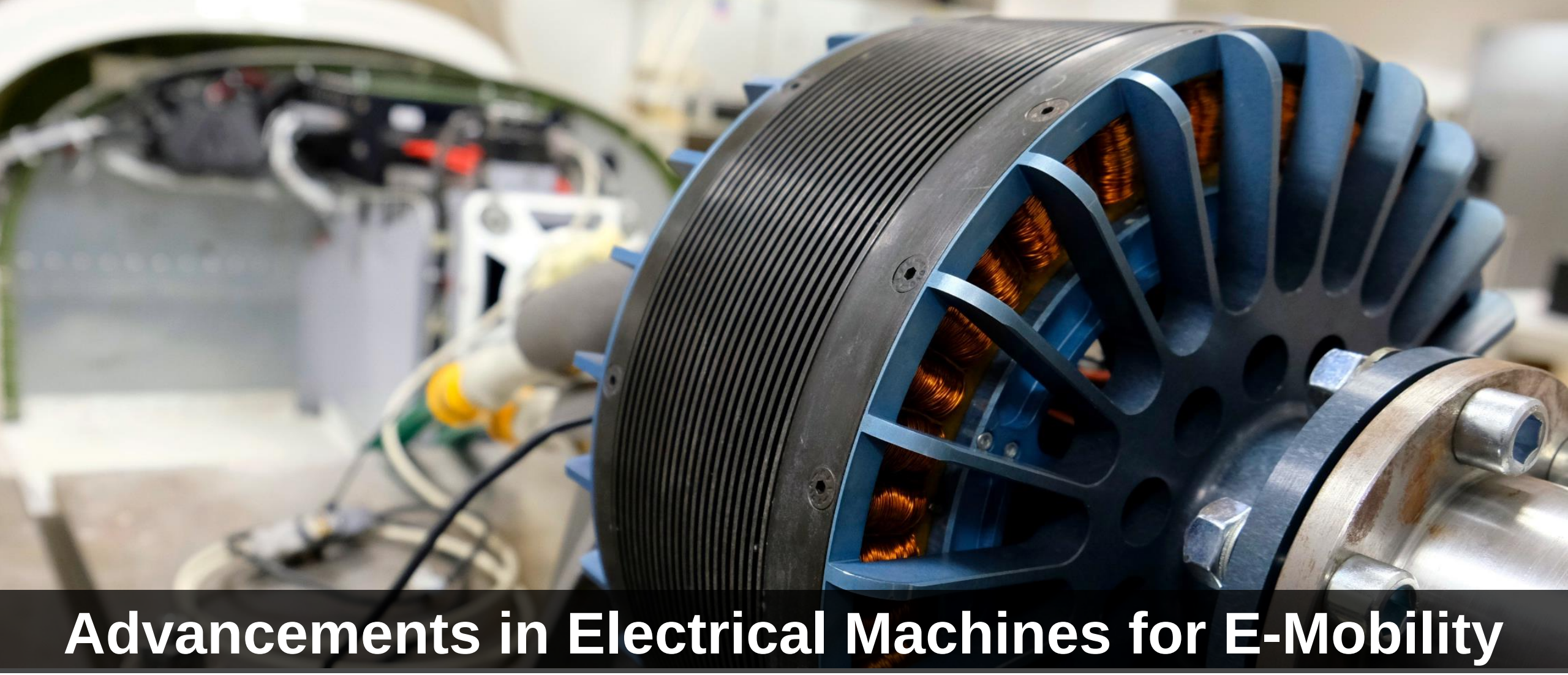

Advancements in Electrical Machines for E-Mobility

BRNO UNIVERSITY OF TECHNOLOGY

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION

department of power electrical and electronic engineering

Jan Barta

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Transportation Electrification

AVIATION

WATERBORNE

RAIL

ROAD

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Figures: https://trimis.ec.europa.eu/

Electrical machines in automotive

ROAD

Electrical machines in automotive

ROAD

Alternator

Figure: https://generatorexchange.net/

Windshield wiper motor

Figure: https://www.bosch.com/

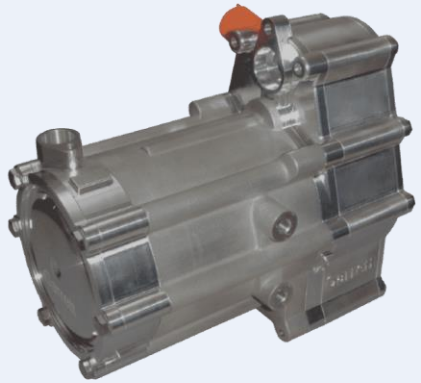
Electrical machines in automotive

Alternator

Figure: https://generatorexchange.net/

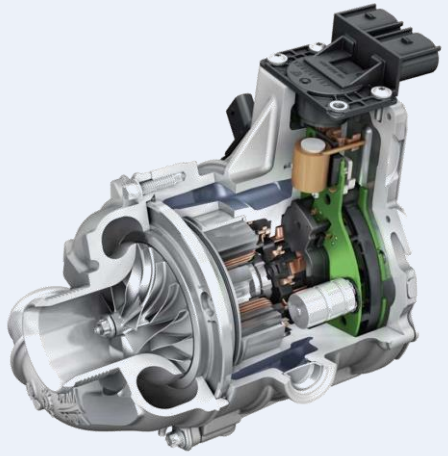
Windshield wiper motor

Figure: https://www.bosch.com/



E-cooling compressors

Electric vehicle propulsion



E-turbo

Fuel cell compressor

Figures: https://www.garrettmotion.com/

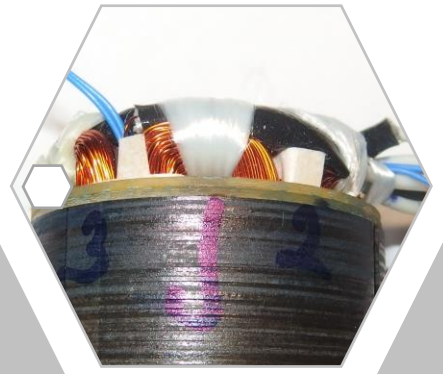
Challanges in developing machines for E-mobility

- **Cost** – prototyping and testing are costly
- **Complexity** – multidisciplinary design (electromagnetic, thermal and mechanical)
- **Efficiency** – every % counts
- **Power density** – higher power density = less mass
- **Reliability** – resistance of the electrical motor to the failure
- **Certificaiton** – safety, EMC…

Primary Technology Themes

Figure: BMW

Material Development



Machine Architectures and Integration

Thermal Management

Manufacturing Innovations

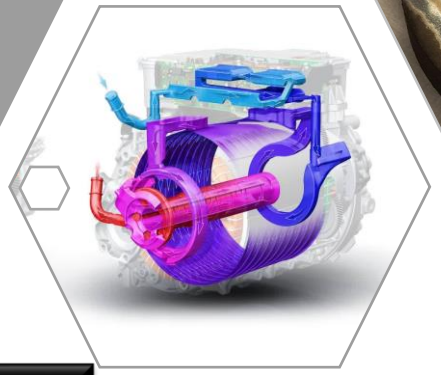


Figure: AUDI

Life Cycle

Figure: Volkswagen

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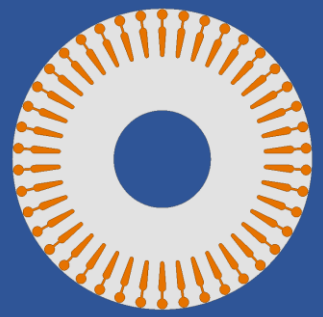
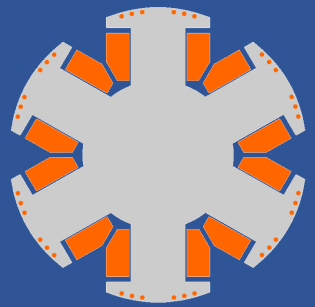
Themes are selected based on: Electric Machines Roadmap 2020, Narrative Report, Automotive council UK, Advanced Propulsion Centre UK

