ADVANCES IN ELECTRIC VEHICLE POWERTRAINS: FROM BATTERY TO WHEELS

CUCEE

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TAL TECH
MECHATRONICS AND AUTONOMOUS SYSTEMS RESEARCH GROUP

Welcome!

- **Name & Title**
  - Mahmoud Ibrahim
  - Researcher, Department of Electrical Power Engineering and Mechatronics, TalTech

- **Academic Background**
  - PhD in Electrical Power Engineering & Mechatronics, TalTech, Estonia
  - MSc in Electric Power and Machines, Zagazig University, Egypt
  - BSc in Electrical Engineering, Zagazig University, Egypt
  - 9+ years academic & research experience

- **Research Areas:**
  - Electric Vehicles & Propulsion System
  - Intelligent Control Systems
  - Digital Twins for EV applications

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Agenda

1. Historical Overview
2. EV Global Snapshot
3. EV Anatomy
4. Advances in EV Batteries
5. Advances in EV Motor Drive Systems
5. Future Directions

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Ice-breaker Poll

- **When wa**
  (A) 183(**0s**

"1830s – Scottish inventor Robert Anderson"

A Very Short History

1899
La Jamais Contente electric car
106 km/h max

1900
38% of U.S. taxi
EV

1972
BMW 1602 e
32 KW

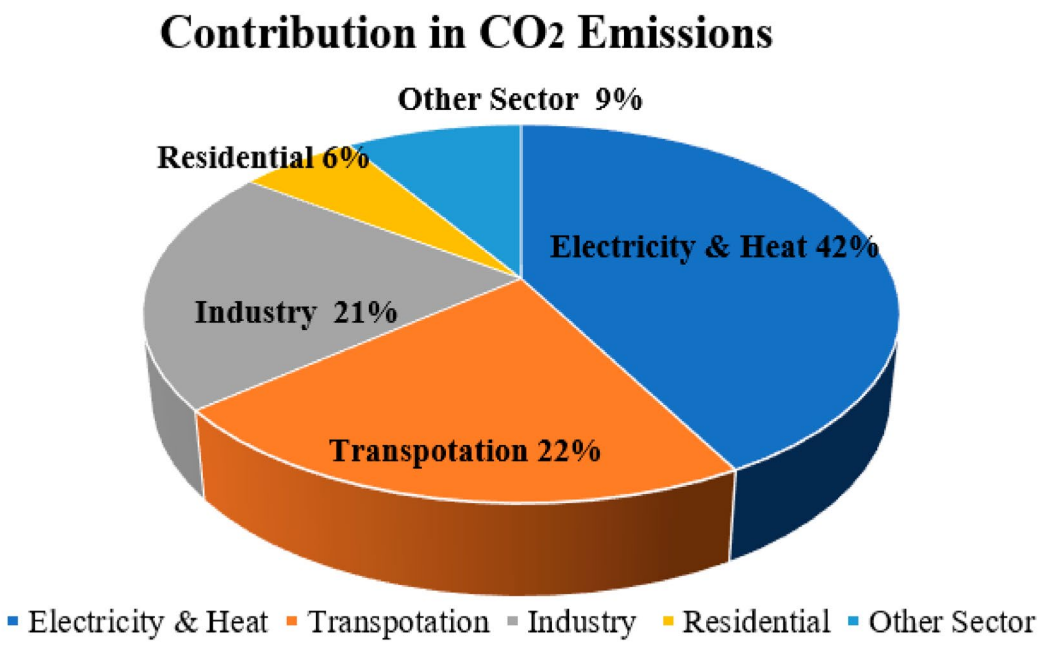
1996
GM EV1

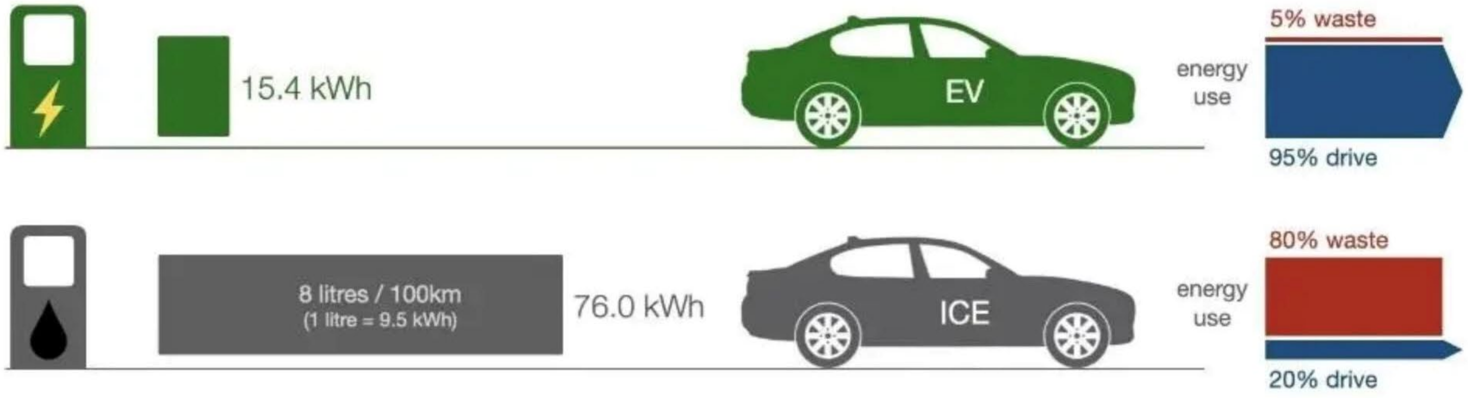
2010
Tesla Roadster

2025
17 million EV sold around the world

Why Transportation Electrification?

- Reduced emissions
- Improved air quality
- Energy efficiency
- Lower operating costs
- Quieter operation





