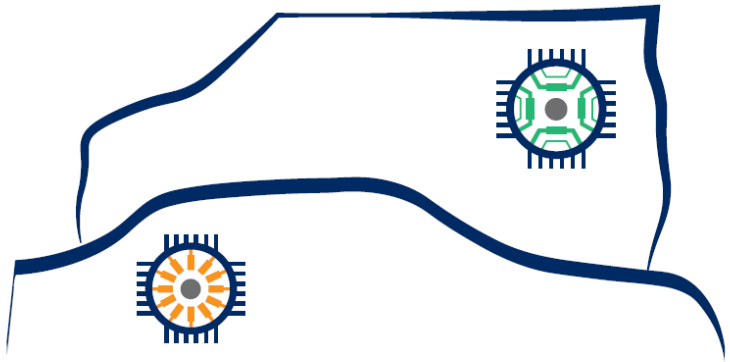

ReFreeDrive

Rare earth free e-drives featuring low manufacturing cost

Rare earth free E-drives for electric vehicle application

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Cu European Copper Institute
Copper Alliance

T. Jezdinsky, European Copper Institute

G. Fabri, University of L'Aquila

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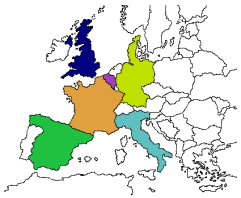
ReFreeDrive Project Overview

13 partners, 6 European countries



Motor Design & Manufacturing

- Università degli Studi de L'Aquila
- Motor Design Limited
- IFP Energies nouvelles
- Tecnomatic group – turn knowledge into value

Power electronics

- Università degli Studi de L'Aquila
- R13 Technology

Vehicle integration & testing

- Fundación cidaut – Investigación y Desarrollo en Transporte y Energía
- prive – progettazione ricerca ingegnerizzazione veicoli elettrici

Project coordination

- Fundación cidaut – Investigación y Desarrollo en Transporte y Energía

Copper

- Cu European Copper Institute – Copper Alliance
- Aurubis
- hb breuckmann eMobility

OEM Validation

- Jaguar
- Land Rover

Steel

- RINA 1861 CSM Centro Sviluppo Materiali

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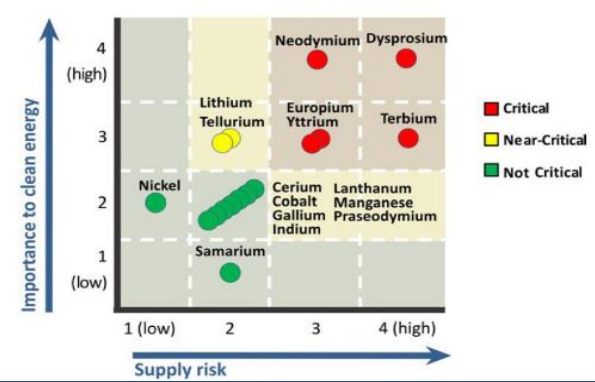
ReFreeDrive Project Overview

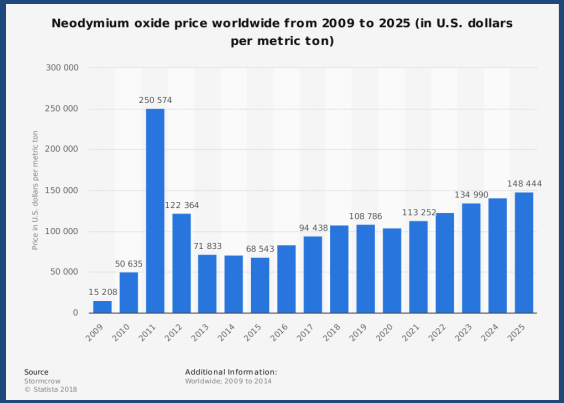
Why rare earth elements free solutions?

Supply risk

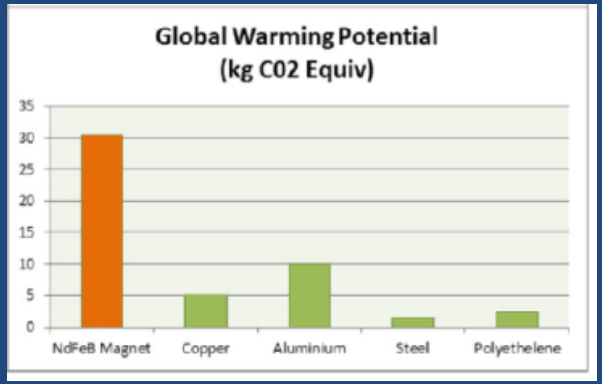


Cost

Market uncertainties



Environment & LCA



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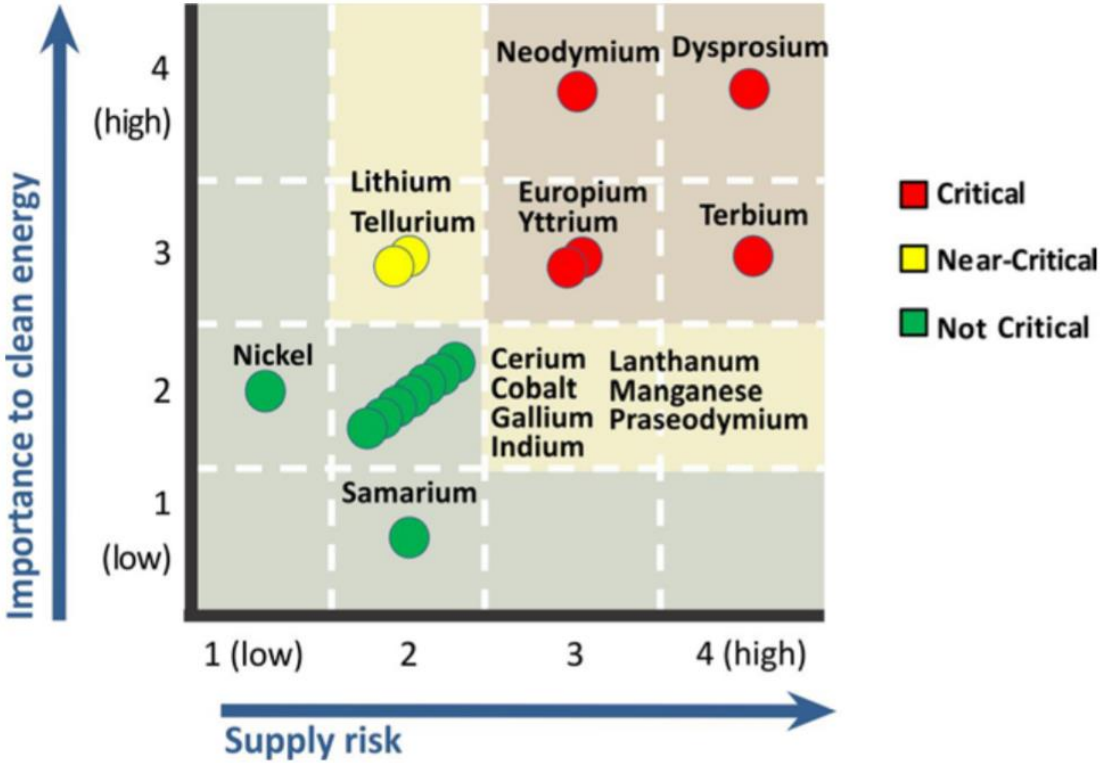
ReFreeDrive Project Overview

Why rare earth elements free?

SUPPLY RISK



Medium-Term (2015–2025) Criticality Matrix

U.S. Department Of Energy - Critical materials strategy - December 2011
https://www.energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf

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ReFreeDrive Project Overview

Why rare earth elements free?

COST

Fig. 6. Materials cost in a 30 kW traction motor for a motor with rare earth magnets ('interior permanent magnet motor') and two options without [8].

