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

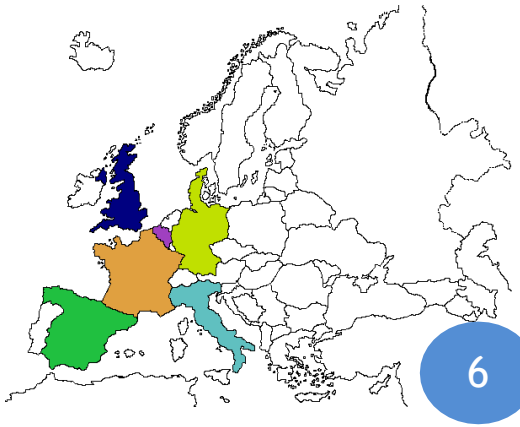
**Title:** Rare earth free e-Drives featuring low cost manufacturing

**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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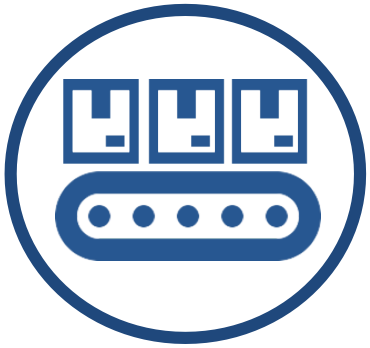
# ReFreeDrive Project Overview

## 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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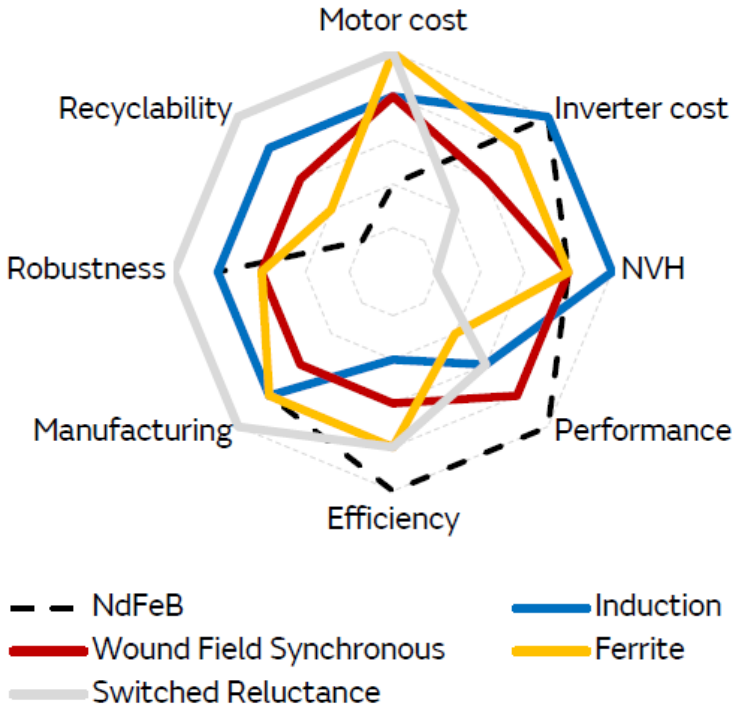
# ReFreeDrive Project Overview

## 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 | + | - | ++ | - | ++ |

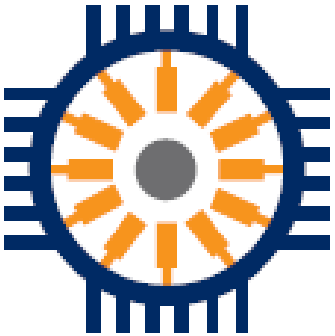



*Each traction motor must be tailored to vehicle requirements, customer expectations, architectures, scalability, volumes and even current status of material supply and supplier capability, making each type of motor a potential candidate within a vehicle to benefit a specific purpose*

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

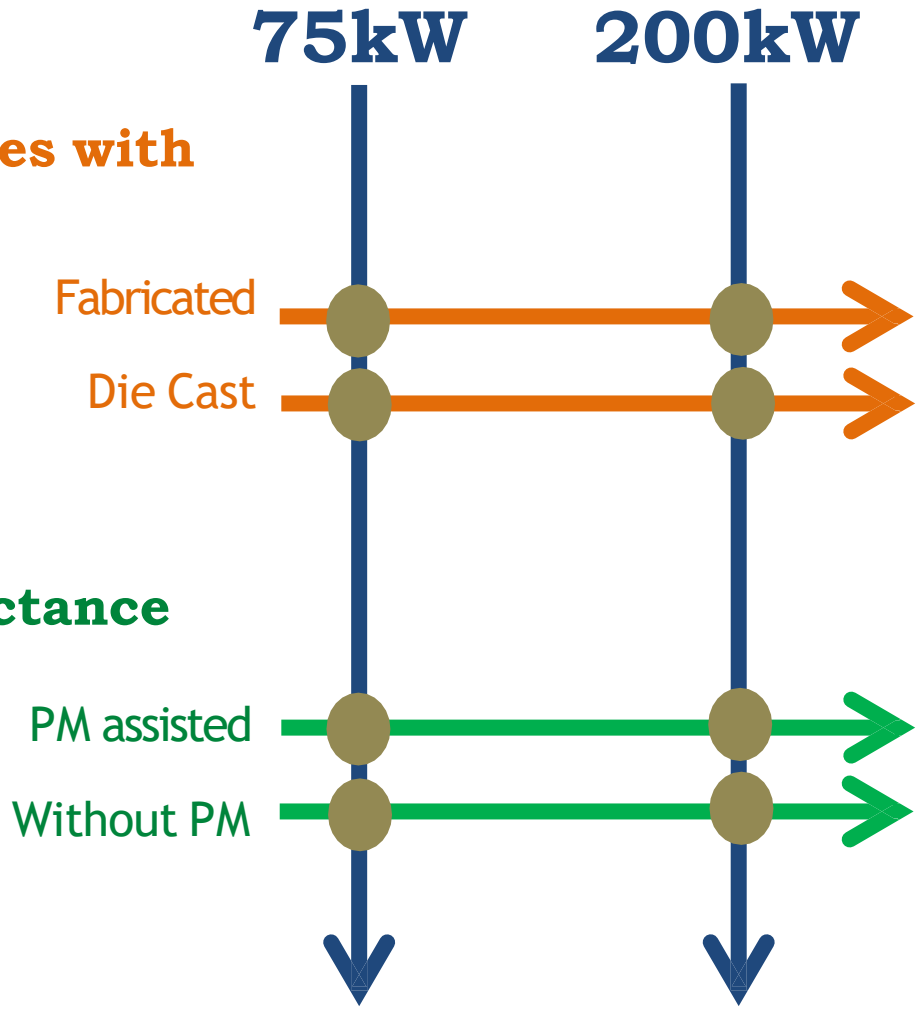
# ReFreeDrive Project Overview

## Project Technologies



**Induction machines with copper rotor**

**Synchronous reluctance machines**



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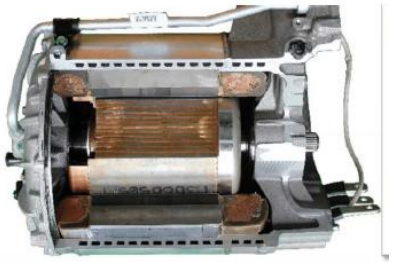
# ReFreeDrive Project Overview

## 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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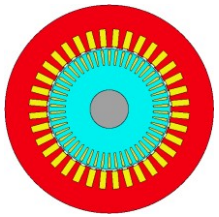
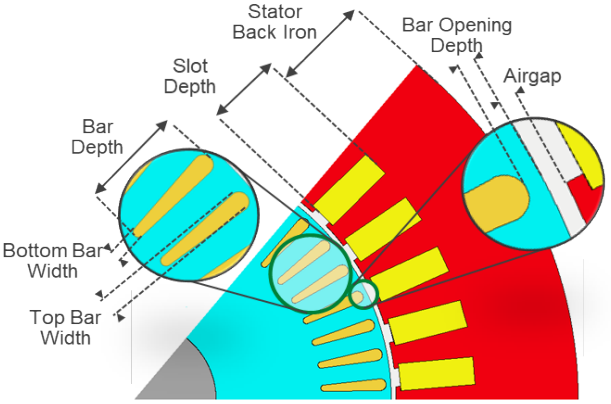
# ReFreeDrive Project Overview