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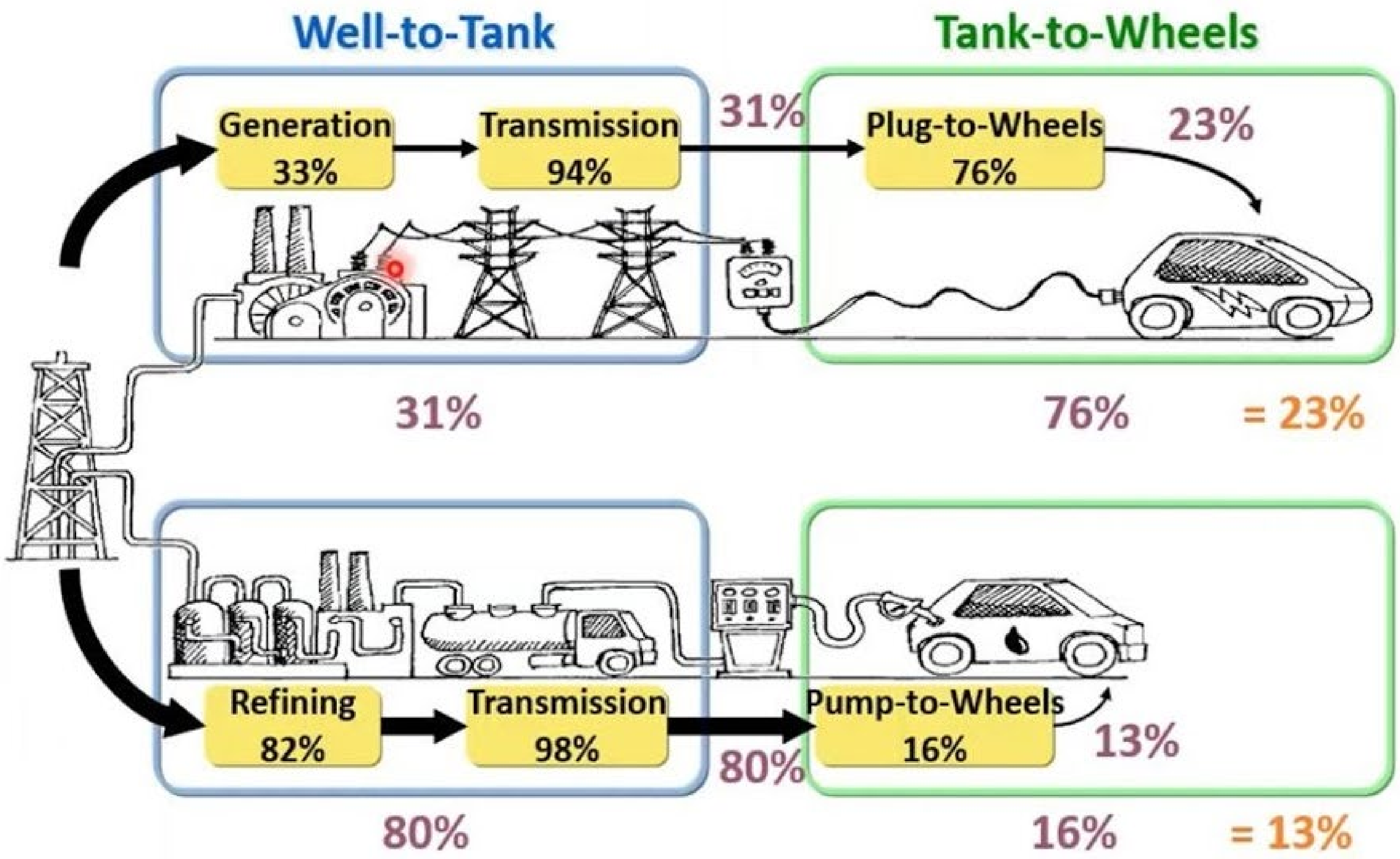
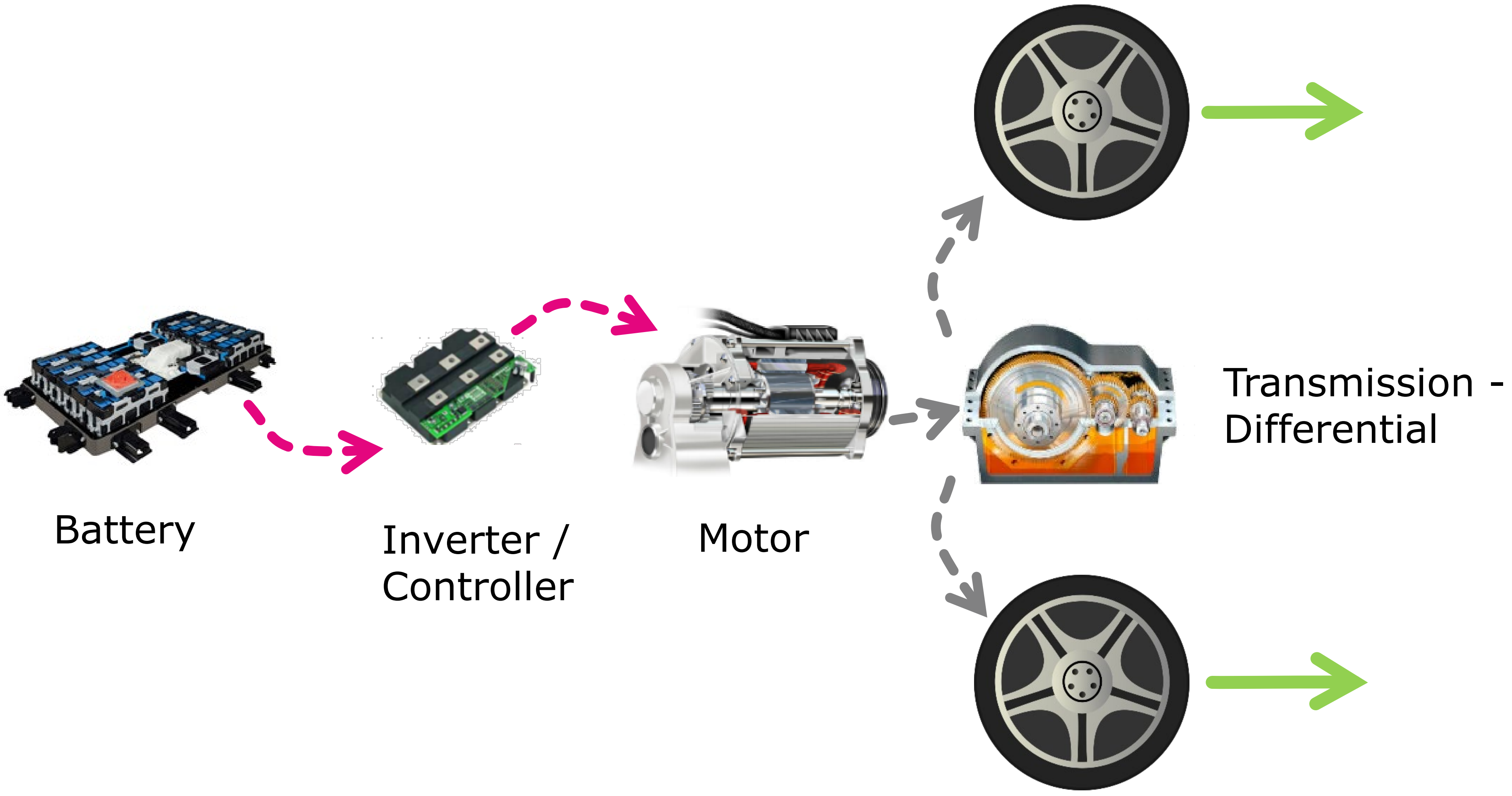
Well to Wheel Efficiency



EV Anatomy

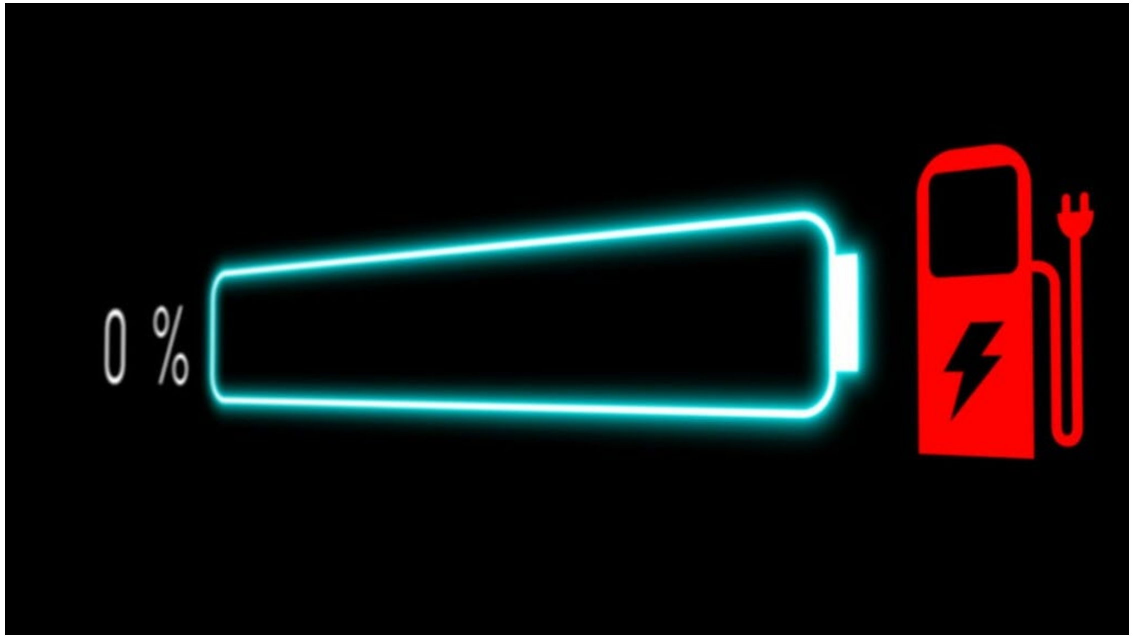

Battery
Inverter / Controller
Motor
Transmission - Differential

Why Battery is Critical in Transportation?

- Determines range, performance, and safety.

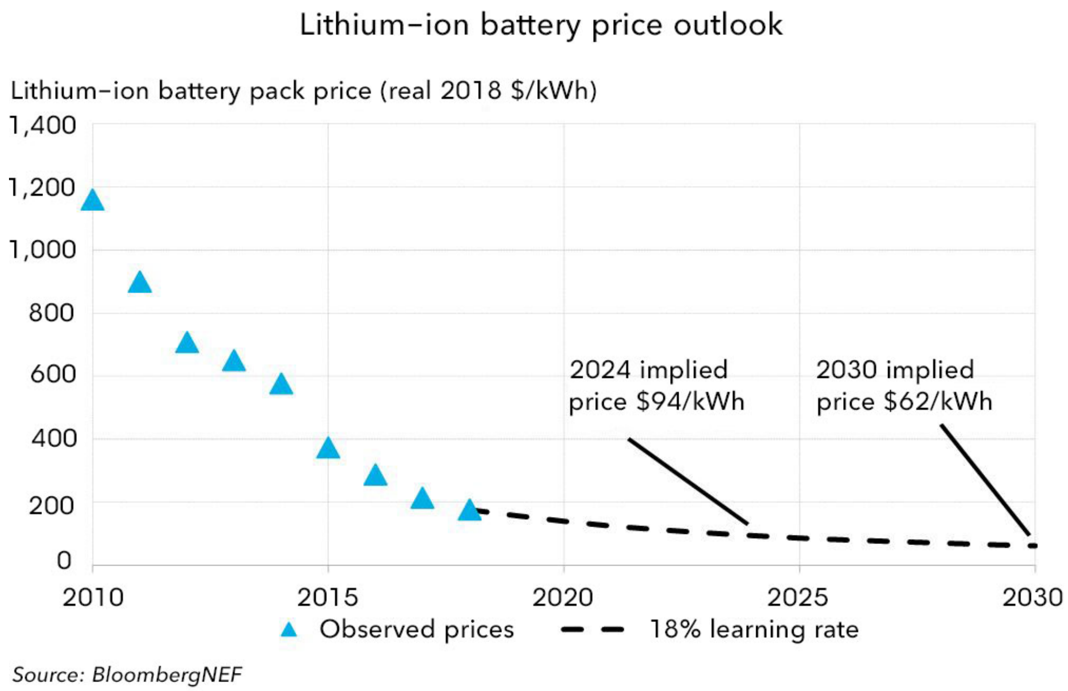
- 30-40% of vehicle cost (ESS and related)

