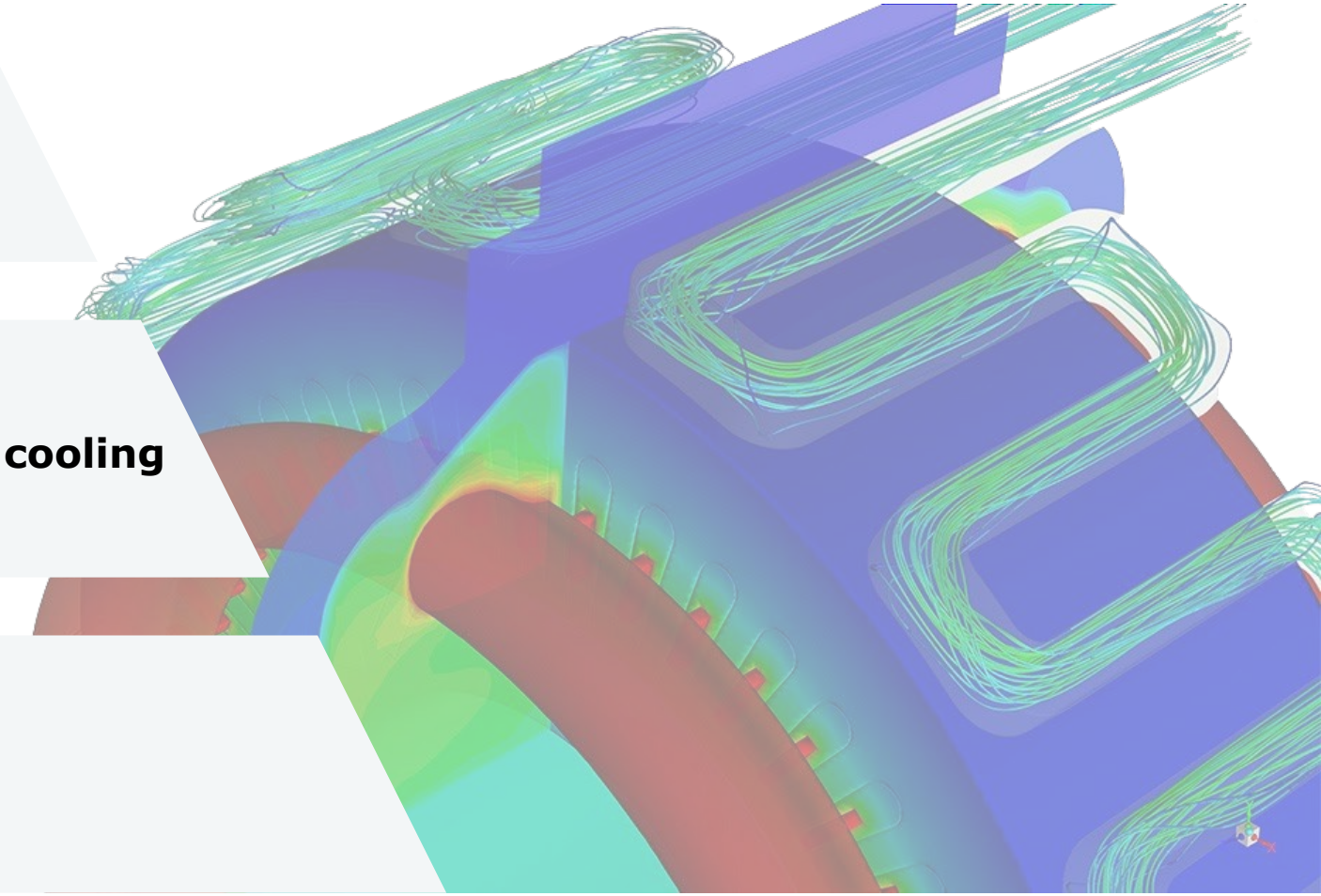
Quo vadis stator lamination stack? - Current innovations and future trends for stator lamination stacks in electric traction drives

Vienna, Electrical Steel Summit, 05th of May 2026

Content



Source: Ansys

Introduction

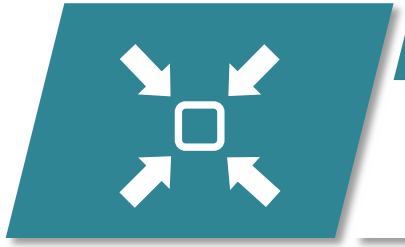
Necessity of cooling systems in electric drives

Improving peak performance

Motor **peak** and **continuous performance** is **limited** by **thermal capabilities** of several motor components. **Increased motor temperature** causes for example **premature failure** of the **insulation** systems.

Motor efficiency

The **electrical resistance** of **copper** has a **positive temperature coefficient**, i.e. the **higher** the motor **temperature**, the **higher** the **winding resistance** and the **lower** the **efficiency** of the **motor**.



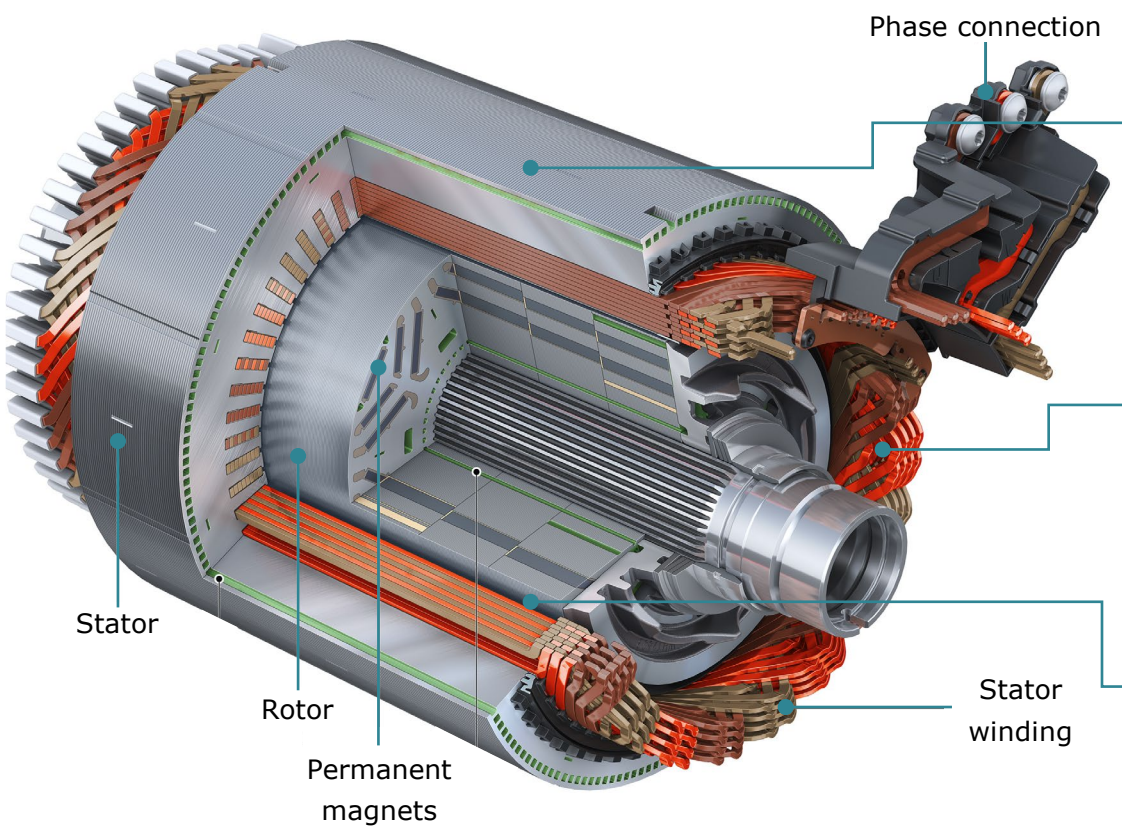
Downsizing

A **reduction** in the **motor installation** space with the same output power results in a **smaller surface area** available for heat dissipation and **therefore requires** a **more powerful cooling system**.

An **efficient cooling system** forms the basis for **powerful**, **efficient** and **cost-reduced electric motors**.

Introduction

Heat sources in electric traction drives



Iron losses

- Occur in the laminations and are dependent on the speed
- Subdivided into hysteresis, eddy current and additional losses
- Generate heat within the sheet lamination components

Ohmic losses

- Occur in the current-carrying conductors due to their electrical resistance
- Dependent on the specific electric resistance of the material, the length and the cross-sectional area

Additional losses

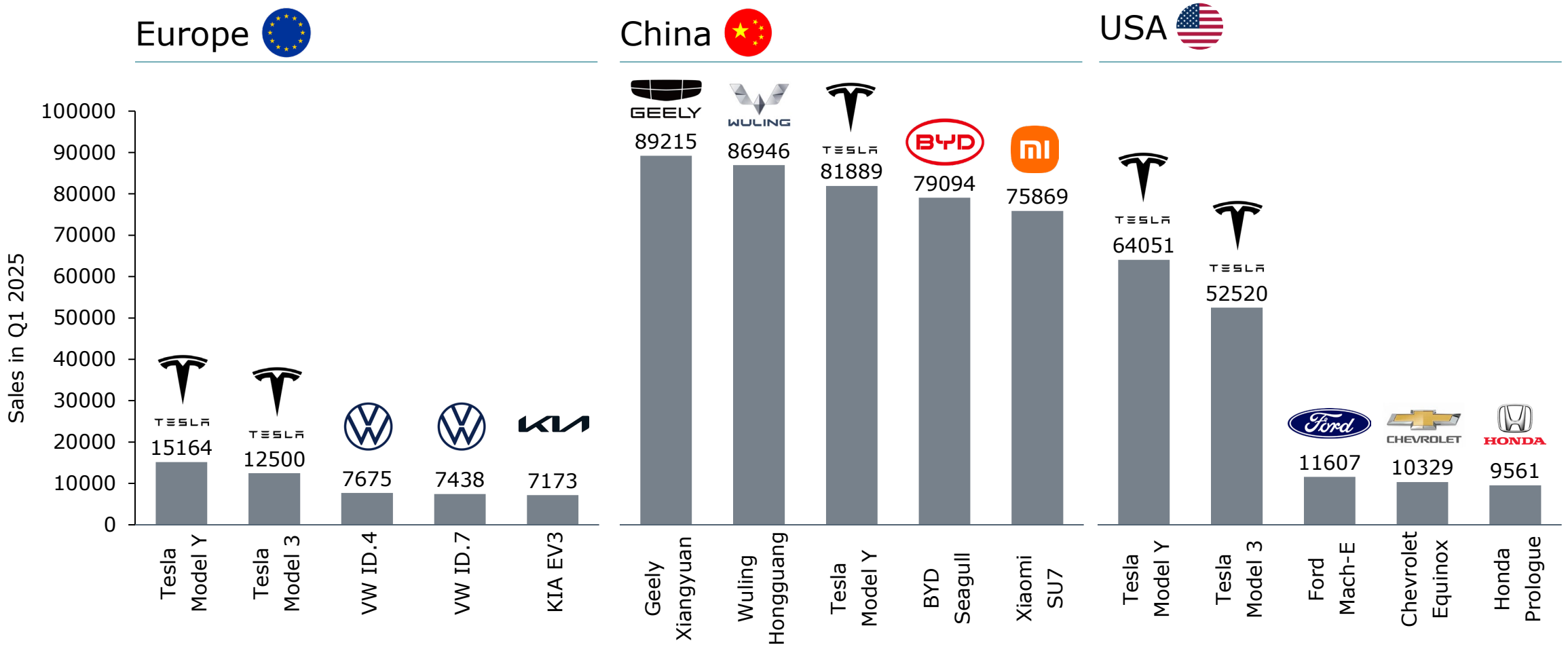
- Frictional losses in the bearings for holding the rotor shaft
- Ventilation losses inside the air gap and depend on the rotational speed as well as the form of the rotor

Since the **stator windings** account for a **significant portion** of **motor losses**, **effective cooling** of the stator winding is **crucial** for **efficient electric motor** operation.