Machine Architectures

Magnet Free machines



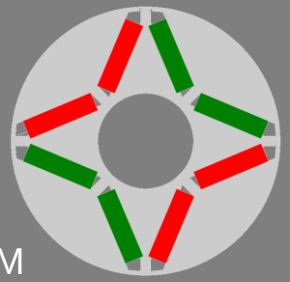
IM



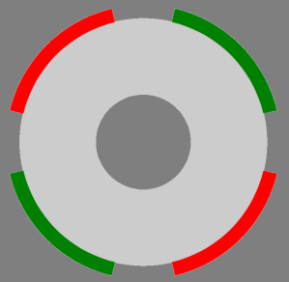
WRSM

RSM

Permanent magnet based



PMSM



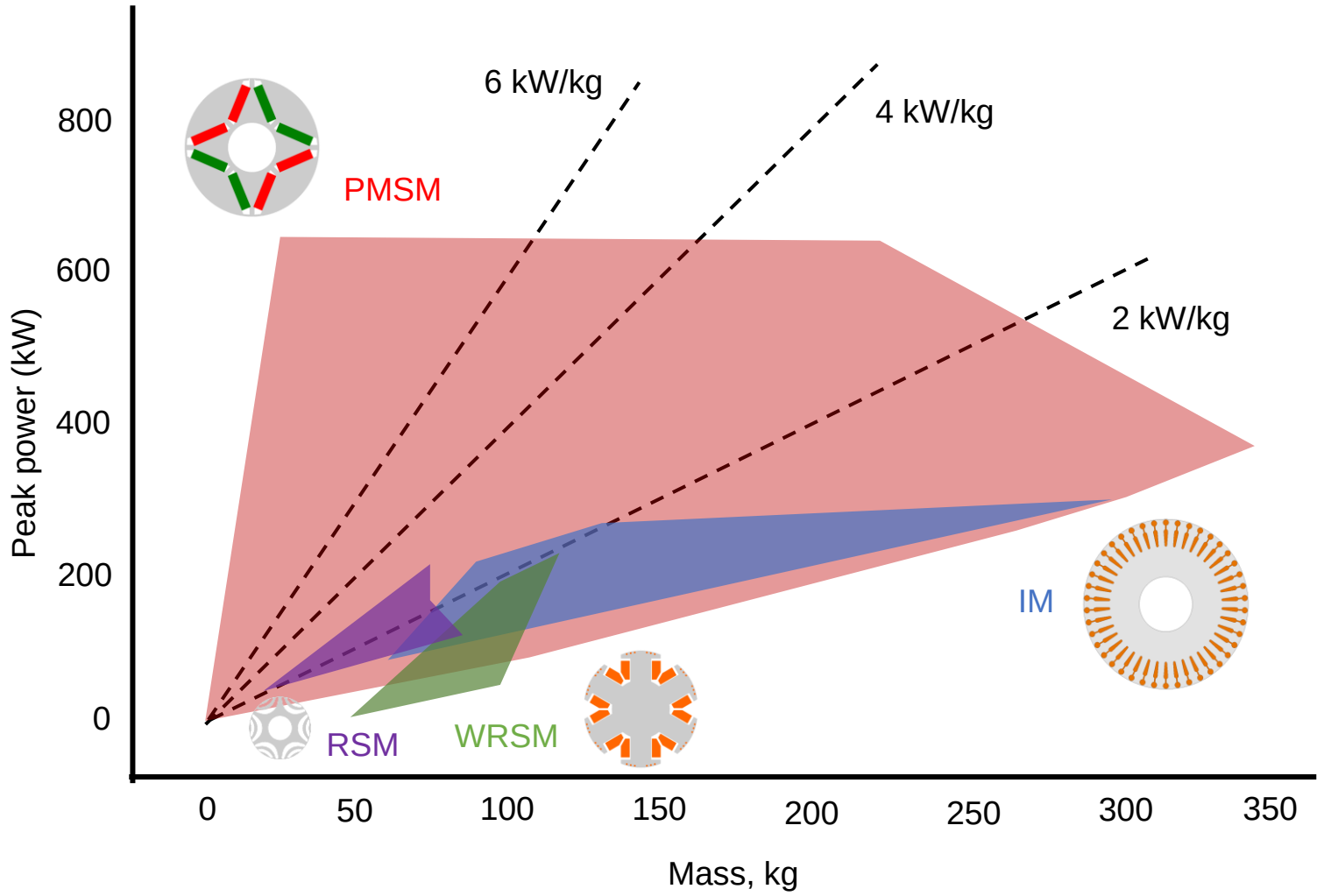
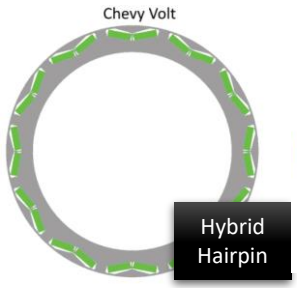
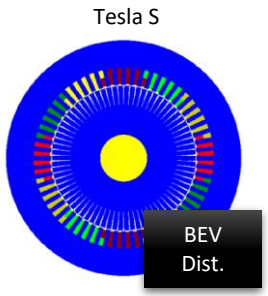


Figure based on data from: IDTechEx Research

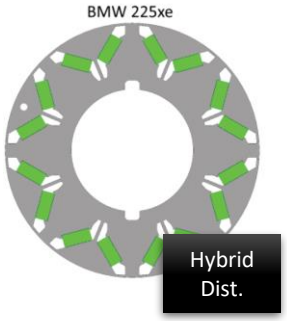
Machine Architectures - Time line

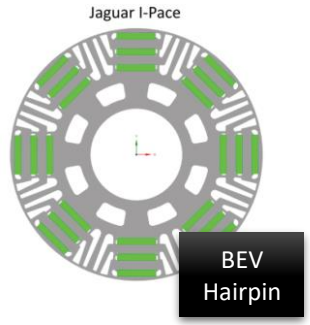


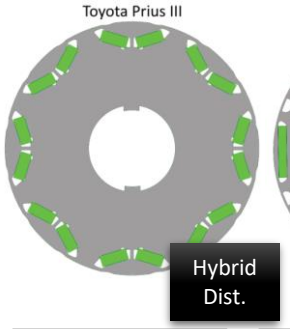


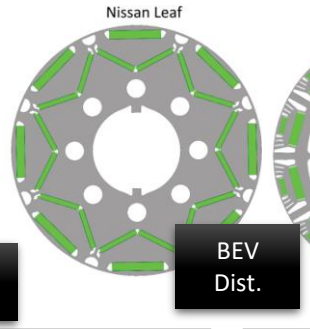
Fill factor 85%
(source: Mitsubishi)

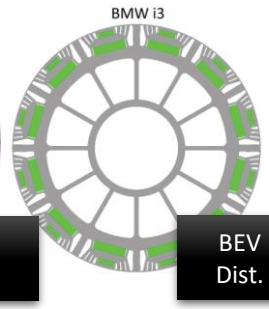
Fill factor 40%
(source: Brusa)