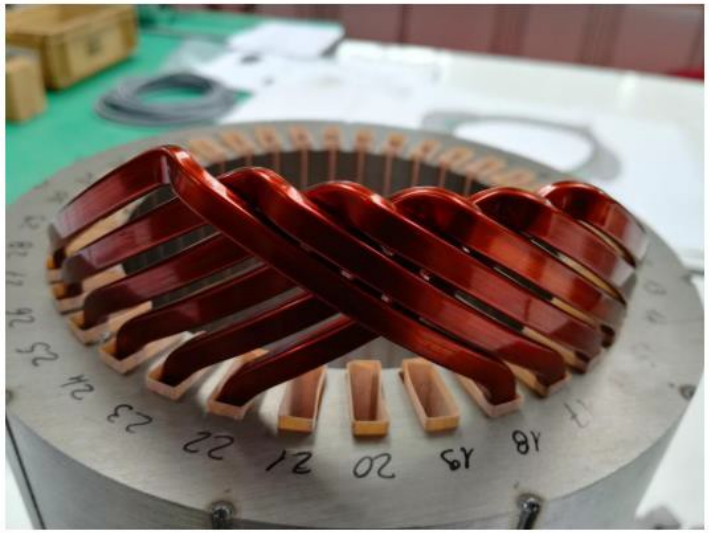
## Induction motor design

**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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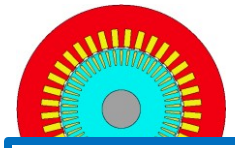
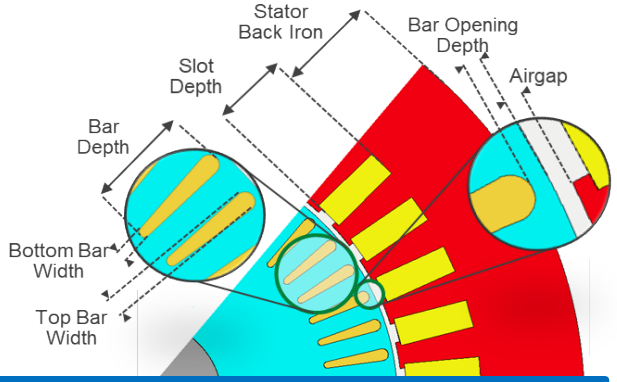
# ReFreeDrive Project Overview

## Induction motor design

**Radial Geometry**



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




### 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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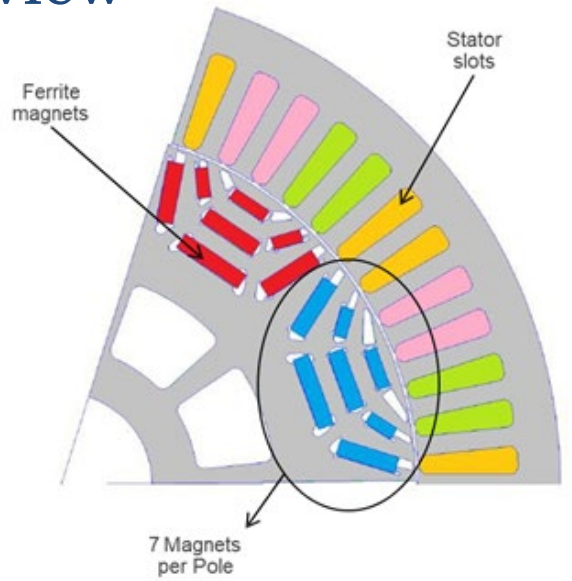
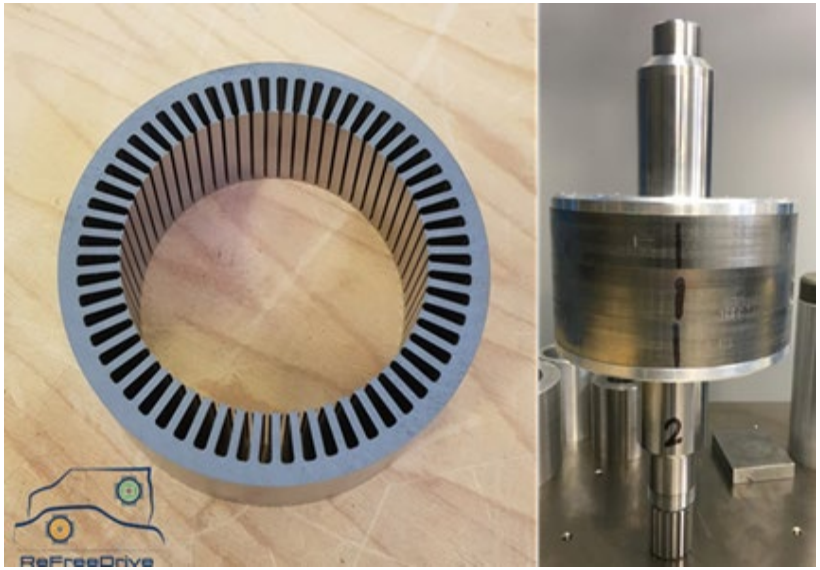
# ReFreeDrive Project Overview

## 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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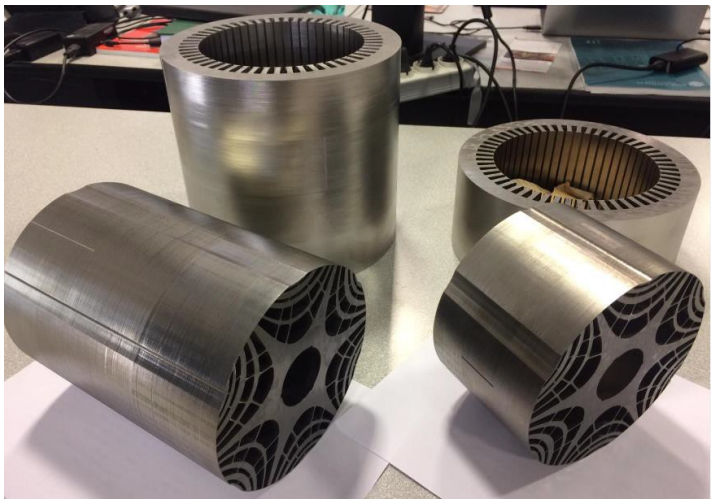
# ReFreeDrive Project Overview

## 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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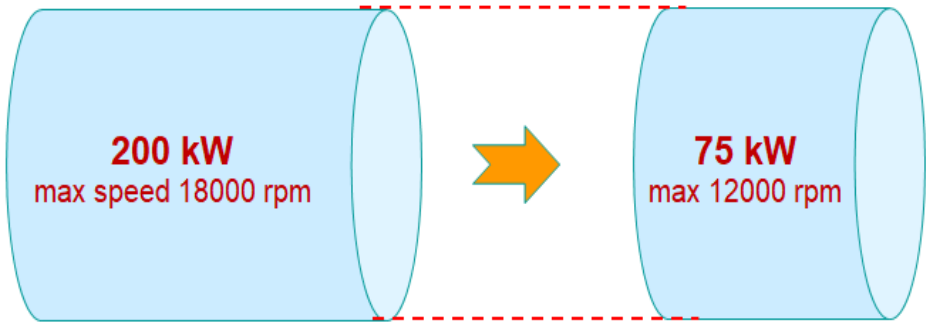
# ReFreeDrive Project Overview

