Energy-power spectrum across applications

Propulsion systems are tailored to specific power and energy demands, based on their use case and duty cycle. The graph below presents an outline of principle mass-market products.

The 2020 roadmap provides values for

1. Cost effective, high volume indicators. Values for

2. Power dense, high performance and

3. High power, ultra-high efficiency applications will be developed with industry in due course.

1. **Cost effective, high volume orientated:**
   Achieving economies of scale at a low cost is paramount for these products. Applications include high volume passenger car and delivery vans (majority 400V).

2. **Power dense, high performance orientated**
   High power densities are required with cost a less decisive factor. Applications include performance passenger cars, buses and some medium duty vehicles (800V prevalent).

3. **High power, ultra high efficiency orientated**
   High power densities and reliability are needed for these applications but efficiency is key to maximise energy use. Applications include 44 tonne trucks and large, off-highway vehicles (700-1,200V).
Technology indicators for cost effective, high volume applications

Technology indicators that industry is likely to achieve in a mass-market competitive environment. All the cost and performance metrics are ambitious, but relate to the same technology.

<table>
<thead>
<tr>
<th>Electric Machine Indicators</th>
<th>2020</th>
<th>2025</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ($/kW)</td>
<td>6</td>
<td>4.8</td>
<td>3.3</td>
</tr>
<tr>
<td>Volumetric Power Density (kW/l)</td>
<td>8</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Gravimetric Power Density (kW/kg)</td>
<td>4</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>WLTP Average Efficiency</td>
<td>93%</td>
<td>95%</td>
<td>97%</td>
</tr>
</tbody>
</table>

The below table represents the indicator specifications used for the roadmap. These are for reference only, and do not reflect a target spec.

<table>
<thead>
<tr>
<th>Electric Machine Indicators Spec</th>
<th>2020</th>
<th>2025</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power</td>
<td>100kW</td>
<td>100kW</td>
<td>100kW</td>
</tr>
<tr>
<td>Continuous Power</td>
<td>50kW</td>
<td>50kW</td>
<td>70kW</td>
</tr>
<tr>
<td>Input voltage (nominal)</td>
<td>400V</td>
<td>400V</td>
<td>800V</td>
</tr>
<tr>
<td>Output current (max)</td>
<td>450A rms</td>
<td>450A rms</td>
<td>225A rms</td>
</tr>
<tr>
<td>Coolant inlet temperature</td>
<td>65ºC</td>
<td>65ºC</td>
<td>65ºC</td>
</tr>
<tr>
<td>Production volume</td>
<td>&gt;100k</td>
<td>&gt;100k</td>
<td>&gt;200k</td>
</tr>
</tbody>
</table>

Notes:
- The electric machine indicators above refer to "Cost effective, high volume" applications. See page 1 for other indicators which present other product applications.
- The cost indicator represents the price an OEM would be expected to pay for a cost effective, high volume electric machine.
- All masses and volumes include the active electromagnetic components of the motor, the shaft, casing and any heatsinks. They should not include the mass of any cooling fluid, external radiator or fluid pump. Electrical filters and power electronic components should not be included.
- Continuous power and torque should be sustainable for at least 15 minutes.
- Power is Net Power, as defined in ECE R85.
- WLTP Average efficiency refers to powertrain efficiency. This should be read as the motor, inverter and the transmission achieve the indicated efficiency value for 2025 and 2035.
### Machine Architectures and Integration

- **Advanced architectures (e.g. PM free, axial flux, transverse, flux, new rotor designs, high speed motors)**
- **Radical architectures (e.g. HTS, coreless rotors)**
- **1st gen integrated drives (packaged closely)**
- **Functionally integrated drives (i.e. housing, embedded electronics, high speed gearbox)**
- **New machine designs via enhanced simulation techniques**
- **ALM-enabled new machine designs with adaptive / flexible features**

### Thermal Management

- **Isolation materials for electrical strength and thermal conductivity (e.g. film insulations)**
- **Advanced electrically insulating, thermally conductive materials**
- **Direct liquid cooling (i.e. windings termination, laminations)**
- **Advanced cooling concepts (i.e. phase change cooling)**
- **Integrated thermal management (e.g. converge inverter and motor cooling)**

### Material Developments - Windings

- **Enhanced copper windings (e.g. alloys, litz wire, laminated, enhanced coatings)**
- **High performance windings (e.g. graphene, HTS)**
- **Alternative low-cost windings (e.g. aluminium,aluclad)**
- **Cost-competitive ALM windings with alternative materials**
- **Reduced heavy rare earths content**
- **Blends of primary and secondary rare earth magnets**
- **100% recycled rare earth magnets**
- **Alternatives to sintered NdFeB for mass market applications (e.g. iron ferrite, SmCo, bonded NdFeB)**
- **Enhanced e-steels (i.e. higher Si content, thinner laminations)**
- **Cost competitive next gen. e-steels (e.g. CoFe alloys, localised properties)**
- **SMCs tailored for high volume automotive (i.e. smaller grain sizes, reduced saturation)**

### Manufacturing Innovations

- **High volume winding techniques with high fill factor (e.g. cont. hairpin)**
- **New winding processes for high performance (e.g. casted windings, ALM)**
- **Reduced wastage of stator / rotor stacking (e.g. slinky stators)**
- **Net shape, zero waste integrated magnetics**
- **Reduced wet manufacturing processes in machine assembly**
- **Eliminate wet processes**
- **Enhanced magnet manufacturing processes (e.g. laminations)**

### Life Cycle

- **Pilot recycling plants**
- **Mass market e-machine recycling**
- **Closed loop value chain for e-machines**
- **Design for LCA and disassembly**
- **Highly decarbonised manufacturing and recycling**
- **LCA focussed value chains**

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**Transition:** Transitions do not mean a phase out from market but a change of R&D emphasis.

**Dotted line bar:** Market Mature — technology has reached maturity. Likely to remain in mass market until it fades out where it’s superseded.

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This roadmap represents a snapshot-in-time view of the global automotive industry propulsion technology forecast for mass market adoption. Specific application-tailored technologies will vary from region to region.