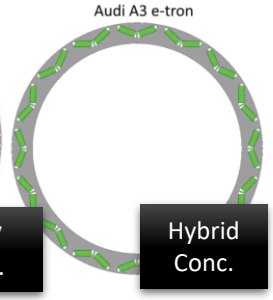


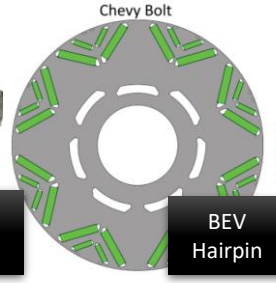


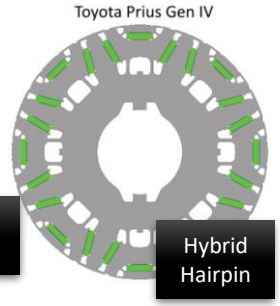


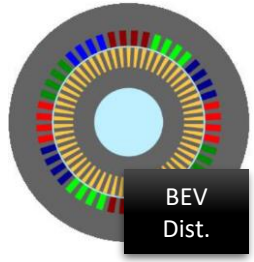


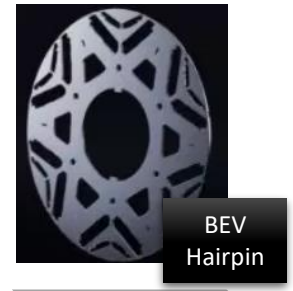












2010 2012 2013 2014 2015 2016 2017 2018 2019 2025

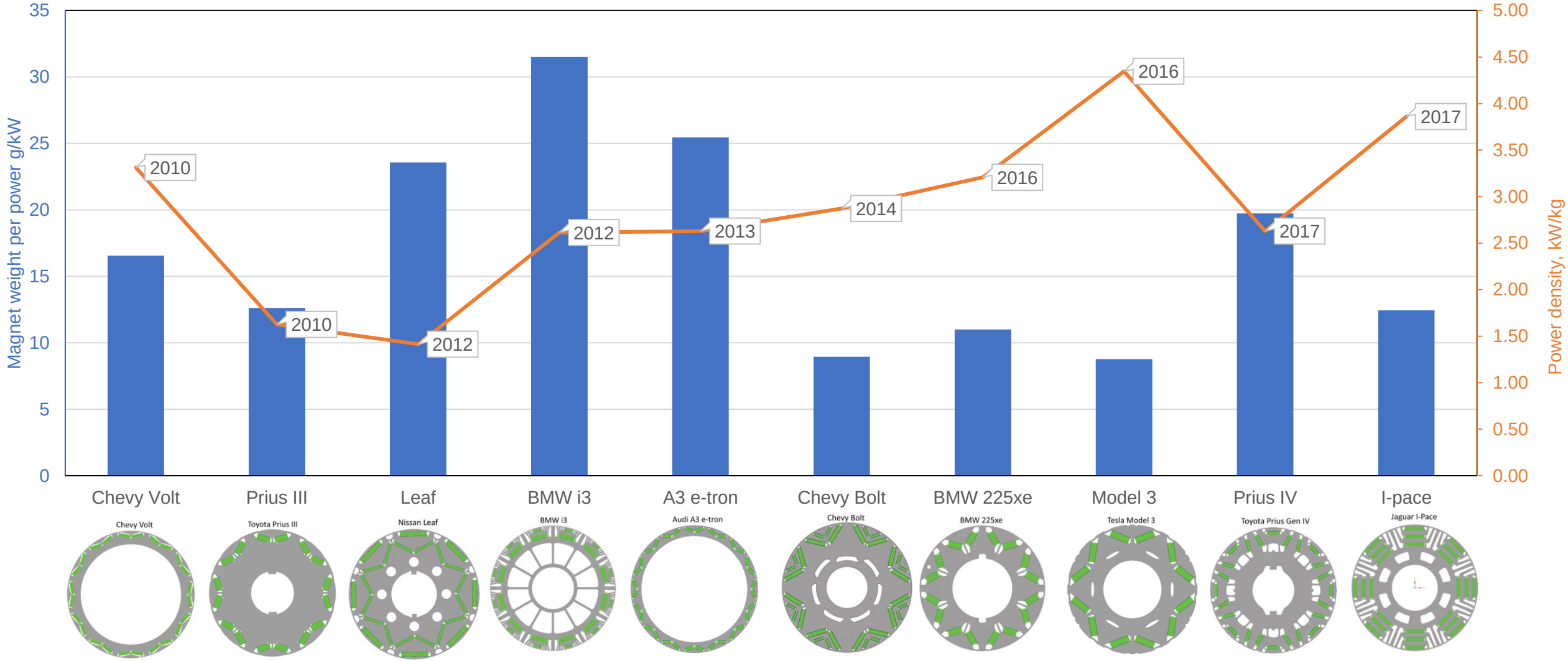
Figures: A. Krings and C. Monissen, "Review and Trends in Electric Traction Motors for Battery Electric and Hybrid Vehicles," *2020 International Conference on Electrical Machines (ICEM)*, 2020, pp. 1807-1813, doi: 10.1109/ICEM49940.2020.9270946.

Figures: F. Graffeo, S. Vaschetto, A. Tenconi and A. Cavagnino, "Fast Sizing Procedure for Salient-Pole Wound Field Synchronous Motors for Transportation Electrification," 2023 IEEE International Electric Machines & Drives Conference (IEMDC), San Francisco, CA, USA, 2023, pp. 1-7, doi:

Figures: R. Thomas, H. Husson, L. Garbuio and L. Gerbaud, "Comparative study of the Tesla Model S and Audi e-Tron Induction Motors," *2021 17th Conference on Electrical Machines, Drives and Power Systems (ELMA)*, Sofia, Bulgaria, 2021, pp. 1-6, doi: 10.1109/ELMA52514.2021.9503055.

Figures: https://www.mi.com/

Machine Architectures - Time line



Figures and Data: A. Krings and C. Monissen, "Review and Trends in Electric Traction Motors for Battery Electric and Hybrid Vehicles," *2020 International Conference on Electrical Machines (ICEM)*, 2020, pp. 1807-1813, doi: 10.1109/ICEM49940.2020.9270946.

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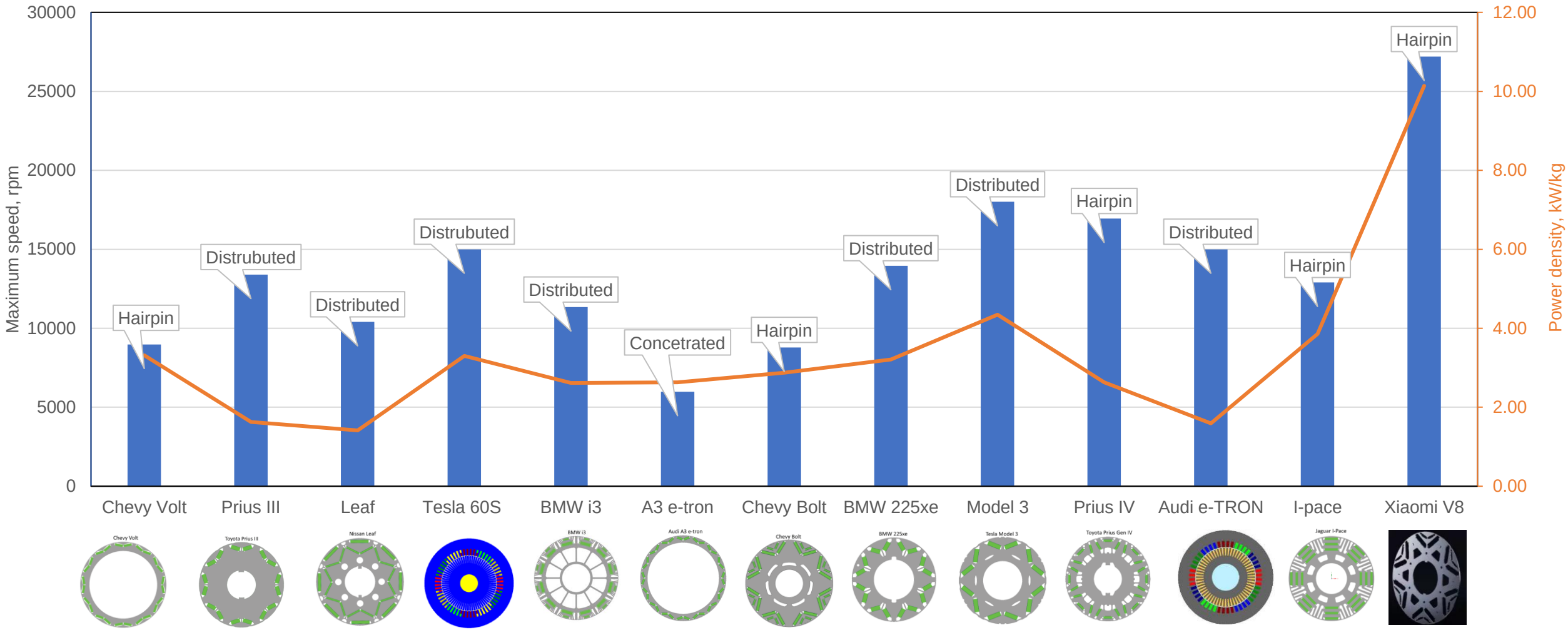

Figures and Data: A. Krings and C. Monissen, "Review and Trends in Electric Traction Motors for Battery Electric and Hybrid Vehicles," *2020 International Conference on Electrical Machines (ICEM)*, 2020, pp. 1807-1813, doi: 10.1109/ICEM49940.2020.9270946.

