European Copper Institute
Copper Alliance

ReFreeDrive

How copper contributes to sustainable mobility
The ReFreeDrive project

Fernando Nuño – European Copper Institute
3rd September 2020

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

ReFreeDrive Project Overview

General Figures

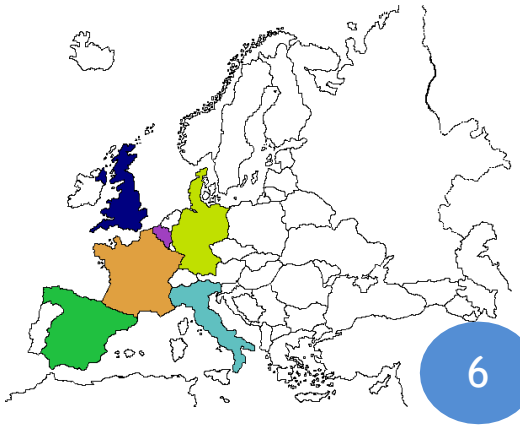
Title: Rare earth free e-Drives featuring low cost manufacturing

Grant Agreement No: 770143

Topic: GV-04-2017

Project Total Costs: 5,999,131.25€

Total EU Contribution: 5,999,131.25€



3 UNITED KINGDOM
European Copper Institute
Motor Design Limited
Jaguar Land Rover

1 BELGIUM
Aurubis

1 FRANCE
IFP Energies nouvelles

6 ITALY
Universitá degli studi dell'Aquila
Centro Sviluppo Materiali
Tecnomatic
Mavel
R13 Technology
Privé

1 GERMANY
MetallGiesserei
Breuckman

1 SPAIN
Fundación Cidaut

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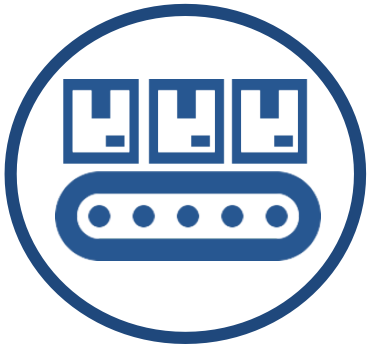
ReFreeDrive Project Overview

Project Objectives

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

LOWER COSTS

INDUSTRIAL FEASIBILITY



MASS PRODUCTION

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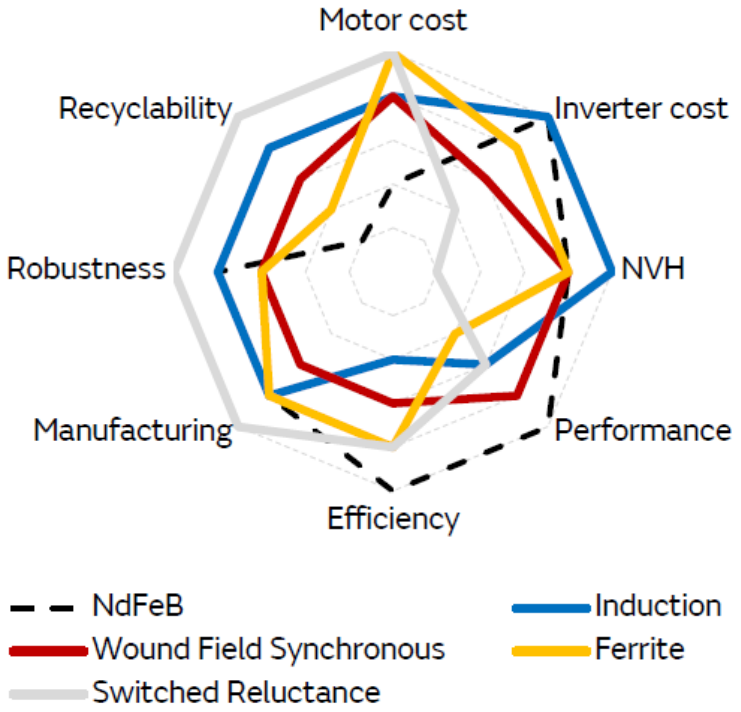
ReFreeDrive Project Overview

Generic Technology Comparison

	PM	IM	WS	FM	SR
Performance	++	0	+	-	0
Efficiency	++	-	0	+	+
Motor cost	-	+	+	++	++
Inverter cost	++	++	0	+	-
Robustness	+	+	0	0	++
Overload	0	++	+	-	+
Stall torque	0	++	0	0	0
Manufacturing	+	+	0	+	++
NVH	+	++	+	+	- -
Recyclability	- -	+	0	-	++
Power @ max. speed	+	-	++	-	++

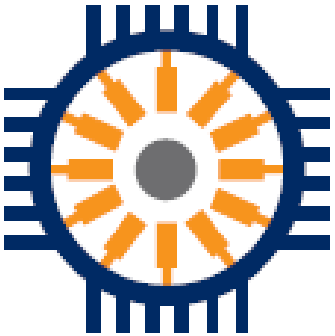


Each traction motor must be tailored to vehicle requirements, customer expectations, architectures, scalability, volumes and even current status of material supply and supplier capability, making each type of motor a potential candidate within a vehicle to benefit a specific purpose

Source: Jaguar Land Rover – Coiltech 2019 presentation - http://www.refreedrive.eu/download-our-coiltech-2019-presentations

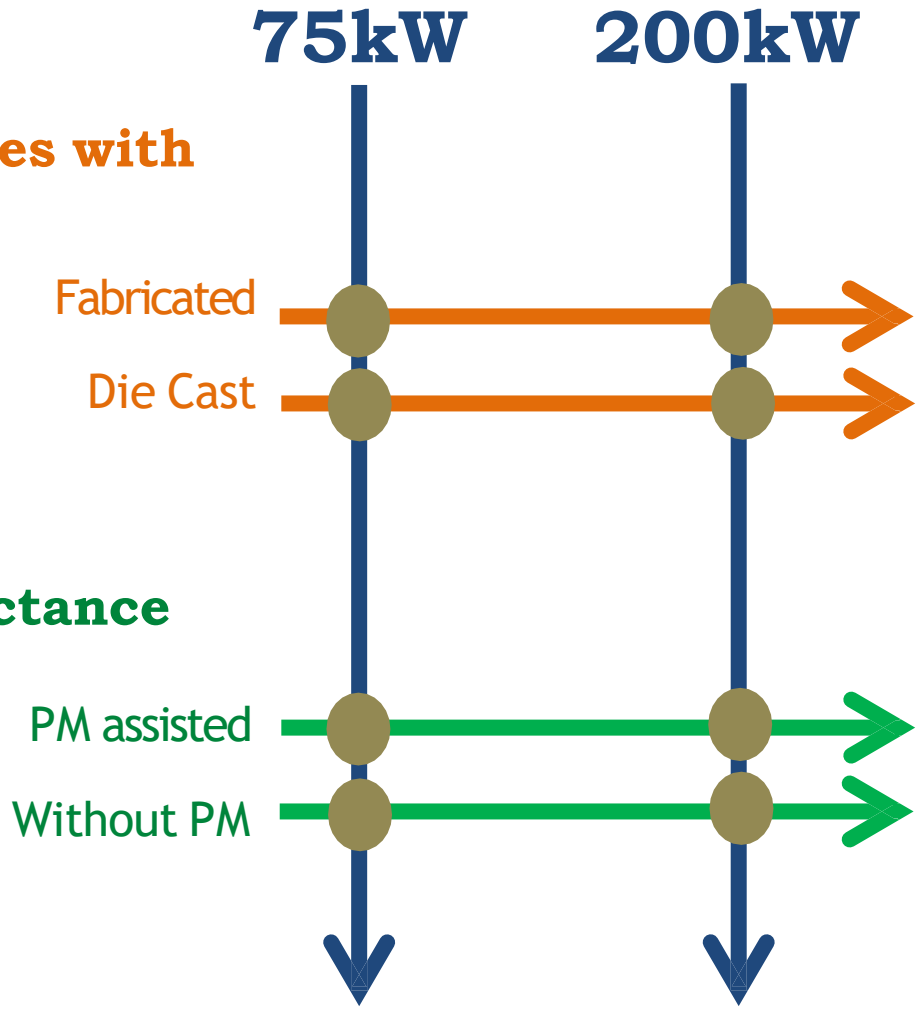
ReFreeDrive Project Overview

Project Technologies



Induction machines with copper rotor

Synchronous reluctance machines



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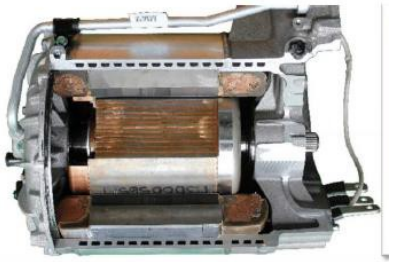
ReFreeDrive Project Overview