Source: Audi Mediacenter

Current technologies for stator cooling

Top 5 sold BEV in Europe, USA and China in Q1 2025 (Top 5 cars each)



Source: pwc; JATO; CARSCOOPS

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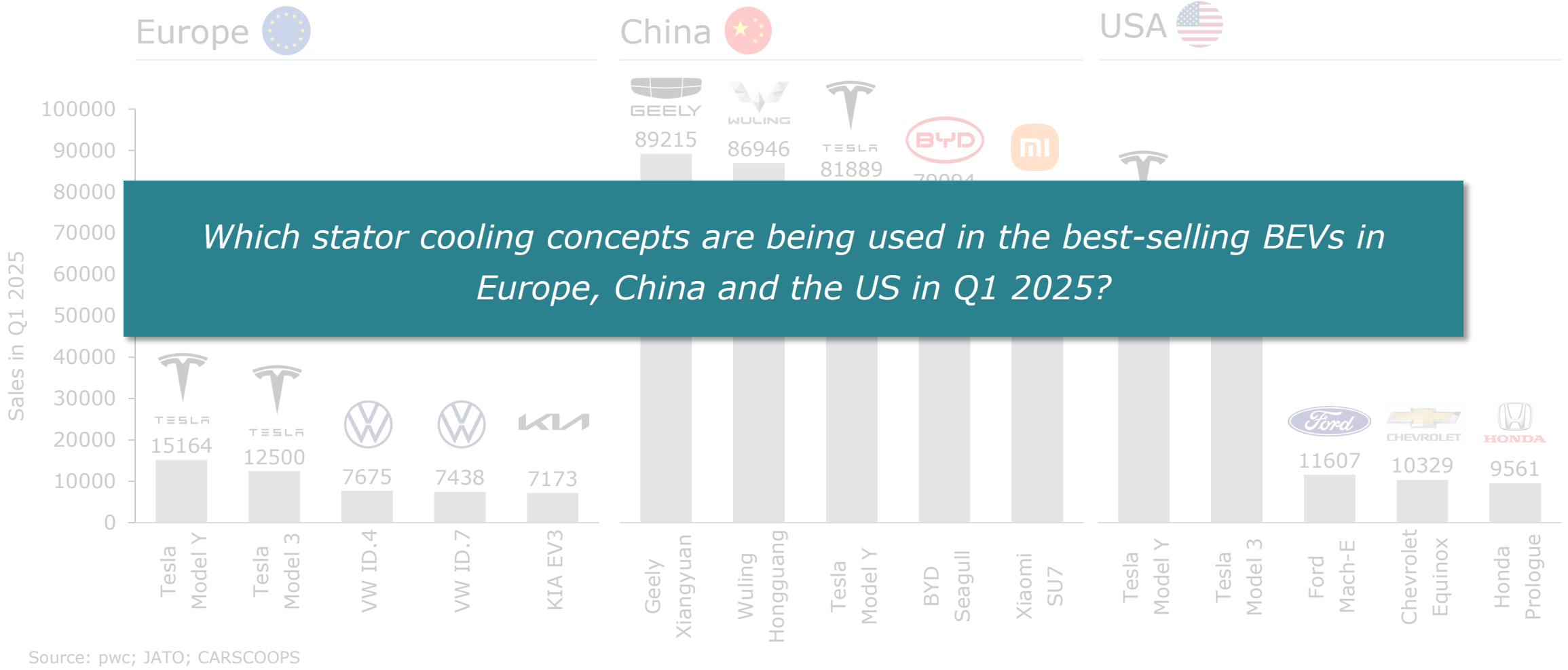


Which stator cooling concepts are being used in the best-selling BEVs in Europe, China and the US in Q1 2025?

Source: pwc; JATO; CARSCOOPS

Current technologies for stator cooling

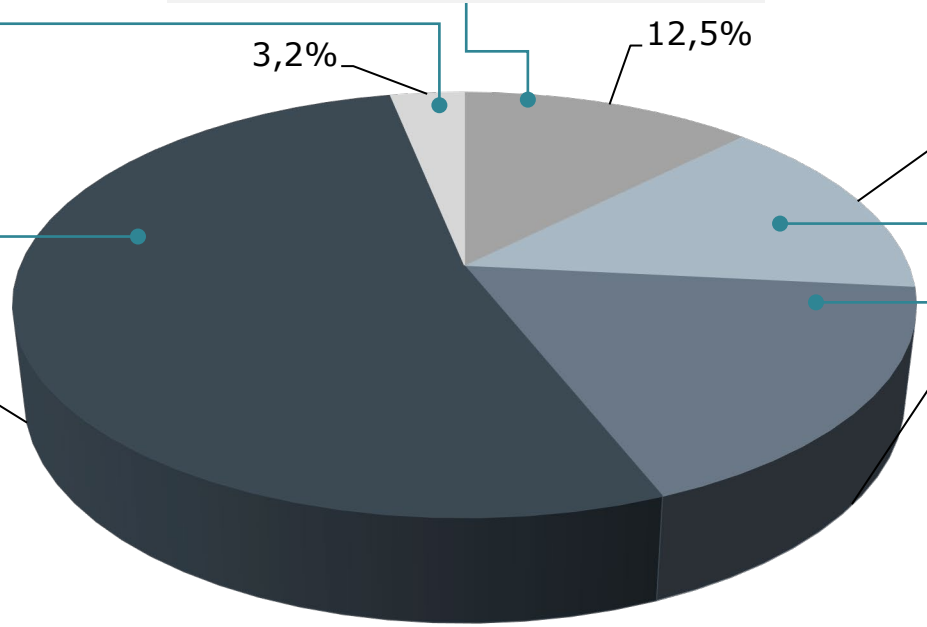
Analysis of most sold BEVs in Europe, USA and China Q1 2025

Share of the respective cooling concept on the total market volume under consideration

Liquid cooling jacket and direct winding head cooling
- VW ID.7, ID.4 and 5
- Skody Enyaq

Air cooled stator housing/ jacket
- Wuling Hongguang EV Mini

Liquid cooling jacket/ housing
- BMW iX1 and i4
- BYD Yuan Plus/ Atto 3
- Wuling Bingo
- VW ID.3



Direct winding head cooling and lamination stack cooling
- Tesla Model Y, 3, Cyber Truck
- Audi Q6 e-tron (PPE-Platform)
- Xiaomi SU7

Direct winding head cooling
- Renault 5
- BYD Seagull
- Hyundai IONIQ 5
- Ford F-150
- Ford Mustang Mach-E

* - Excluded from evaluation since no information regarding cooling technique could be identified:Chevrolet Equinox, Honda Prologue, Geely (Geome) Xingyuan, Xpeng Mona M03, Geely Panda

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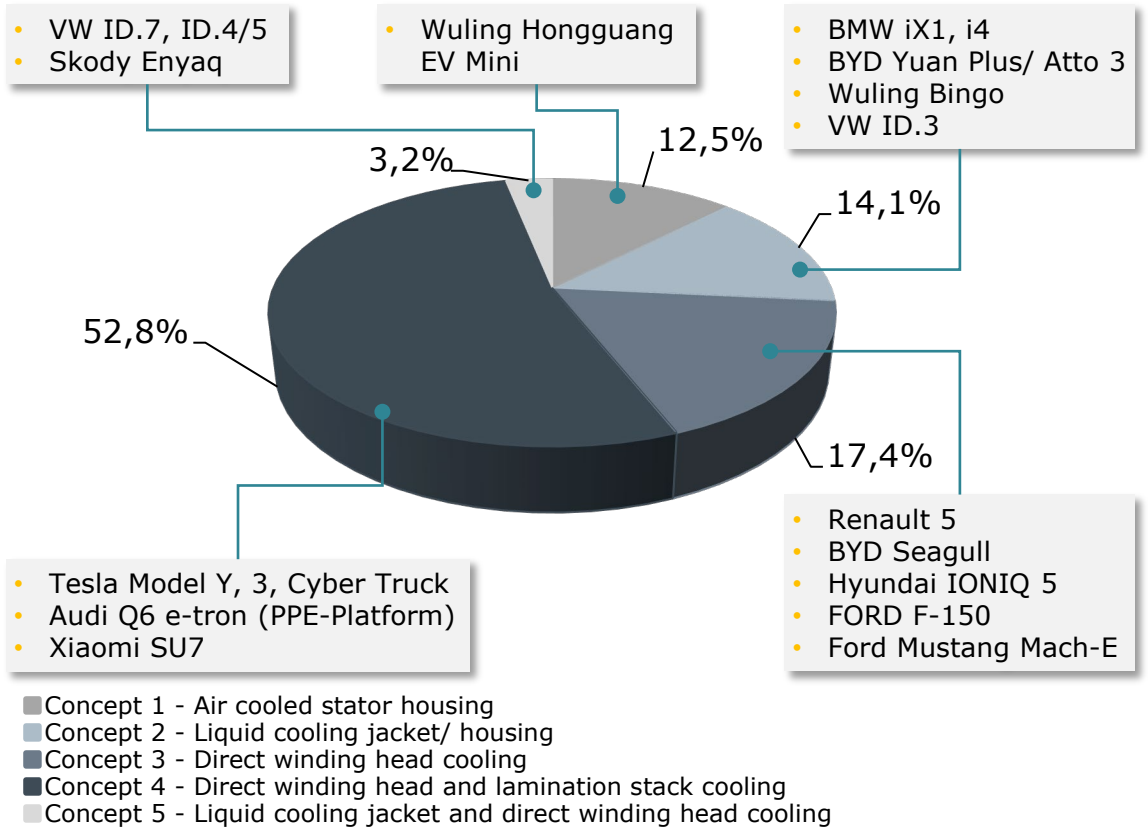

