seasonal use patterns and high power demands.**



### Construction

- » Great variety of machinery, power levels and duty cycles
- » Sites are usually temporary, location in proximity to grid feeders
- » Change in power requirements during the project period

**Equipment is likely to be used for a variety of applications over its lifetime.**



### Mining

- » Different equipment requirements during the different stages of mine development
- » Long life requirements up to 25 years
- » Site remoteness: May require on-site large-scale renewable power generation or battery-swapping

**Wide variety of requirements with highly variable duty cycles and high power demands.**

## Architectures



### Battery type

- » Battery is the only energy storage unit
- » Suitable wheel machineries as the battery need to be recharged regularly
- » Sites where the power grid is not convenient, or the machines need to walking around frequently

**Work completely disconnected from any external power source.**



### Tethered battery type

- » Can be powered by power grid or battery
- » Size of the battery can be reduced considerably
- » Suitable for most working conditions
- » Other combinations conceivable: e.g. power grid type with external power type

**Possibility of using vehicle during charging.**

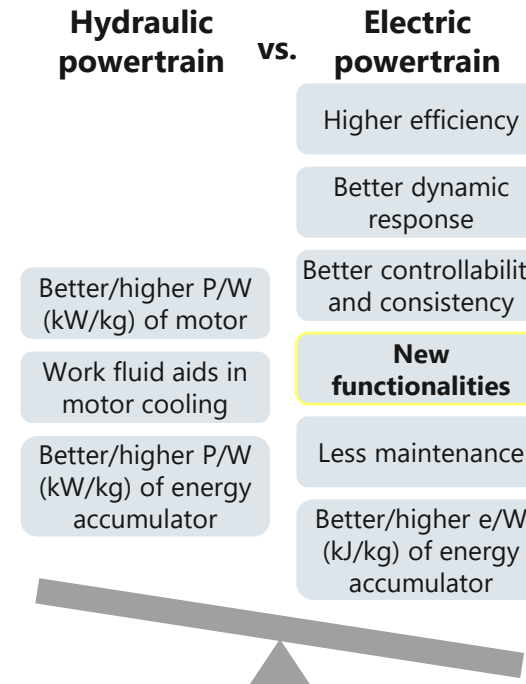
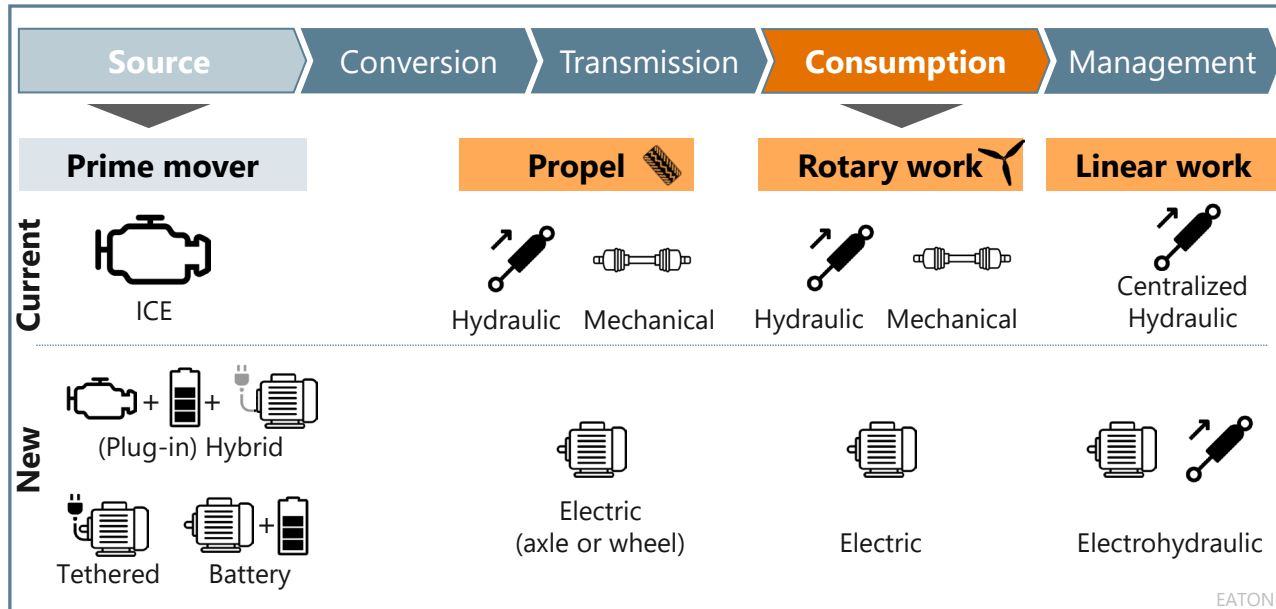


### Tethered type

- » Constant physical connection to an external electric source needed
- » Working scope is limited and working flexibility is greatly reduced
- » Possibility to electrify even extremely large excavators

**Needs constant physical connection to an external electric source.**

# Use case driven electrification approaches with commonalities in terms of primary movement and power consumption that can be exploited at scale