Target figures

Benchmark Tesla S60



INCREASE SPECIFIC TORQUE BY 30%

REDUCE MOTOR ENERGY LOSSES BY 50%

15% COST REDUCTION AGAINST SIMILAR SOLUTIONS

INCREASE POWER DENSITY IN POWER ELECTRONICS BY 50%

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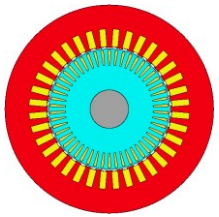
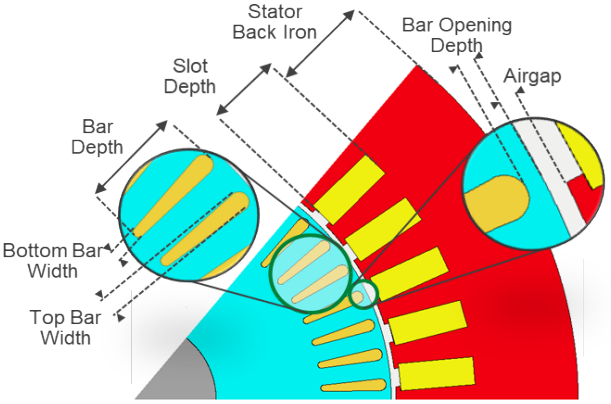
ReFreeDrive Project Overview

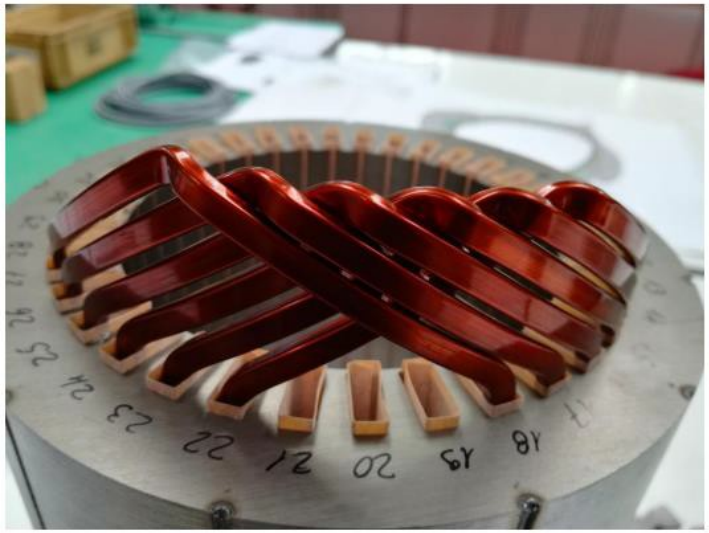
Induction motor design

Radial Geometry



Peak performance is met and the efficiency over the WLTP3 drive cycle is about 95% (motoring).





Motor variant	Induction
DC-link voltage	720 V
Max. modulation	0.98
Max. current	500 Arms
Required inv. kVA	430 kVA
Peak torque	380 Nm
Maximum speed	20,000 rpm
Gear ratio	13.55
Peak overall power	300 kW
Peak power @nmax	150 kW

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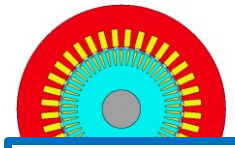
ReFreeDrive Project Overview

Induction motor design

Radial Geometry



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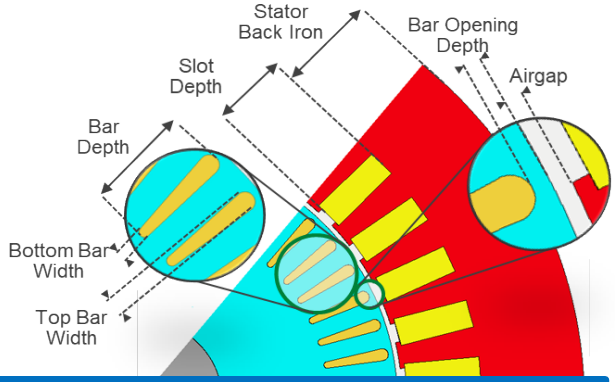

Scaling results for final design

Rated peak power [kW]	Peak torque [Nm]	Maximum efficiency [%]	Maximum DC voltage [V]	RMS line current [Arms]	Maximum speed [rpm]
200	378	96	720	500	20000
75	192	95	350	275	13000

Peak overall power	300 kW
Peak power @nmax	150 kW

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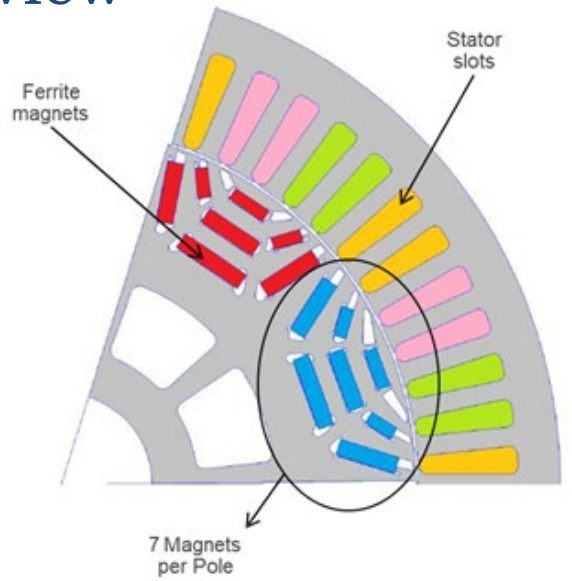
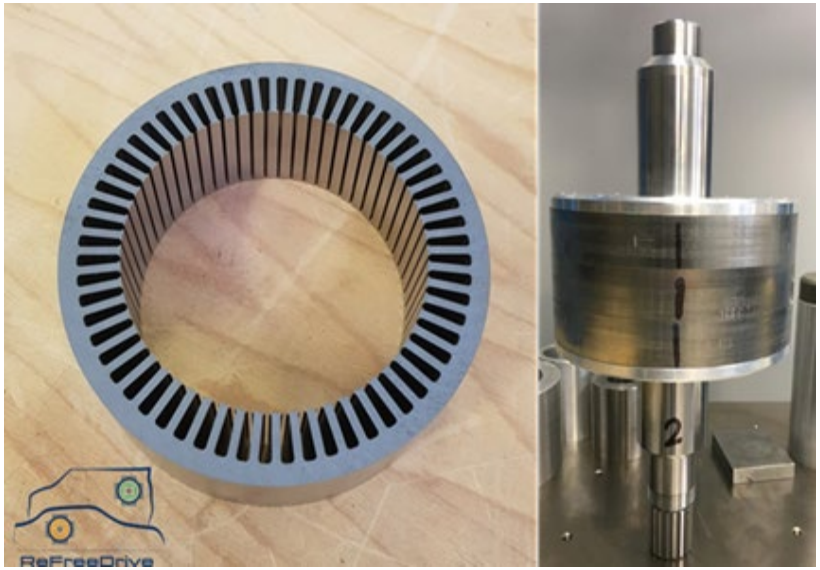
ReFreeDrive Project Overview

PM Synrel motor design

Peak performance is met and the efficiency is about 96% (motoring).



Motor variant	Ferrite SynRel
DC-link voltage	720 V
Max. modulation	0.98
Max. current	636 Arms
Required inv. kVA	550 kVA
Peak torque	470 Nm
Maximum speed	18,000 rpm
Gear ratio	12.19
Peak overall power	250 kW
Peak power @nmax	90 kW



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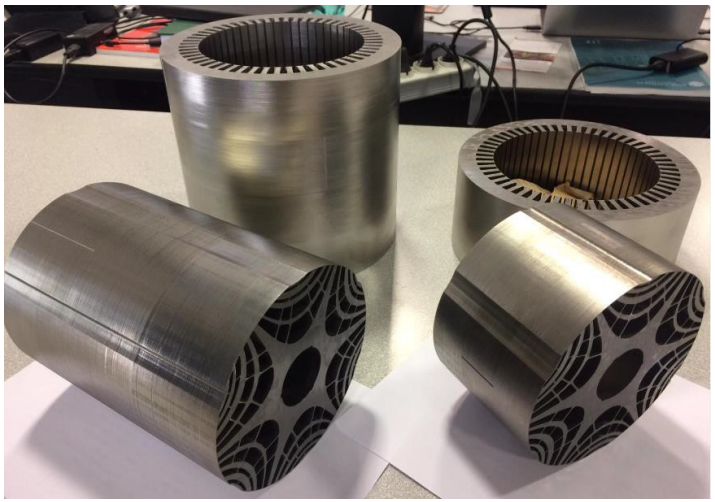
ReFreeDrive Project Overview

Pure Synrel motor design

Asymmetric shape with multiple ribs

Peak performance is met and the efficiency is about 96% (motoring).