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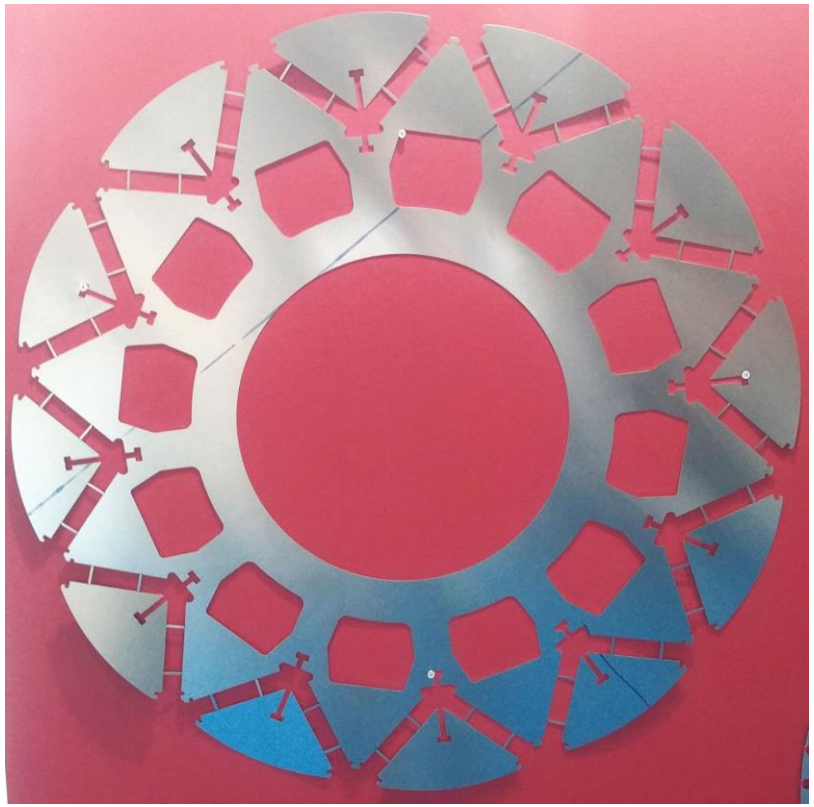
Figures and Data: R. Thomas, H. Husson, L. Garbuio and L. Gerbaud, "Comparative study of the Tesla Model S and Audi e-Tron Induction Motors," *2021 17th Conference on Electrical Machines, Drives and Power Systems (ELMA)*, Sofia, Bulgaria, 2021, pp. 1-6, doi: 10.1109/ELMA52514.2021.9503055.

Figures and Data: https://www.mi.com/

Moving towards High-Speeds



The Tesla S Plaid's carbon sleeve rotor can maintain a maximum speed of 23,300 rpm (source insideevs).