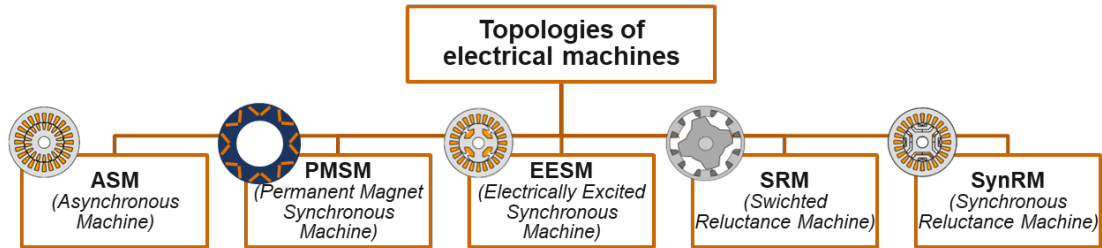


- Energy recovery:**
- » Besides the braking system, other options include **energy recovery from power tools** employed by off-road equipment
  - » Prominent examples are the boom and swing of excavators

- » Off-highway electrification brings **focus to more than just the prime mover**
- » While ICEs usually require mechanical devices and/or hydraulic systems for power transfer, electric motors can be distributed differently on the vehicle platform
- » Possibilities of **exploiting the benefits of torque vectoring** are even more profound in off-highway compared to on-highway



# Off-highway sector with specific requirements – however, experience gained in the on-road sector can be leveraged to push electrification



	ASM	PMSM (IPM)	EESM	SRM	SynRM
Cost	++	-	0	+	++
Torque/Power Density	0	++	+	0	0
Efficiency	+	++	+	+	+
Simplicity/Manufacturability	++	0	-	++	++
Controllability	+	+	0	0	+
Reliability	++	+	+	++	++
Weight/Volume	+	++	0	+	+
...					
Field Weakening	++	+	++	++	++
Fault Tolerance	++	-	++	++	+
Thermal Limitations	+	-	+	++	++
NVH	++	++	+	-	-
...					
Max. Speed	++	0	+	++	+
...					

Legend	General assessment	Dominating advantage	Dominating disadvantage
+	+	green	red
-	-		

Main properties of most common electric motors in both the automotive and the off-highway industries

- » ASM and PMSM are best suited to meet BEV/HEV requirements in passenger cars, while SRM has almost no relevance due to NVH performance
- » By now, ASM and PMSM are mostly used in off-highway applications as well, however, SRMs have been highlighted as the biggest future improvement in electric motors by combining the best of ASM & PMSM
- » **SRM is of great interest** because of the absence of rare earth elements and the advantages of simple structure, low cost, high efficiency and reliability
  - » Disadvantage of **NVH may not be as relevant for some off-highway applications as it is in the automotive sector**
  - » However, development efforts in **power electronics for NVH improvement remain in focus**

# Different use cases in the off-highway sector can lead to alternative energy storage systems like supercapacitors for specific operations

	Lead-acid battery	Flywheel	Super-capacitors	Hydraulic accumulator	Ni-MH battery	Li-ion battery
<b>Specific power (W/kg)</b>	75-300	400-1500	500-5000	2000-19,000	150-200	250-340
<b>Specific energy (Wh/kg)</b>	30-50	10-30	2.5-5.5	2	100-120	75-200
<b>Energy density (Wh/l)</b>	50-80	20-80	35	5	150-180	200-500
<b>Cycles</b>	500-1500	20,000	100,000	100,000	2500	2000-10,000
<b>Efficiency (%)</b>	<80	<96	<95	90	90	95

- » Along with li-ion batteries, supercapacitors as well as hydraulic accumulator interesting to meet high power demands
- » Hybrid energy storage solutions conceivable

## Challenges differ from those in the automotive sector:

- » Job sites differ in terms of conditions and duty cycles, so equipment within the same category can benefit from different technologies depending on its intended use
  - » Long service life of the devices can lead to them being exposed to different conditions
- » Facing deep charge and discharge, which puts forward higher requirements on the cycle times
- » Special working conditions that require the electric motor to operate in high torque mode with near zero speed
- » **Key requirements:** ensure the minimum operating time of the machinery and the dynamic performance of continuous large current discharge in case of sudden large load

# Summary and potential questions for your businesses

## Summary

- » **Diversified industry** requires different strategies for electrification
- » However: Commonalities within the off-highway industry and **expertise from on-highway** industry that **can be leveraged**
- » **Mid-term: Retrofitting** is key to success in electrification due to the long product life
  - » Potential for **standardization and scalability**
- » **Long-term: Purpose-built** architectures with the benefit of flexibility and greater possibility for torque vectoring
- » Technologies discussed on-highway may offer higher added value off-highway due to other requirements, however, **solutions remain site-specific:**
  - » Electric motor: SRM of great interest
  - » Energy storage: Supercapacitors and hydraulic accumulator as supplement or alternative
  - » Approach of battery swapping for large equipment

## Potential questions for your businesses

- » ***How do regulatory requirements for carbon reduction affect short-, mid- and long-term electrification approaches?***
- » ***How can I leverage my on-highway expertise and expand my portfolio to off-highway at large scales?***
- » ***How can I beneficially scale up my off-highway electrification activities?***
- » ***Are FCEVs inevitable for the electrification of large off-highway equipment?***
- » ***What partners are suited to guide the way?***



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