## 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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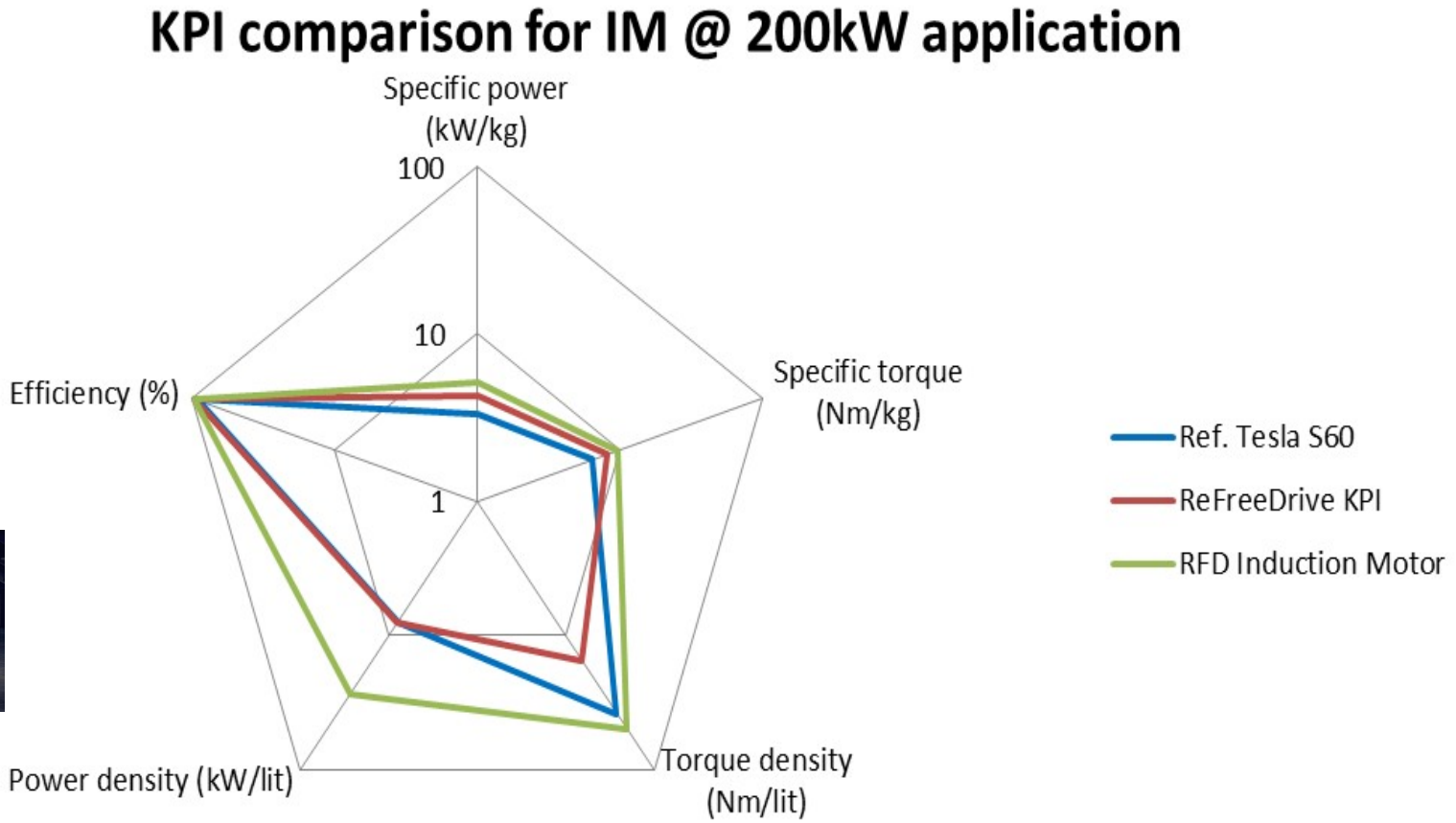
# ReFreeDrive Project Overview

## Achieved figures

**Benchmark Tesla S60**



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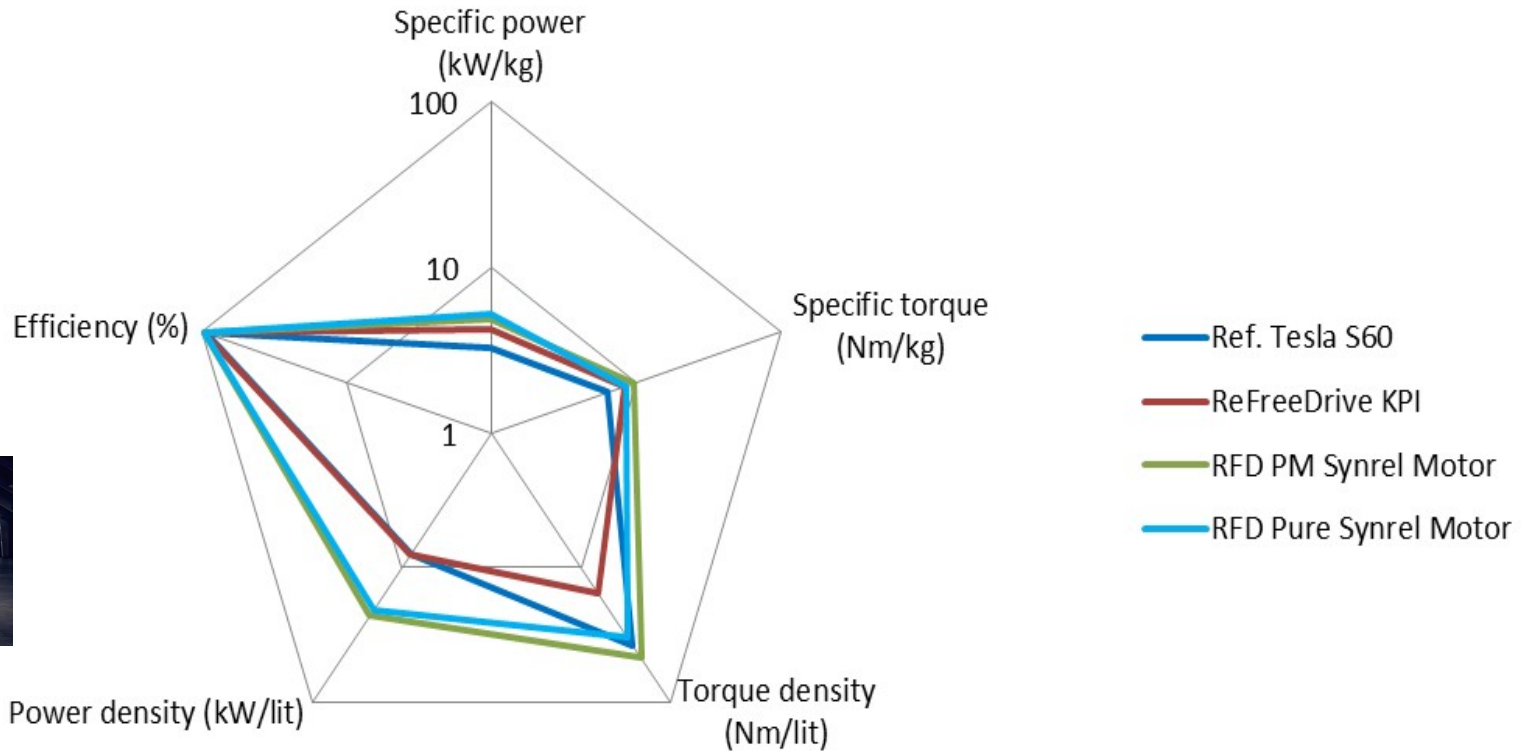
# ReFreeDrive Project Overview