J.D. Widmer, et al., Electric vehicle traction motors without rare earth magnets, (2015), https://www.sciencedirect.com/science/article/pii/S2214993715000032?via%3Dihub

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ReFreeDrive Project Overview

Why rare earth elements free?

MARKET UNCERTAINTIES

https://www.statista.com/statistics/450152/global-reo-neodymium-oxide-price-forecast/

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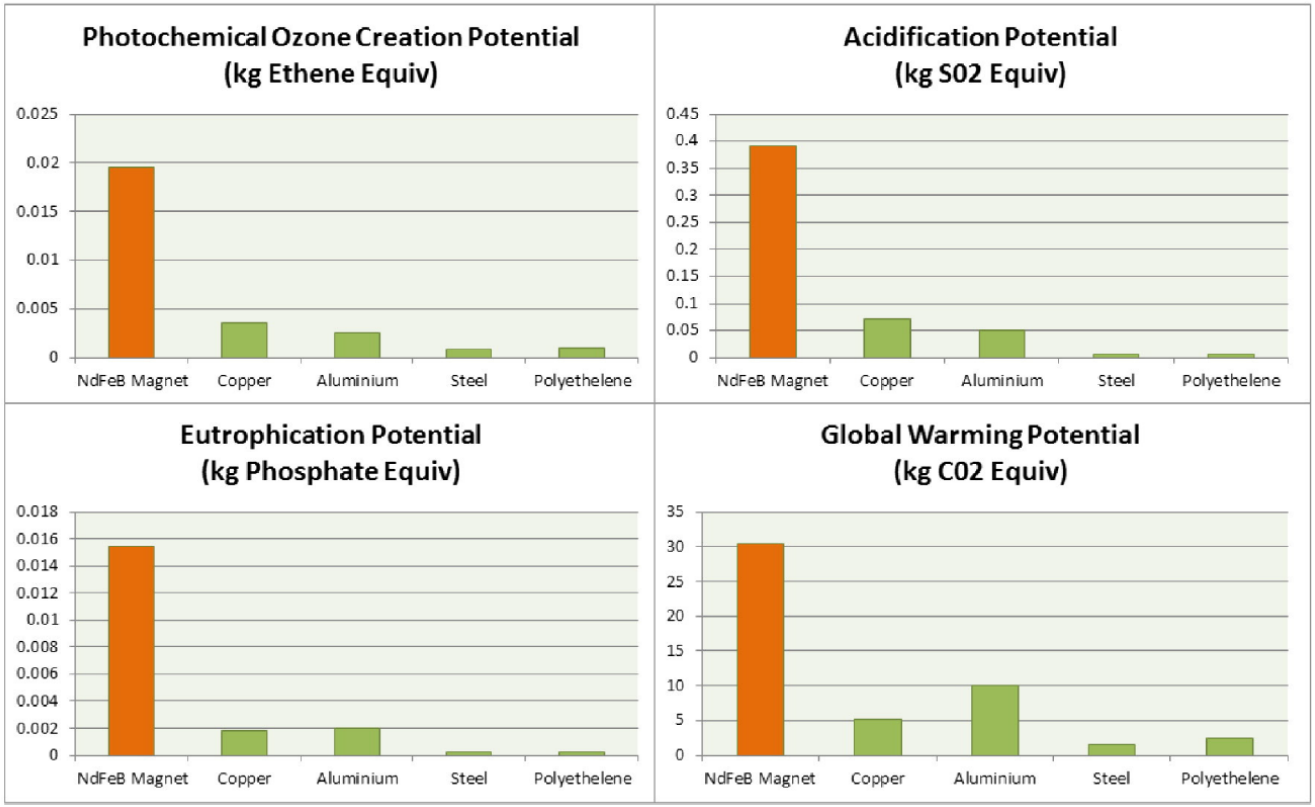
ReFreeDrive Project Overview

Why rare earth elements free?

ENVIRONMENT & LCA

J.D. Widmer et al. / Sustainable Materials and Technologies xxx (2015) xxx–xxx



J.D. Widmer, et al., Electric vehicle traction motors without rare earth magnets, (2015), https://www.sciencedirect.com/science/article/pii/S2214993715000032?via%3Dihub

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ReFreeDrive Project Overview

What about **copper**? Not a critical raw material

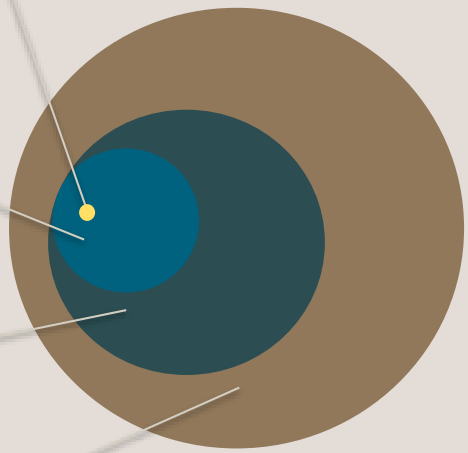
Primary route: mining (~70% of demand)

Annual production
21 Mtonnes

Reserves
830 Mtonnes
(40 years)

Identified resources
2100 Mtonnes
(100 years)

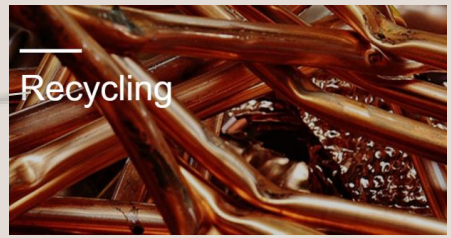
Total resources
5000 Mtonnes
(250 years)



Deep sea deposits excluded

Secondary route: recycling (~30% of demand)

400 Mtonnes available in the "urban mine"
(20 years)



Copper can be recycled repeatedly without downgrading

Most of copper alloying elements can be recovered

Diversified geographic availability

Meeting future copper demand: https://sustainablecopper.org/meeting-future-copper-demand/
The World Copper Factbook 2018: https://www.icsg.org/index.php/component/jdownloads/finish/170/2876
Dynamic Analysis of Global Copper Flows. https://pubs.acs.org/doi/10.1021/es400069b
US Geological Survey (USGS), 2019: https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/mcs-2019-coppe.pdf

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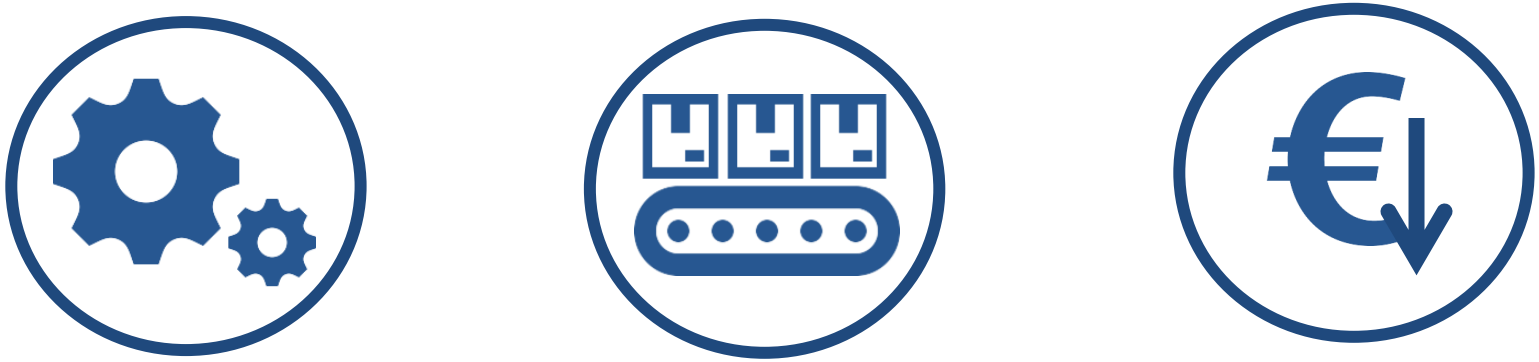
ReFreeDrive Project Overview