- ESS allows capture and reuse of kinetic energy during braking, improving overall vehicle efficiency

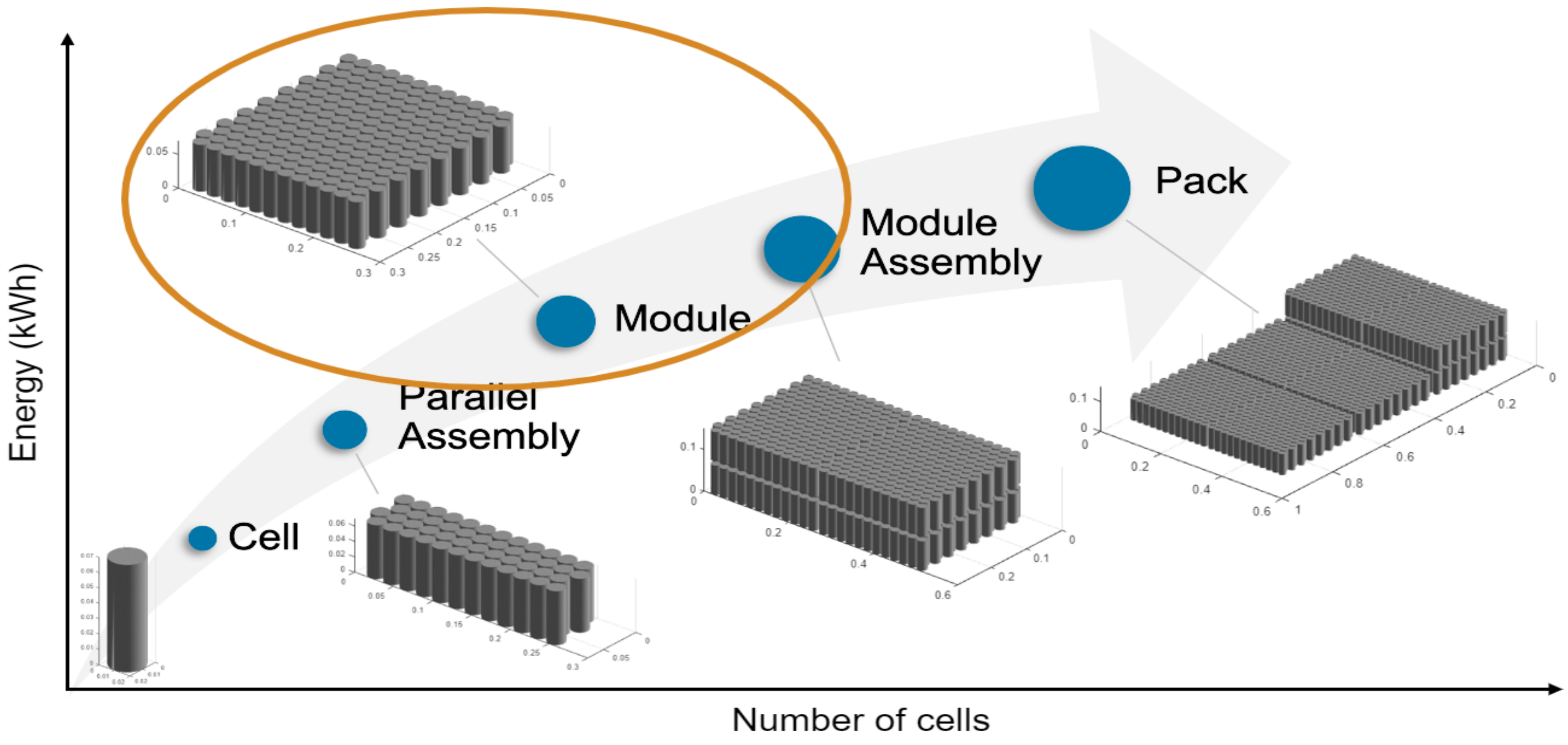


The Battery Cost Cliff

- Battery pack prices dropped nearly 90% in 13 years
- 2010: $1,160/kWh
- 2020: $137/kWh
- 2024: ≈$115/kWh (BNEF data)



EV Battery System Structure



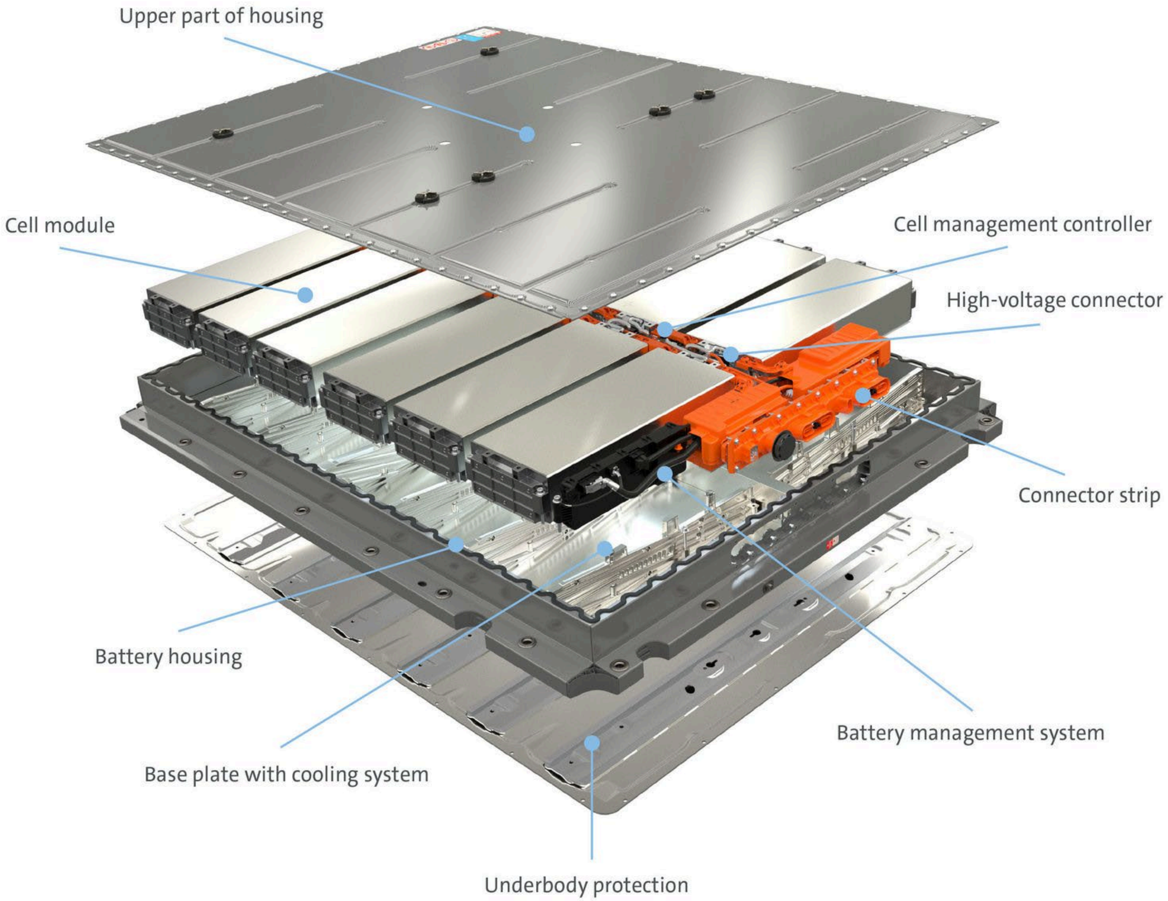
EV Battery System

System Components

Battery Pack:
The central component that stores the energy needed for the vehicle's operation

•**Battery Management System (BMS):** A critical electronic component that monitors the battery's SOC, balances cell performance, and ensures the safety and longevity of the battery.

Thermal Management System: Maintains the battery pack at its optimal operating temperature, which is essential for its performance, safety, and lifespan.