Motor variant	Pure SynRel
DC-link voltage	720 V
Max. modulation	0.98
Max. current	636 Arms
Required inv. kVA	550 kVA
Peak torque	415 Nm
Maximum speed	18,000 rpm
Gear ratio	12.19
Peak overall power	290 kW
Peak power @nmax	80 kW

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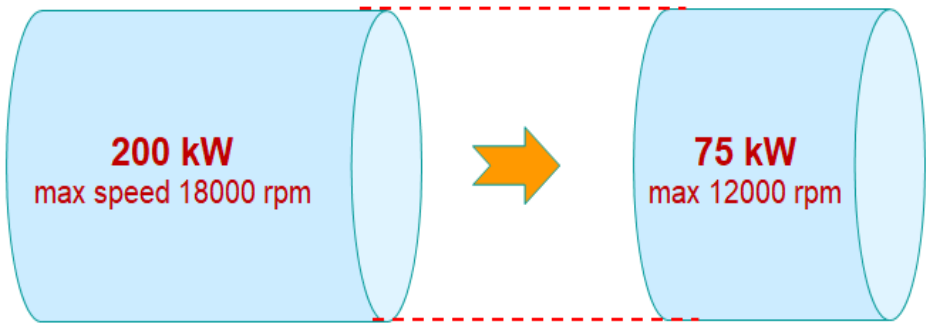
ReFreeDrive Project Overview

Pure Synrel motor design

The lower power machine (75 kW) has been **scaled** from the 200 kW design by only changing the stator winding and stack length (→ same housing).



Peak power @nmax	80 kW

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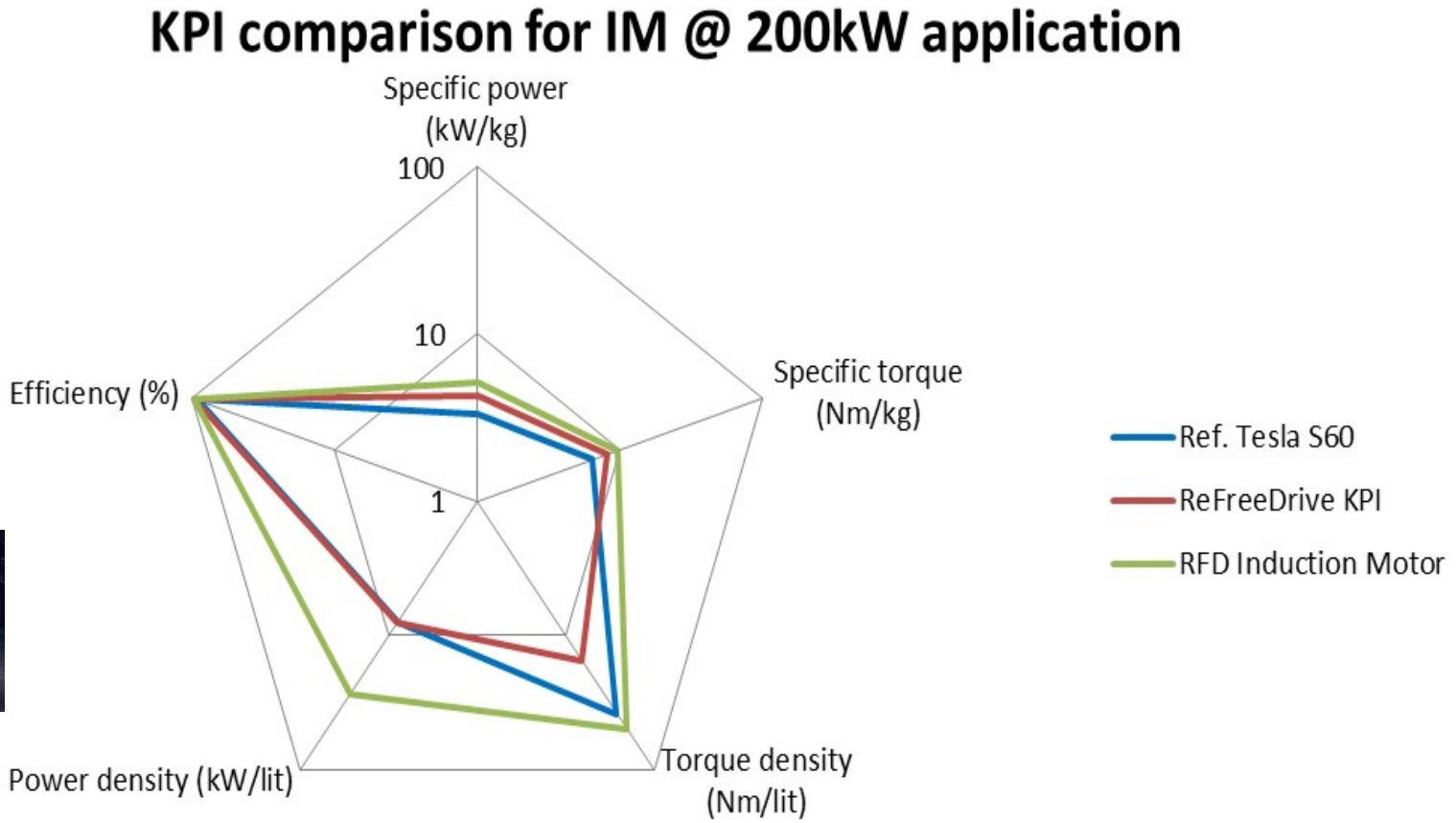
ReFreeDrive Project Overview

Achieved figures

Benchmark Tesla S60



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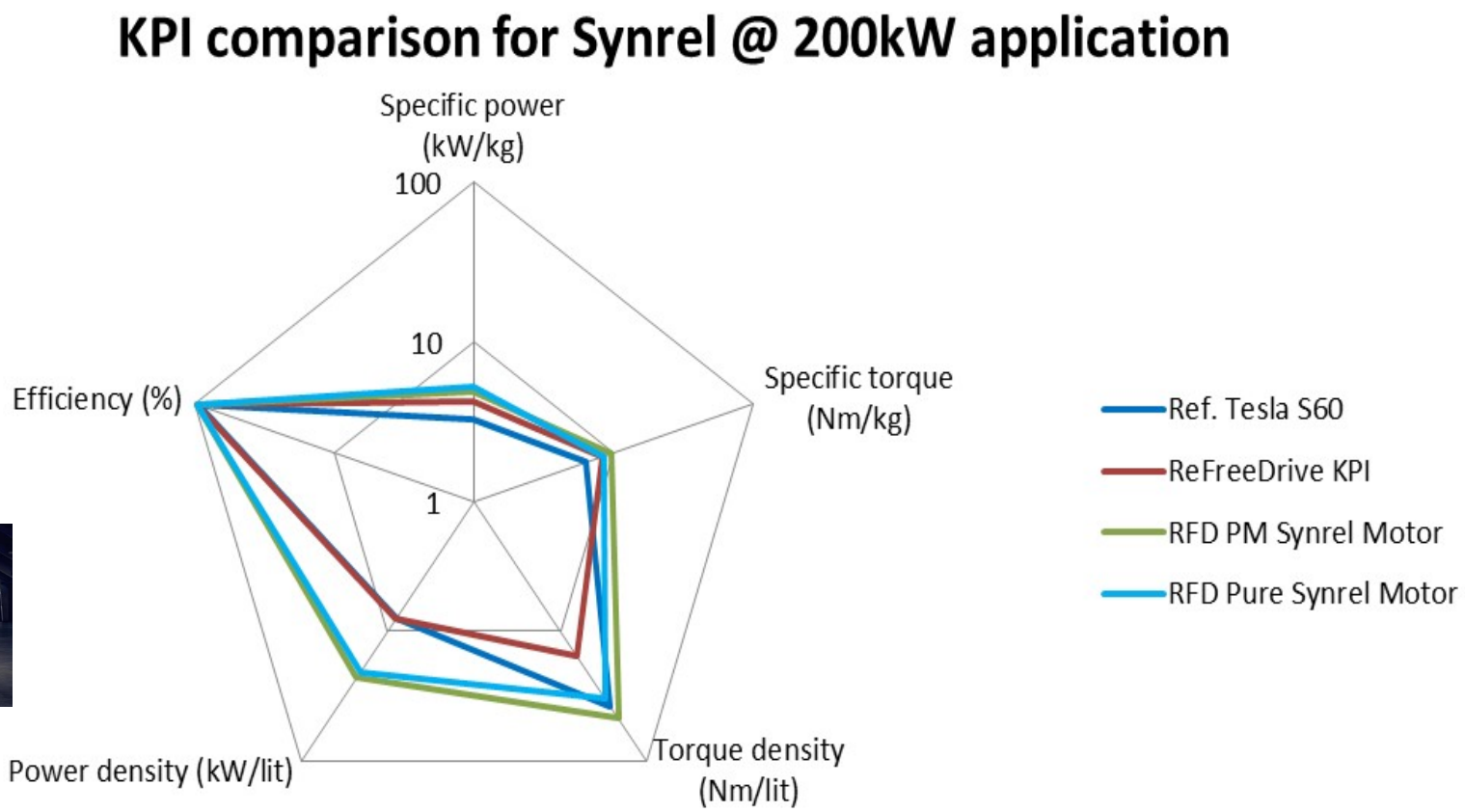
ReFreeDrive Project Overview

