Hybrid Electric Vehicle (HEV) Powertrains

4A13

References:
Topological overview of hybrid electric and fuel cell vehicular power system architectures and configurations
A. Emadi and K. Rajashekara and S. S. Williamson and S. M. Lukic
IEEE Transactions on Vehicular Technology 54 763-770 (2005)
https://www.scopus.com/inward/record.uri?eid=2-s2.0-21244492011&doi=10.1109%2fTVT.2005.847445&partnerID=40&md5=6f4d454dd2fd824dcf2fa576ce00dd4e
https://doi.org/10.1109/TVT.2005.847445

Ehsani, M., Gao, Y, Longo, S. , Ebrahimi, K., Modern Electric, Hybrid Electric and Fuel Cell Vehicles, 3rd. Ed., CRC Press.

Combustion vs electric vehicle powerplants

ICE

- High energy density of liquid fuels
- Low cost
- Established infrastructure

- Poor efficiency:
  - low part load efficiency
  - throttling (SI)
  - low transient efficiency
- Pollutant emissions

Electric

- High efficiency
- Low direct emissions
- Energy recovery during braking

- Low battery energy density
- Low range
- Creates demands on the electricity system
- Incomplete infrastructure
- Carbon benefits depend on decarbonisation of grid
- Environmental impacts of materials

Do hybrids offer the best of both worlds?

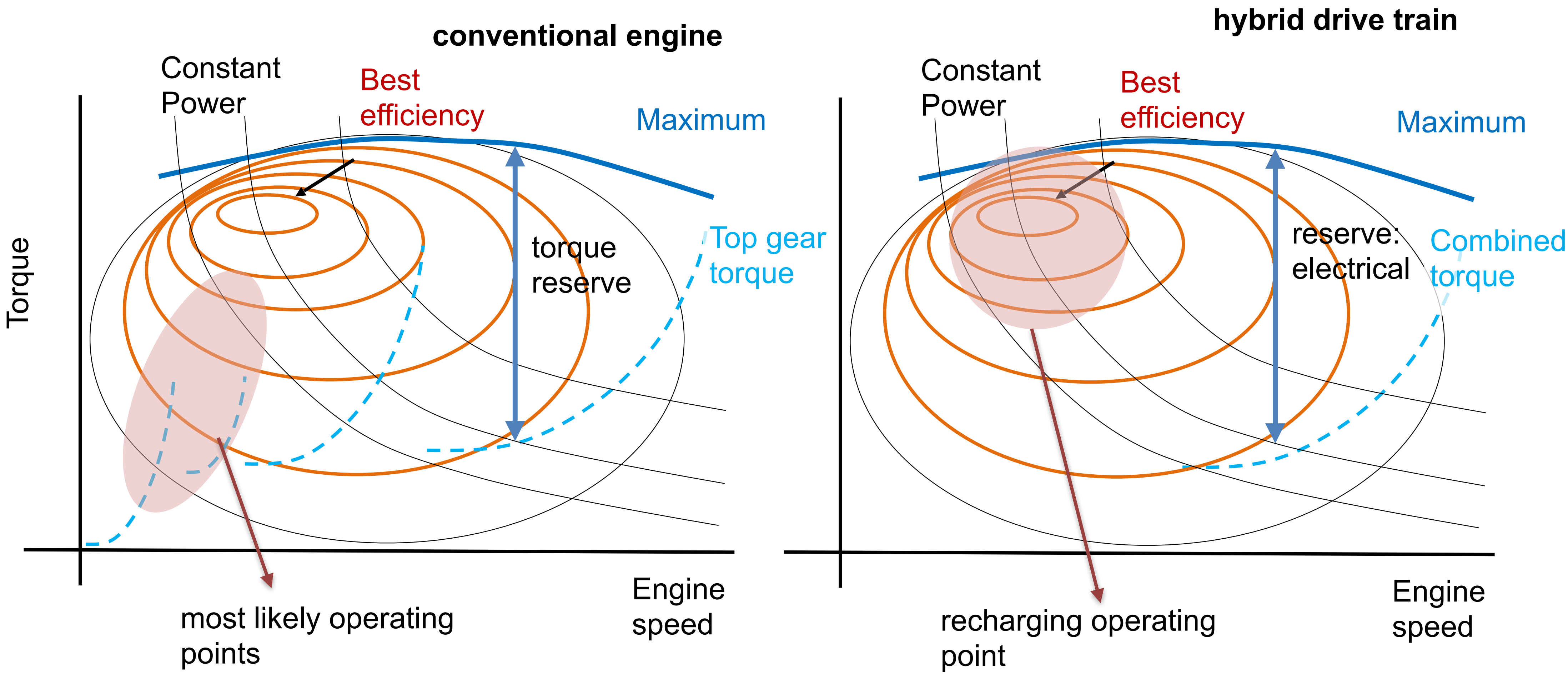
Pros

- Fuel economy: up to 30% higher (depending on cycle)
  - primary engine operates more efficiently
  - regenerative braking
- engine downsizing
- lower emissions (only during IC engine operation)

Cons

- Additional weight: motors, battery, torque and DC converters
- Additional complexity and control
- Efficiency losses in additional systems
- Higher cost

Hybrid engines allow change in the best operation point



HEV topologies

Series

engine
generator
power converter
motor
transmission
battery

Pros

- ICE runs around optimal combination of speed and torque (high efficiency)

Cons

- Two energy conversion stages (ICE/generator and generator/motor), with losses.