Project Objectives

- The main aim of this project is to develop **rare earth-free traction technologies**



INDUSTRIAL FEASIBILITY

MASS PRODUCTION

LOWER COSTS

- Material selection
- Manufacturing processes
- Design optimisation
- Scalability

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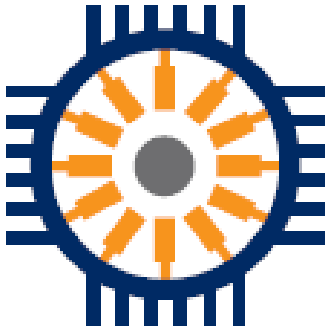
ReFreeDrive Project Overview

Project Technologies: we will design & manufacture
8 different e-motors for electrical powertrains



Induction machines with copper rotor

Fabricated

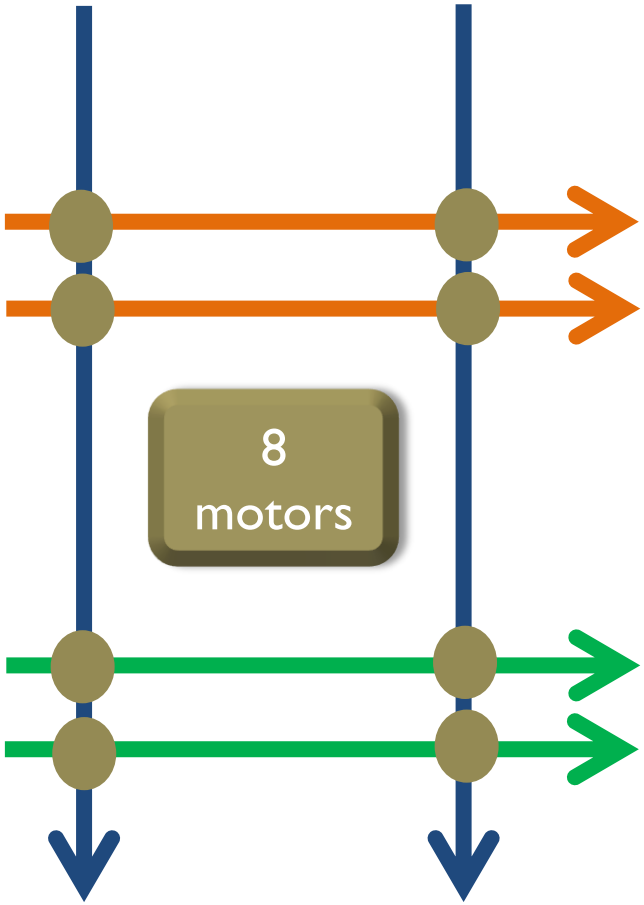
Die Cast

Synchronous reluctance machines

PMassisted

Without PM

75kW and 200kW



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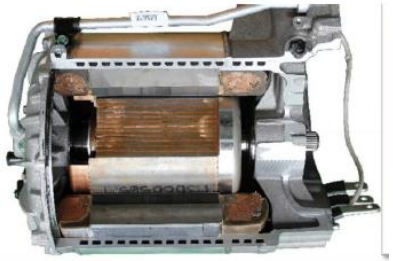
ReFreeDrive Project Overview

Target figures

Benchmark Tesla S60



30% INCREASE SPECIFIC TORQUE

50% MOTOR LOSSES REDUCTION

15% COST REDUCTION

50% INCREASE OF POWER DENSITY IN POWER ELECTRONICS

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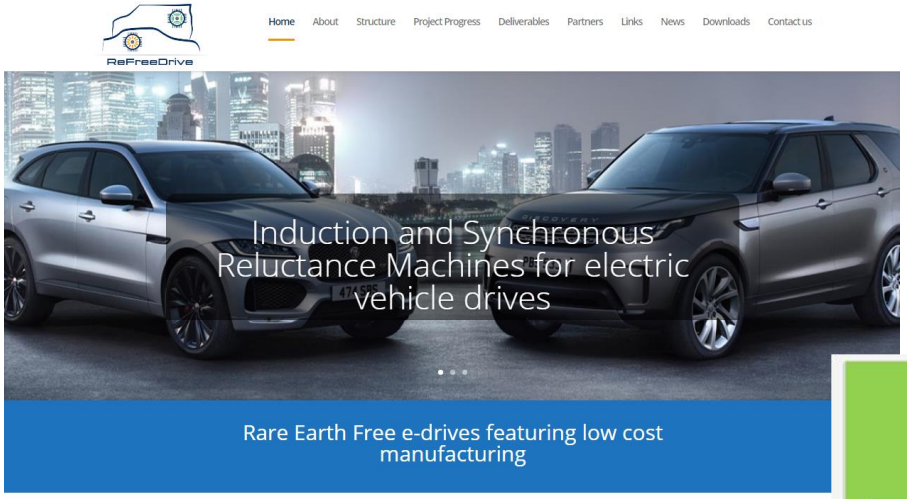
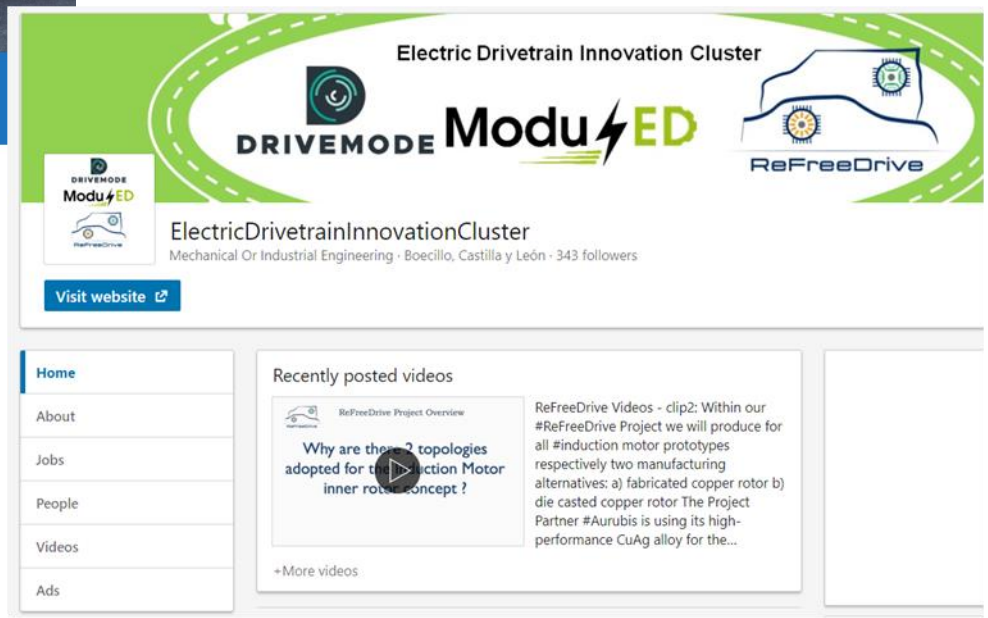
ReFreeDrive Project Overview