Achieved figures

Benchmark Tesla S60



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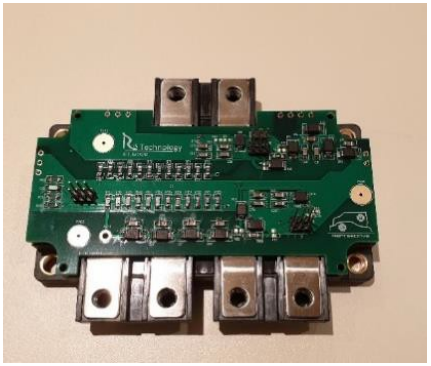
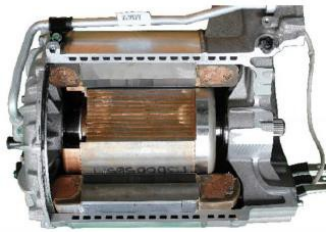
ReFreeDrive Project Overview

Achieved figures

200kW Benchmark: Tesla S60



75kW Benchmark: Nissan Leaf 2012



Parameter (unit)	Tesla S60	Nissan Leaf 2012	75 kW design	200 kW design
Specific Power (kW/kg)	13,3	4,9	7,5	18-20
Power Density (kW/lit)	11,7	5,7	9,47	20-22
Efficiency (%)	-	95	98,7	98,5
Power electronics Cost ($/kW)	-	13	6	3

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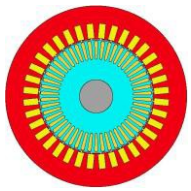
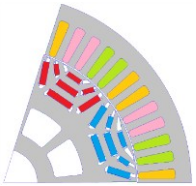
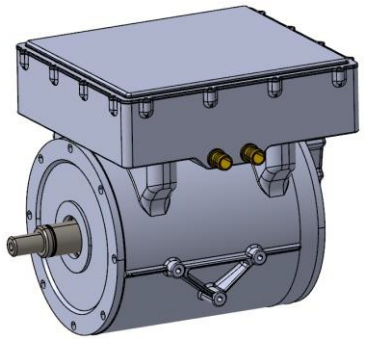
ReFreeDrive Project Overview

3 technologies comparison

Three rare-earth free motor variants were developed within ReFreeDrive to allow integration within a Jaguar Land Rover high performance vehicle: an induction motor, a ferrite-assisted synchronous reluctance motor and a pure synchronous reluctance motor

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
			



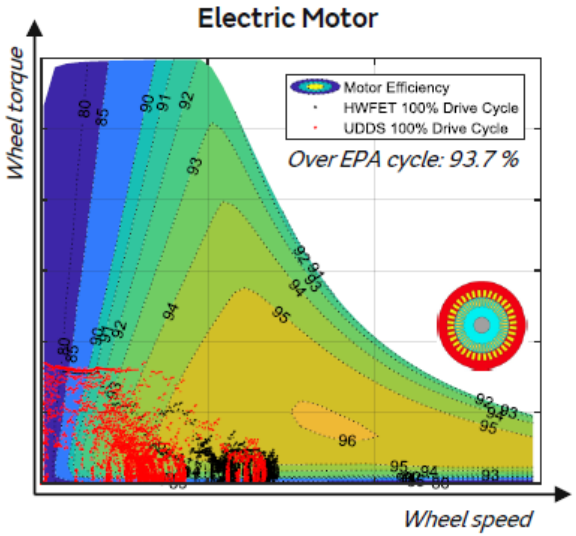
Motor and inverter of the high performance EDU

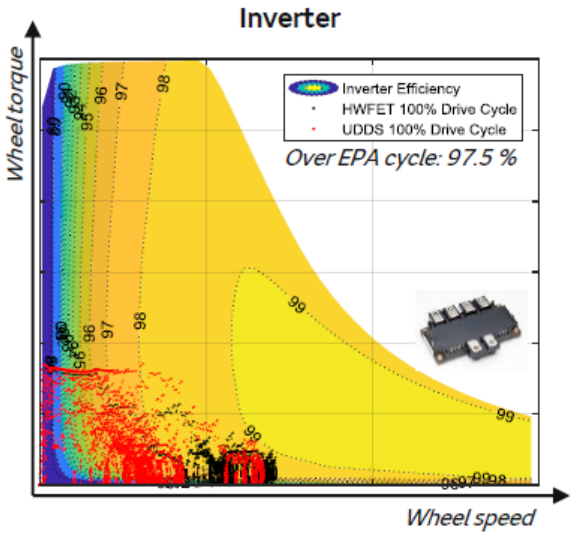
Mitsubishi FMF800DX-24ASiC module

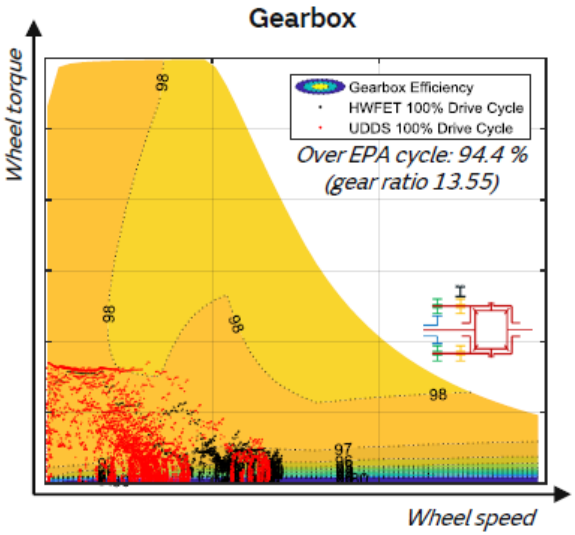
Source: Jaguar Land Rover, Coiltech Expo 2019 - http://www.refreedrive.eu/downloads