## Achieved figures

**Benchmark Tesla S60**



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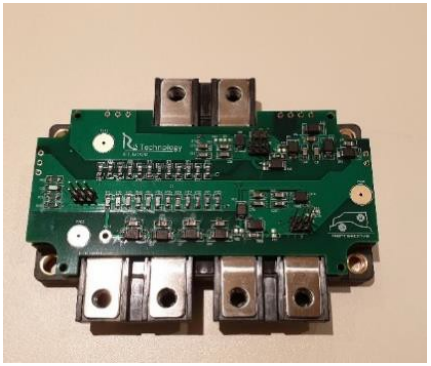
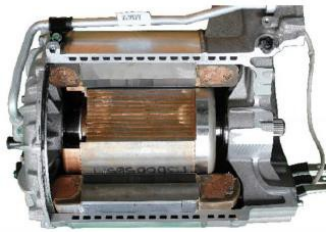
# ReFreeDrive Project Overview

## 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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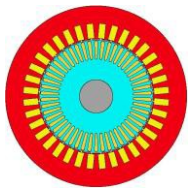
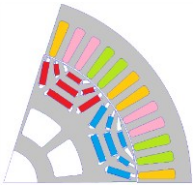
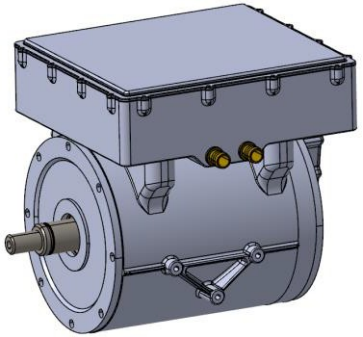
# ReFreeDrive Project Overview

## 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 |
| |  |  | |



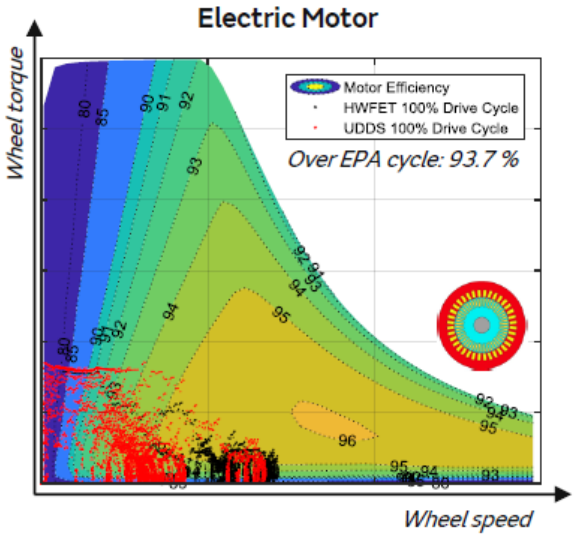
*Motor and inverter of the high performance EDU*

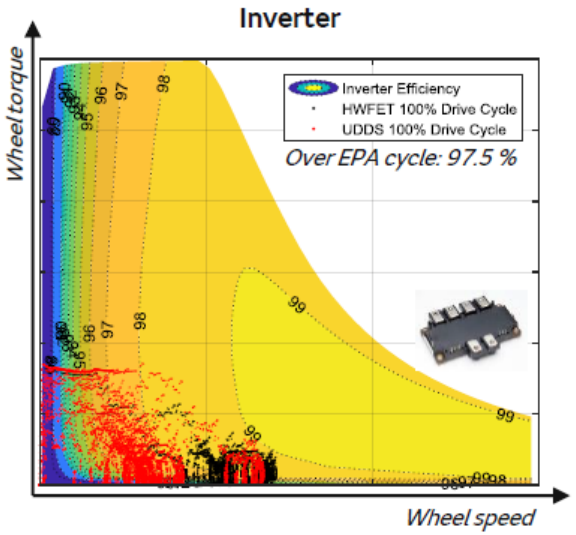
*Mitsubishi FMF800DX-24ASiC module*

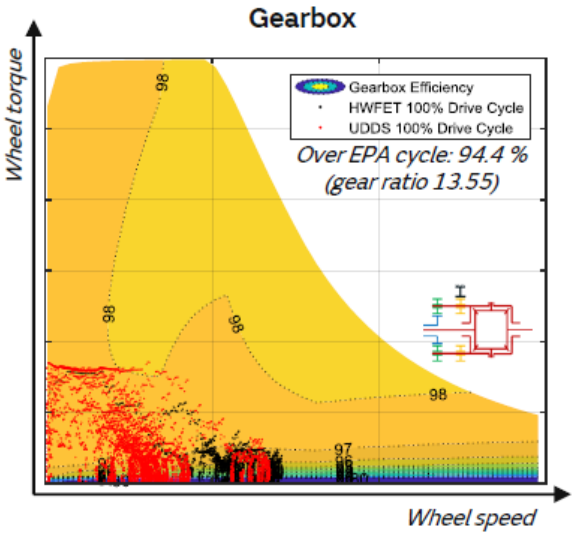
Source: Jaguar Land Rover, Coiltech Expo 2019 - http://www.refreedrive.eu/downloads

# ReFreeDrive Project Overview

## System level efficiency analysis – EPA cycle



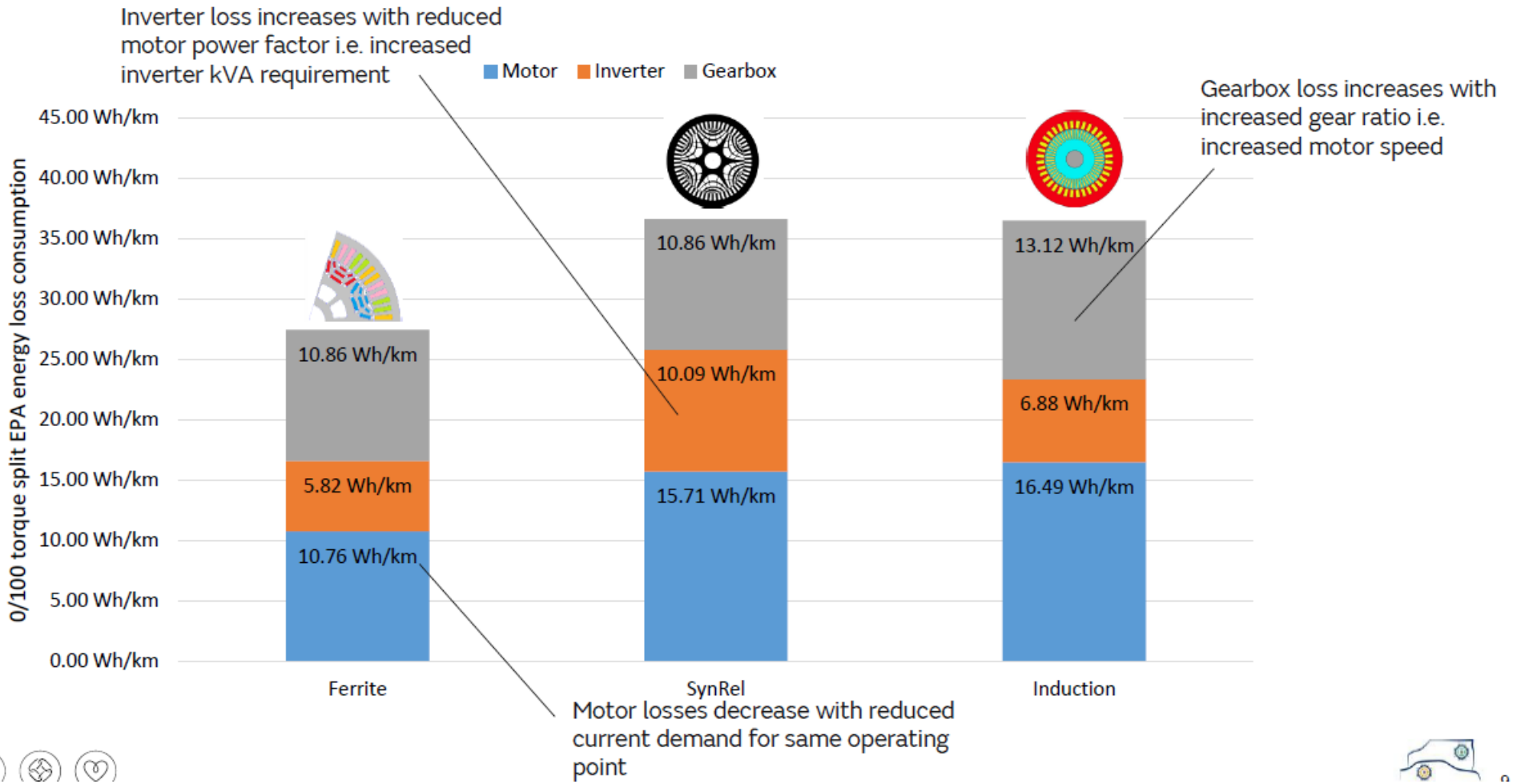




Source: Jaguar Land Rover, Coiltech Expo 2019 - http://www.refreedrive.eu/downloads