Please visit:
www.refreedrive.eu

and

ElectricDrivetrainInnovationCluster in LinkedIn





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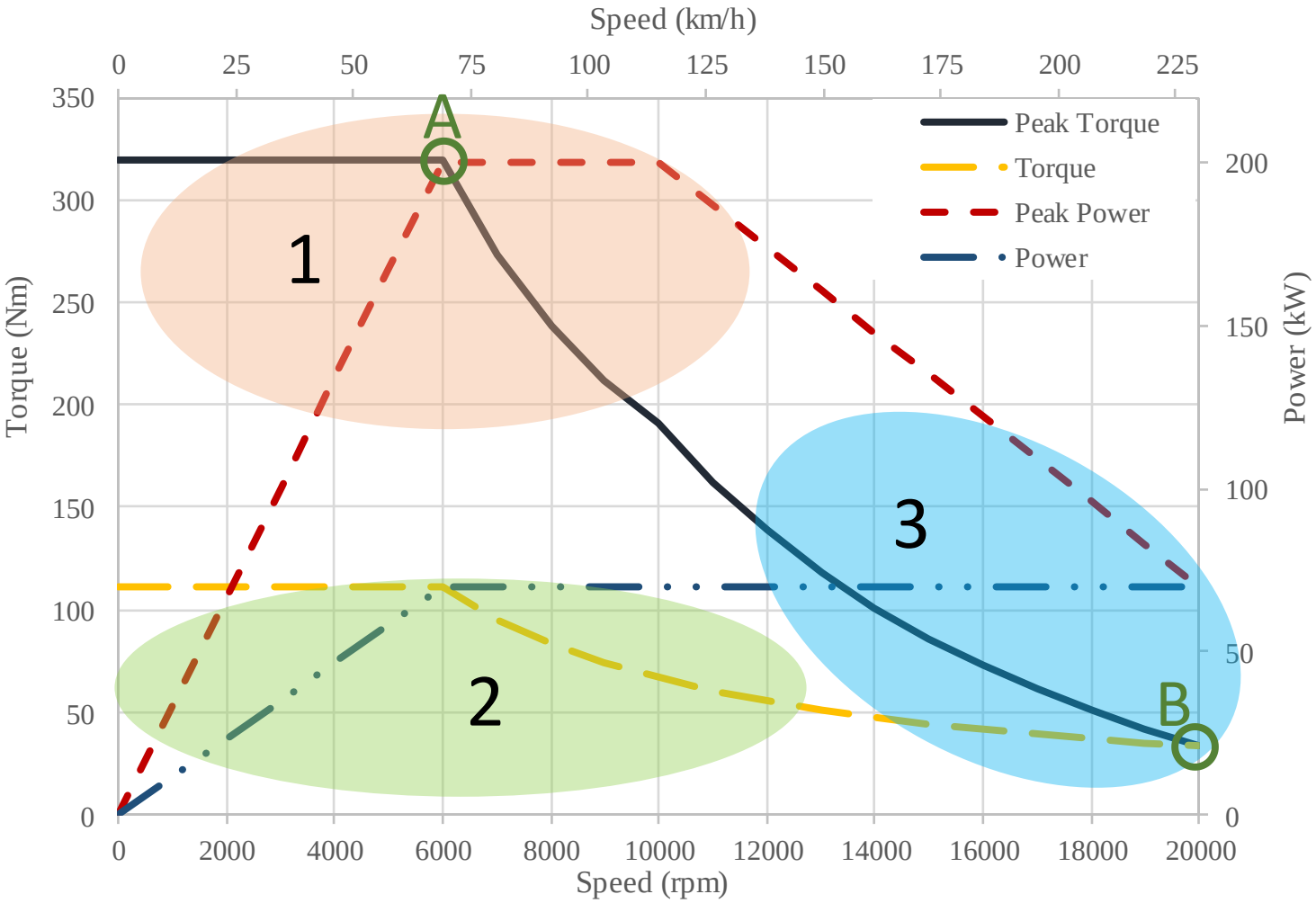
ReFreeDrive Project Overview

EV powertrains requirements



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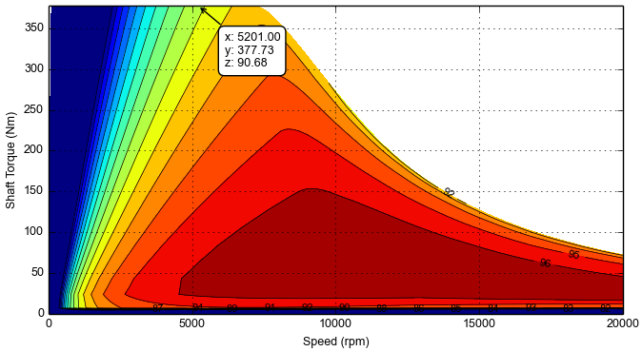
ReFreeDrive Project Overview

Induction Motors

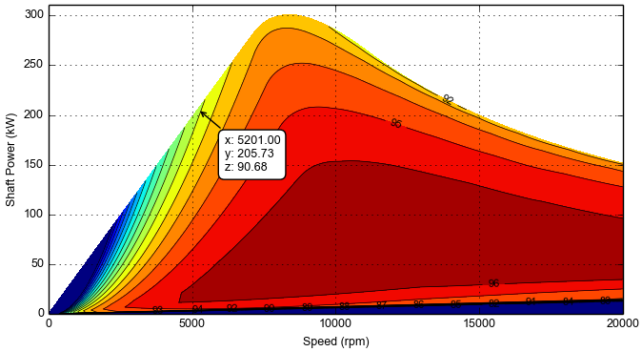
Electromagnetic Design

- Machine topology:
  - 4-pole, 36-slot, 50-bar
- Geometry:
  - OD = 190mm
  - L = 161mm
- Materials
  - M235-35A steel (rotor & stator)
  - CuAg0.04 (fabricated rotor cage)
  - Cu-ETP (die-casted rotor cage)
- Stator winding:
  - Turns / Phase = 12
  - Packing factor (%) = 73
- Power supply:
  - DC Voltage = 350V/720V
  - Current = 350Arms/500Arms

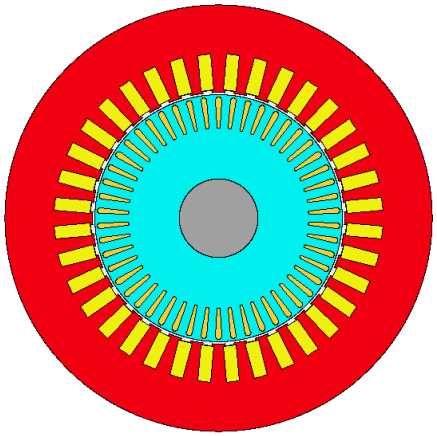
Torque-Efficiency Map



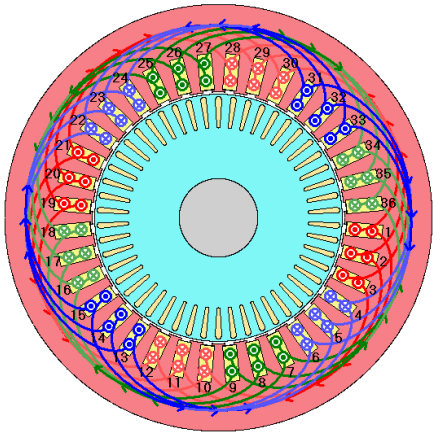
Power-Efficiency Map



Radial Geometry



Winding pattern



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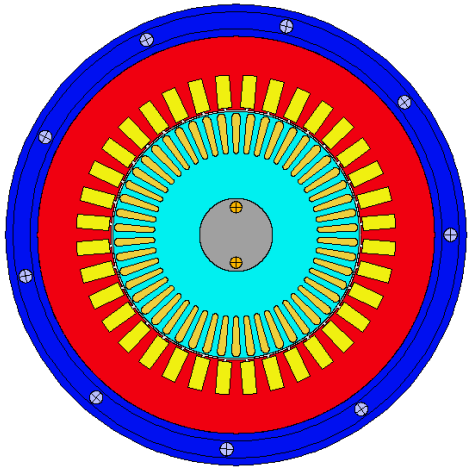
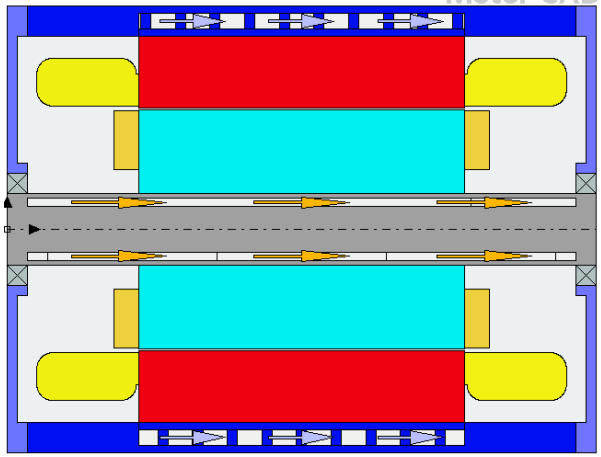
ReFreeDrive Project Overview