ReFreeDrive Project Overview

System level efficiency analysis – EPA cycle



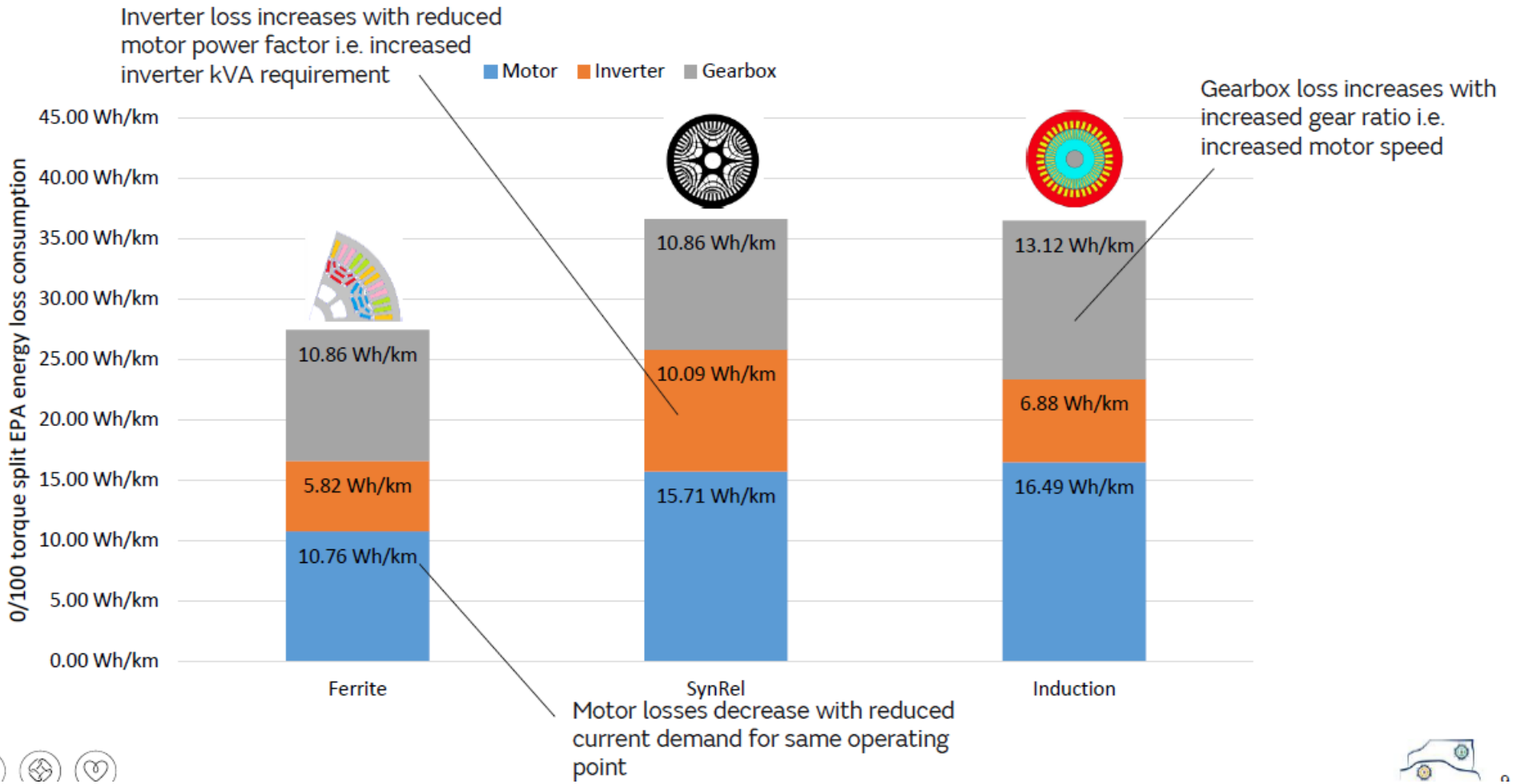




Source: Jaguar Land Rover, Coiltech Expo 2019 - http://www.refreedrive.eu/downloads

ReFreeDrive Project Overview

System level efficiency analysis – Energy loss splitdown



Source: Jaguar Land Rover, Coiltech Expo 2019 - http://www.refreedrive.eu/downloads

ReFreeDrive Project Overview

System level efficiency analysis – Energy loss splitdown

	Ferrite SynRel	Pure SynRel	Induction
Overall EPA efficiency	88.9%	85.8%	86.2%
Machine speed	18,000	18,000	20,000
Best overall efficiency	UDDS	Around HWFET drive cycle	At highway cruising speeds and beyond

HWFET: Highway Fuel Economy Test cycle
UDDS: Urban Dynometeter Driving Schedule

Source: Jaguar Land Rover, Coiltech Expo 2019 - http://www.refreedrive.eu/downloads

ReFreeDrive Project Overview

Next steps

Ongoing → Late 2020 → Late 2020 / Early 2021

Prototypes manufacturing	Integrated powertrain testing	In-vehicle integration

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ReFreeDrive Project Overview

Two power level prototypes

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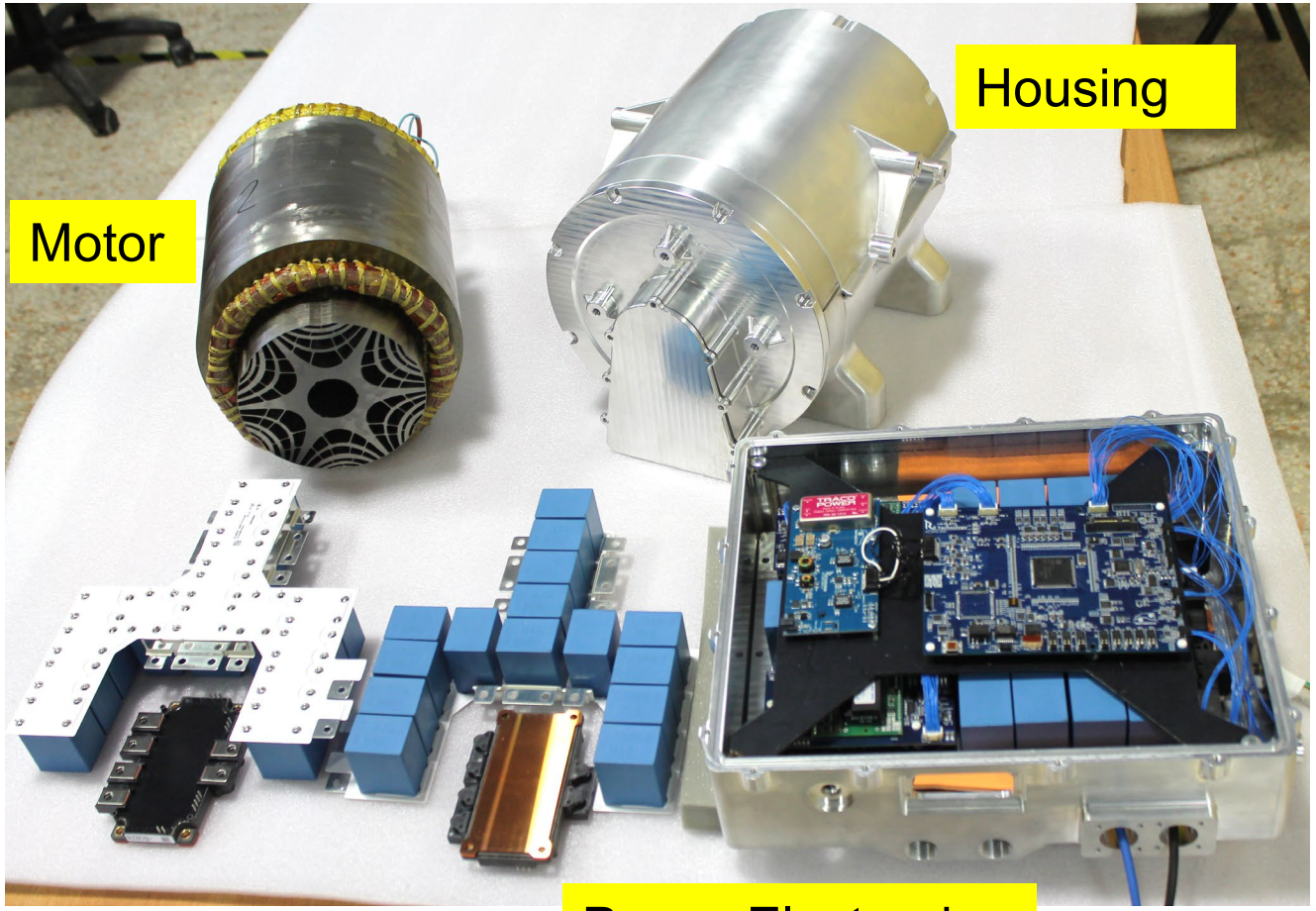
ReFreeDrive Project Overview