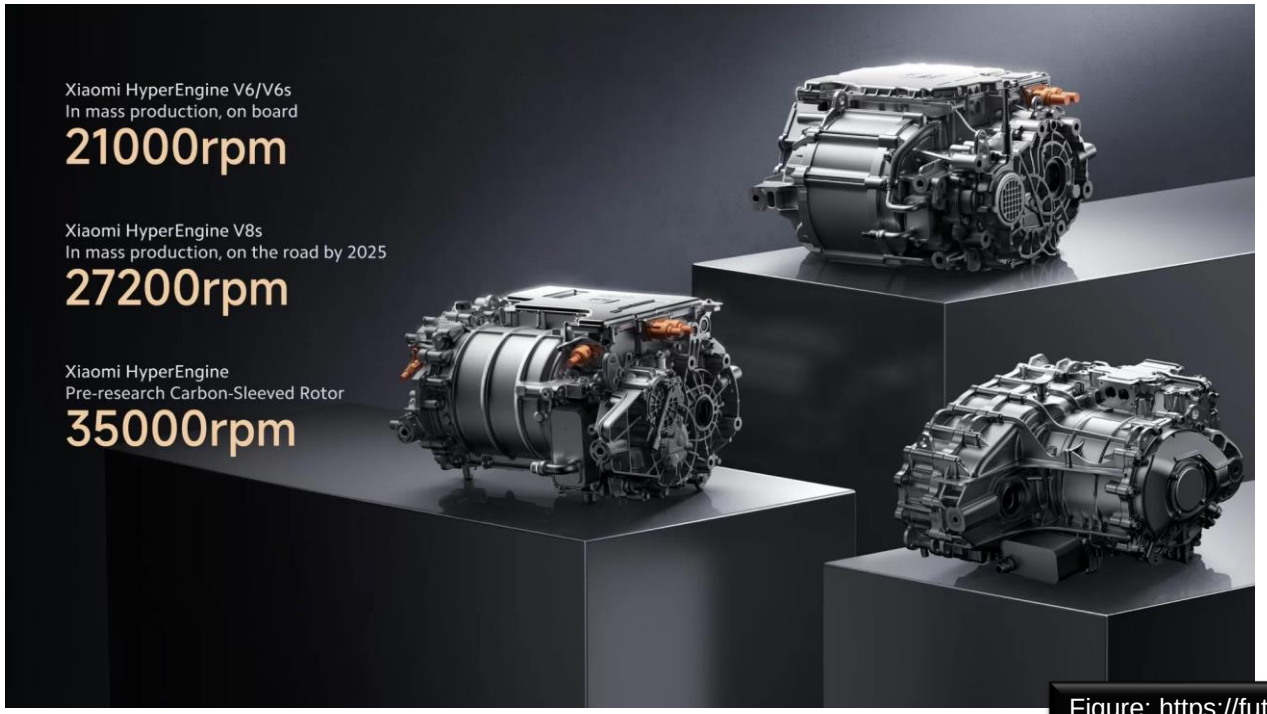


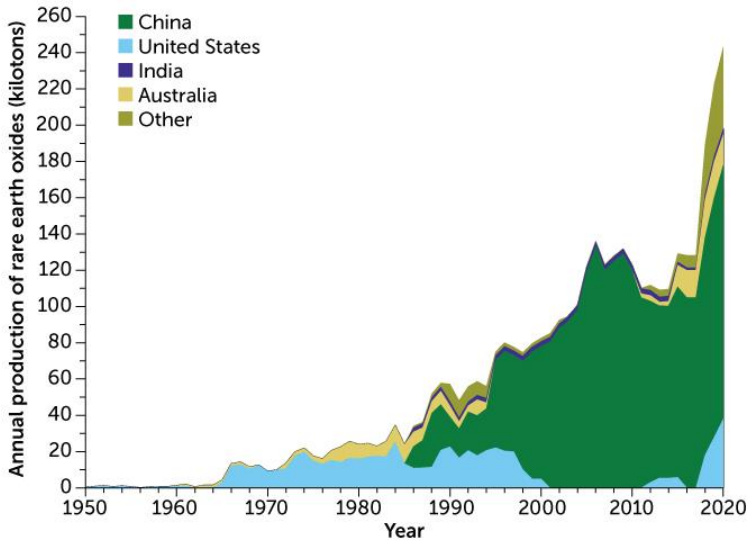
Figure: https://futurride.com

Garrett 3-in-1 E-Axle for Electric Vehicles

Over 30 000 rpm

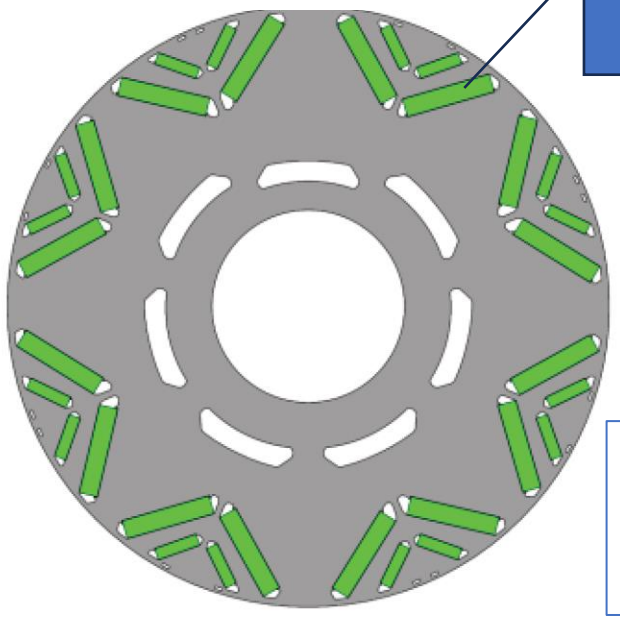
https://www.garrettmotion.com/

Moving from PMSM to PM-Re Free



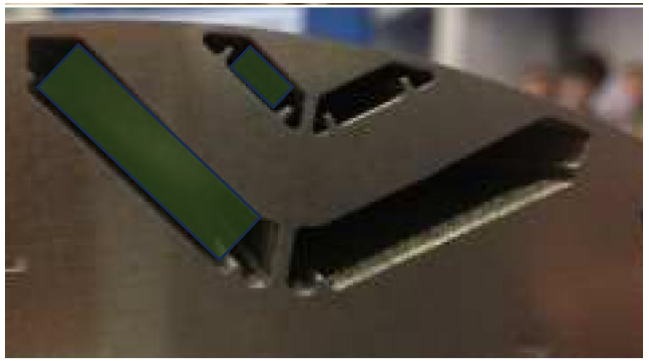
Source: Electric Machine Roadmap 2020, narrative report, February 2021
Figures: https://www.sciencenews.org/article/rare-earth-mining-renewable-energy-future

Chevrolet Volt



12 pole - IPM
100 kW
12 000 rpm

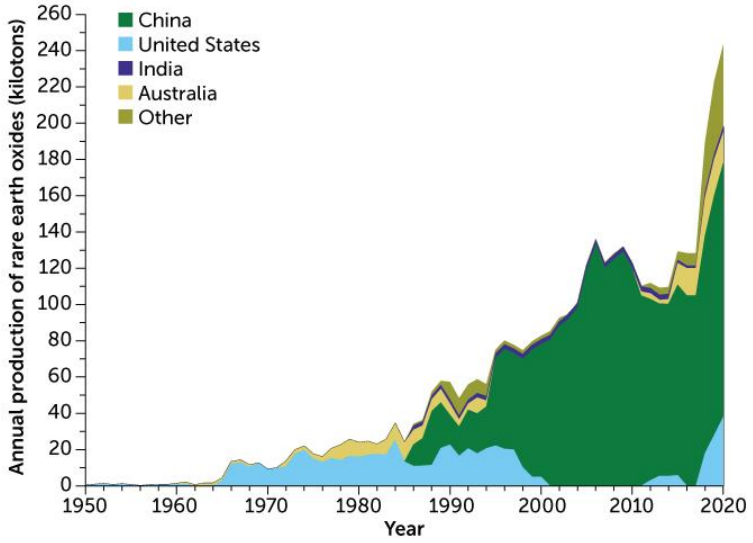
12 pole – Ferrite IPM
50 kW
11 000 rpm



Figures: A. Krings and C. Monissen, "Review and Trends in Electric Traction Motors for Battery Electric and Hybrid Vehicles," *2020 International Conference on Electrical Machines (ICEM)*, 2020, pp. 1807-1813, doi: 10.1109/ICEM49940.2020.9270946.

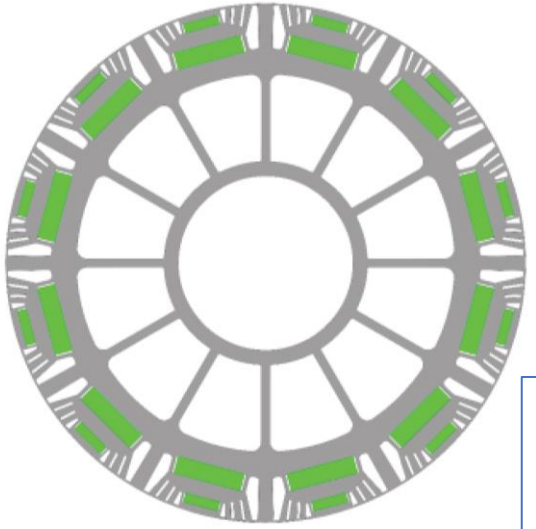
Data z: A. Krings and C. Monissen, "Review and Trends in Electric Traction Motors for Battery Electric and Hybrid Vehicles," *2020 International Conference on Electrical Machines (ICEM)*, 2020, pp. 1807-1813, doi: 10.1109/ICEM49940.2020.9270946.

Moving from PMSM to WRSM

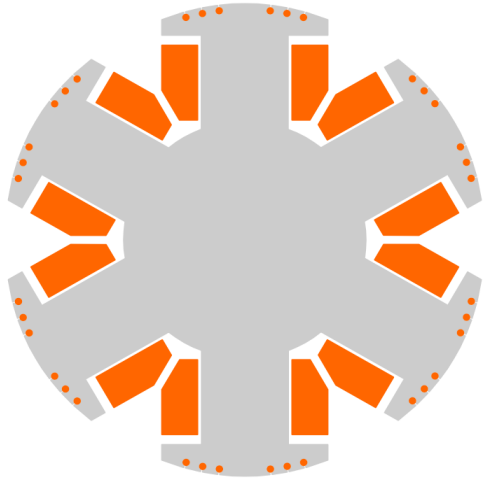


Source: Electric Machine Roadmap 2020, narrative report, February 2021
Figures:
https://www.sciencenews.org/article/rare-earth-mining-renewable-energy-future