# 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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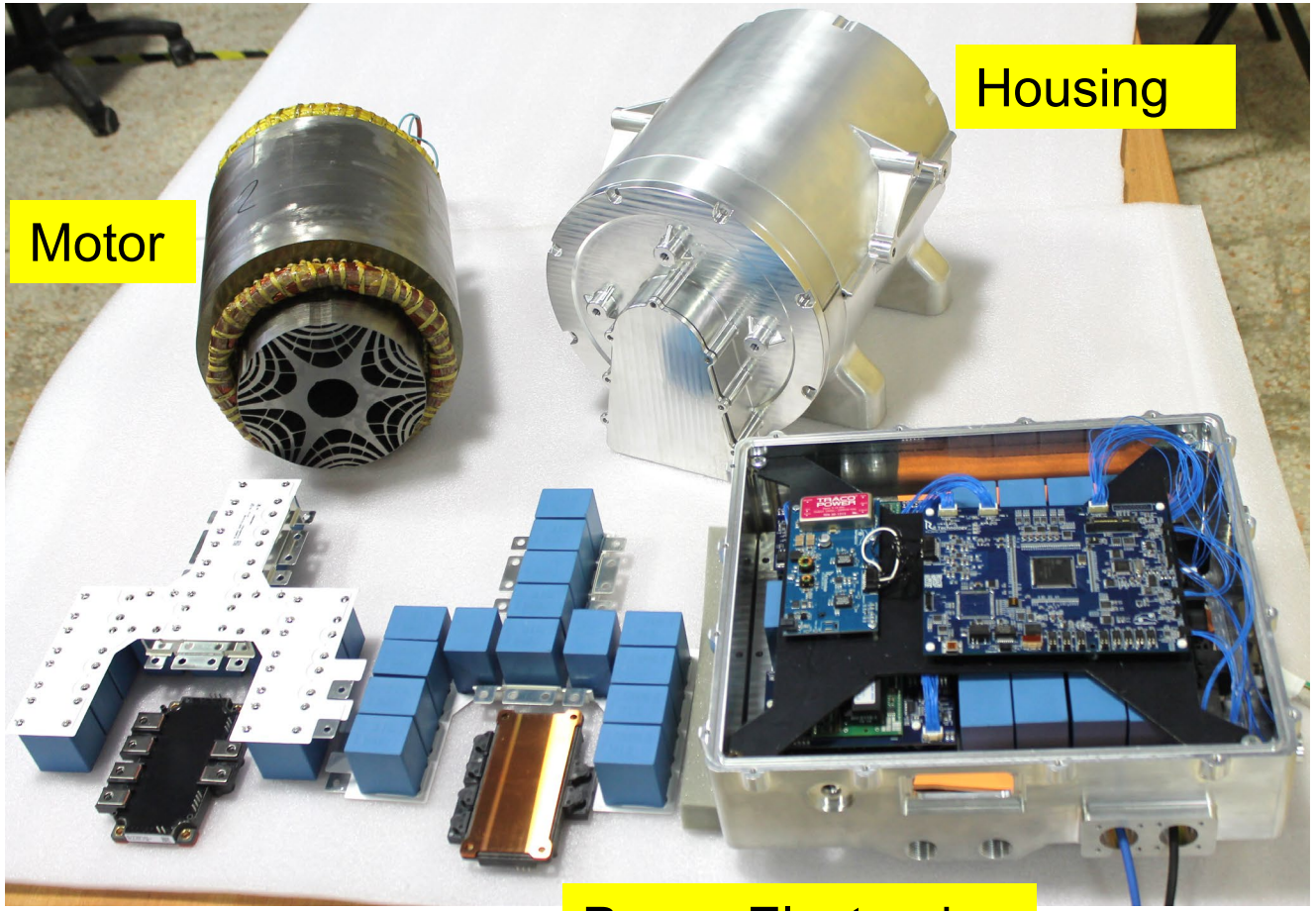
# ReFreeDrive Project Overview

## Prototyping the motor, housing and power electronics



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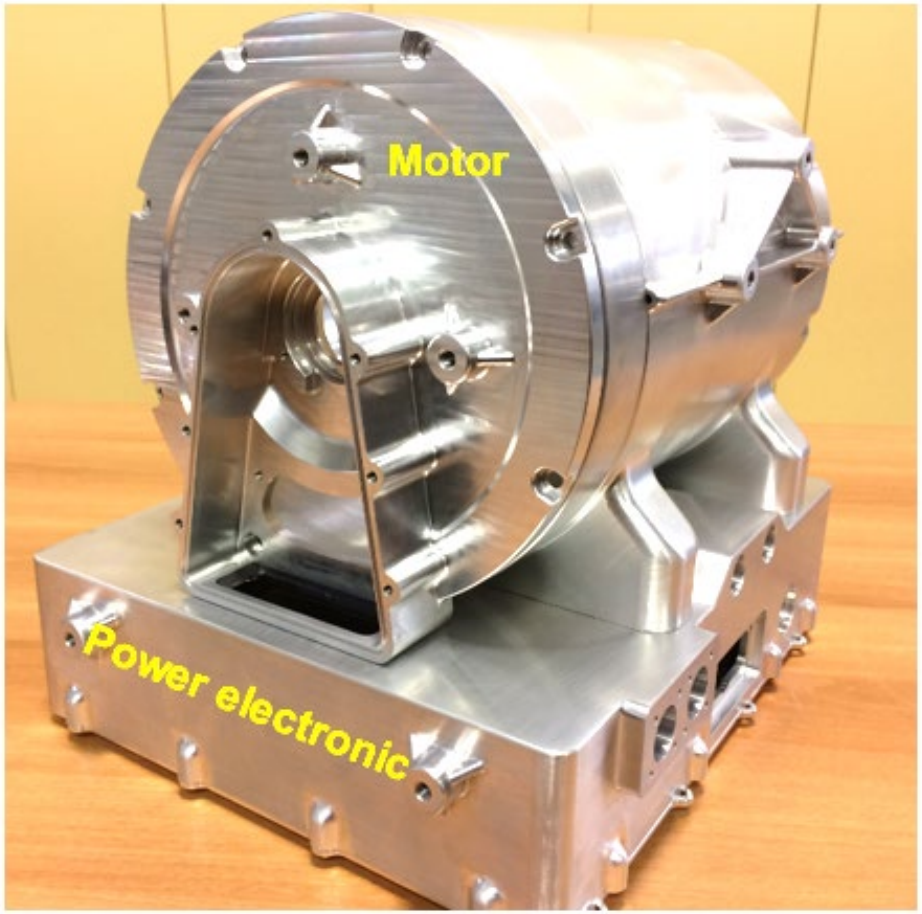
# ReFreeDrive Project Overview