Prototyping the motor, housing and power electronics



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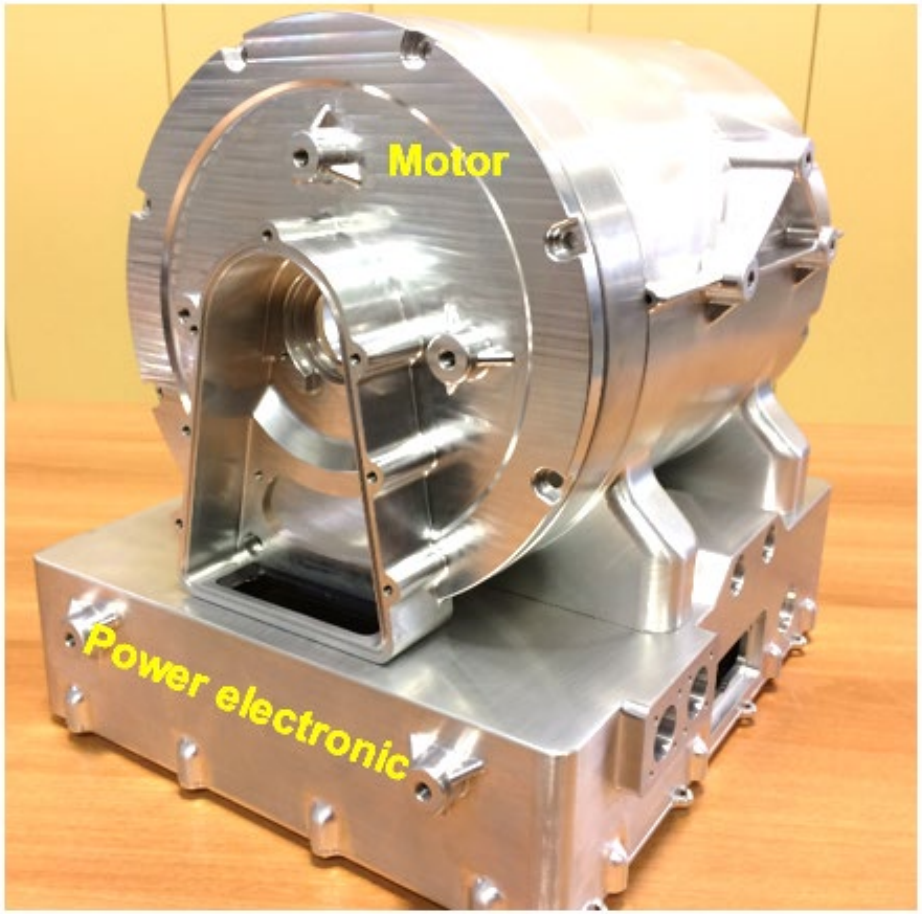
ReFreeDrive Project Overview

Integrated motor + power electronics
Shared liquid cooling



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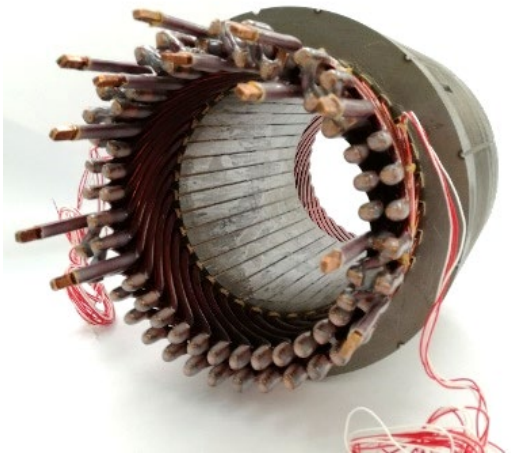
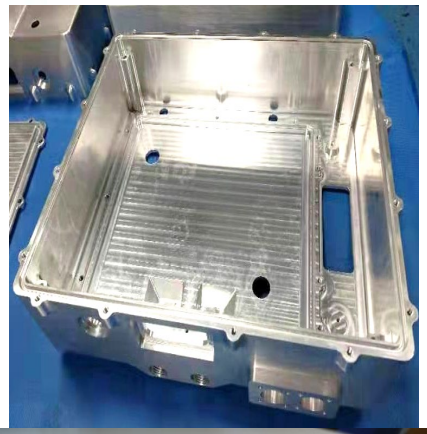
ReFreeDrive Project Overview

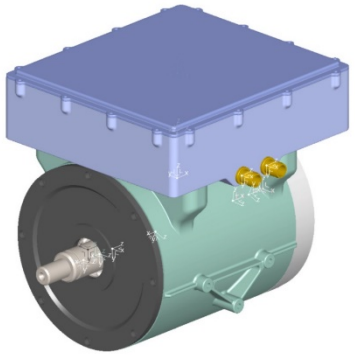
Induction motor prototype manufacturing

Stator Assembly with Hairpin Winding



Inverter Box and Motor Assembly





Die-cast Copper Rotor

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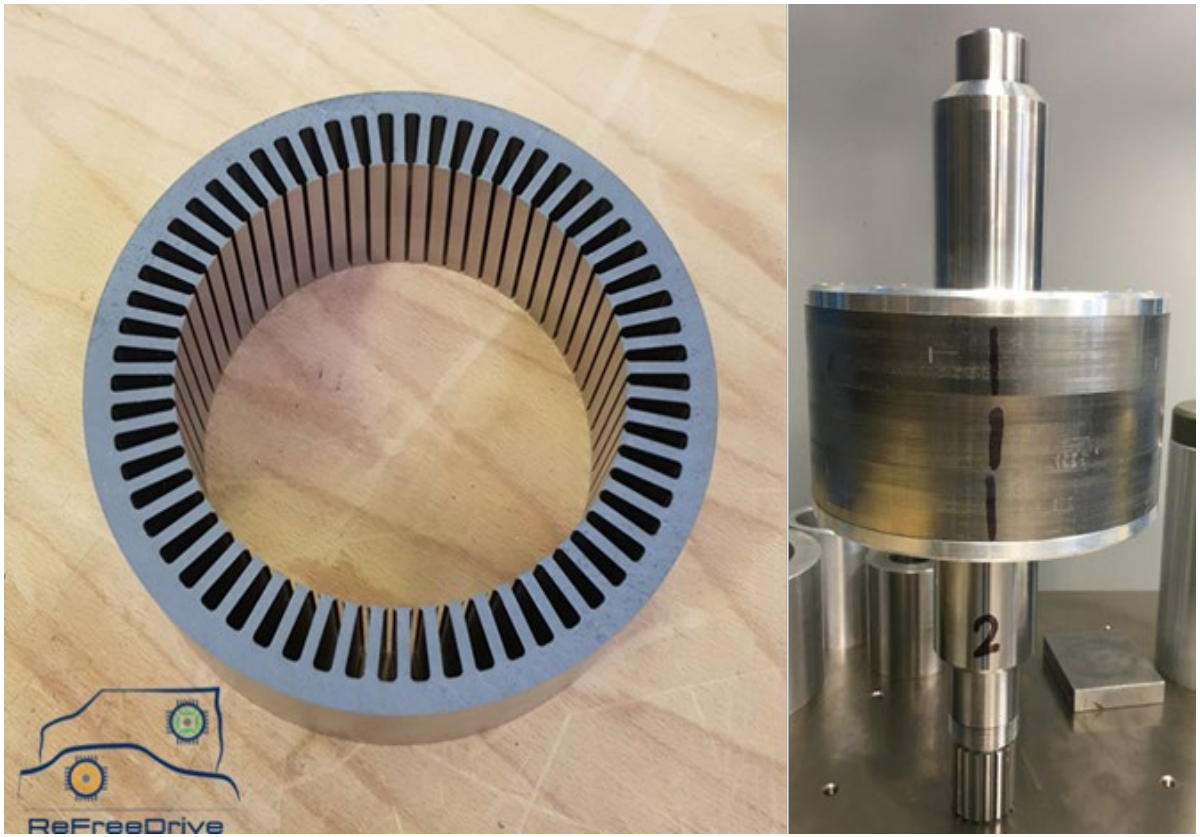
ReFreeDrive Project Overview