BMW i3



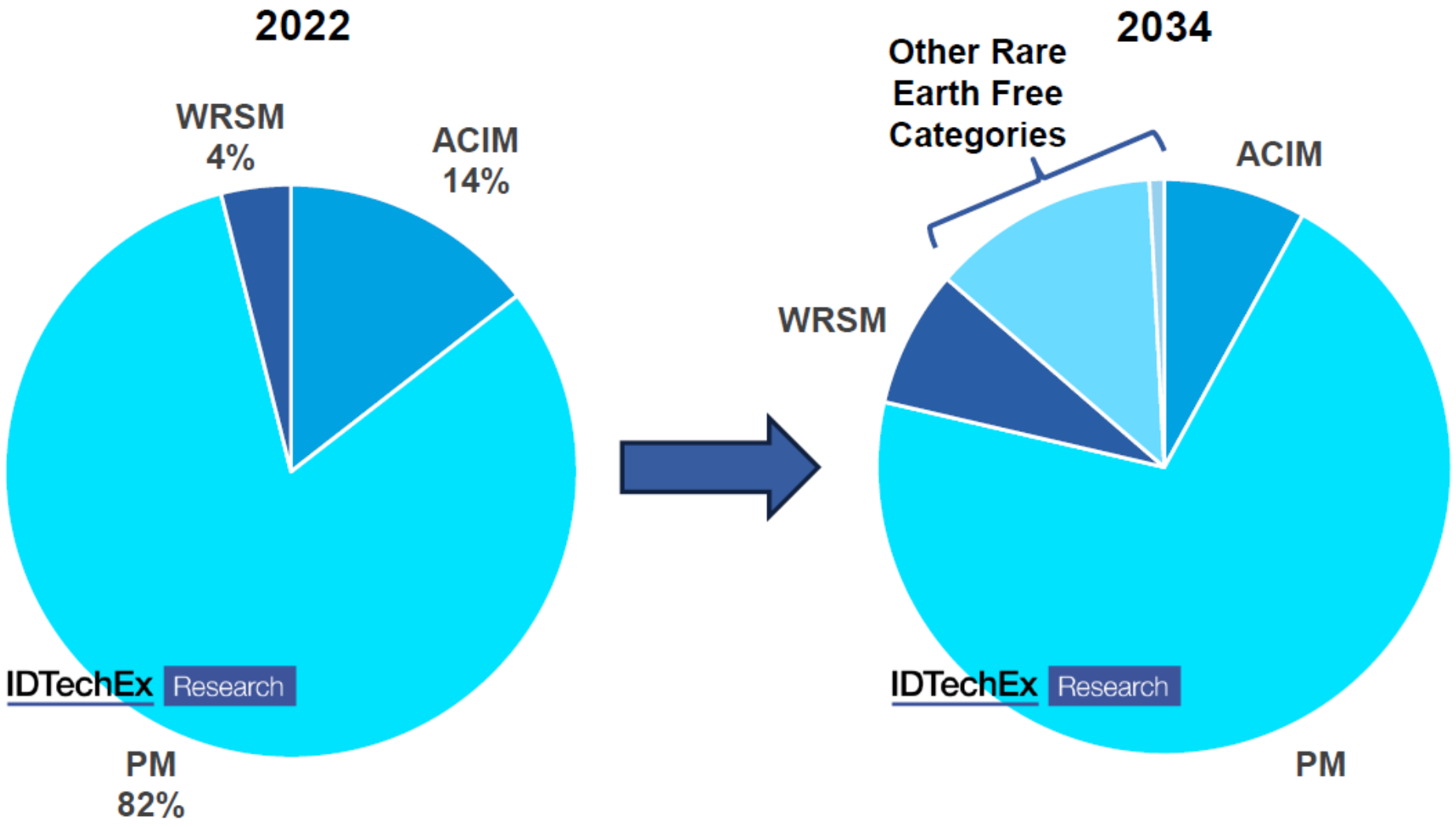
8 pole
127 kW
11 400 rpm



Data z: A. Krings and C. Monissen, "Review and Trends in Electric Traction Motors for Battery Electric and Hybrid Vehicles," *2020 International Conference on Electrical Machines (ICEM)*, 2020, pp. 1807-1813, doi: 10.1109/ICEM49940.2020.9270946.

Figure: https://evkx.net/

Machine Architectures



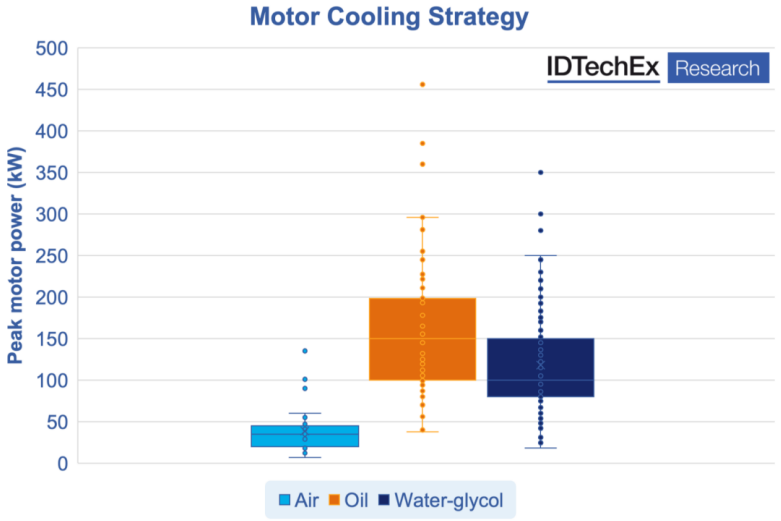
Thermal Management

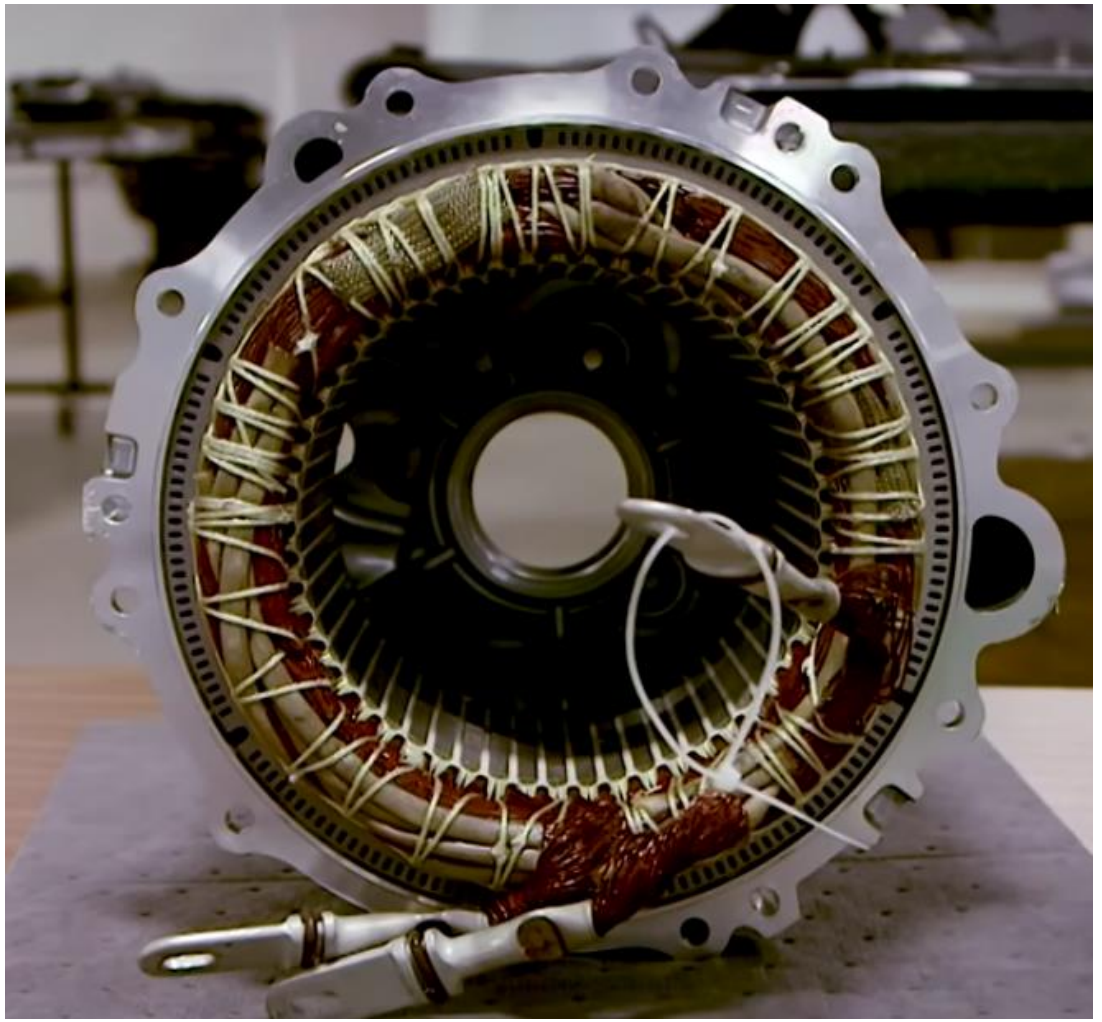
The standard solution is a **Water - glycol** with a cooling jacket

Advanced solutions are gaining ground:

- Oil spray cooling of the end winding
- Direct stator cooling
- Rotor cooling

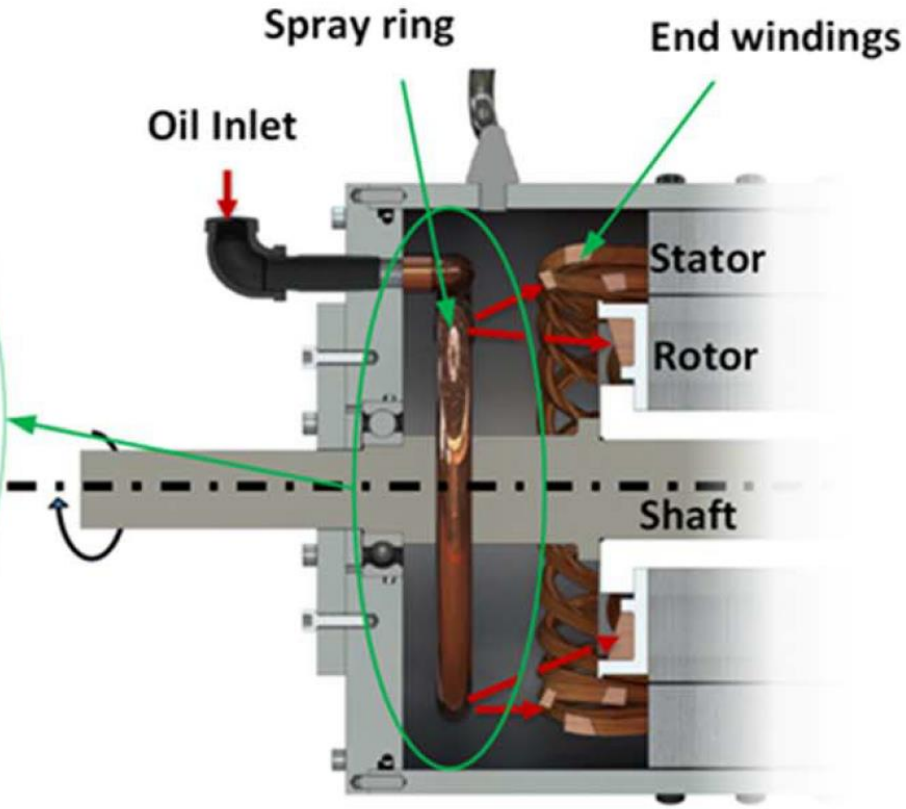
Oil cooling is gradually replacing water cooling.