- Air-cooled electric drives in Micro- /A-segment cars, but only suitable for lower performance requirements
- Water jacket cooling is still a good, uncomplicated cooling technology, but is being used less and less due to its comparatively reduced cooling capacity
- Direct winding cooling using oil becoming increasingly established in Asia and also in vehicle models from European manufacturers
- Newer European manufacturers: PPE Platform from Audi and Porsche, the APP550 from VW and the Gen6 from BMW
- Variety of systems with different degrees of complexity:
  - Simple: Single or multiple number of spray nozzles/ rings (Renault 5, Hyundai IONIQ 5)
  - Complex: Application via the stator sheet lamination core or a hollow rotor shaft
- The ‘Direct winding head and lamination stack cooling’ represent the largest proportion and are also increasingly being used in newer vehicles due to the effectiveness and performance of the cooling system

* - Excluded from evaluation since no information regarding cooling technique could be identified:Chevrolet Equinox, Honda Prologue, Geely (Geome) Xingyuan, Xpeng Mona M03, Geely Panda

Current technologies for stator cooling

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Liquid cooling jacket / housing

- BMW iX1 and i4
- BYD Yuan Plus/ Atto 3
- Wuling Bingo

More than 70% of BEVs sold in Q1 2025 in Europe, USA and China use direct winding head cooling, in more than 50% of cases the cooling medium is fed through the stator sheet lamination stack.

Direct winding head cooling and lamination stack cooling

- Tesla Model Y, 3, Cyber Truck
- Audi Q6 e-tron (PPE-Platform)
- Xiaomi SU7

Direct winding head cooling

- Renault 5
- BYD Seagull
- Hyundai IONIQ 5
- Ford F-150
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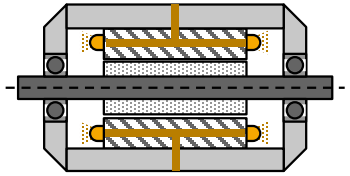
Current technologies for stator cooling

Direct winding head and lamination stack cooling

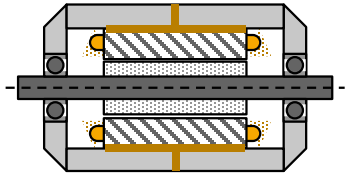
Technology description

- Oil is be sprayed onto the winding via cooling channels inside the sheet lamination stack
- Stack is also cooled by the flow of the oil through the sheet lamination stack
- Cooling channels can be positioned either at the outer edge of the stack (4.2) or in the area of the teeth (4.1)
- Function integration of cooling into the stator sheet lamination stack

Schematic sketch of technology variants



Spraying through slots in the stator lamination teeth



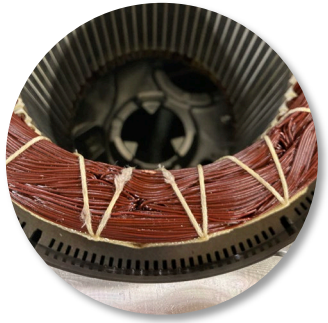
Spraying through slots in the out diameter of the stator lamination stack

Qualitative assessment[1]

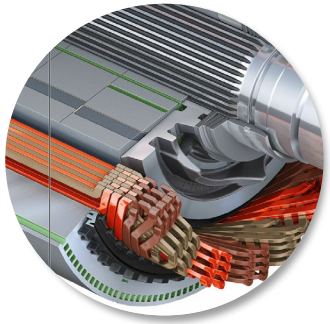
Cooling performance	1	2	3	**4**	5
Operation costs	1	**2**	3	4	5
Production costs	1	**2**	3	4	5
Technical integration effort	1	2	**3**	4	5

1 – 1 = Low / 5 = High; 2 – Benchmarking study by PEM RWTH; 3 – AUDI AG

Product examples



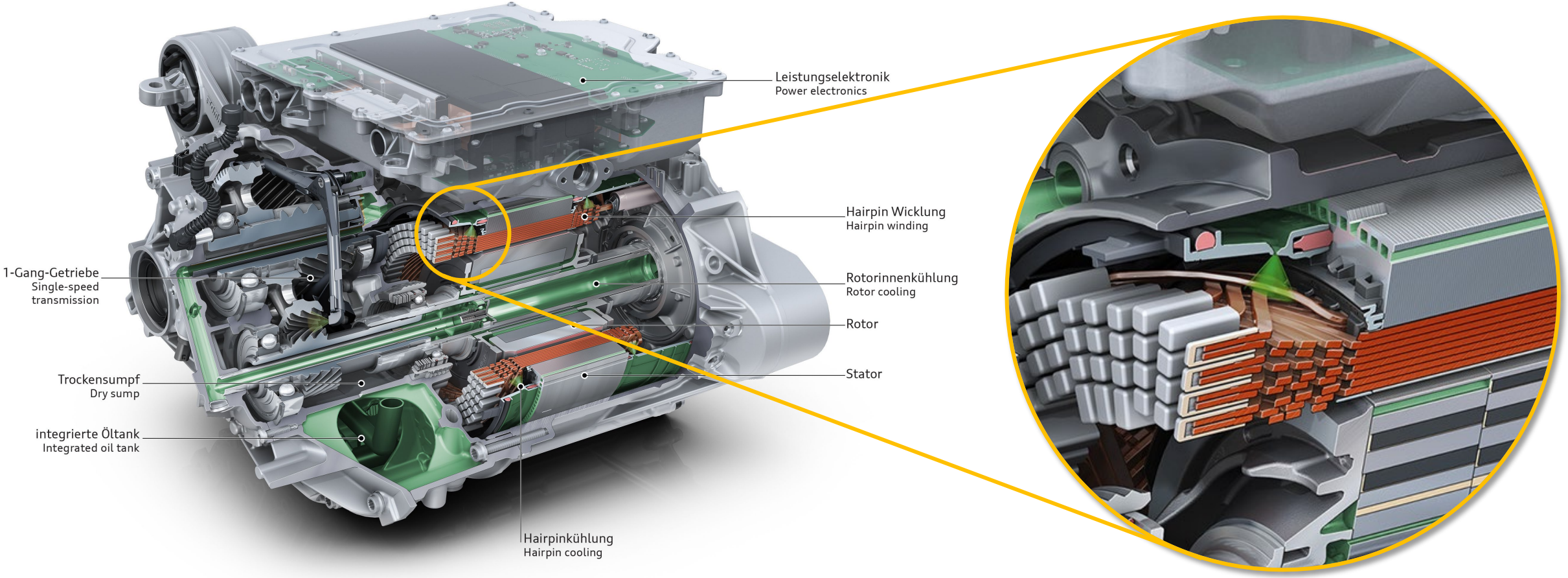
Tesla Model 3/ Y/ Cyber Truck[2]



Audi Q6 e-tron (PPE-Platform)[3]

Current technologies for stator cooling

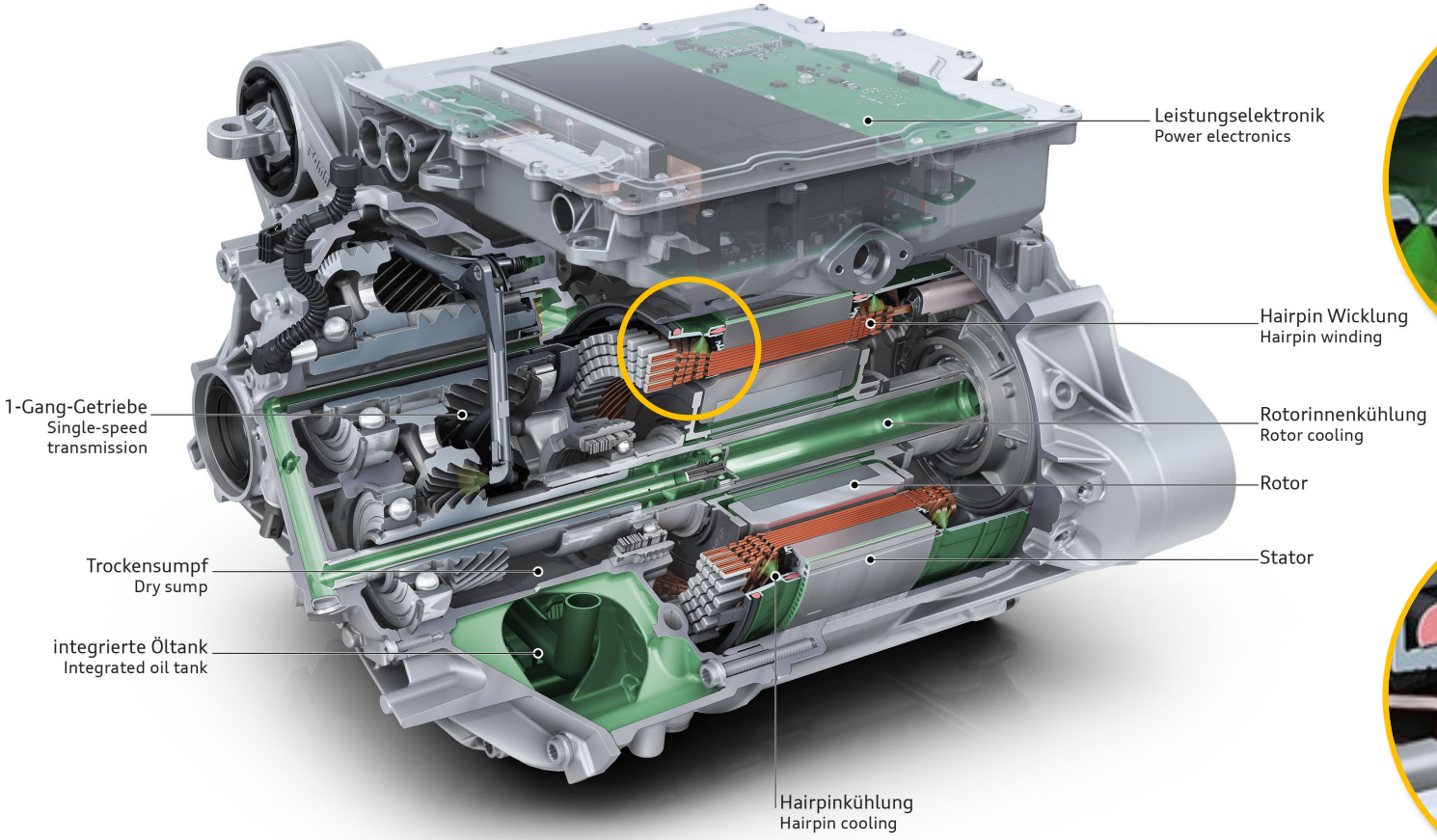
Direct winding head and lamination stack cooling – DeepDive: Audi Q6 e-tron (PPE-Platform)