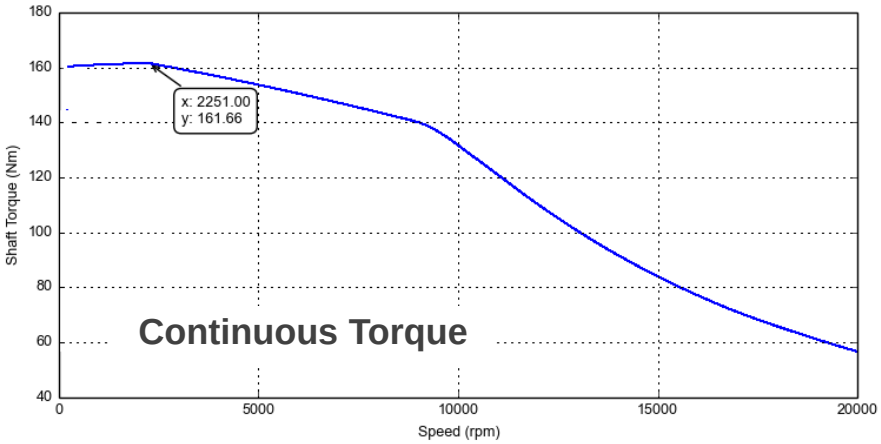
Induction Motors

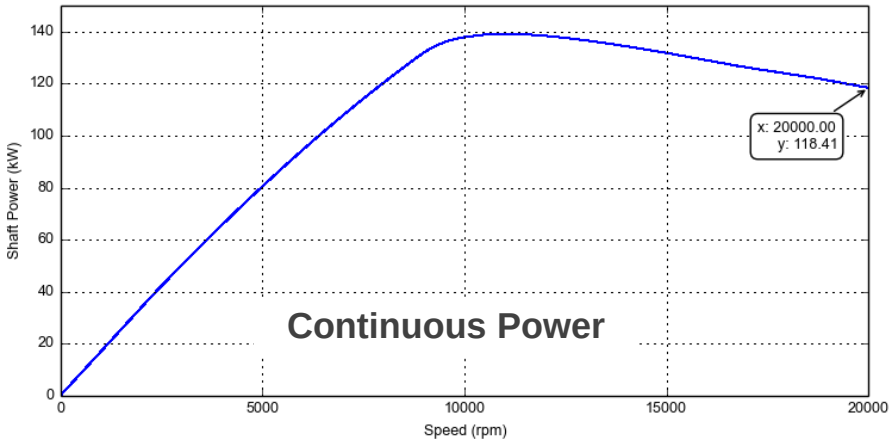
Thermal Design

- Series Cooling system:
- Stator jacket
- Rotor groove
- EWG 50/50
- Flow rate 10 l/min









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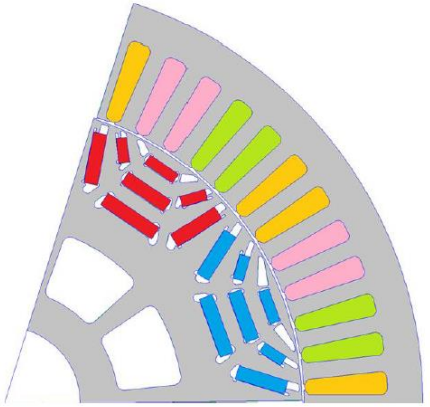
ReFreeDrive Project Overview

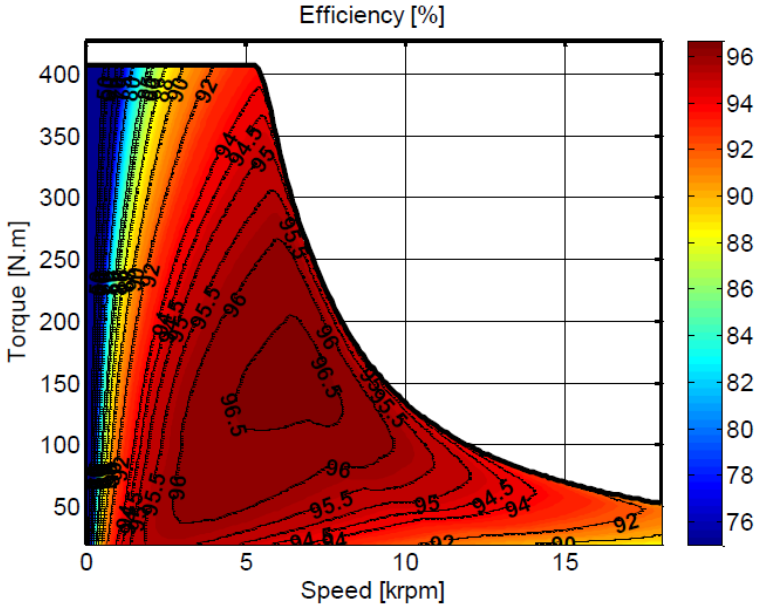
PM assisted Synchronous Reluctance Motor



Design Characteristics:

- Distributed round wire windings;
- Optimized rotor geometry;
- Rare Earth Free Ferrite Magnets
- 10 poles, 60 stator slots

Parameter (unit)	KPI	ReFreeDrive
Specific peak power (kW/kg)	> 4.3	4.9
Peak power density (kW/lit)	> 8.0	22.6
Specific peak torque (Nm/kg)	> 8.2	9.5
Peak torque density (Nm/lit)	> 15.4	46.5
Maximum speed (rpm)	15000÷20000	17500
Peak efficiency (%)	> 96	96
Active parts weight (kg)	< 47	45.5



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ReFreeDrive Project Overview

Pure SynRel motors

Motor Design

- Pros:
  - Simple stator (close to IM)
  - cost effective rotor solution,
  - no magnets no copper in the rotor
  - No cooling issues in the rotor
  - High Efficiency
- Cons:
  - Very challenging design for high speed
  - Poor power factor
  - Torque ripple
- Machine topology:
  - 6-pole, 54- stator slot
  - Round wire windings
- Geometry:
  - OD = 220mm
  - L = 200mm
- Materials
  - M235-35A steel (rotor & stator)
- Power supply:
  - DC Voltage = 350V/720V
  - Current = 350Arms/635Arms

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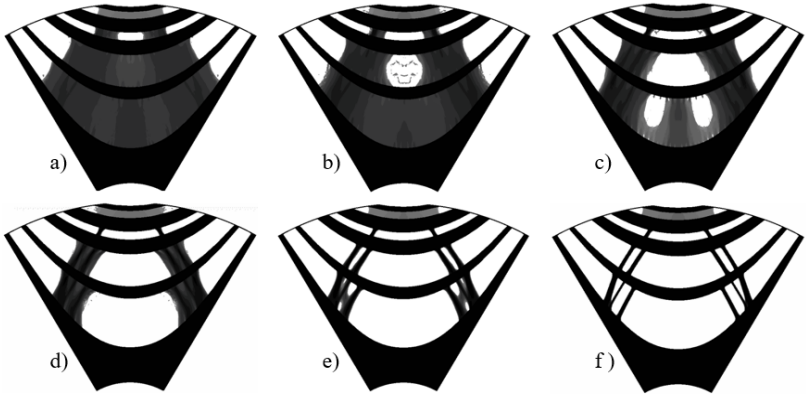
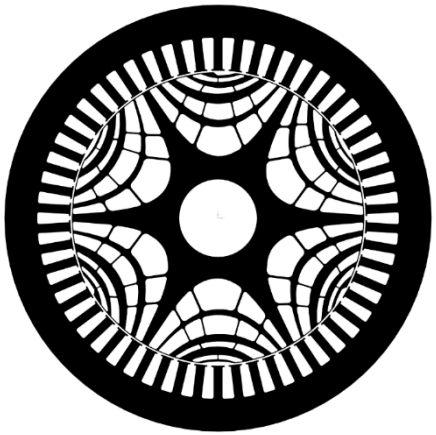
Rotor design aided by topology optimization



