ROADMAPPING THE EV FUTURE
Battery technology, mass manufacturing and the prospects ahead
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University of Warwick

- Located in heart of UK
- Founded 1965, UK Russel Group
- 5000 staff, 23,000 students,
  - 43% postgraduate,
  - 36% international,
  - 34% in science and engineering
- Annual turnover £459M
- 7th in RAE for Research Excellence
  - 87% of research rated “World Leading” or “Internationally Excellent”

WMG Founded by Lord Bhattacharyya in 1980

- Focused on industrial impact and manufacturing
- Strong relationships with 1000 companies
- Over 450 people across 6 buildings on campus
- High international visibility
- Cross-sectoral and interdisciplinary programmes
- Teaching at School, Apprenticeship, Undergraduate, Industrial and Postgraduate levels
Drivers for Electrification in Automotive

Energy Security

Climate Change & Air Quality

Industrial Opportunity

Consumer demand

Source: Cornell University from Edwards 2001

Source: Adweek
Regulations drive CO₂ and air quality improvement in most markets

- EU regulations have put a price on CO₂ at €95/g/km through fines
- US CAFE does similarly
- China prevents sale of non-compliant vehicles
- Currently passenger-car focus, but other sectors likely to follow.

- Metropolitan mayors moving to ban diesel and promote zero emissions
Powertrain roadmap for cars is well understood by manufacturers.
## Degrees of Electrification

<table>
<thead>
<tr>
<th>Degrees of Electrification</th>
<th>Engine</th>
<th>Motor</th>
<th>“Battery”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>100kW</td>
<td>12V</td>
<td>3kW, 1kWh</td>
</tr>
<tr>
<td></td>
<td>Full transient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild Hybrid</td>
<td>90-100kW</td>
<td>3-13kW</td>
<td>12-48V</td>
</tr>
<tr>
<td></td>
<td>Full transient</td>
<td></td>
<td>5-15kW, 1kWh</td>
</tr>
<tr>
<td>Full Hybrid</td>
<td>60-80kW</td>
<td>20-40kW</td>
<td>100-300V</td>
</tr>
<tr>
<td></td>
<td>Less transient</td>
<td></td>
<td>20-40kW, 2kWh</td>
</tr>
<tr>
<td>PHEV</td>
<td>40-60kW</td>
<td>40-60kW</td>
<td>300-600V</td>
</tr>
<tr>
<td></td>
<td>Less transient</td>
<td></td>
<td>40-60kW, 5-20kWh</td>
</tr>
<tr>
<td>REEV</td>
<td>30-50kW</td>
<td>100kW</td>
<td>300-600V</td>
</tr>
<tr>
<td></td>
<td>No transient</td>
<td></td>
<td>100kW, 10-30kWh</td>
</tr>
<tr>
<td>EV</td>
<td>No Engine</td>
<td>100kW</td>
<td>300-600V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Full EV mode</td>
<td>100kW, 20-60kWh</td>
</tr>
</tbody>
</table>
Biggest challenge for commercialization is battery cost
Batteries are a major commercial opportunity

**Conventional Vehicle**
- One third of conventional vehicle cost is powertrain
- UK manufactures 1.7M cars per year, EU makes 18M per year
- Assuming constant volumes and average battery pack cost of £6000 car, and 50% EV/PHEV share by 2035
  - *This represents a UK supply chain opportunity of >£5bn/year by 2035*
  - *EU supply chain opportunity of over £50bn/yr at 2035*
  - Rate of EV/PHEV market growth determined by customer uptake
    - Uptake will be determined by vehicle cost, range, charging infrastructure and fiscal regime

**Electric Vehicle**
- Motor and power electronics cost around 60% of conventional powertrain
- Battery costs around 3-5x current powertrain
- Rest of vehicle costs similar as before – increased costs for HVAC, brakes and suspension systems
- Battery is >50% of overall vehicle value
Battery is the defining component of an electrified vehicle.
Lithium Ion batteries are improving rapidly

- Costs have fallen dramatically due to technology, production volume and market dynamics
- Pack cost fallen from $1,000/kWh to $250/kWh in less than 8 years

- Volumetric energy density is increasing due to better materials and cell structure
- Doubled in 15 years
- Requires continuous chemistry and materials innovation to continue
• 98% of UK journeys are <50 miles one way (similar in EU and US)
• 93% are less than 25 miles Average total daily distance is 24 miles
• 200+ mile battery costs £10,000 more and weighs 350kg more than 100+ mile battery – and pays back for just 2% of typical journeys

Source: DfT 2002/2006
Do batteries need to be this big?