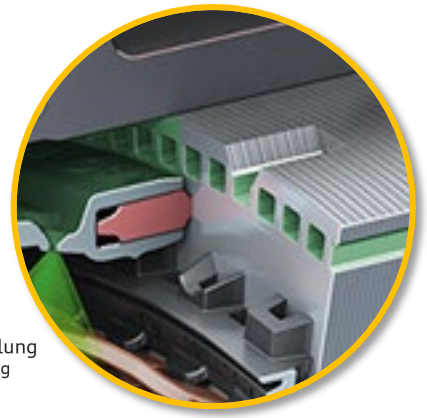
Source: AUDI AG

Resulting requirements

Additional requirements for the motor components



Source: AUDI AG

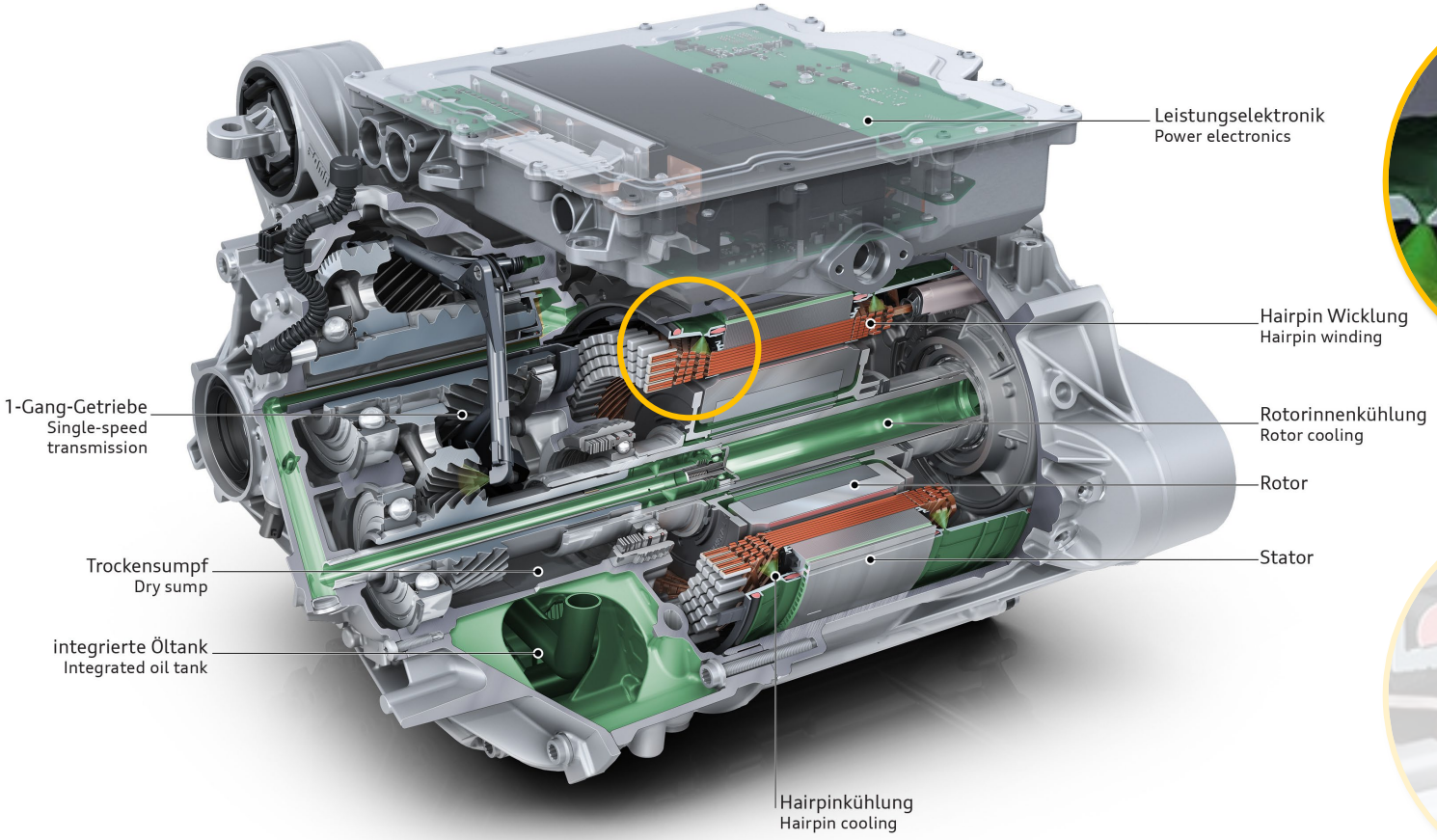


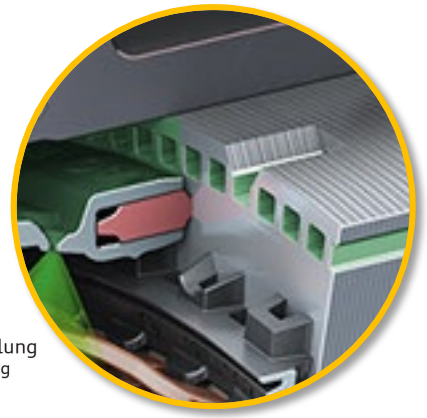
Leak tightness of the stator sheet lamination stack

Chemical stress on and ageing of the stator insulation system

Resulting requirements

Additional requirements for the motor components – Stator sheet lamination stack





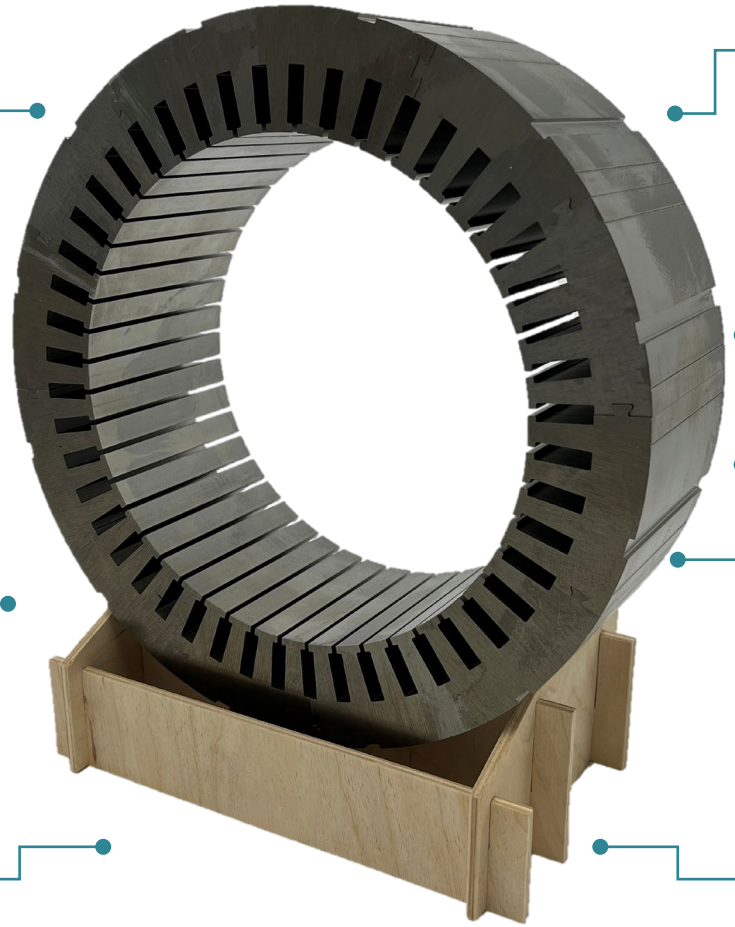
Leak tightness of the stator sheet lamination stack

Chemical stress on and ageing of the stator insulation system

Source: AUDI AG

Requirements for the stator lamination stack

Additional requirements for stator sheet lamination stack due to integration of cooling



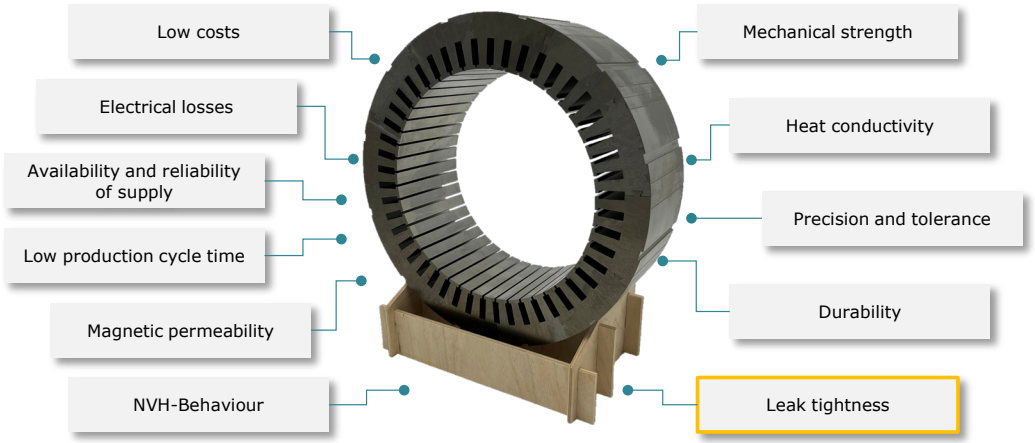
- Low costs
- Electrical losses
- Availability and reliability of supply
- Low production cycle time
- Magnetic permeability
- NVH-Behaviour
- Mechanical strength
- Heat conductivity
- Precision and tolerance
- Durability
- Leak tightness