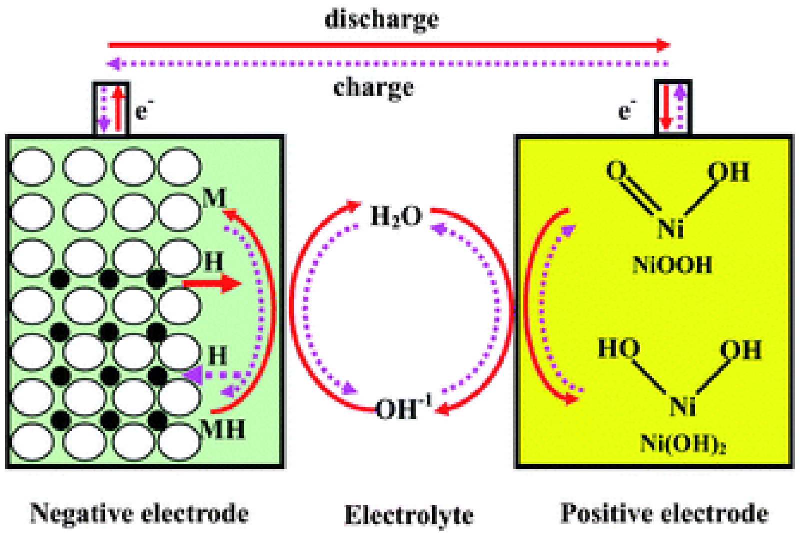
EV Battery

Types used in EVs

- NiMH
- NMC
- LPF
- LTO
- Na-ion
- Solid state
- NCA

Battery Types
NiMH (Nickel-Metal Hydride)- Legacy

Overview:
Energy density: 60–80 Wh/kg
Cycle life: ~1,500 cycles
Cost: 150-300$/KWh
Self-discharge: 20-30% month
Advantages:
Reliable, no thermal runaway
acceptable lifetime, environmentally friendly
Disadvantages:
Heavy and low energy density
Superseded by Li-ion
Typical Use:
Early HEVs



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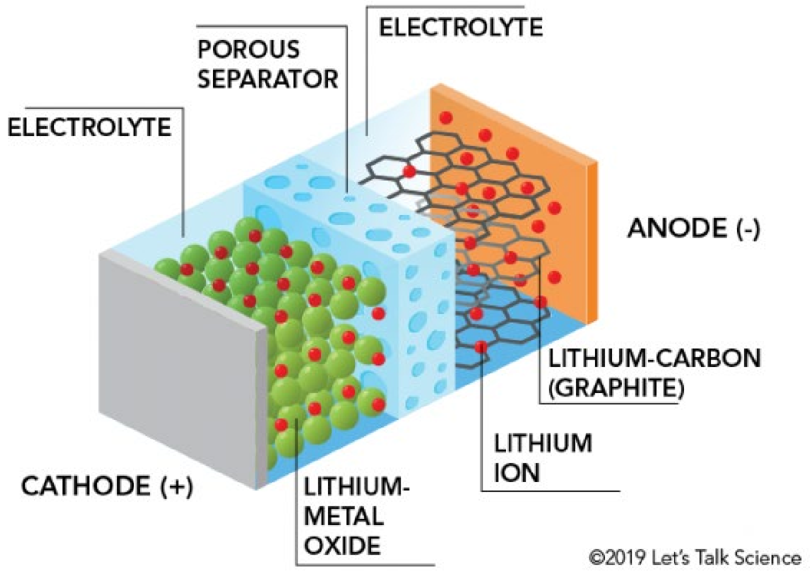
Battery Types
Lithium-Ion NMC/NCA

Overview:
•Energy density: **200–300 Wh/kg**
•Cycle life: ~1,000–2,000 cycles
•Cost: 120-140$/KWh
•Self discharge:2%
Advantages:
•High range in compact space
•Good power performance
•Widely used in passenger EVs
Disadvantages:
•Expensive materials (nickel, cobalt)
•Lower cycle life and higher thermal risk

•**Typical Use:**
high-performance EVs
Examples: Tesla Models – Nissan – Kia



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Battery Types

LFP (Lithium Iron Phosphate)

Overview:
Energy density: **150–205 Wh/kg**
Cycle life: **2,500–9,000+ cycles**
Cost: 80-90$/KWh
Self discharge: 1-3% per month
Advantages:
Exceptionally safe and stable
Long-lasting, Low cost, no cobalt used
Disadvantages:
Lower range per pack
Requires larger volume for same energy
Typical Use:
Budget EVs, e-buses, grid storage, trolleys and trains
Example: BYD blade batteries most models (China)

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Battery Types
LTO (Lithium Titanate Oxide)

Overview:
Energy density: **60–110 Wh/kg**
Cycle life: **10,000–30,000+ cycles**
Cost: 150-200$/KWh
Self-discharge: 3% per month
Advantages:
- Ultra-safe and fast-charging
- Extremely high cycle count
- Operates in extreme temperatures

Disadvantages:
low energy density
High cost and size-heavy
Typical Use:
E-buses, industrial equipment, backup systems

Battery Types
Sodium-Ion Batteries (Na-Ion) (Emerging Technologies)

Overview

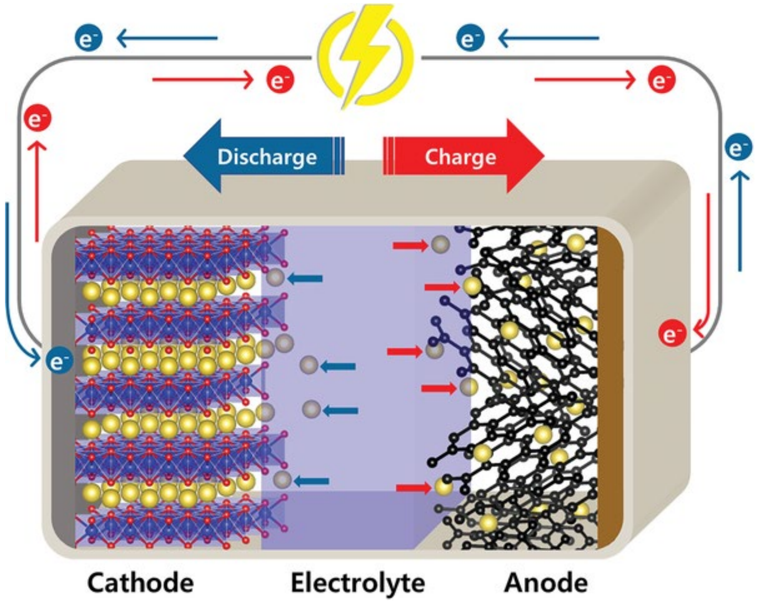
- **Energy density**: 75–200 Wh/kg
- **Cycle life**: 1,000–3,000+ cycles
- **Cost**:80-90$/kWh
- **Self discharge: 1-2%** per month

Advantages

- Low-cost and abundant sodium resources
- Good performance in extreme cold (retains ~93% capacity at −30 °C)
- No cobalt/nickel dependency → better sustainability

Disadvantages

- Lower density → heavier packs
- Still in early commercial stage → infrastructure limited



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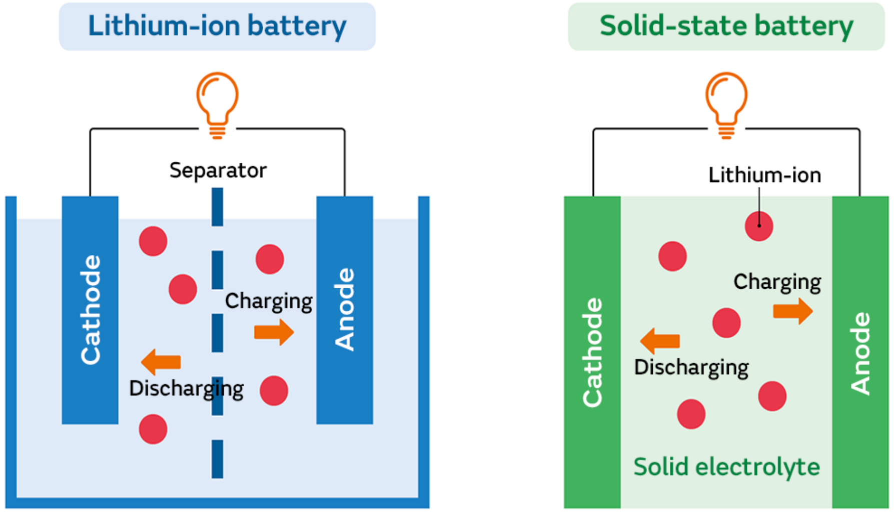
Battery Types
Solid-State (Emerging Technologies)

Overview:
Energy density: **400–500 Wh/kg (theoretical)**
Cycle life: 5,000–10,000+
Cost: High (R&D) 400-600$/kWh
Safety: Solid electrolytes eliminate flammable
Advantages
Higher density = longer rangeFaster charging (<1
min for 15→90%)
Improved safety & thermal stability
Disadvantages
Complex to manufacture
High cost in early commercial stages
Scaling remains a challenge (though technologies like QuantumScape's "Cobra" process are promising)