## Integrated motor + power electronics
## Shared liquid cooling



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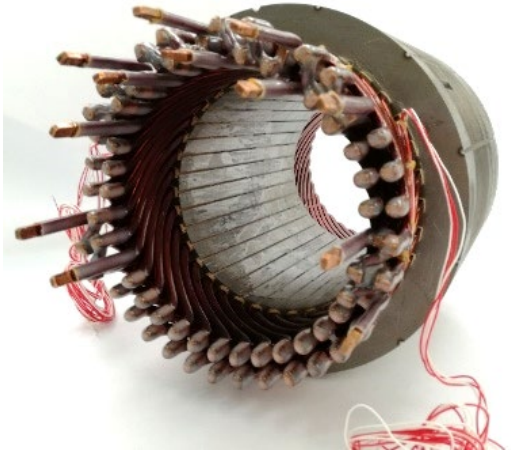
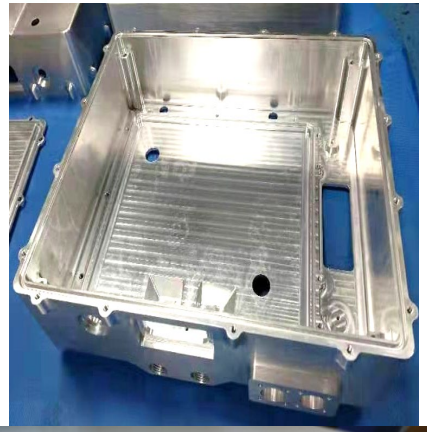
# ReFreeDrive Project Overview

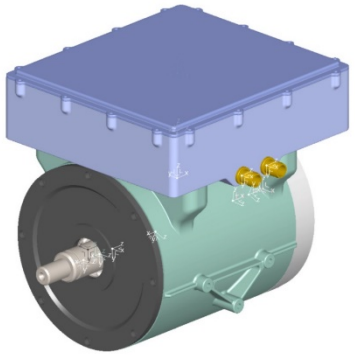
## Induction motor prototype manufacturing

### Stator Assembly with Hairpin Winding



### Inverter Box and Motor Assembly





### Die-cast Copper Rotor

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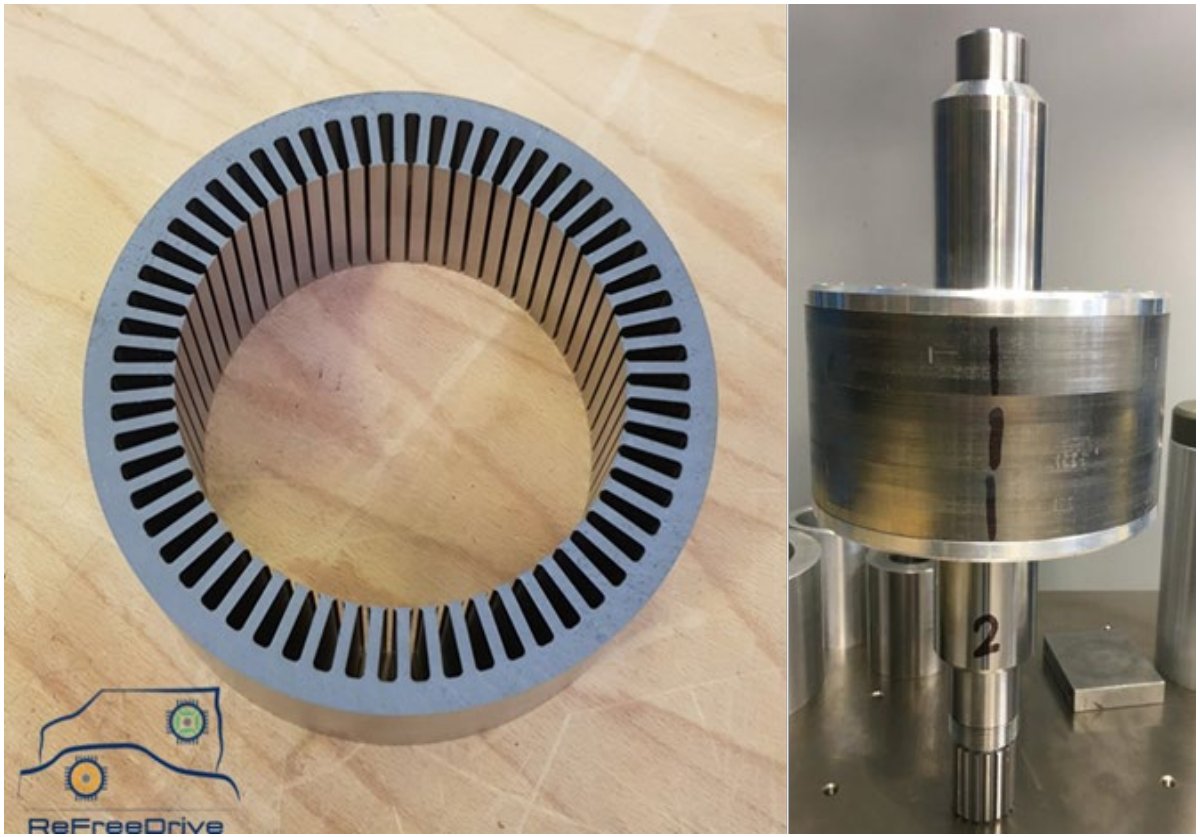
# ReFreeDrive Project Overview

## PM Synrel motor prototype manufacturing



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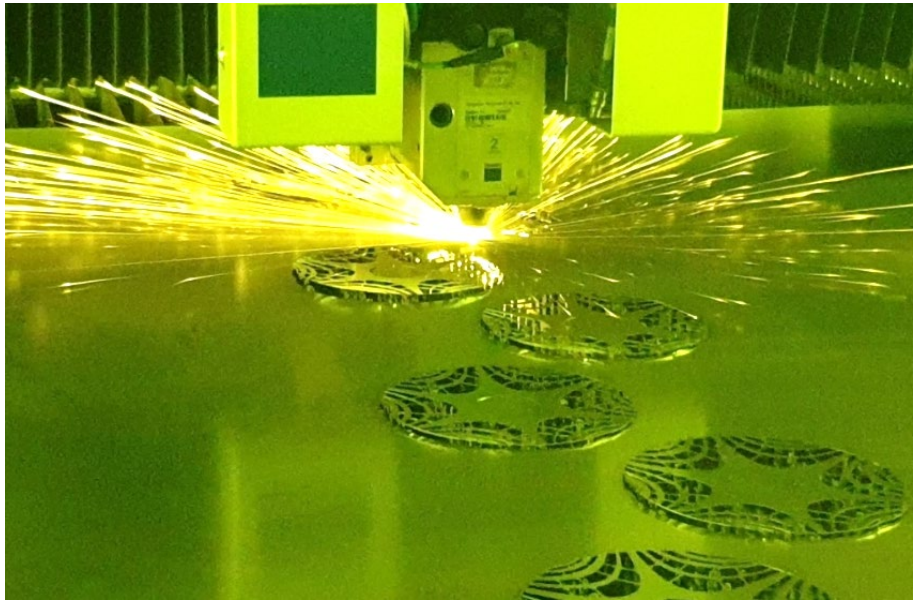
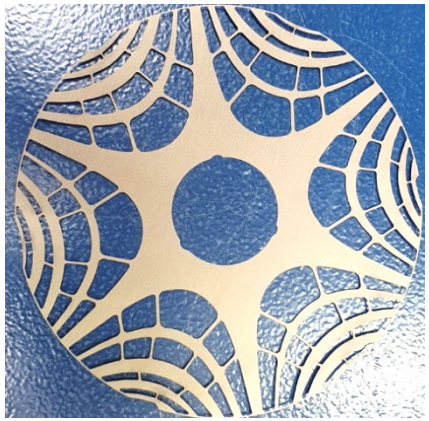
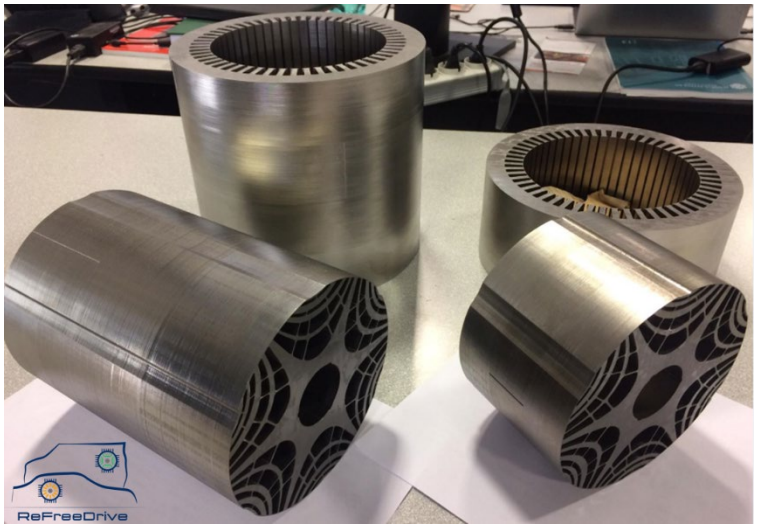
# ReFreeDrive Project Overview