Source: Bennion, Moreno, Convective Heat Transfer Coefficients of Automatic Transmission Fluid Jets With Implications for Electric Machine Thermal Management, DOI:10.1115/IPACK2015-48382

Thermal Management



Source: P. Shams Ghahfarokhi, A. Podgornovs, A. Kallaste, A. J. Marques Cardoso, A. Belahcen and T. Vaimann, "The Oil Spray Cooling System of Automotive Traction Motors: The State of the Art," in *IEEE Transactions on Transportation Electrification*, vol. 9, no. 1, pp. 428-451, March 2023, doi: 10.1109/TTE.2022.3189596.

Material developments - Hairpin winding

Fill factor 85%
(source: Mitsubishi)

Fill factor 40%
(source: Brusa)

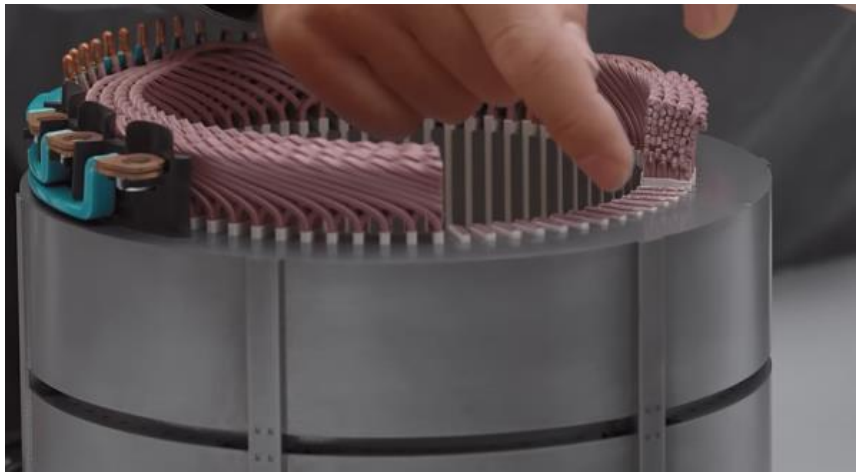
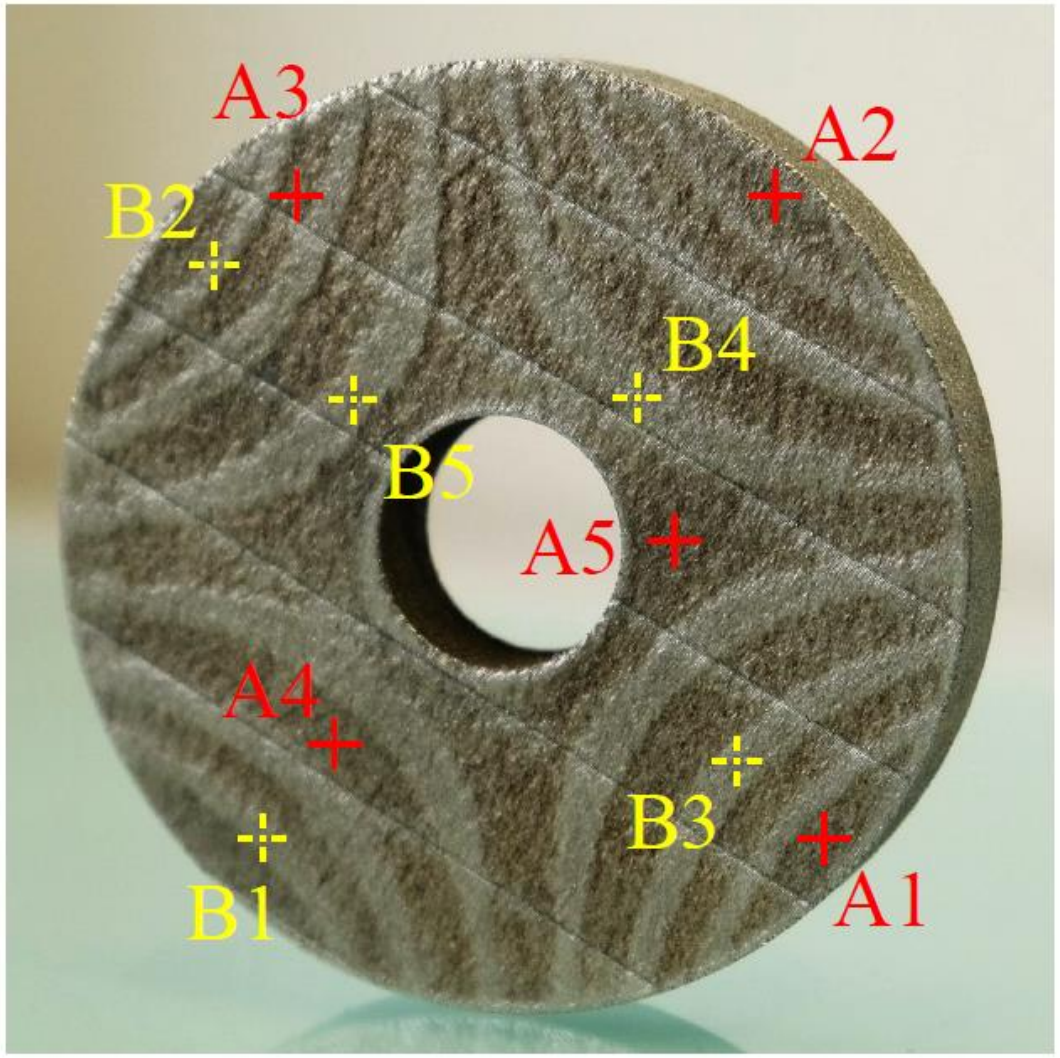
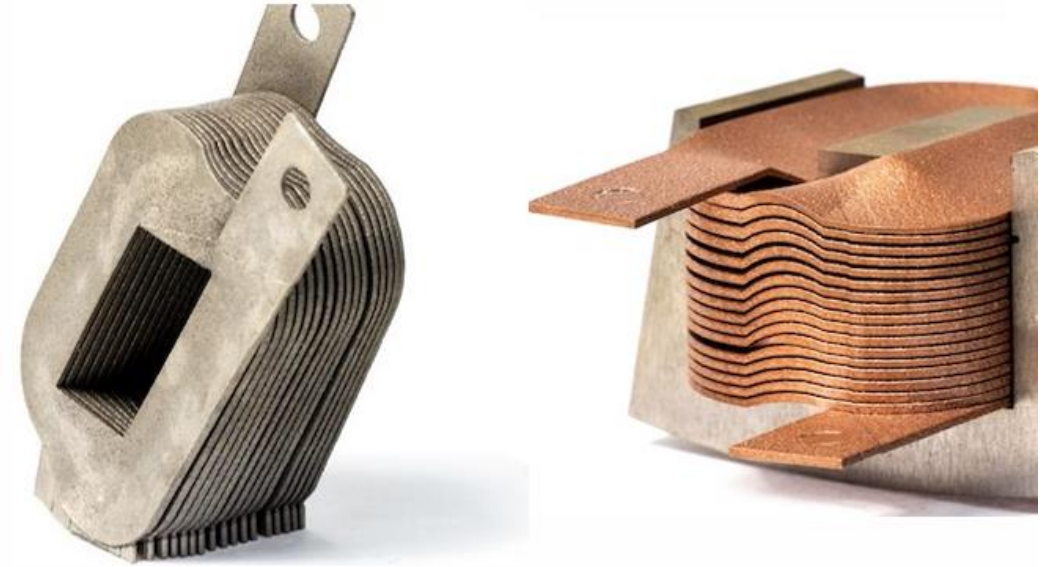


Figure: Mohit Mistry, The Ultimate Showdown: Round Wire vs. Hair Pin Motor Winding, Tech simplified

Manufacturing innovations – 3D printing



Manufacturing innovations – 3D printing



University of BRISTOL

N. Simpson, D. J. North, S. M. Collins and P. H. Mellor, "Additive Manufacturing of Shaped Profile Windings for Minimal AC Loss in Electrical Machines," in IEEE Transactions on Industry Applications, vol. 56, no. 3, pp. 2510-2519, May-June 2020, doi: 10.1109/TIA.2020.2975763.