PM Synrel motor prototype manufacturing



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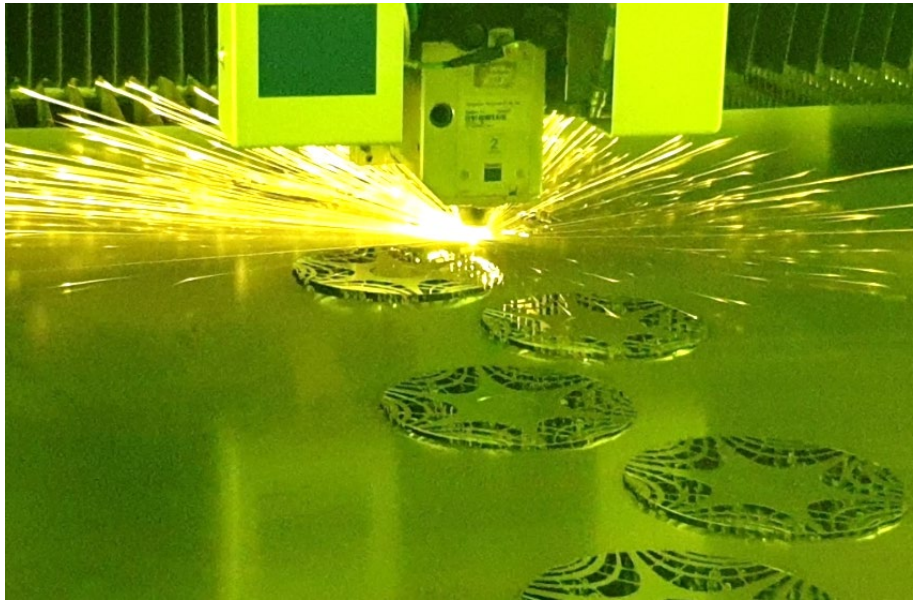
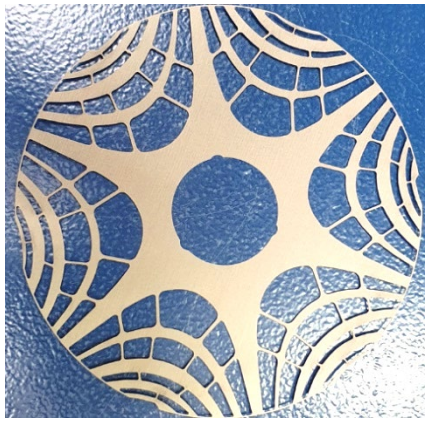
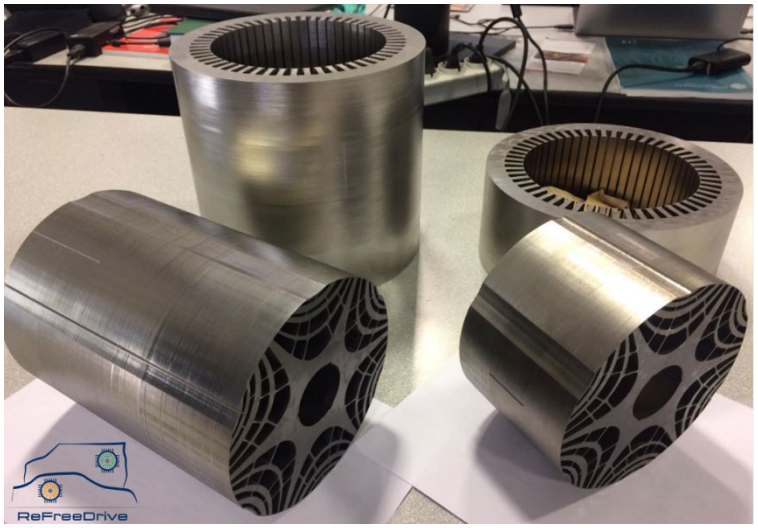
ReFreeDrive Project Overview

Pure Synrel motor prototype manufacturing







Laser cut of the electrical steel (courtesy of LCD)

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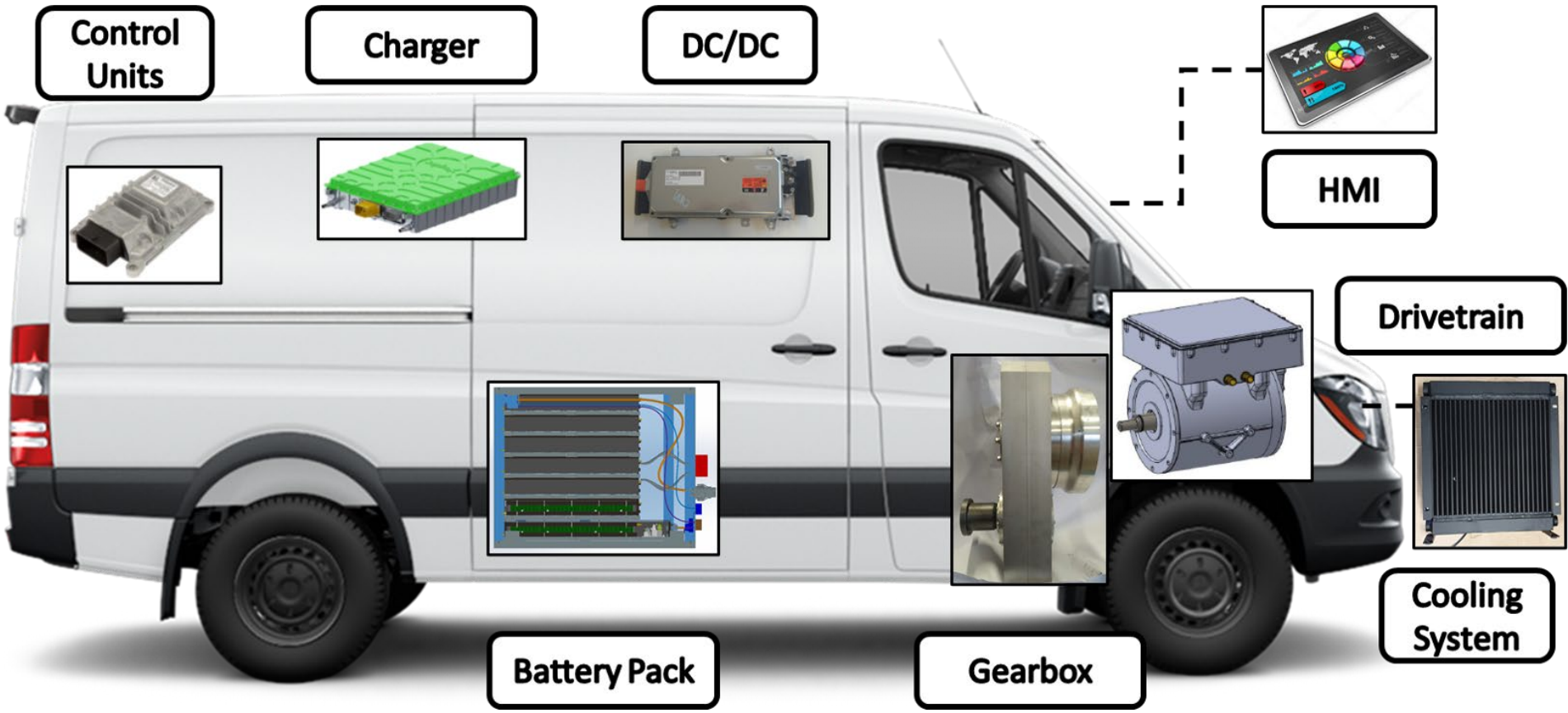
ReFreeDrive Project Overview

In-vehicle integration



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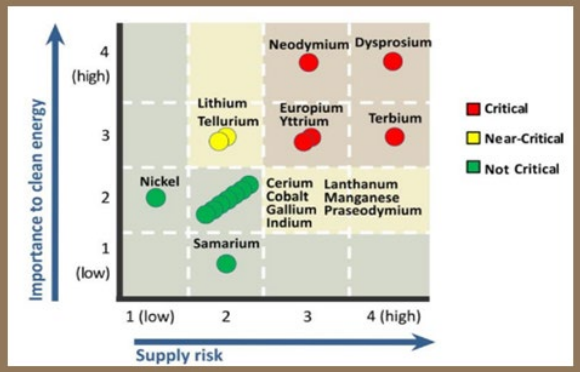
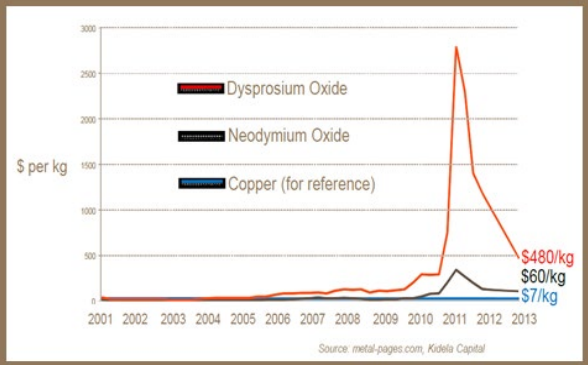
The rare earth issue