## Pure Synrel motor prototype manufacturing








Laser cut of the electrical steel (courtesy of LCD)



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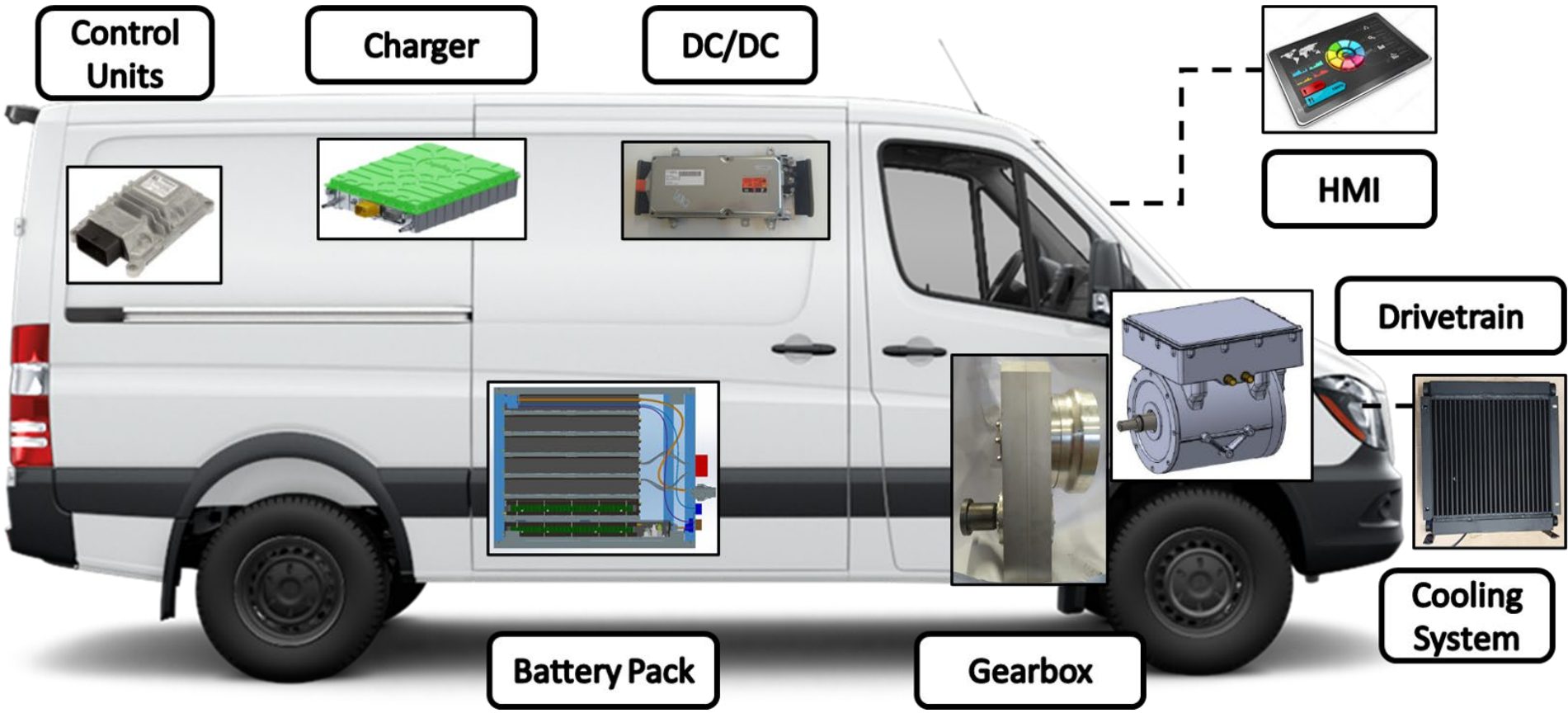
# ReFreeDrive Project Overview

## In-vehicle integration



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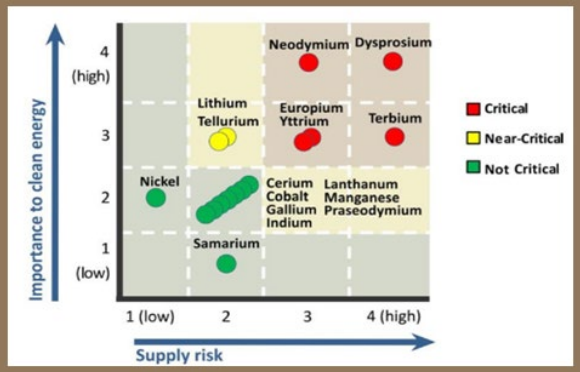
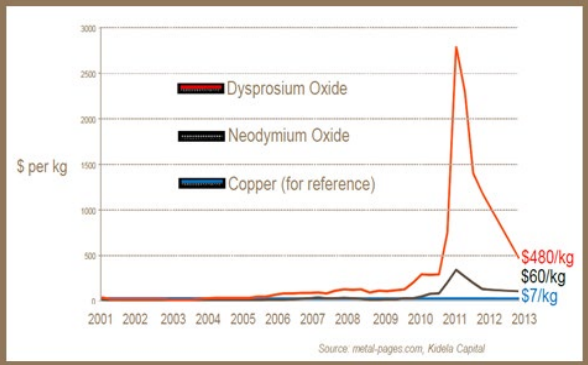
# The rare earth issue