A. Credo, G. Fabri, M. Villani and M. Popescu, "Adopting the topology optimization in the design of high-speed synchronous reluctance motors for electric vehicles," ***IEEE Transactions on Industry Applications***

A. Credo, G. Fabri, M. A. Villani and M. Popescu, "A Robust Design Methodology for Synchronous Reluctance Motors," in ***IEEE Transactions on Energy Conversion.***

www.refreedrive.eu



Optimized for:

- low torque ripple,
- acceptable power factor
- High efficiency
- High speed

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ReFreeDrive Project Overview

Pure SynRel motors

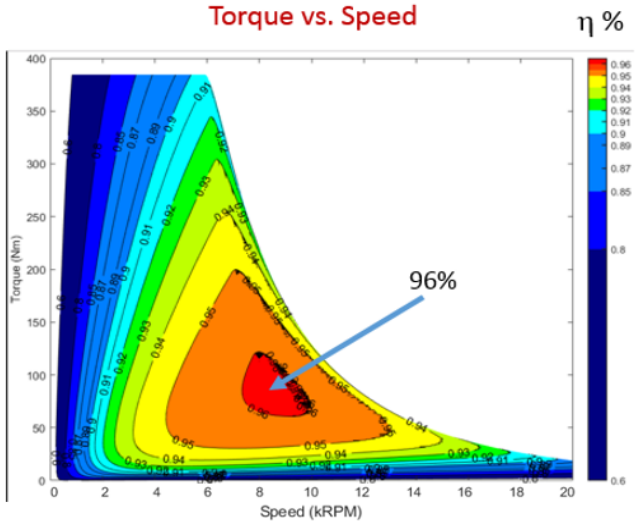
Performance

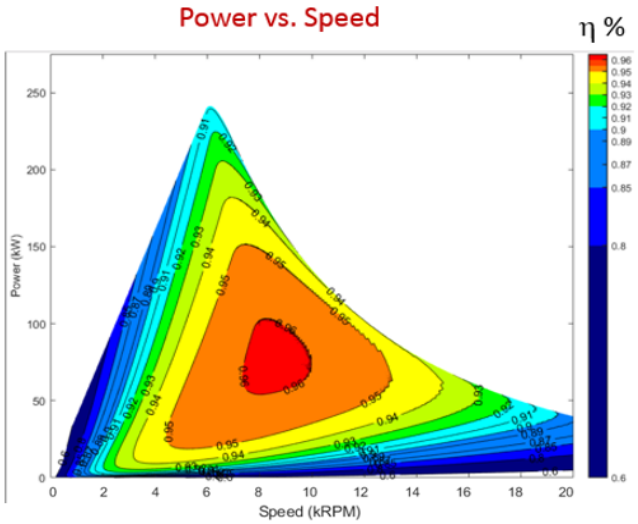
The design matches the challenging requirements

- Very wide speed range;
- High peak efficiency, good efficiency at low speed;
- Acceptable power factor;
- Interesting EV motor technology for less demanding application.

And the research continues…

Parameter	unit	Tesla Model S	RFD Goals	SynRel design
Motor type		Induction Motor		SynRM
Cooling		Liquid		Liquid
Specific Peak Power (*)	kW/kg	3.3	> 4.3	5.3
Specific Peak Torque	Nm/kg	6.32	> 8.2	8.4
Maximum speed	krpm	14500	15000 ÷ 18000	18000
Peak efficiency	%	92	> 96	96
Active parts weight	kg	68	< 47	46
Motor dimensions (+): Total Length	mm	225	< 310	310





* active parts only
\+ housing included
\# efficiency maps include mechanical losses

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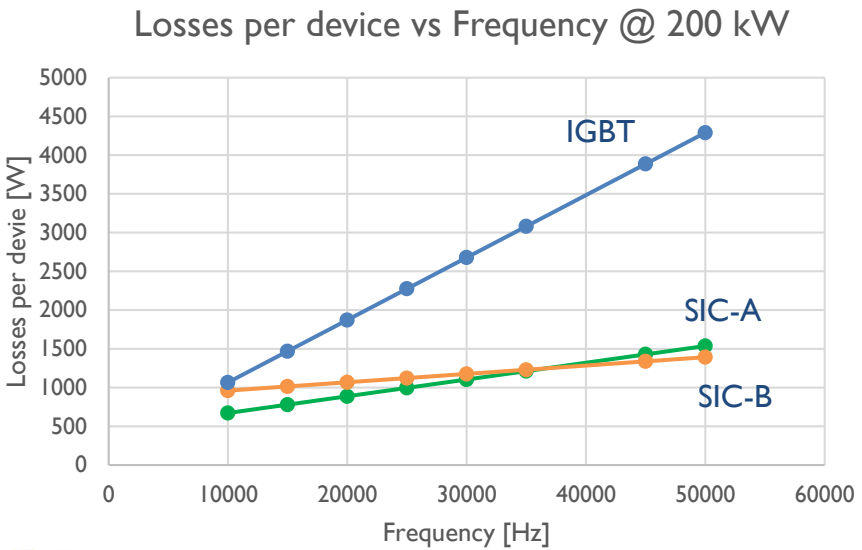
ReFreeDrive Project Overview

Power Electronics

Design Characteristics:

- SIC Based Power Electronics;
- Thin Film capacitors;
- Laminated DC bus bar;
- Integrated PE and motor cooling.



1200V rated Power modules provide a better specific power respect to lover voltage ratings (i.e. 750V).

Mitsubishi SIC Module

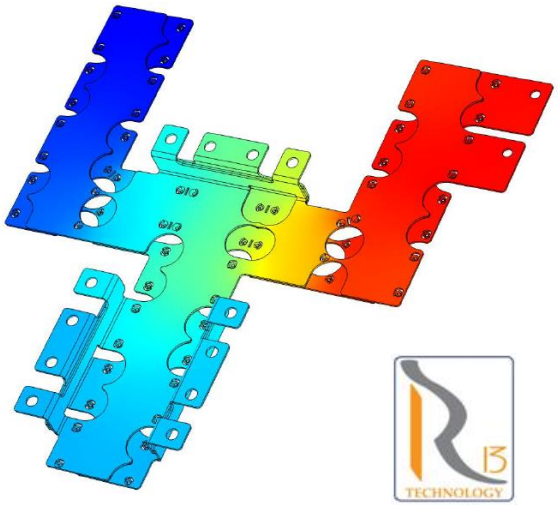
FMF800DX-24A (1200V, 800 A)

Cost: about 1500€ (few samples)

Estimated cost in 2023:

120€ (mass production-3€/kW PE)