EV Motor

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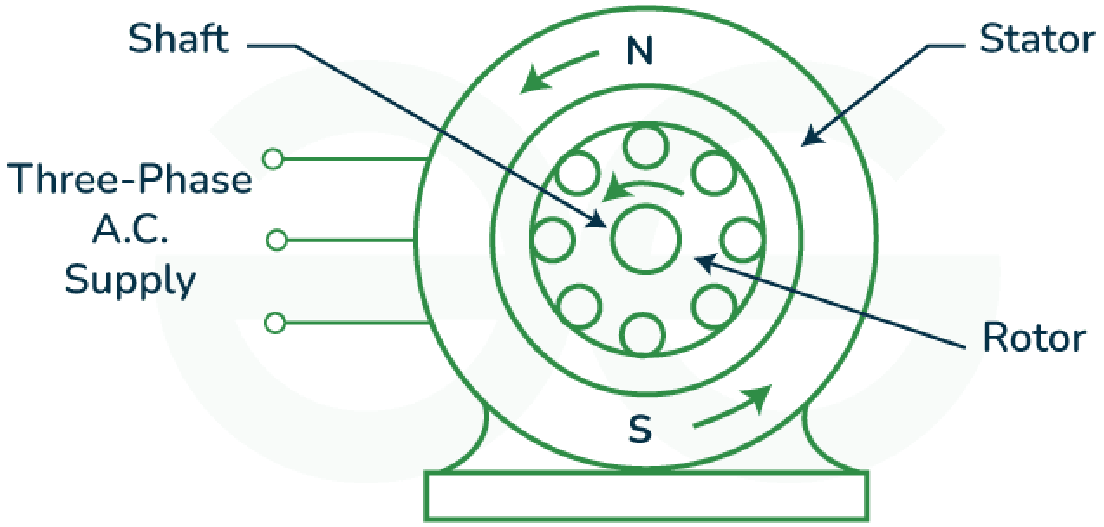
EV Motor
Principles

- **Core Operating Principles**

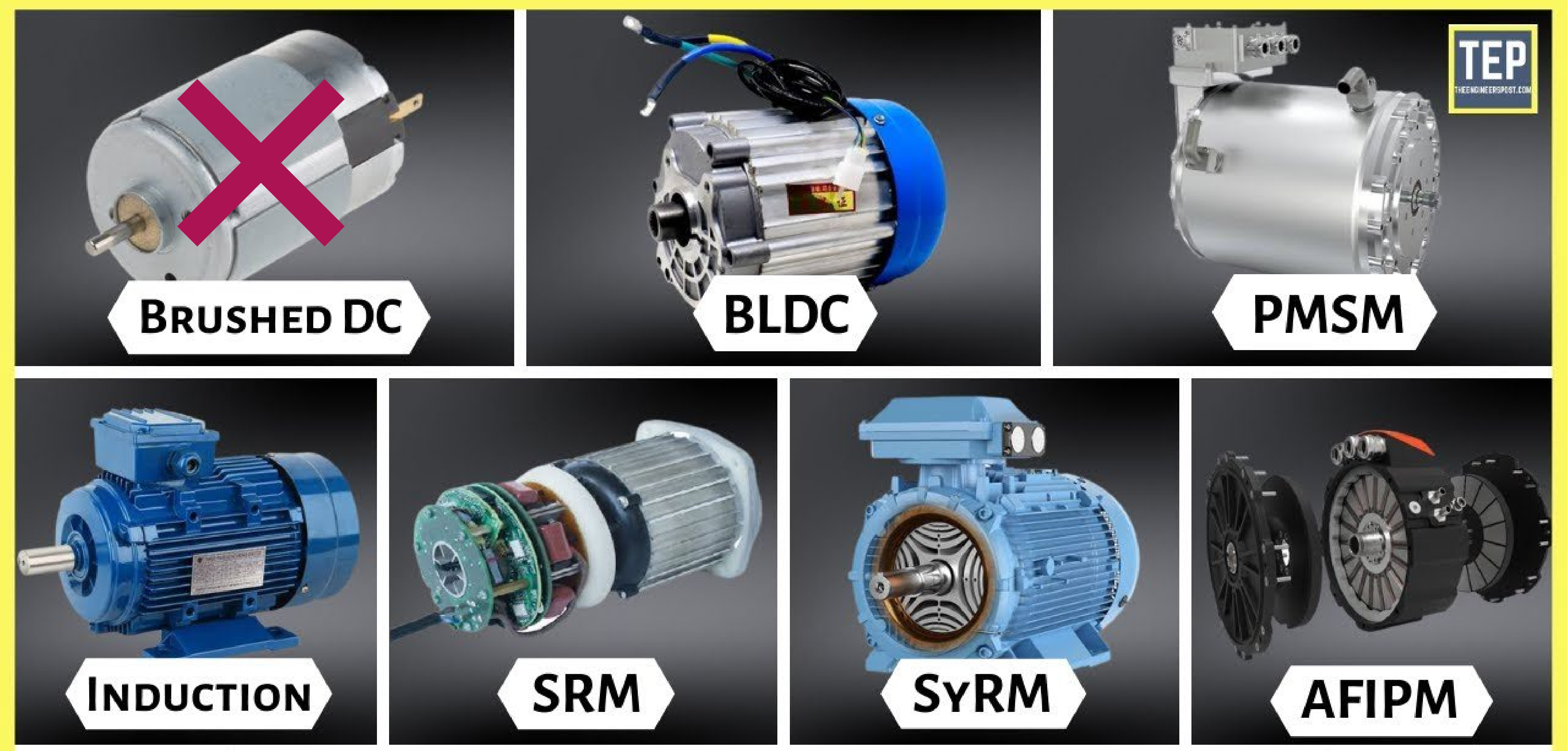
All EV traction motors convert electrical power into mechanical power (T, N) and vise versa via either way:

- **Electromagnetic induction** (AC induction motors)
- **Permanent magnet field interaction** (PMSM, BLDC)
- **Reluctance torque** (SRM)

These principles govern how:
•Stator magnetic fields is generated
•Rotors respond via torque-inducing forces
•Controllers regulate speed, position, and torque in real time

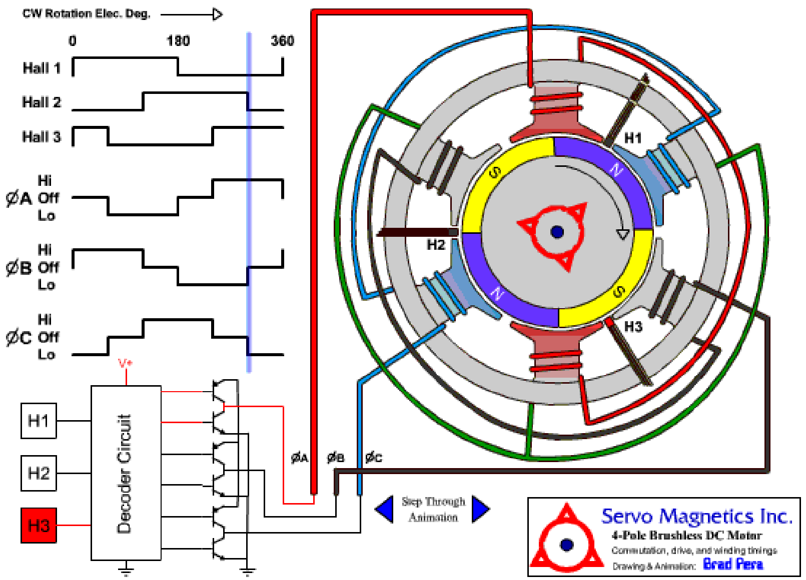


EV Motor Types



BLDC

Working Principle: PM filed interaction + commutation



Key Features:

•High Efficiency 90-95%

•Compact and ideal for small EVs

Drawbacks

- Vibrations, Heat Generation, limitation to few kW.

Examples in EVs:

Xiaomi M365 E-scooter or *NIU E-moped- drones*

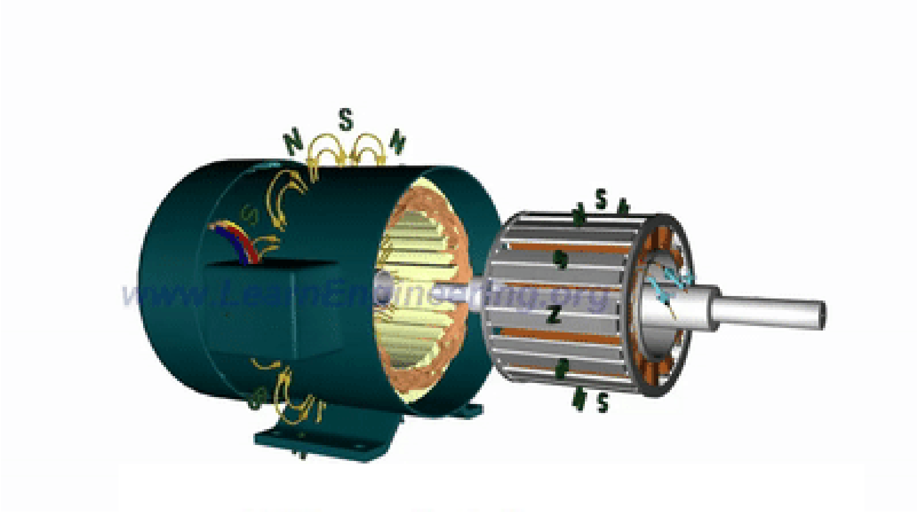
Permanent Magnet Synchronous Motor (PMSM)