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

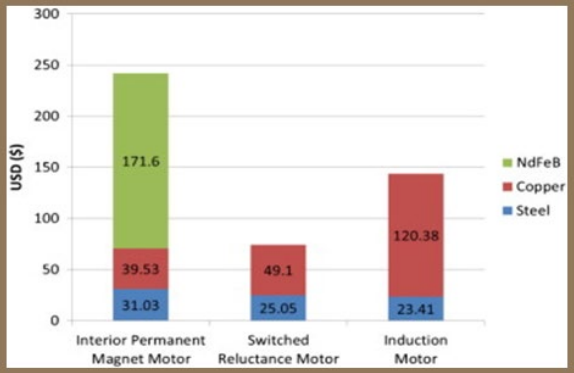
### Supply risk



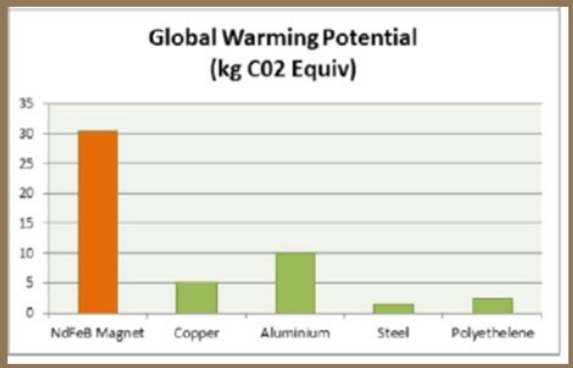

### Market uncertainties




### Cost




### Environment & LCA

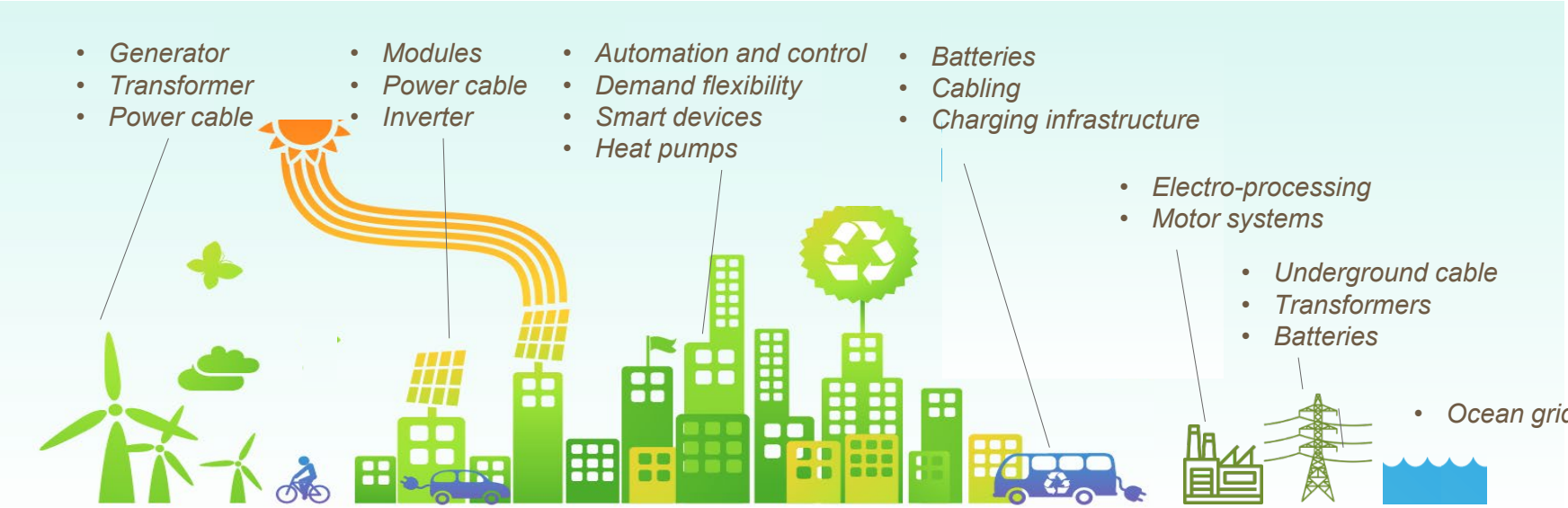


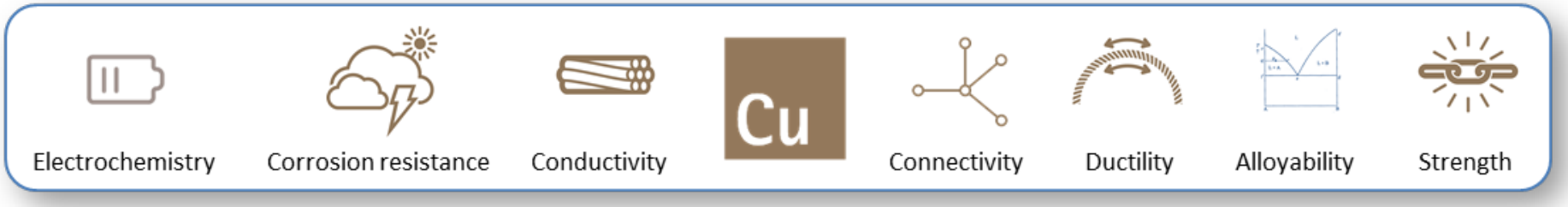



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 770143

# Why copper?

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



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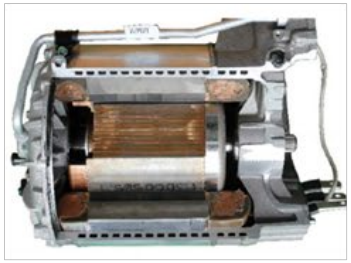
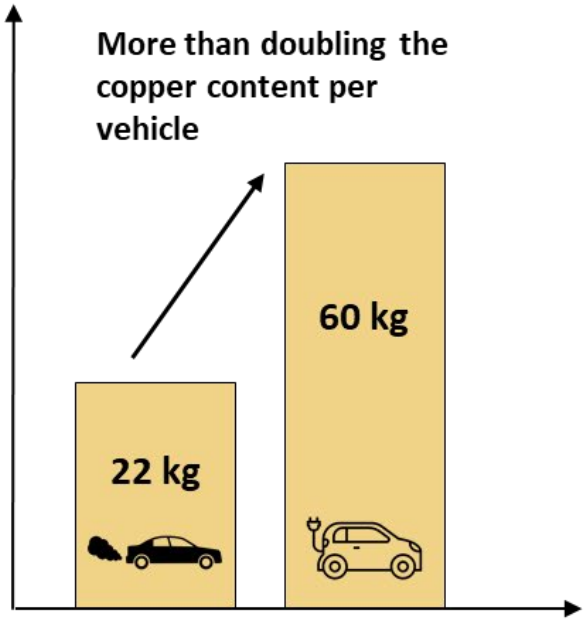
# Why copper?

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

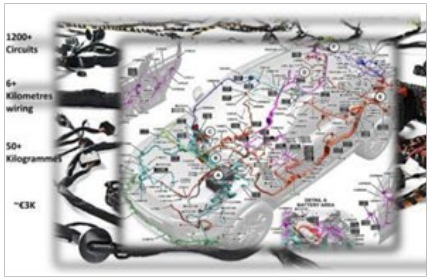
**Battery**
(copper foil, connectors)



**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

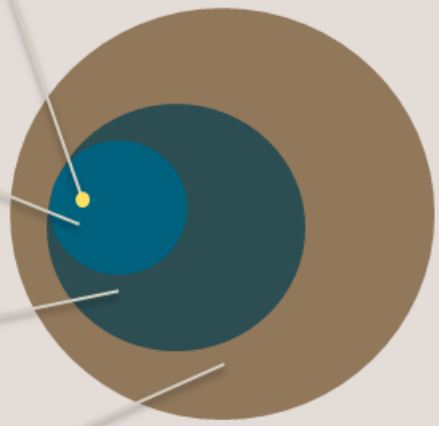
### Primary route: mining (~70% of demand)

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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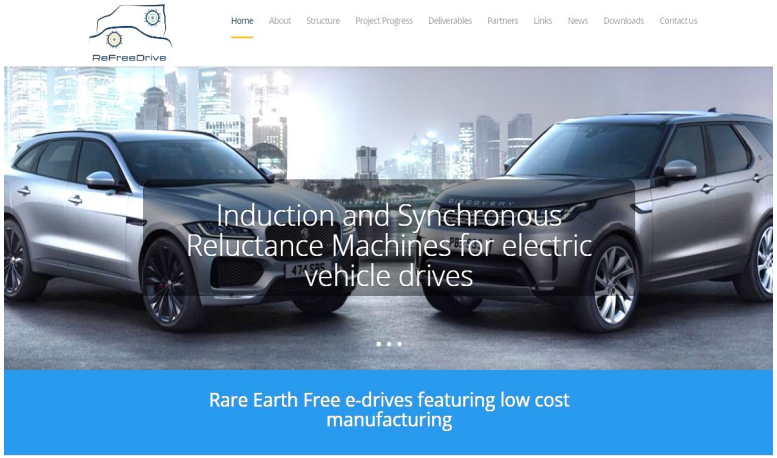
www.refreedrive.eu




LinkedIn

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



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