Laminated busbars



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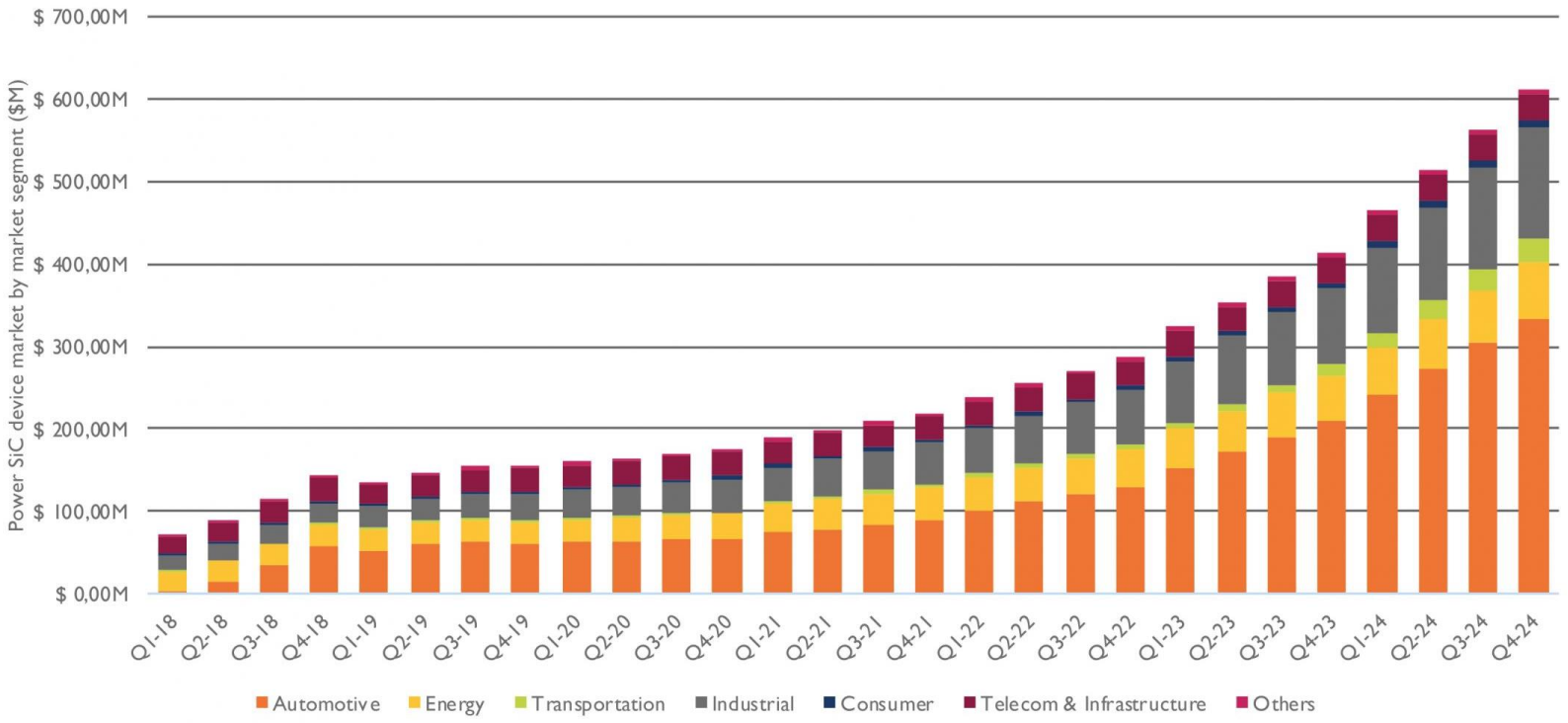
ReFreeDrive Project Overview

SiC market

Power SiC device market Forecast by segment

(Source: CS Market Monitor, Yole Développement, Q4 2019)



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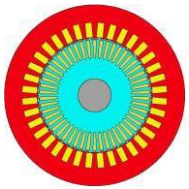
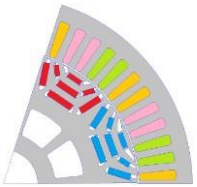
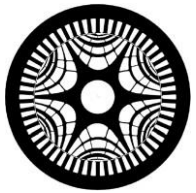
ReFreeDrive Project Overview

Motors performance

Motor variant	Induction	Ferrite SynRel	Pure SynRel
DC-link voltage	720 V	720 V	720 V
Max. modulation	0.98	0.98	0.98
Max. current	500 Arms	636 Arms	636 Arms
Required inv. kVA	430 kVA	550 kVA	550 kVA
Peak torque	380 Nm	470 Nm	415 Nm
Maximum speed	20,000 rpm	18,000 rpm	18,000 rpm
Gear ratio	13.55	12.19	12.19
Peak overall power	300 kW	250 kW	290 kW
Peak power @nmax	150 kW	90 kW	80 kW
			

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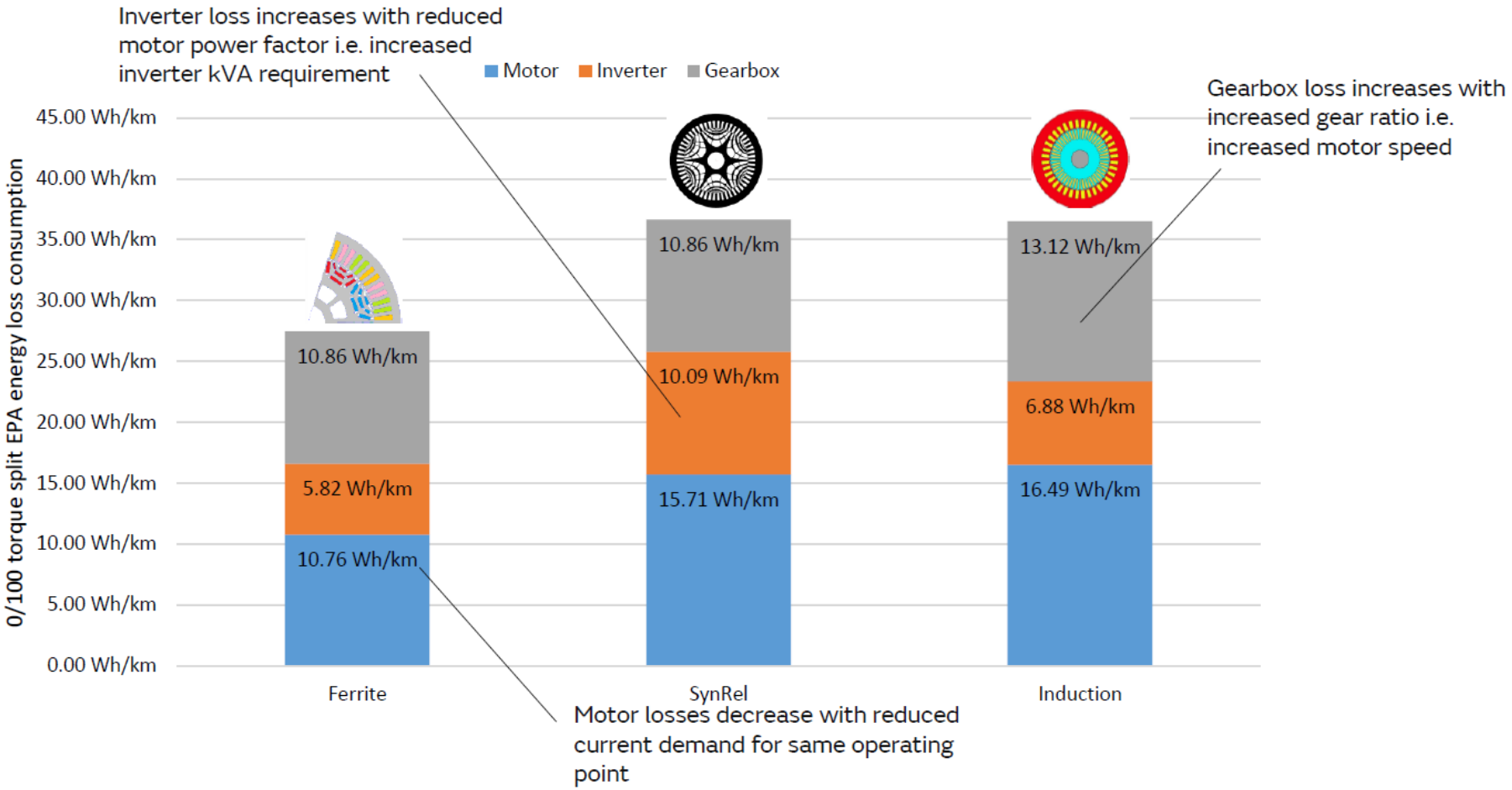
ReFreeDrive Project Overview

Efficiency over EPA cycle (Preliminary), dual motor configuration with one motor fully loaded.