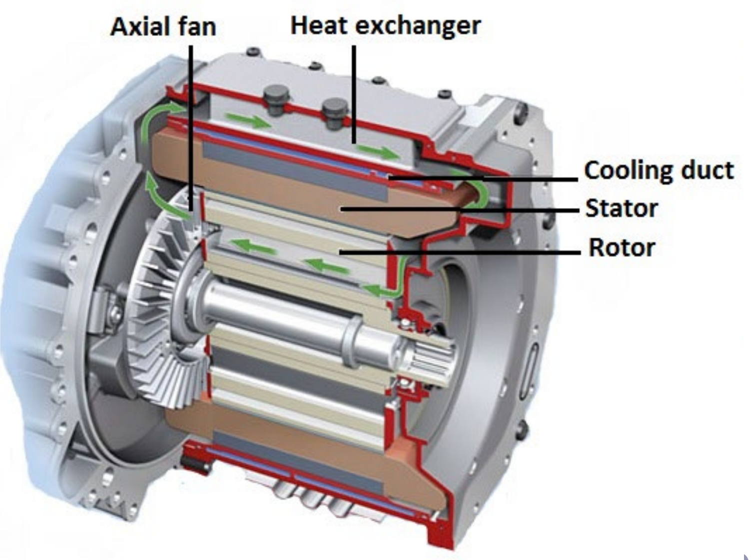
Working Principle: PM field interaction.

Key Features:
- High efficiency (up to 97%)
- High torque and power density
- Quiet and compact

Drawbacks:
- Expensive materials
- Temperature Sensitivity & Cooling Requirements

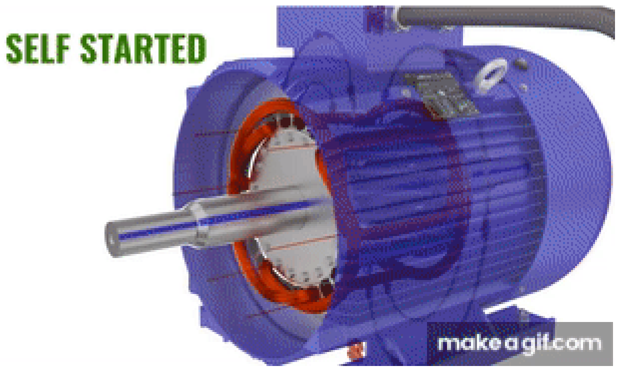
Example EVs:
Nissan Leaf, BMW i5, Hyundai Ioniq 5

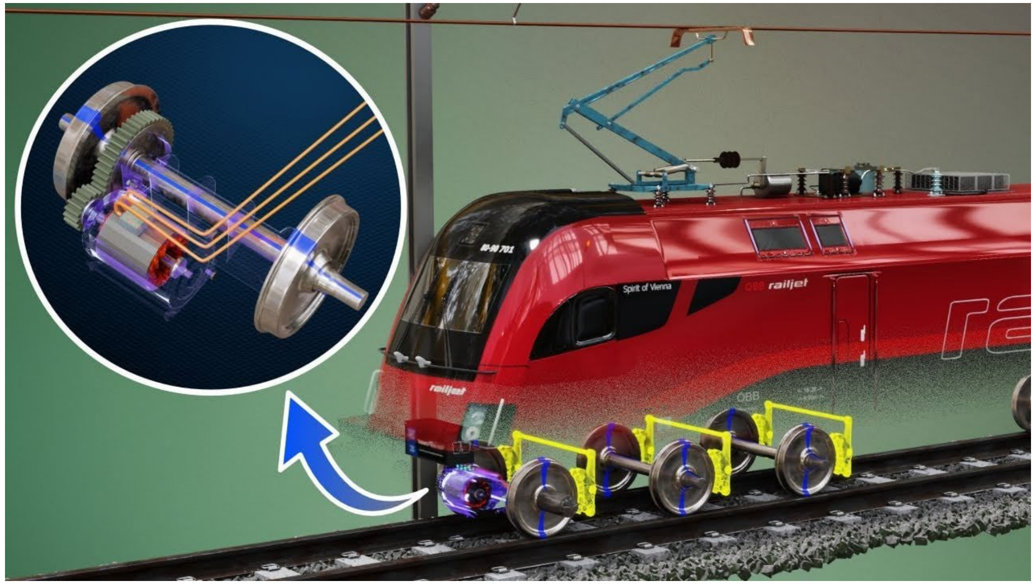




Induction Motor (IM)

Working Principle:
Electromagnetic induction
Key Features:
•No magnets (cost-saving)
•Robust and thermally stable
Drawbacks
•Lower peak efficiency 80-87%
•Low Starting Torque
Example Vehicle:
Older versions of the Tesla Model S
Most of the E-locomotives





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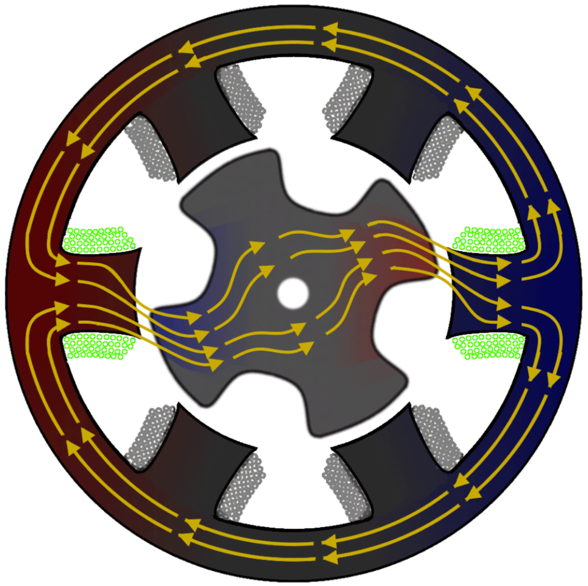
Switched Reluctance Motor (SRM)

Working Principle: Reluctance

Key Features:
- Simple and cheap construction
- Very robust

Drawbacks:
- Acoustic noise and complex control

Example Vehicle:
Still in prototyping no actual use in EVs



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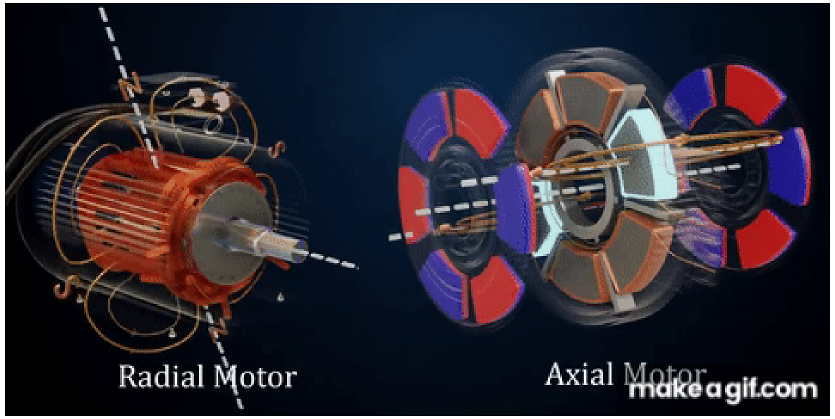
Axial Flux Motor (Pancake Motor)

Working Principle: PM filed interaction

Key Features:
•Extremely compact
•High torque/weight ratio
•Ideal for space-constrained or in-wheel designs