Source: PEM RWTH Aachen

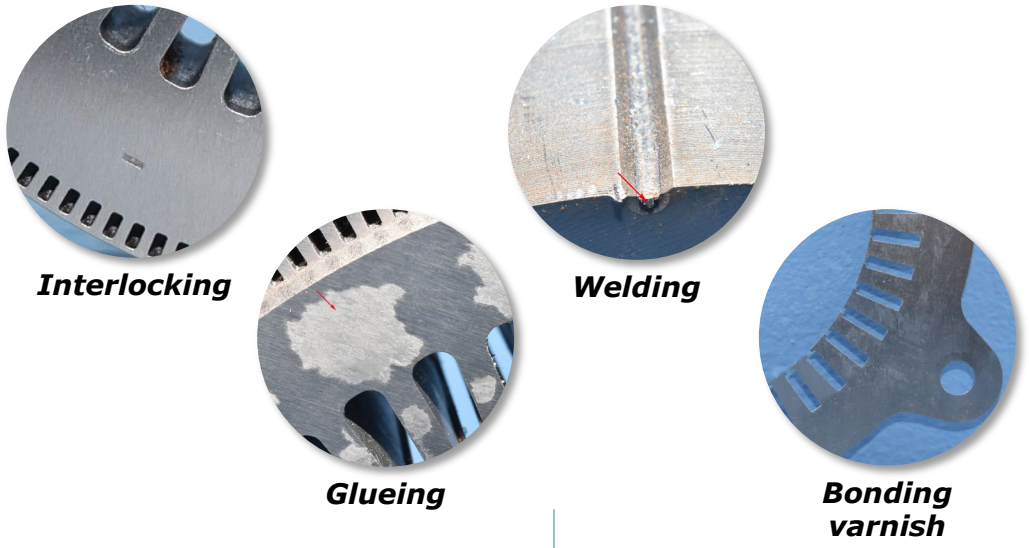
Requirements for the stator lamination stack

Examination of the available process against the background of new requirement

Additional requirement on stator lamination stack for leak tightness



Standard packaging technologies



Compatibility of packaging technologies and requirements for stator lamination stack remains questionable.

The established **packaging technologies** and their **combinations must** be **examined against** the background of the **new requirements.**

Source: PEM RWTH Aachen

Requirements for the stator lamination stack

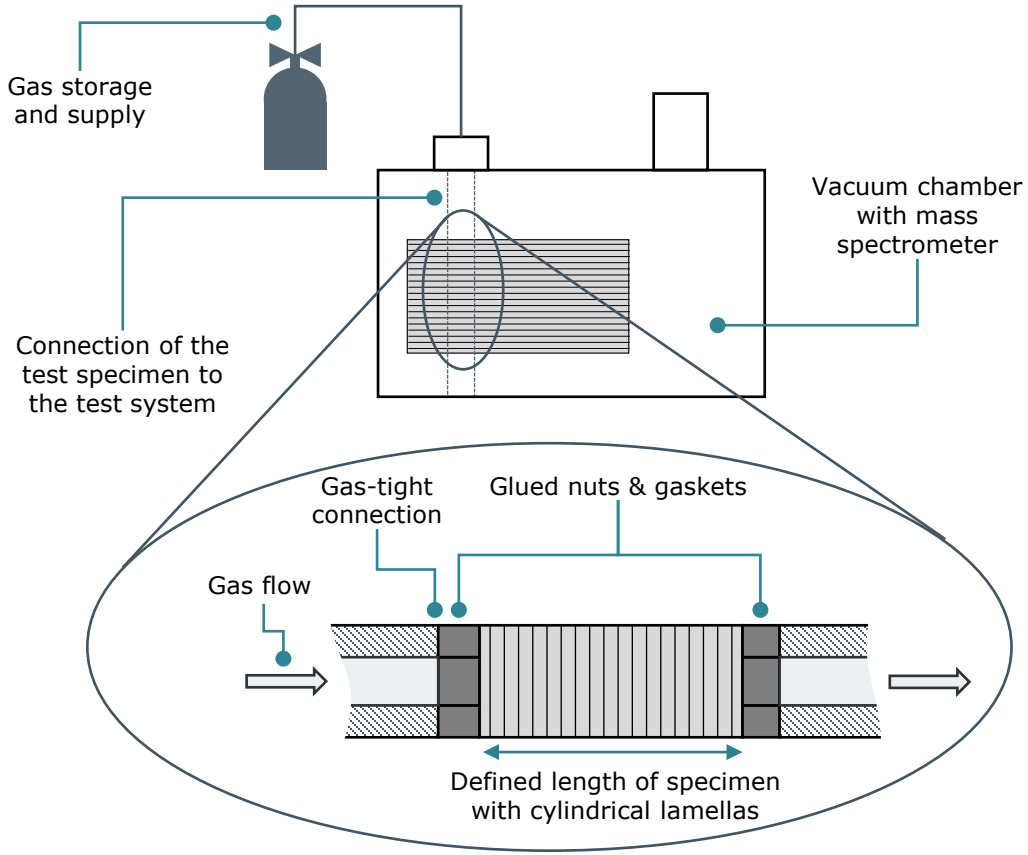
Test procedure for checking leak tightness

Test description

- Test specimen with a cooling channel is manufactured
- Test specimen in a vacuum chamber is connected to a gas supply
- Vacuum is applied and a gas fluid is directed into the cooling channel
- Gaseous fluid escaping from the cooling channel is detected with a mass spectrometer

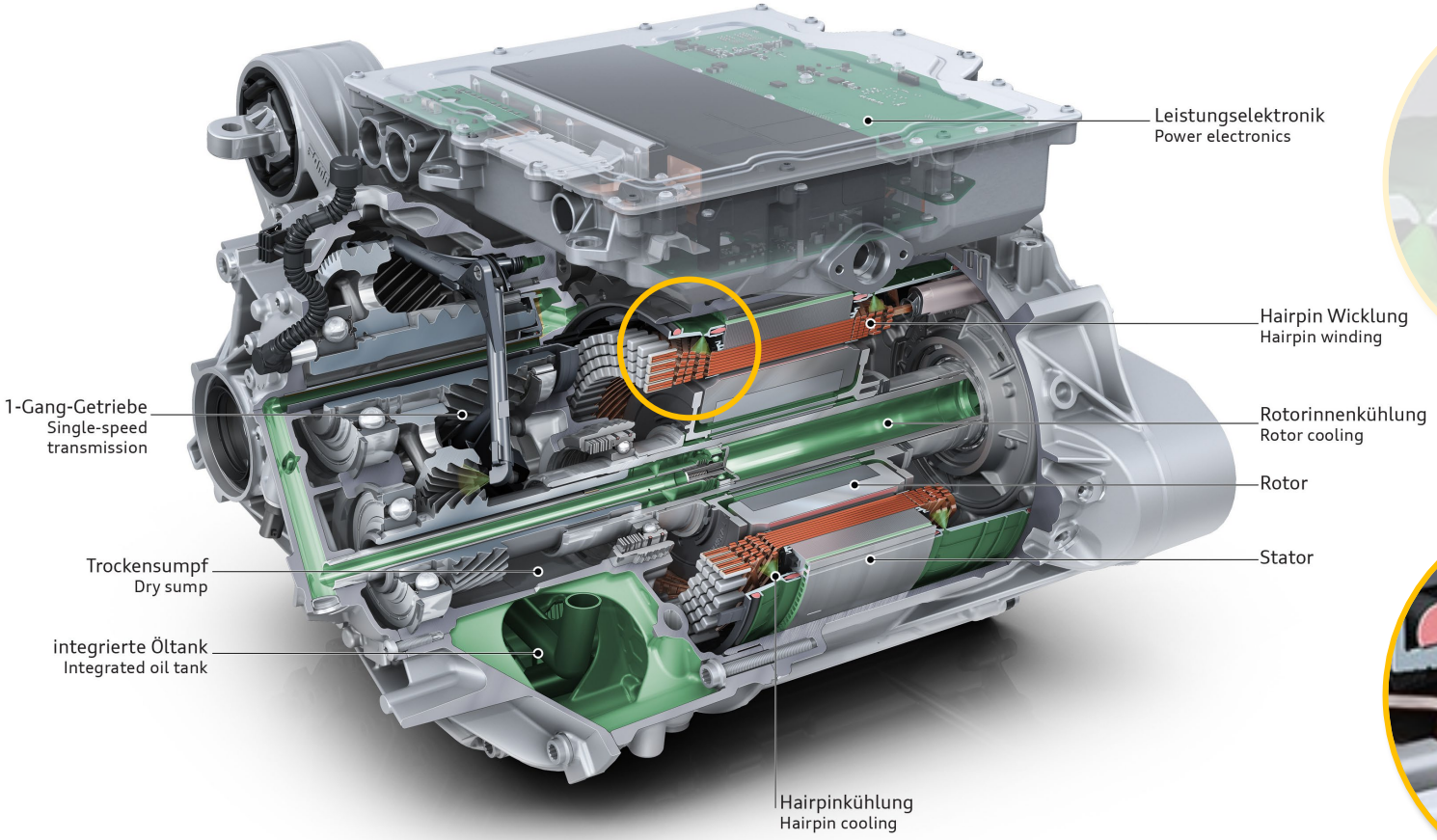
Source: DIN EN 1779; EP 4 329 167 A1

Schematic illustration of test setup



Resulting requirements

Additional requirements for the motor components – Stator insulation system



Source: AUDI AG

Leak tightness of the stator sheet lamination stack

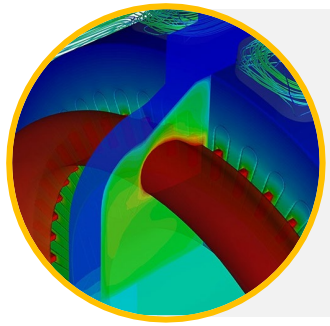
Chemical stress on and ageing of the stator insulation system

Requirements for the stator isolation system

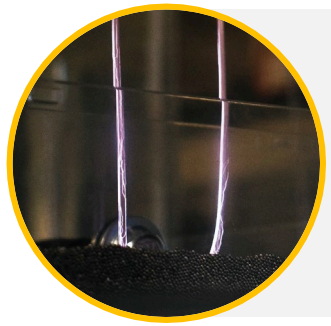
Chemical resistance of the insulation system components is becoming increasingly important

Initial electrical insulation characteristics → x → **z(x,y) = ?** → z → **Resulting electrical properties**