The use of rare earth-based magnets is challenging for multiple reasons

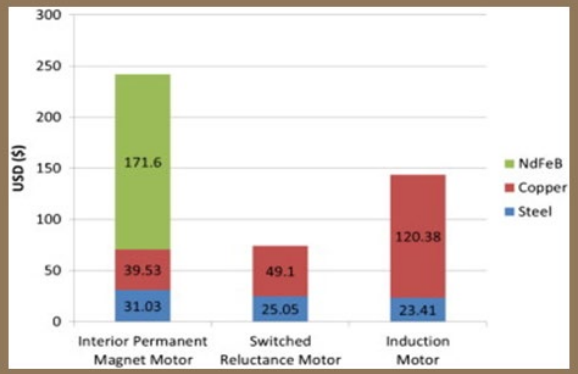
Supply risk



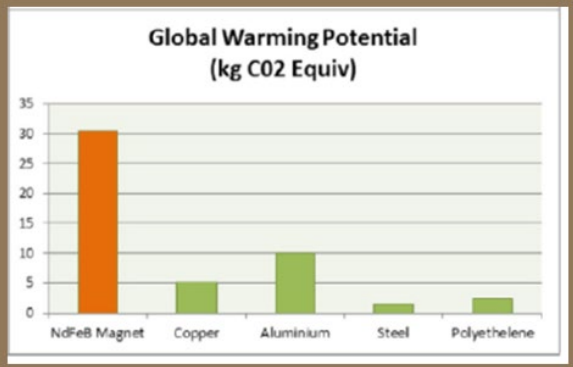
Market uncertainties



Cost



Environment & LCA



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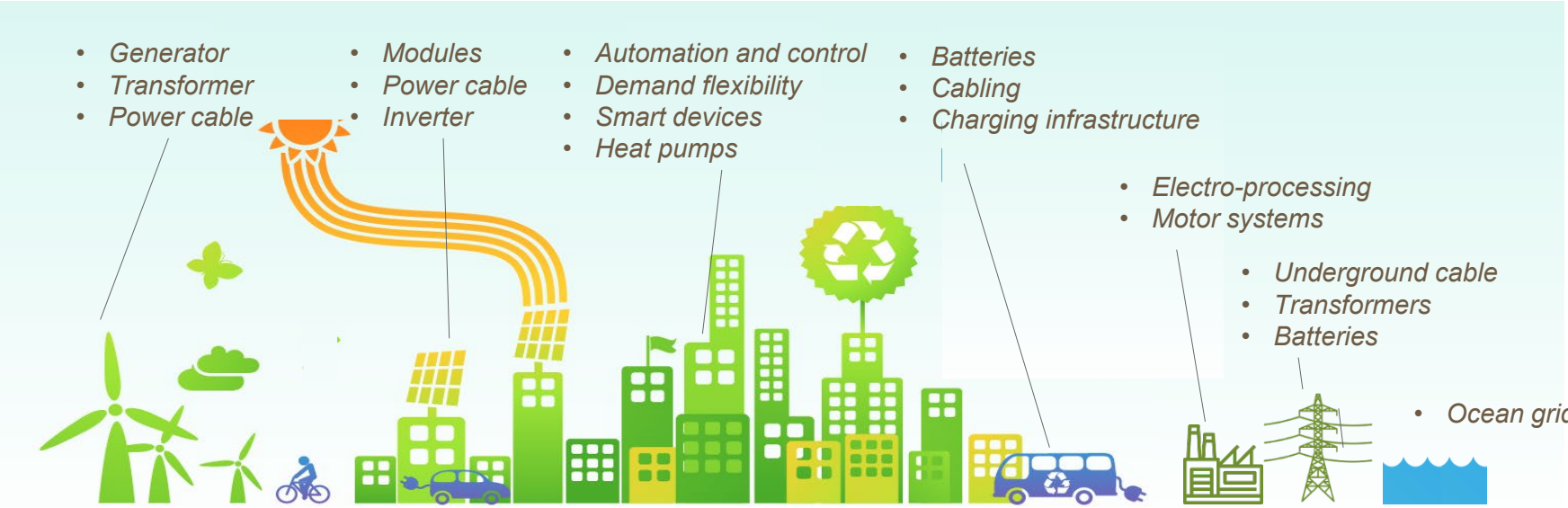
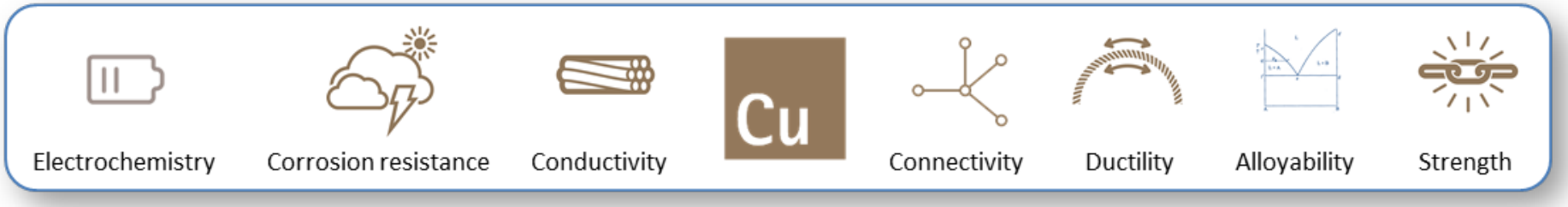
Why copper?

Thanks to its excellent conductivity and properties, copper plays a central role in the energy transition



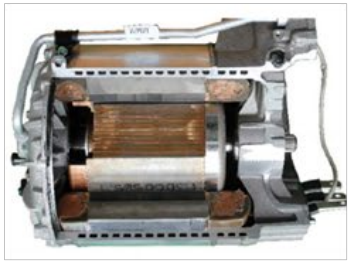


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 770143

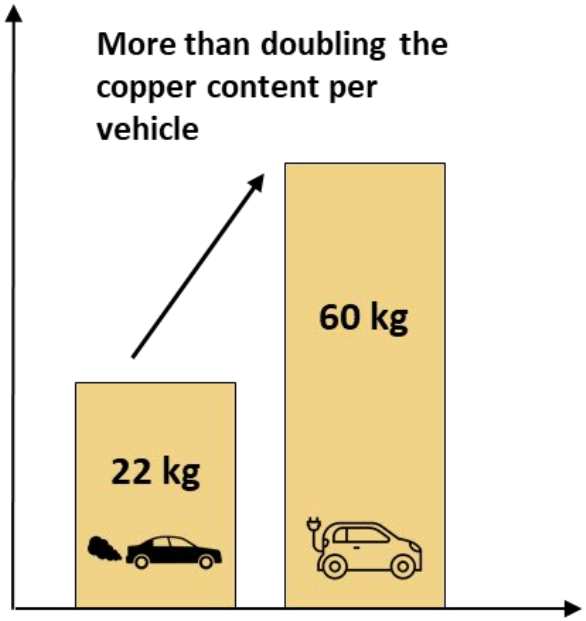
Why copper?

New electromobility components need copper to operate efficiently, driving demand up

Battery
(copper foil, connectors)



Electric motor
(stator windings and, in some cases, rotor)



High voltage wiring

Low voltage wiring

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Copper is available

There are sufficient mining and recycling copper reserves & resources worldwide to cope with growth

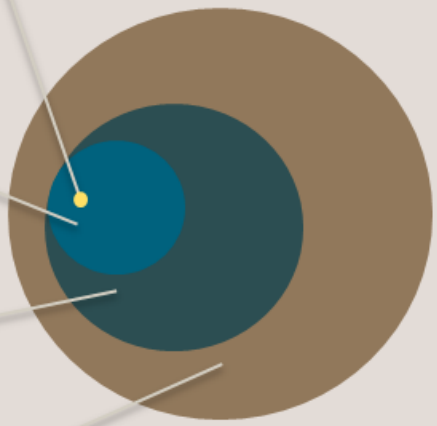
Primary route: mining (~70% of demand)

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

Landfills

150 Mtonnes available in landfills (7 years)

Estimated 110 to 330 megatonnes needed for the world energy transition

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

www.copperalliance.org

International Copper Association
Copper Alliance

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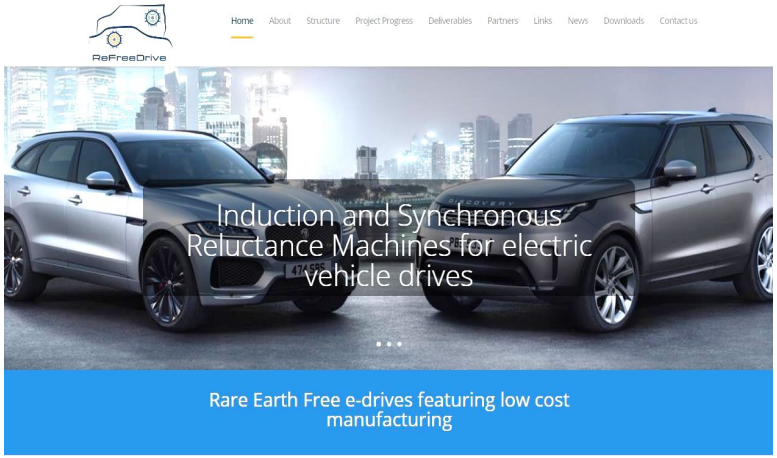
www.refreedrive.eu



LinkedIn

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

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