- For PHEV, the battery should be large enough for typical daily mileage
  - As small as possible for cost and packaging => 20-40 miles
- For mass market EV, 150 miles (real world) covers 98.5% of usage.
- Fast charge, alternative mode or mobility package for remaining 1.5% of journeys
Where could we be in 20 years?

**Cost**
- **Now**: $130/kWh (cell) $280/kWh (pack)
- **2035**: $50/kWh (cell) $100/kWh (pack)

**Energy Density**
- **Now**: 700Wh/l, 250Wh/kg (cell)
- **2035**: 1400Wh/l, 500Wh/kg (cell)

**Power Density**
- **Now**: 3 kW/kg (pack)
- **2035**: 12 kW/kg (pack)

**Safety**
- **2035**: eliminate thermal runaway at pack level to reduce pack complexity

**1st Life**
- **Now**: 8 years (pack)
- **2035**: 15 years (pack)

**Temperature**
- **Now**: -20° to +60°C (cell)
- **2035**: -40° to +80°C (cell)

**Predictability**
- **2035**: full predictive models for performance and aging of battery

**Recyclability**
- **Now**: 10-50% (pack)
- **2035**: 95% (pack)
Automotive Industry Structure for Batteries

Electrochemistry → Electrode, electrolyte, separator, binder → Cell → Pack & BMS → Application (Vehicle /) → 2nd life / Recycling

Industrial Chemists (e.g. 3M) → Materials supplier (e.g. JM) → Cell Supplier (e.g. Panasonic) → Tier 1 → Low Vol OEM → 2nd User? → Recycler → High Vol OEM
How will we get there:

**Short to medium term**
- Li-Ion cathode improvements
- Silicon / graphene anodes
- Binders / solvents
- Electrolyte additives / solid electrolytes
- Separator materials

**Longer term**
- Sodium Ion chemistries ?
- Lithium Sulfur ?
- Lithium metal anodes ?
How will we get there:

**Cells**
- Cell format
  - Cylinder
  - Pouch
  - Prismatic
- Size, materials, aspect ratio
- Joining features

**Smart cells**
- Integrated cooling features (high power)
- Fire suppression measures
- Distributed BMS with integrated sensors?
How will we get there:

- **Modules**
  - Design for manufacturing / disassembly
  - Cell cooling arrangements
  - Cell welding (non-welded ?)
  - Design for end of life

- **Packs**
  - BMS systems to maximise life and SoC utilisation
  - Cooling and heating arrangements
  - Structural integration with vehicle
  - Crash structural considerations
  - Fire propagation limitation
How will we get there:

- **Vehicles**
  - Stabilisation of range requirement?
  - Emergence of L-segment and small vehicles
  - ADAS and CAV technologies
  - Business model changes
How will we get there:

- Home charging will require distribution system upgrades
  - Inductive charging attractive but no standards
- Rapid charging can mitigate need for large batteries
  - Significant power needs in key locations
- Dynamic charging for HGV / Coaches
  - Inductive or conductive
- Battery swap for taxis, light commercial vehicles
How will we get there:

- Recycling
  - EV battery pack weighs 300-900kg
  - Typical life 8-10 years
  - Net cost at disposal around £1000/T

- Pack design should allow easy dismantling
- New processes needed to recover cell materials
- And deployment at scale required

95GWh (950 million tonnes) of scrap batteries will come out of cars by 2025.
What does this mean for the automotive electric machine?

### Efficiency

- Motor efficiency affects battery size
- 1% efficiency = $100-200 pack cost
- Efficiency matters at motorway conditions (130kph / 20-30kW)
- Peak efficiency is irrelevant

### Quality

- 6σ quality at 500,000 – 1M p.a.

### Recyclability

- >95% recovery at minimal cost

### Cost

- $/kW optimised at system level

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*Source: Oak Ridge National Labs*
Reduced cost:
- Reluctance torque supplementing magnetic torque
- Ce in place of Dy for high temperature PM materials
- Moulded magnets in place of sintered
- Aluminium windings
- Reduction of materials – segmented stator
- Elimination of lamination stack bolts and welds
- Short pitching of coils to reduce end winding length
- Design for highly automated or robotic assembly

Increased Power Density
- Materials Selection
- Thermal management
- High speed operation
Thank you

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