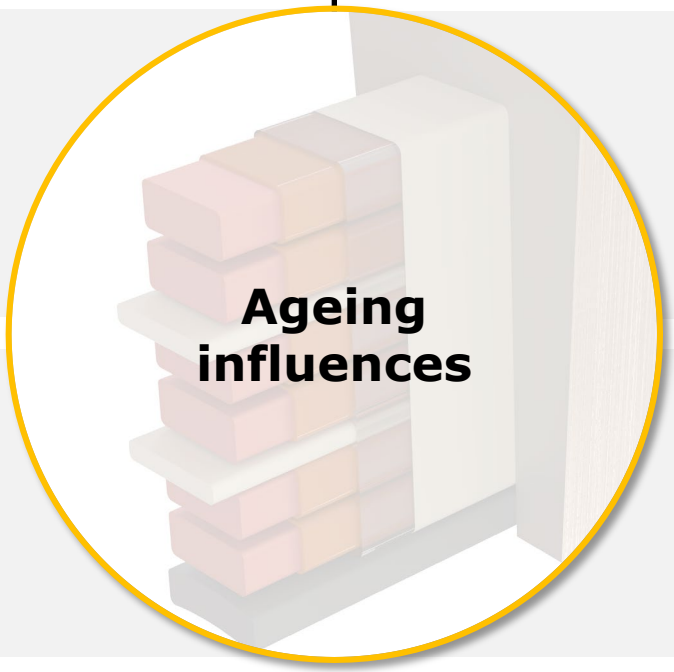
y



Thermal stress

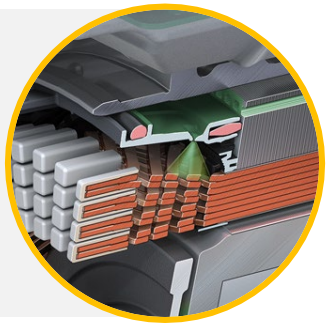


Electrical stress



Mechanical stress

Chemical stress



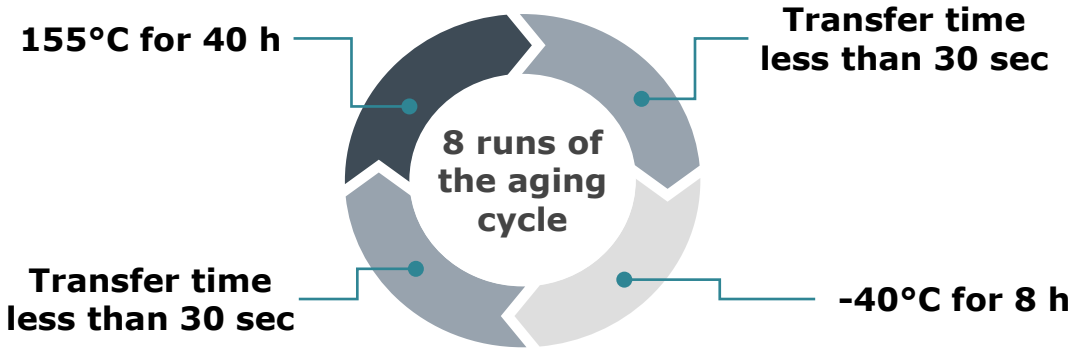
Requirements for the stator isolation system

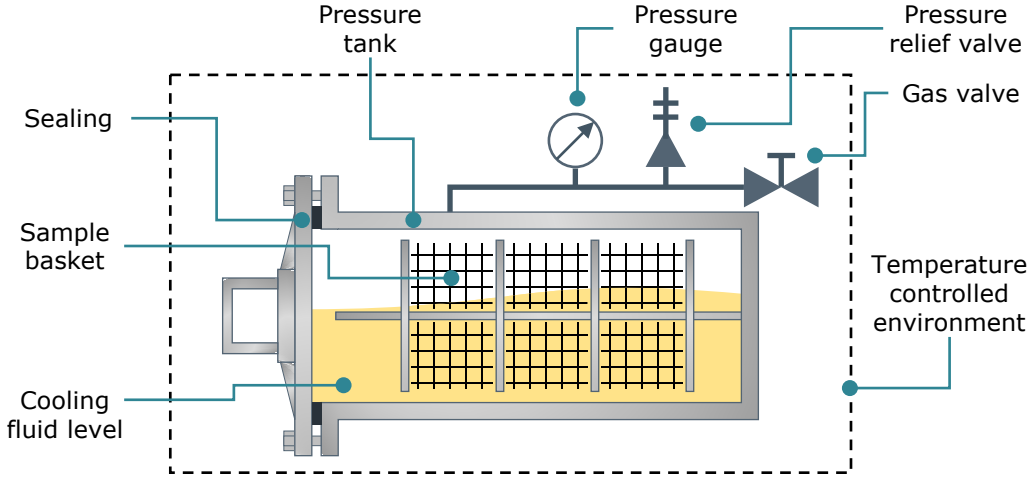
Testing on insulation component level – Concurrently thermal and chemical ageing according to T/CEEIA 415-2019

Test description

- Simultaneous chemical and thermal ageing
  - Adding 0.5 % deionized water to 99.5 % cooling liquid
  - Coolant level at least 75 % of tank volume
  - Temperature cycle between 155°C and -40 °C
  - Water content decisive for decomposition of components

Schematic illustration of test setup and heat cycle



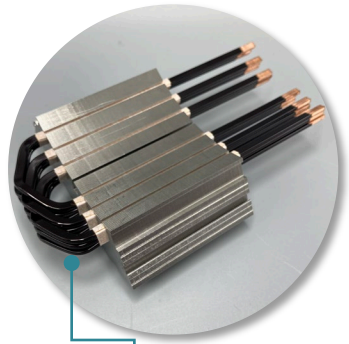


Requirements for the stator isolation system

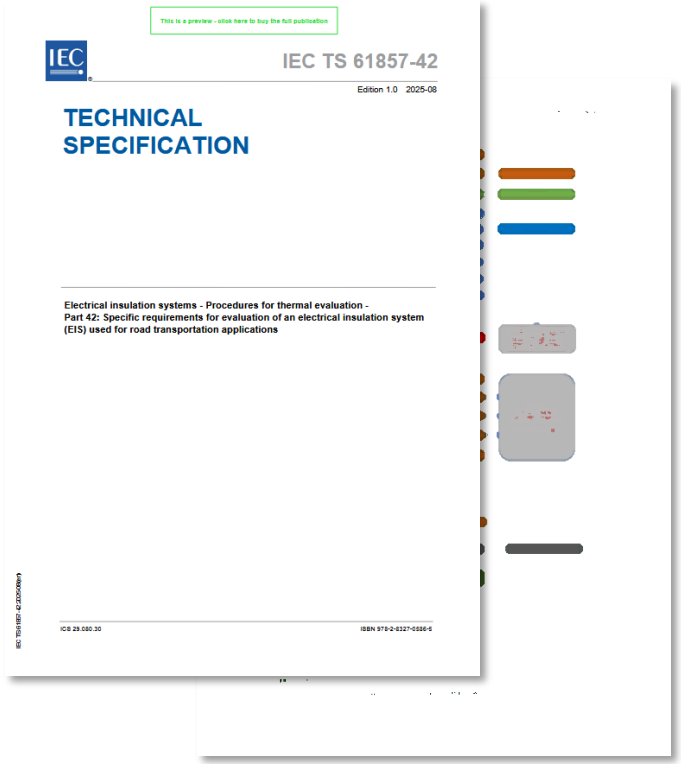
Adaptation of standards to developments in the field of electric traction drives and the testing scope/ level

Existing standards at component level

New standardization initiatives at system level



Specifically designed for flat wire conductor topology



Application-oriented testing at **system level** is a key step in **verifying interaction** and **performance** of the **combined product**.

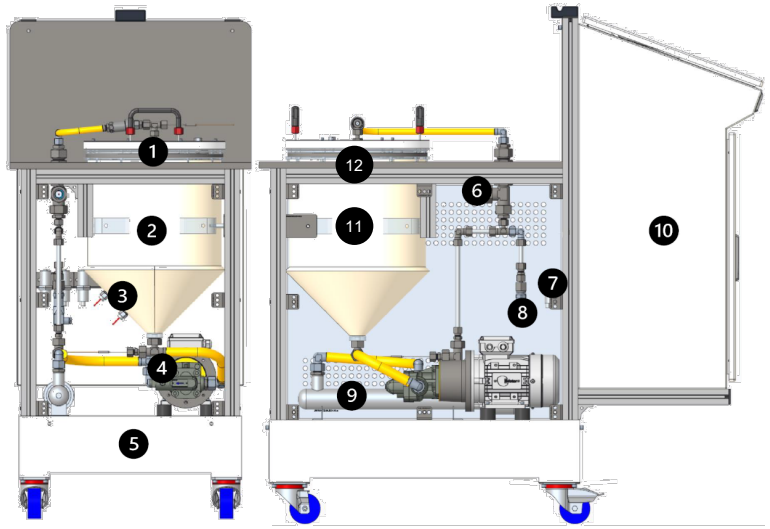
Requirements for the stator isolation system

Testing on stator insulation system level according to IEC 61857 -42 – Simultaneous thermal and chemical ageing

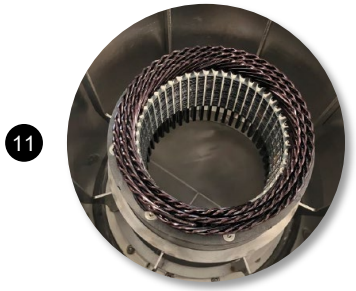
Test description

- Assembly of test specimen according to IEC 61857-42
- Mounting of six statorettes into complete stator assembly
- Aging of different insulation system configurations under same boundary conditions
- Optical, electrical and mechanical test after thermal-chemical aging and comparison with unaged reference

Schematic illustration of test setup and heat cycle



1. Tank cap with oil distribution
2. Test chamber
3. Tank oil level sensor
4. Oil pump
5. Base frame
6. Level sensor heating module
7. Evaluation unit oil level heating unit
8. Pressure valve
9. Heating module
10. Control unit and HMI



11 Test specimens (statorette) in test chamber

12 Oil flow from nozzles in cap onto specimen in chamber

Key findings and next steps

Key-findings

- For **efficient cooling** of the stator winding and stator lamination stack, the **integration** of **cooling channels** into the **lamination stack**, has become an **established cooling concept**
- The **function integration imposes additional requirements** on the stator lamination stack in terms of **leak tightness**