MARQUETTE UNIVERSITY

F. Wu, **A. M. EL-Refaie** and A. Al-Qarni, "Additively Manufactured Hollow Conductors for High Specific Power Electrical Machines: Aluminum vs Copper," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), 2021, pp. 4397-4404, doi: 10.1109/ECCE47101.2021.9595470.

BRNO UNIVERSITY OF TECHNOLOGY

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department of power electrical and electronic engineering

Life Cycle

High-Volume Recycling of E-Machines: Key Challenges

•Key materials to extract: **magnets**, **copper**, and **electrical steels**.

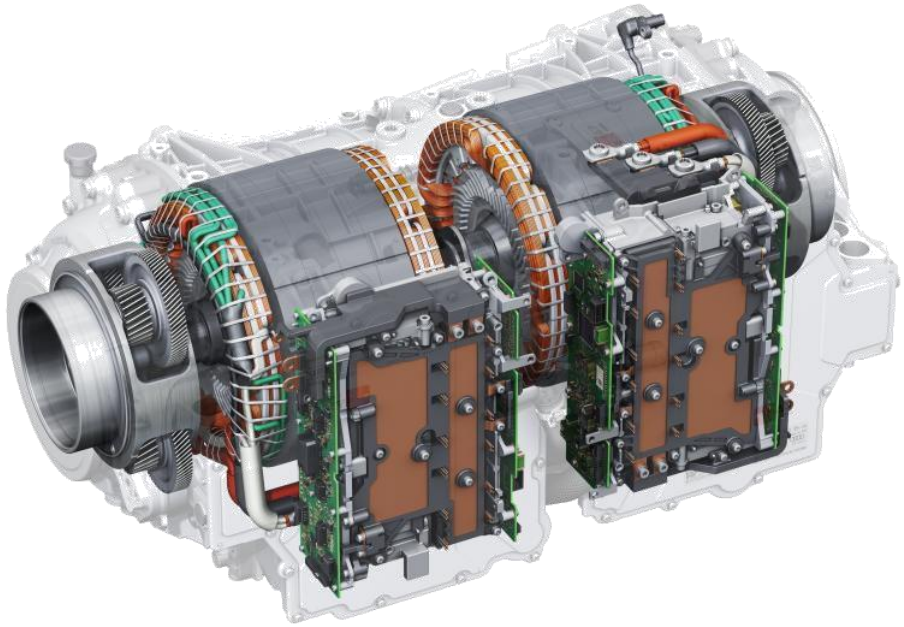
•Challenge: Extracting materials **cost-effectively** without damage.

Sustainability and Material Recovery

•**Minimize environmental impact** in scaled-up recycling processes.

•Ensure **high recovery rates** of critical and non-critical materials.

•Balancing **economic viability** with efficient recycling processes.



Compact and affordable designs are driving greater integration of electric machines into drivetrain components, along with power electronics. This poses a challenge for serviceability, disassembly, and energy-efficient recycling at the end of their life cycle.

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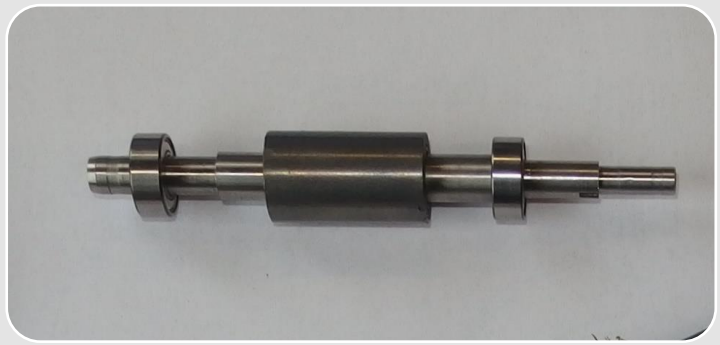
FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION department of power electrical and electronic engineering

Based on: Electric Machines Roadmap 2020, Narrative Report, Automotive council UK, Advanced Propulsion Centre UK

Figures: Audi

Life Cycle



Magnets

- New methods: **Hydrogen injection** for breaking down magnets.

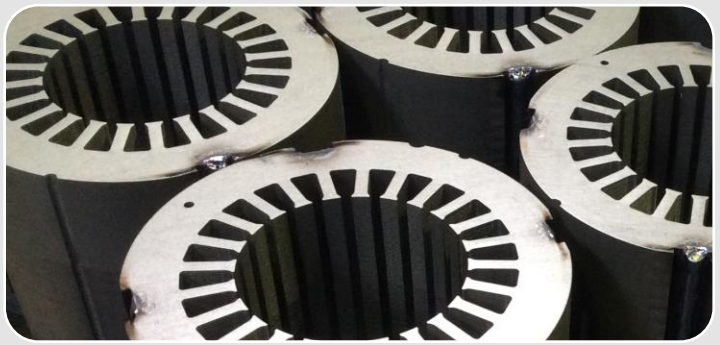
- Use of **solvent extraction** for separating rare earth elements.

- Key goal: Achieve a **circular economy** without using **primary rare earth**

Copper

- can be recycled multiple times without degradation.

- impregnation challenges in extracting copper from components.



Electrical steels

- are difficult to recycle due to insulation layers and high silicon content.

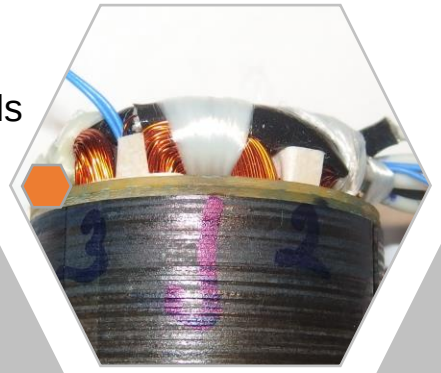
- Cannot be recycled with traditional steel grades.

- Need for **new processes** tailored to electrical steels recycling.

Based on: Electric Machines Roadmap 2020, Narrative Report, Automotive council UK, Advanced Propulsion Centre UK

Summary

- Cost efective winding materials
- Reducing reliance on rare earth materials

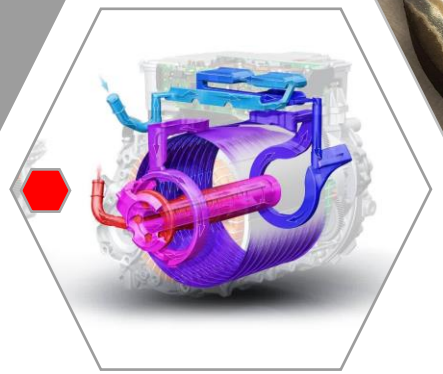


Material Development

Thermal Management

Machine Architectures and Integration

Manufacturing Innovations



Life Cycle

- Improvements in high volume recycling methods for EV
- Many methods emerging for recycling rare earths.

- Trends towards high-speed, high-power dense machines
- Trends towards Rare-earth free designs
- Advances enabling high-power dense machines
- Active cooling with liquid - Oil cooling is gradually replacing water cooling
- High volume winding techniques with aim on high fill factor
- Ambition to have net-shape, zero waste components – additive manufacturing

Thank you for your attention

Touch the power with us

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