Drawbacks:
•Expensive
•Requires special cooling

Example Vehicle:
Ferrari SF90 (YASA motor), Lightyear One

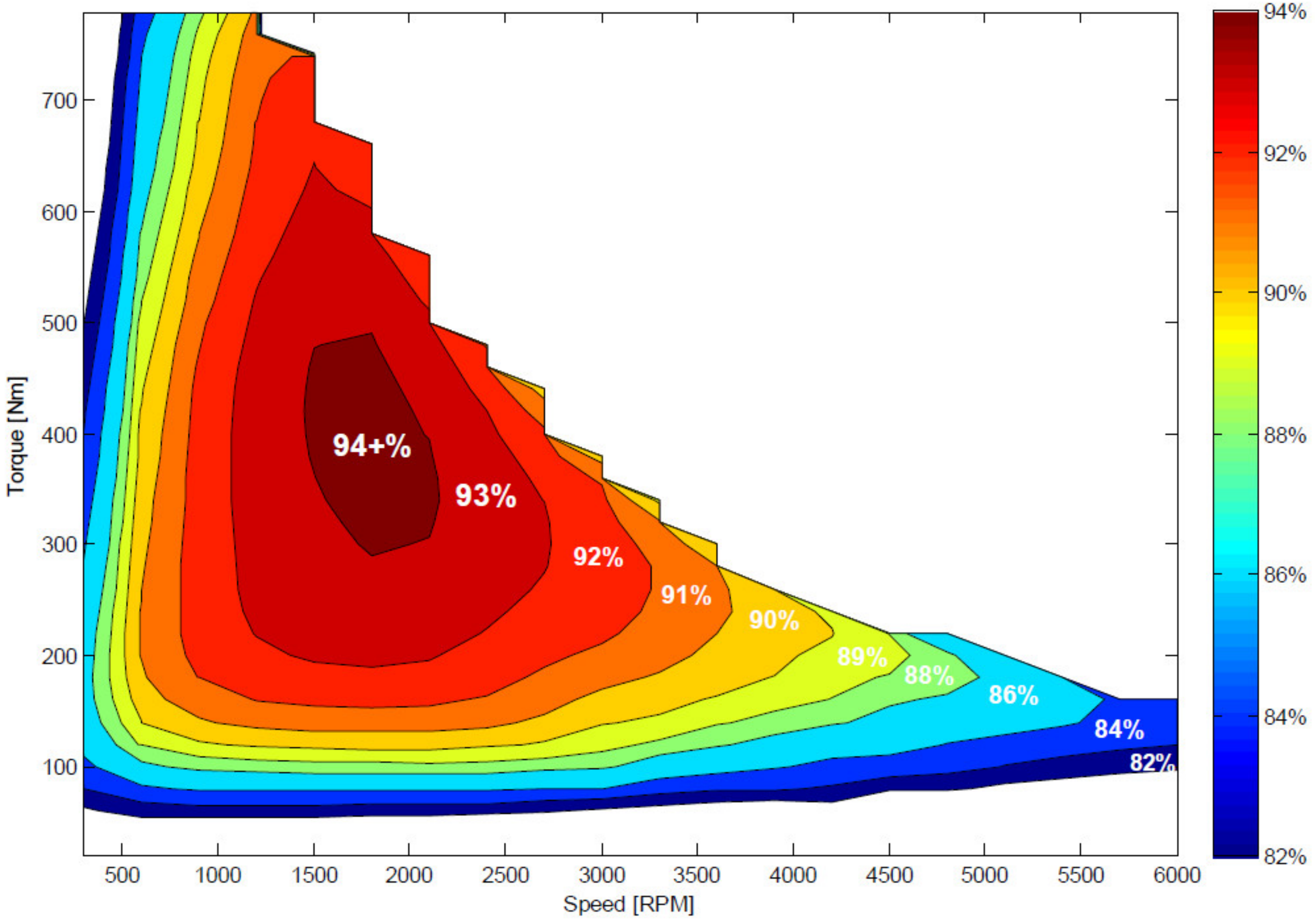


Efficiency Map of Electric Motors

What is an Efficiency Map?

- A contour plot showing motor efficiency (%) across the torque–speed domain

- Each contour line (e.g., 85%, 90%, 95%) represents efficiency at specific torque and speed values
- Efficiency peaks (~93–94%) in the “sweet spot”
- Regions near zero torque/speed and near torque/speed limits show lower efficiency



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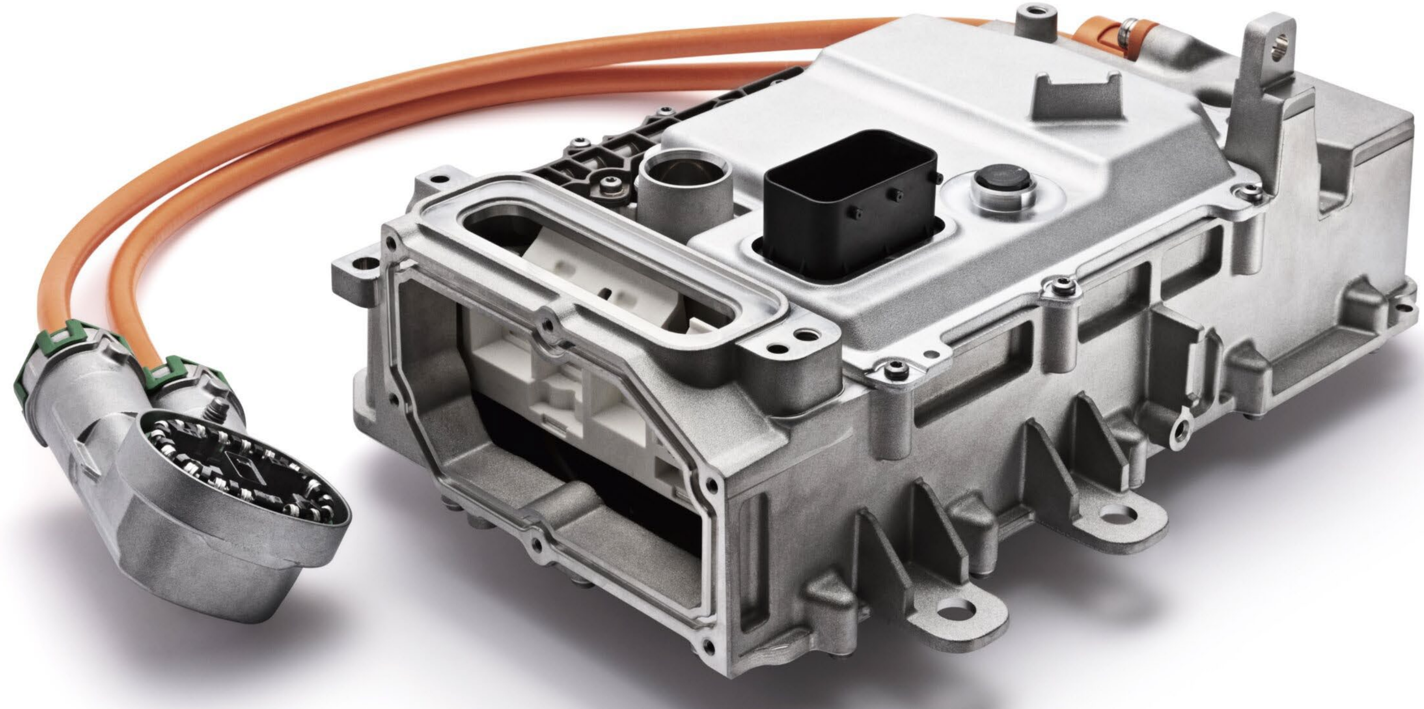
EV Traction Inverter



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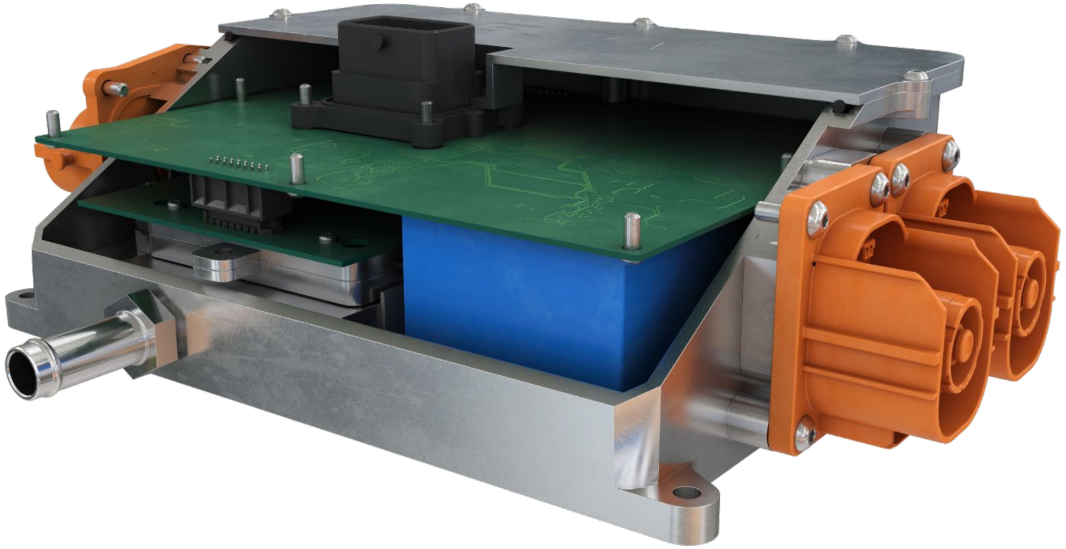
Traction Inverter
Concept