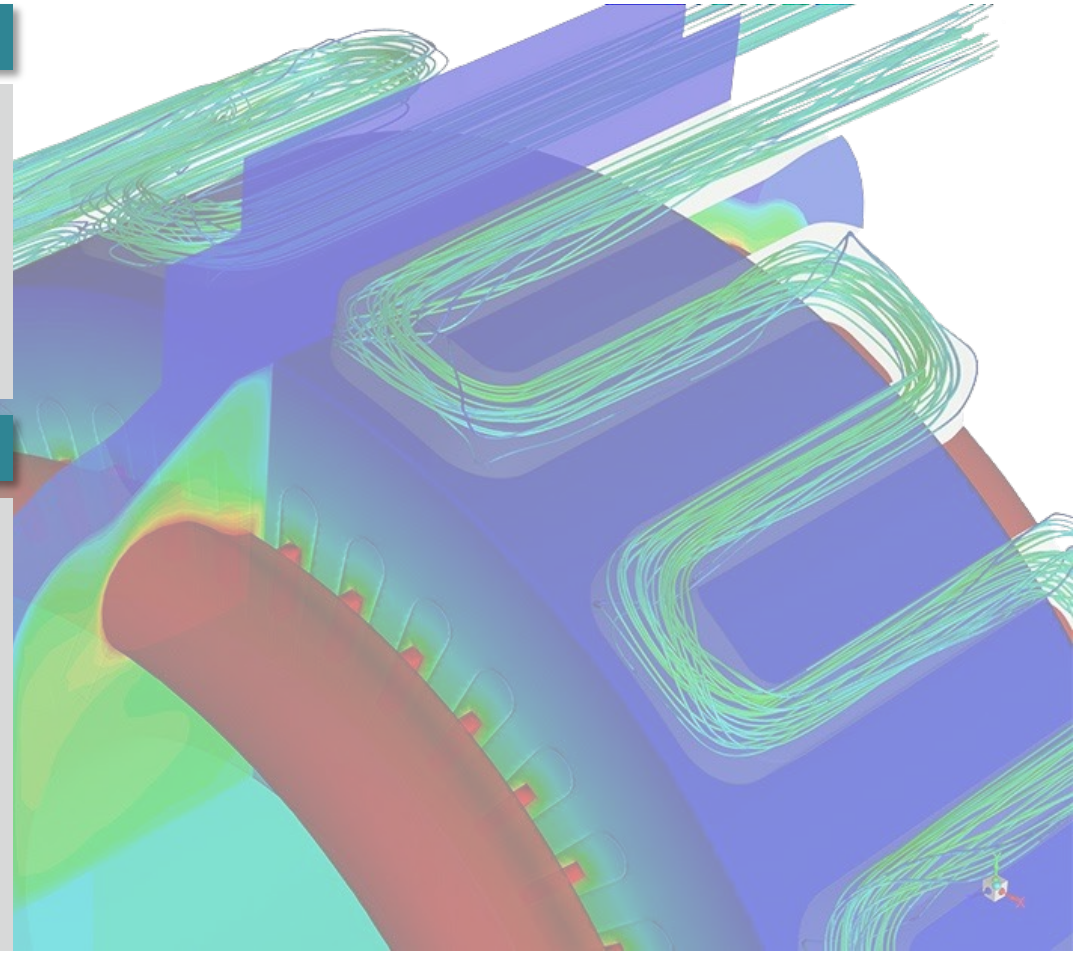
Next steps

Insulation system:

- **Improvement** of existing and **development** of **new**, innovative and higher-performance **materials for the insulation system**
- Initial **validation** and **iteration loops** at **component** level with **final** testing at **overall system level**

Lamination stack:

- **Tests** must be carried out for the **different packaging processes** to check for **leak tightness**
- **Tests** must consider the **stator design** and the **exact** configuration of the **cooling concept**



Source: Ansys

Gefördert durch:

Bundesministerium für Wirtschaft und Energie

aufgrund eines Beschlusses des Deutschen Bundestages

SCALE-UP E-DRIVE

Thank you for your attention!

Aachen, 23rd of April 2026

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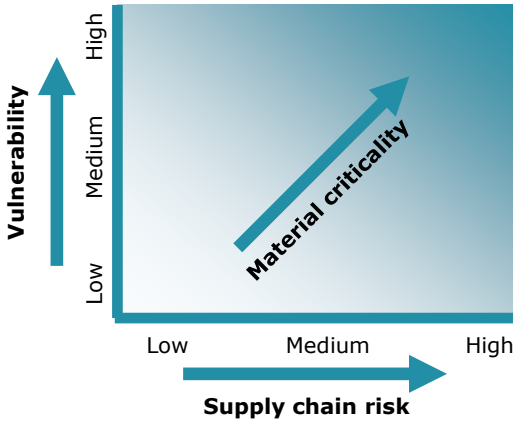
Critical resources

Critical resources in electric traction motors

Criticality: Definition and measures

Criticality: "Great importance of something whose loss would pose an existential threat"

- Critical materials are raw materials that are of **great economic importance** to the EU economy and pose a high supply chain risk
- Mainly raw materials that are needed for **future technologies** and the **energy transition**
- The European Raw Materials Act aims to secure the supply of these critical materials **and strengthen competitiveness** and **strategic autonomy**



EU benchmark targets for domestic capacity along the supply chain by 2030:

10 % Extraction

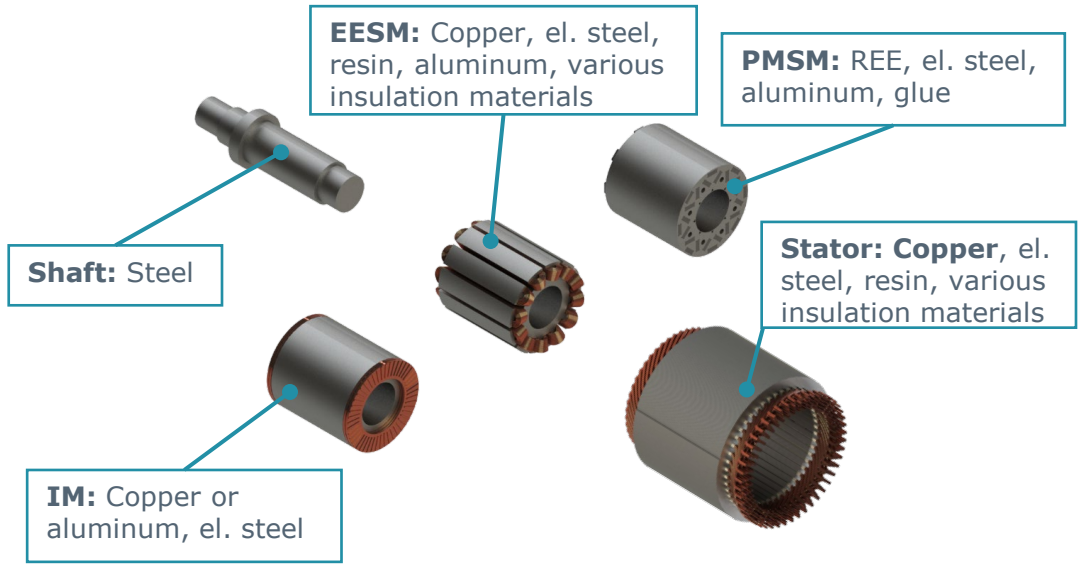
40 % Processing

15 % Recycling

max. **65 %** sourced from a single third country

Source: European Union

Materials in the electric motor

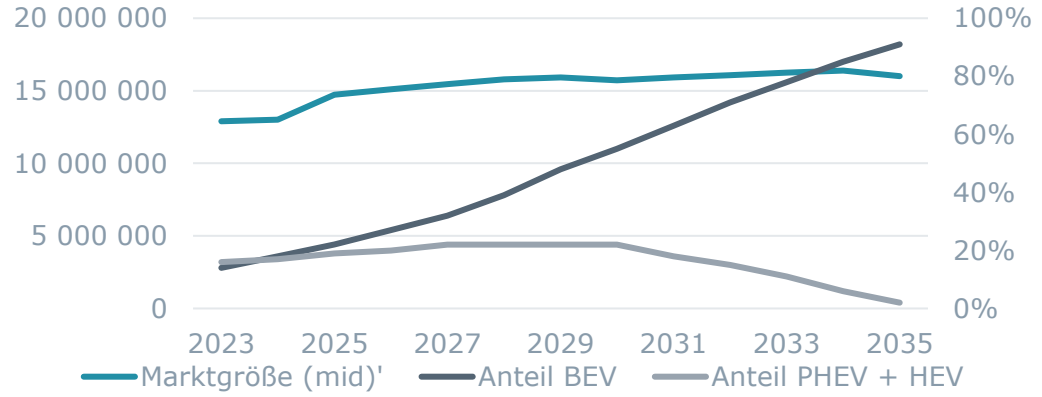


- Wide range of different materials
- High **purity requirements** for individual raw materials to **ensure optimal performance** and power supply
- Wide variety of material-, force-, and form-bonded connections
- Critical materials according to the EU Raw Materials Act: **copper, REE,** aluminum

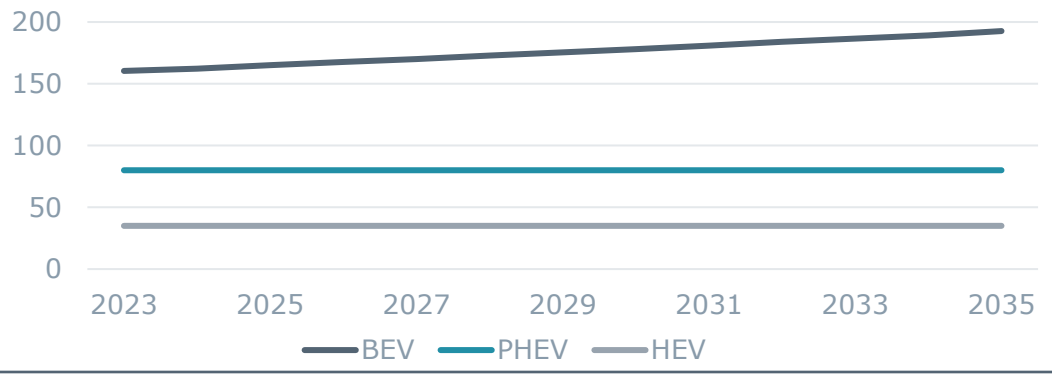
Critical resources on the brink

Demand of materials for electric motors

Forecast passenger cars and light commercial vehicles sales in Europe until 2035*