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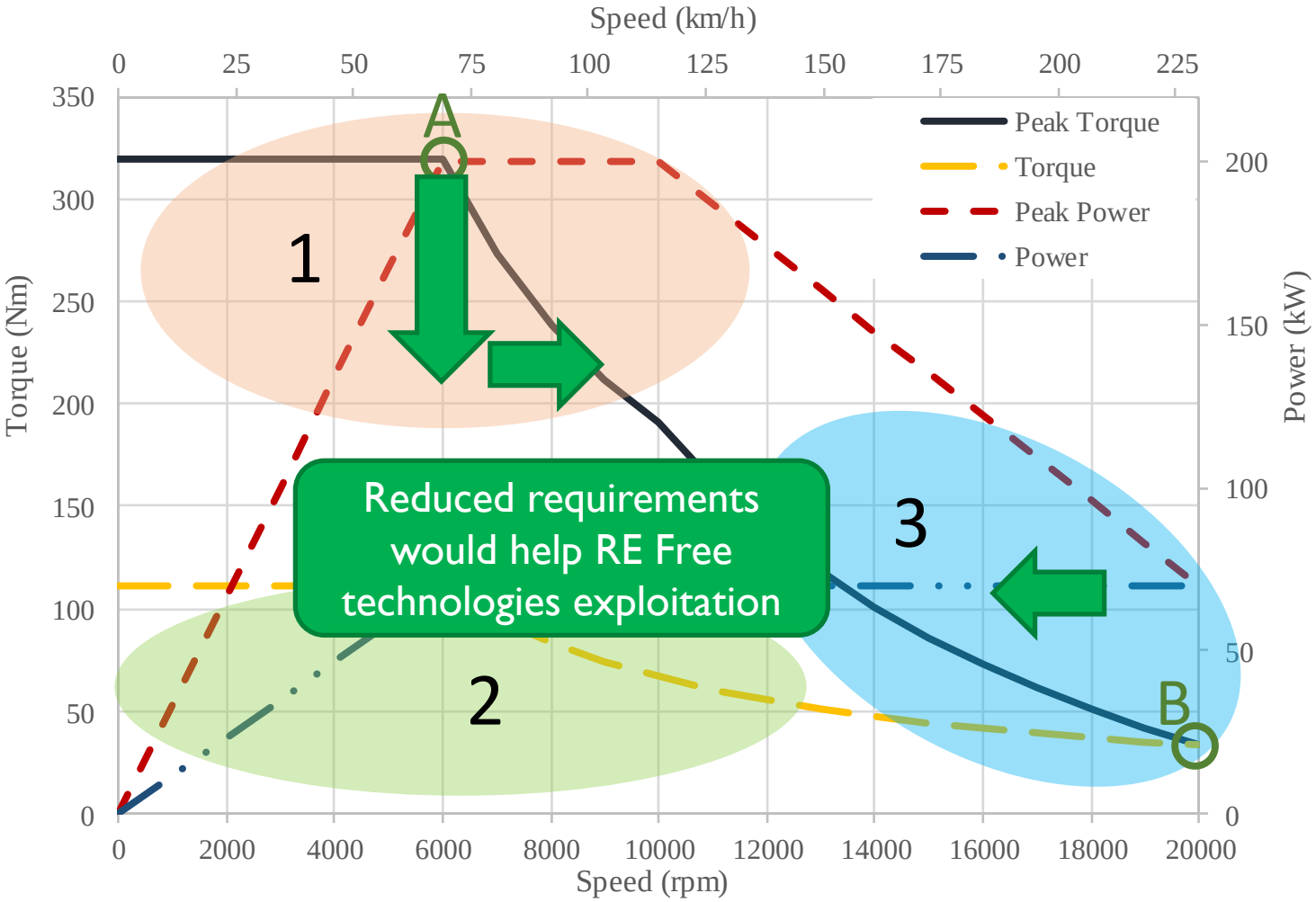
ReFreeDrive Project Overview

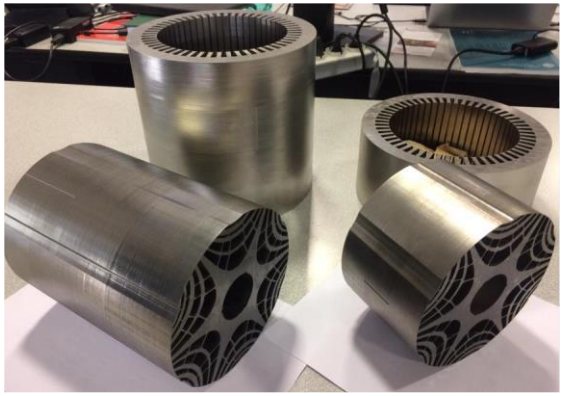
EV powertrains requirements

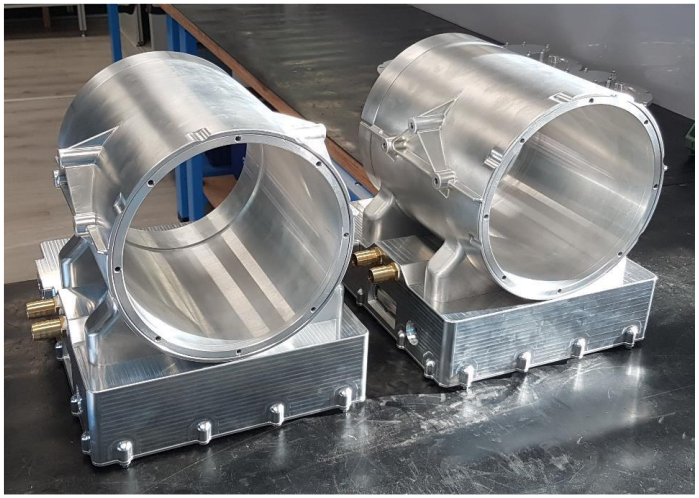


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 770143

ReFreeDrive Project Overview

Prototyping steps





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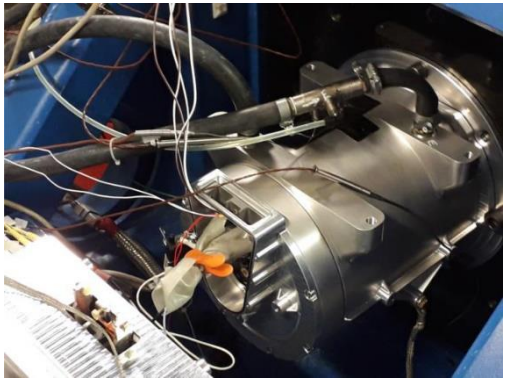
ReFreeDrive Project Overview

Next steps

December 2020 | March 2021

Motor & Integrated powertrain testing	In-vehicle integration



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ReFreeDrive Project

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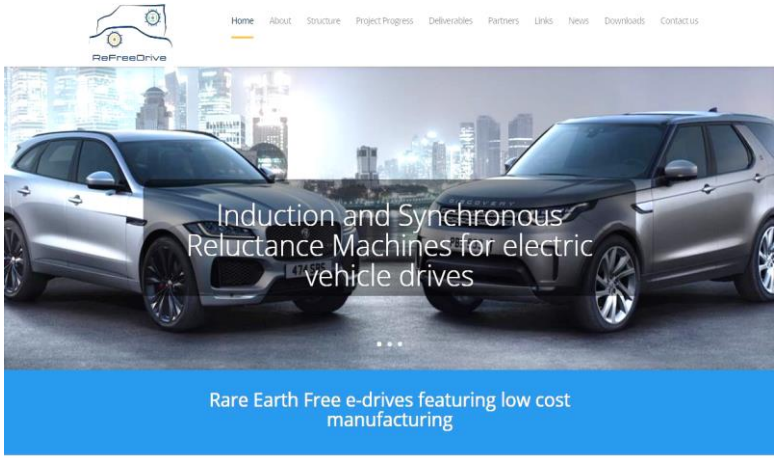

https://www.linkedin.com/company/electric-drivetrain-innovation-cluster/

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ReFreeDrive Project

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