- Converts DC (from battery) to 3-phase AC for traction motor

- Enables precise control of speed, torque, and direction

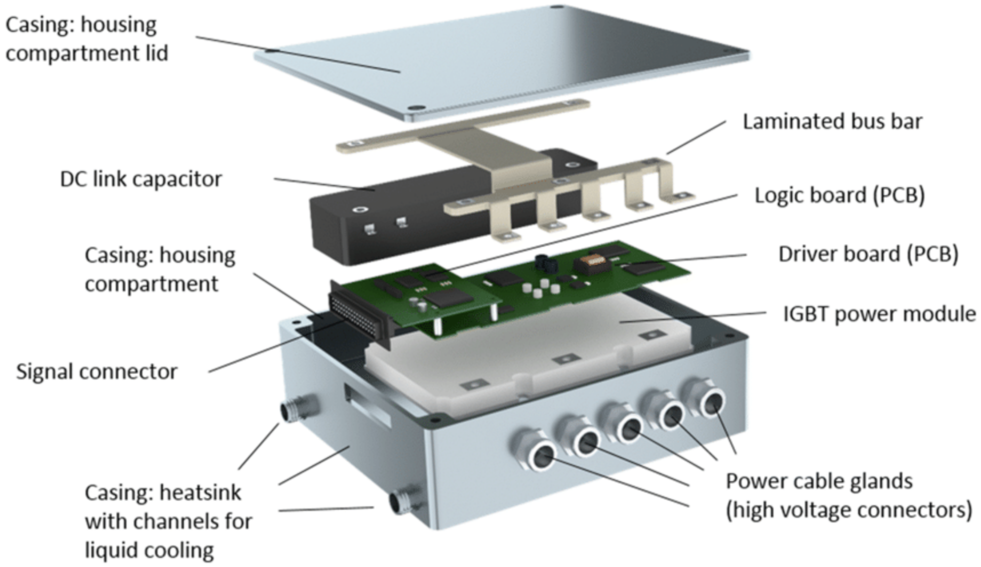
- Essential bridge between energy source and mechanical drive



Traction Inverter
Topology and Operation

1. **Power Electronics Layer (High Voltage)**
    1. Responsible for actual power delivery to the motor
    2. Handles battery voltage (300–800V) and motor current (up to 1000 A)

2. **Control Board (Low Voltage)**
    1. Includes microcontroller/DSP (TI, Infineon, NXP)
    2. Generates PWM signals and executes control algorithms
    3. Measures current, voltage, and position feedback (Hall, resolver, encoder)
    4. Also handles fault detection, safety interlocks, and CAN communication



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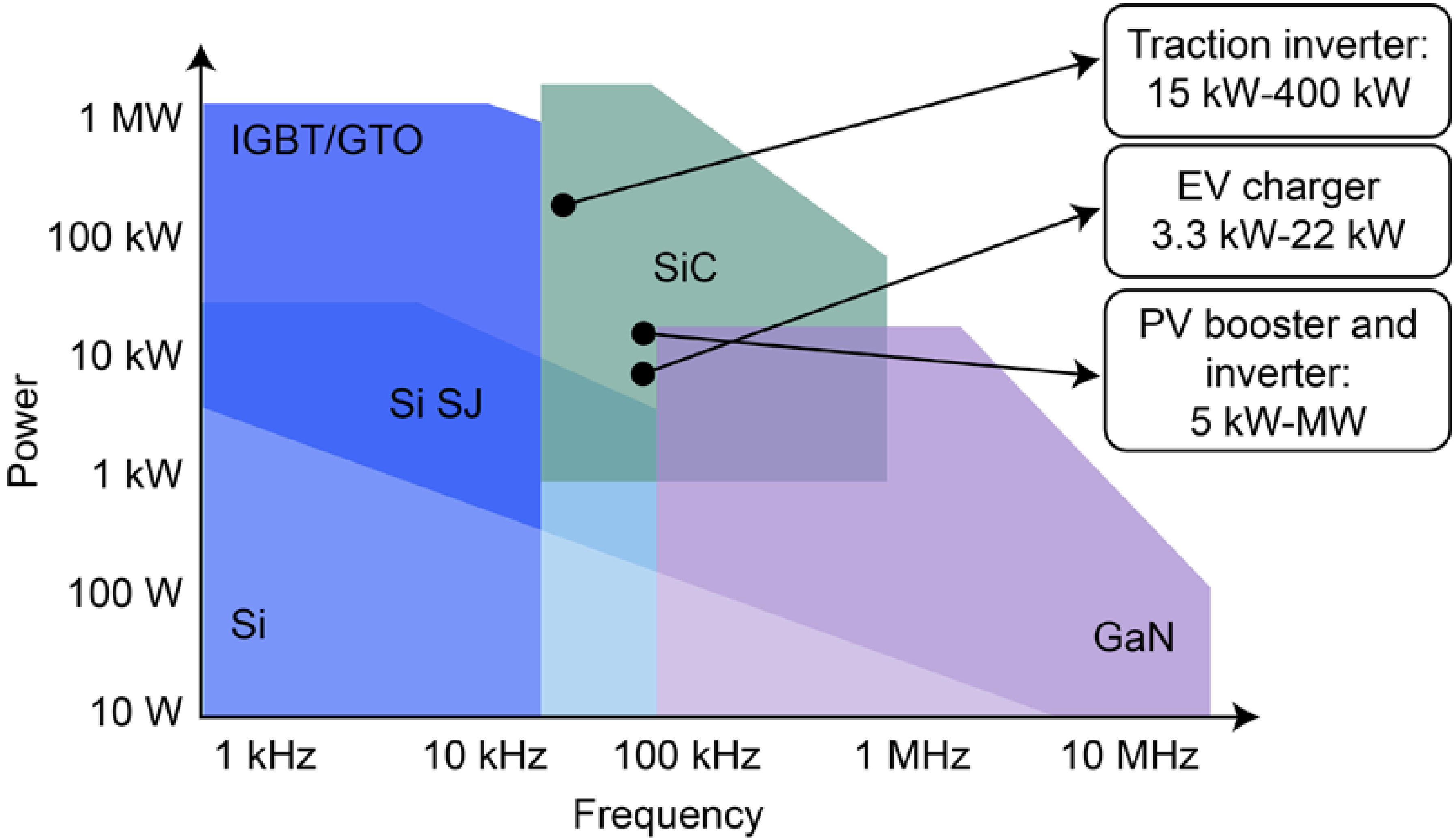
Traction Inverter
Power Electronics



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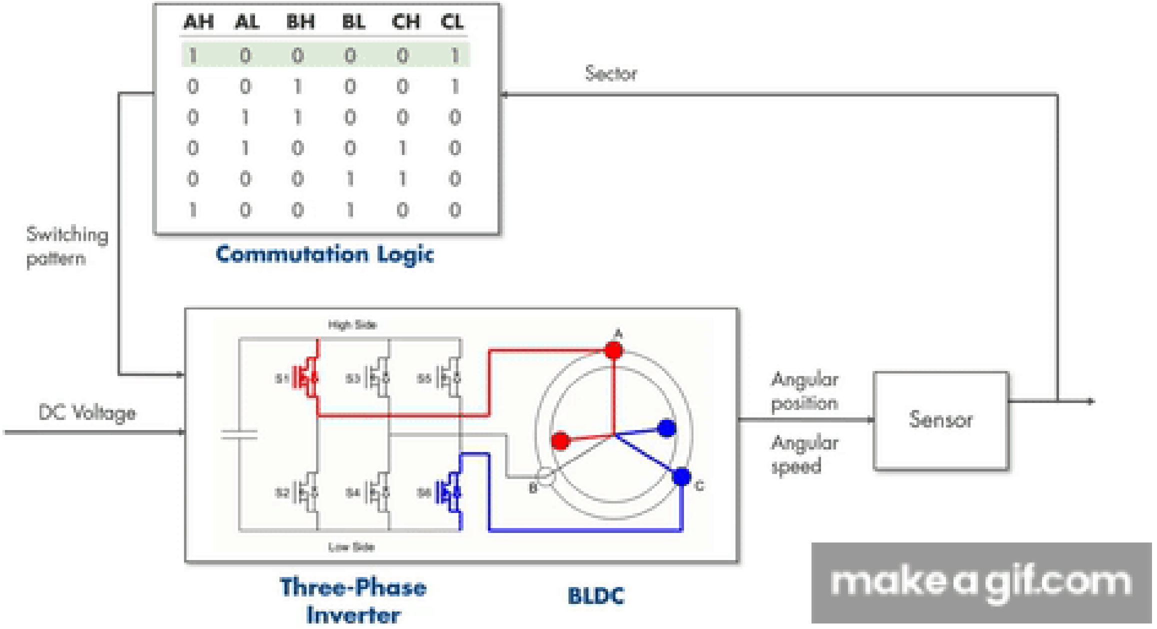
EV Motor Controllers
How it works ?

Controller's purpose:
•Processes sensor data
•Executes real-time control loops
•Sends PWM signals to inverter switches

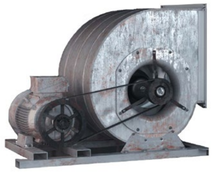
Hardware platforms: DSPs, MCUs, FPGAs (e.g., TI C2000, NXP, Infineon Aurix)Emphasize fast control cycle times (10–50 μs).



Traction Inverter
Control strategies

AC Motor Control Strategies

- **SCALAR CONTROL**
  - V/f
  - V/f²
  - V/√f
- **VECTOR CONTROL**
  - FOC (Field-Oriented Control)
  - DTC (Direct Torque Control)
  - MDP (Model Predictive Control)



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No feedback!

OK

Future Directions

1. **Solid-state batteries**
2. **Axial flux motors**
3. **WBG power electronics for ultra-efficiency**
4. **Wireless dynamic charging technology**
5. **V2G integration**

THANK YOU FOR YOUR ATTENTION!