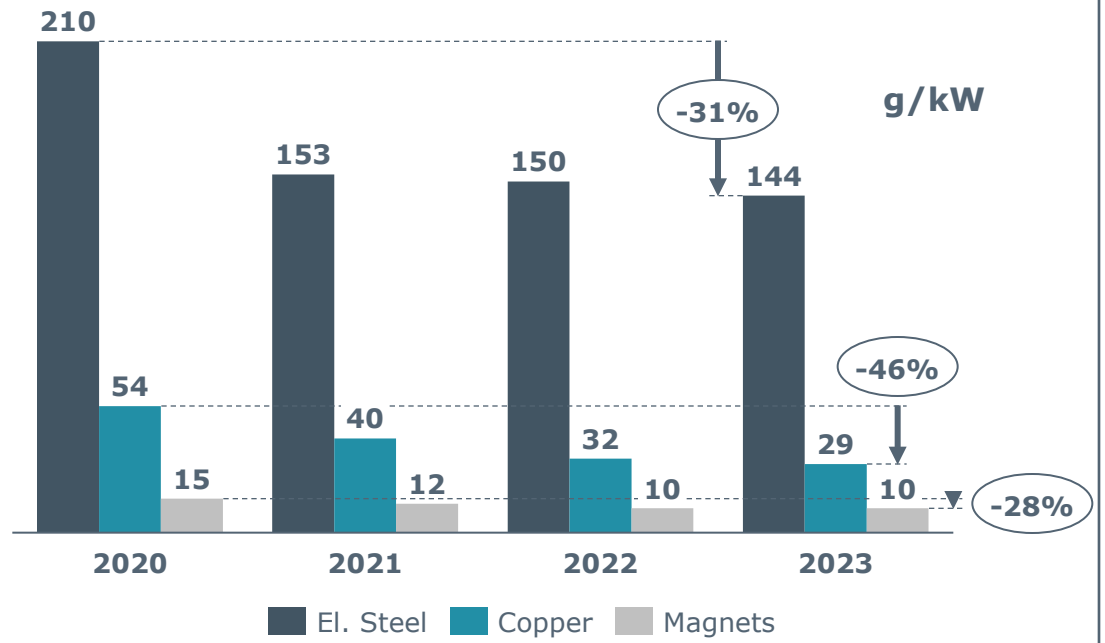
Forecast: Average power per vehicle (kW)**



*Source: PEM market study

**Source: PEM market study, IDTechEx

Material weight per kW in the electric motor***



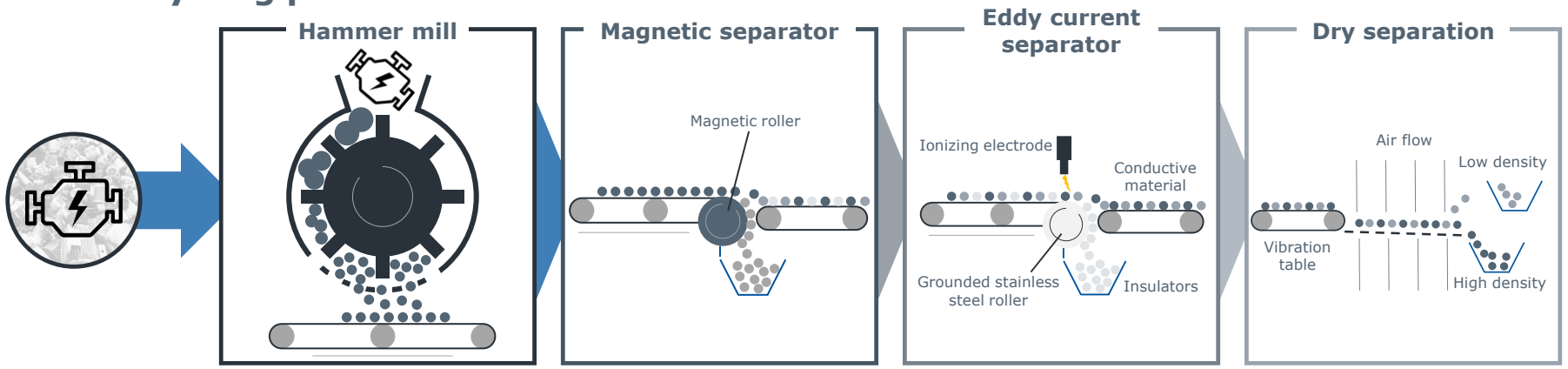
- The **material consumption** of electric motors **per kW** of peak power has **decreased significantly** in recent years
- The reasons for this are **innovations** in areas such as **cooling, winding design, and materials**
- Further reductions can be expected as a result of material and product innovations

***Source: PEM Study incl. A2Mac1 Data

Recycling as a resource source

Challenges in the recycling of electric motors

State of the art recycling process:



Challenges:

Separation of materials
Materials cannot be cleanly separated by shredding due to adhesions and joints in the electric motor.

Production processes
Automated process technology for the high-volume dismantling of electric drives is not currently available.

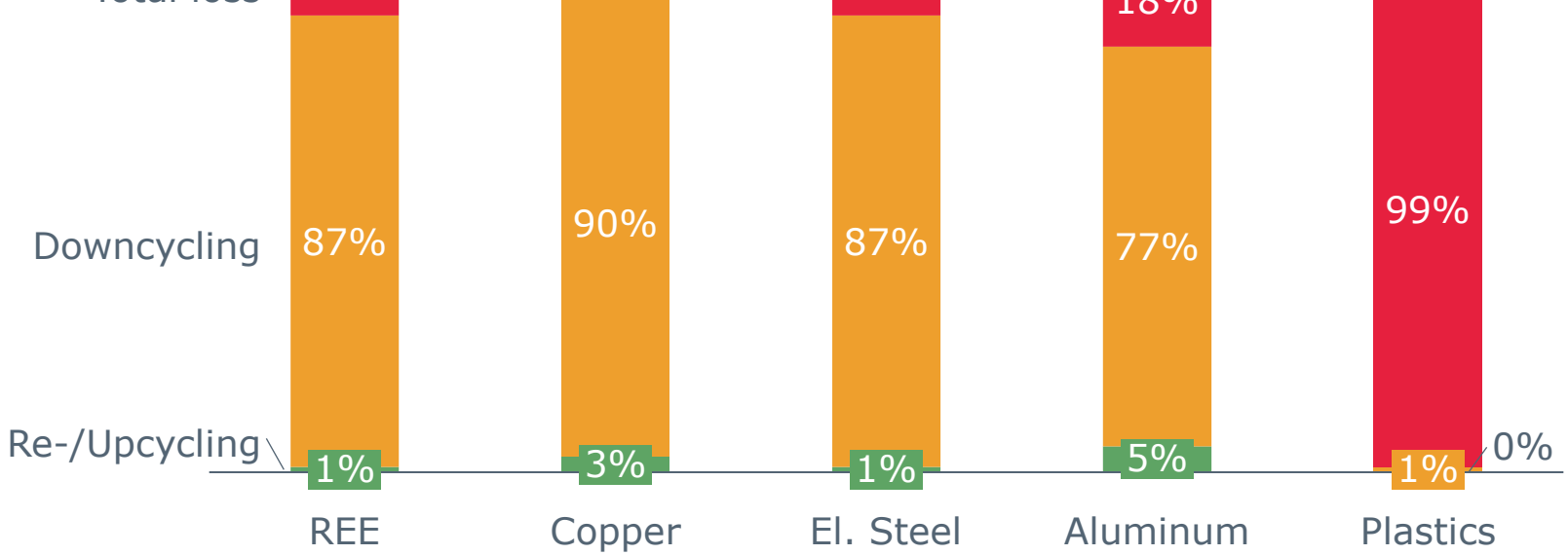
Product topology
Most of the current motor topologies are not designed for the disassembly and the reuse of individual components.

Information
The recycler does not have any product information, such as material compositions that are necessary for reuse or dismantling.

Recycling as a resource source

Recycling rates for critical materials in electric motors

Separation of materials
Materials cannot be cleanly separated by shredding due to adhesions and joints in the electric motor.



Due to the motor design and the recycling processes currently in use, most of the materials in the electric motor are lost during recycling or are no longer suitable for applications with high requirements due to contamination.

Source: JRC Science for Policy Report; PEM Study

Recycling as a resource source

Product and process related challenges in the disassembly and recycling of electric motors

Product-related challenges in the dismantling and recycling of electric motors

- A wide range of **screw, weld, adhesive, and press connections**
- **Poor accessibility** to screws and active components
- **Highly integrated design** including power electronics and gearbox
- **High demands on raw materials** in electric motors, which is why only very **pure secondary materials** can be used.

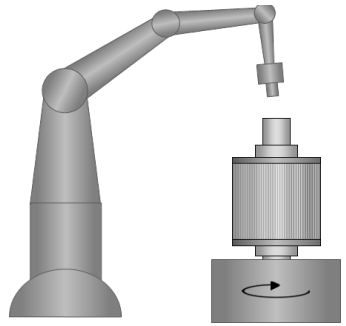
Shredding of electric motors

+ Short cycle times per motor
+ Cost-efficient recycling
– Due to adhesives, fixings, etc. it is not possible to completely separate the materials by type
– Electrical steel in particular is no longer suitable for use in high-quality applications

Manual disassembly of electric motors

+ High degree of purity of the separated materials can be achievied
+ Inexpensive equipment
– Long cycle times
– High labor demand

Automated disassembly



+ High degree of purity of the separated materials can be achieved
+ Low cycle times and therefore potentially economically viable
– Complex control due to product diversity
– Lack of solution concepts, need for development

Research project “ Kreisläufer ”

PEM | RWTH AACHEN UNIVERSITY | SCALE-UP E-DRIVE

Re-X-oriented product and production concepts in the rotor technology

Motivation and objective

- Current product topologies and production processes do **not** take into account the **recyclability** of the rotor, which contains **critical, valuable and emission-intensive raw materials** such as aluminum, copper, electrical steel, and rare earths.
- In addition: To date, there are **no** comprehensive **concepts** for **reuse**, **dismantling**, and **recycling**.
- The overarching project goal is to develop technologies and methods for Re-X strategies (reduce, reuse, recycle, …) for rotor production to efficiently **utilize the potential** of these in a circular economy.

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Duration: 01.09.2025 – 31.08.2028

Project structure and work packages

AP1: Definition of product reference designs and process chains
- Definition and collection of product requirements
- Derivation of generic rotor reference designs and associated production process chains
- Documentation of the status quo for the dismantling of rotors

AP2: Adaption of reference designs and process chains for circular rotor production
- Identification of the circularity value of individual components
- Identification of circularity options for the individual components
- Circular optimization of rotor reference designs
- Developments of concepts for circularity
- Development of circular production and disassembly concepts

AP3: Application-oriented research on the processes for circular production and dismantling
- Concepts for enabling existing infrastructure and new process technology for circular rotor production
- Concepts for enabling existing infrastructure and new process technology for circular rotor disassembly
- Purchasing, commissioning and validation of the equipment for circular rotor production and disassembly

AP4: Cross-value chain concepts for data collection and usage
- Investigation of existing data concepts
- Design of a digital product passport for use in disassembly process
- Integration of data collection into the process stations
- Cross-value chain life cycle analysis