Best for compact systems, stop/start, urban driving

Toyota Prius coupler

Parallel

Pros

- More efficient at high speeds and loads (direct connection)
- Fewer energy conversion stages relatively to series
- Smaller motor required

engine
coupler
transmission
power converter
motor
battery

Cons

- More challenging for optimising at low loads, or with start/stop
- More complex control

Motor used for low speeds (best traction)
Engine used for high speeds
Best for overall heavier load/speed

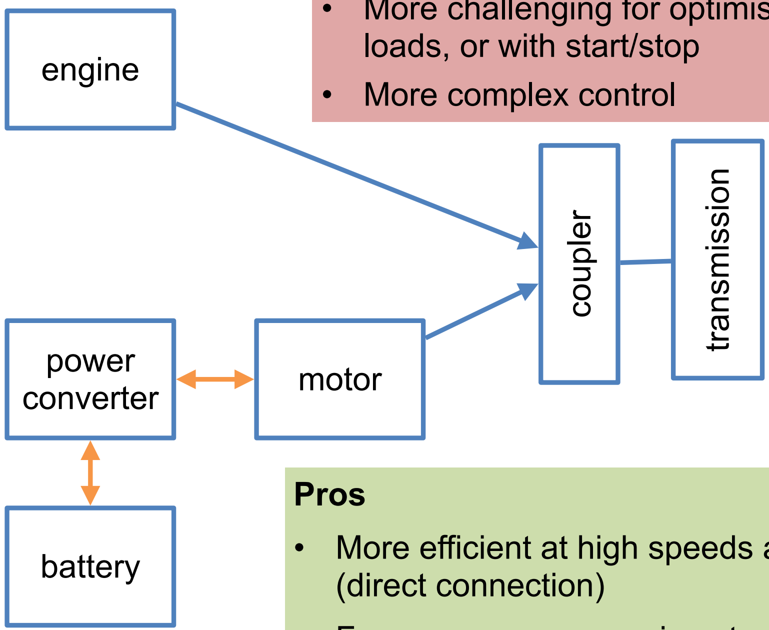
mechanical link — electrical link

HEV topologies

Parallel

Cons

- More challenging for optimising at low loads, or with start/stop
- More complex control



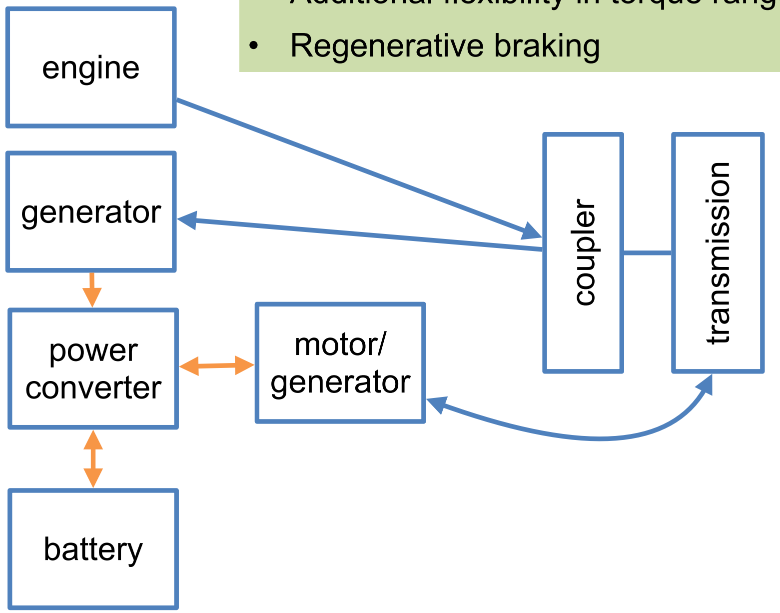
Pros

- More efficient at high speeds and loads (direct connection)
- Fewer energy conversion stages relatively to series
- Smaller motor required

Series-Parallel

Pros

- Additional flexibility in torque range
- Regenerative braking



Motor used for low speeds (avoid poor efficiency)
Engine + motor used for high speeds
Best for overall heavier load/speed
Regenerative braking powers the motor for battery storage
Minimum series-parallel can be used by making the alternator a mini-power booster.

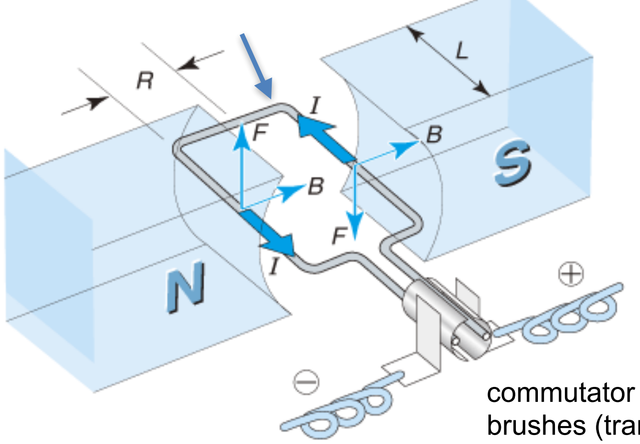
mechanical link — electrical link

Electric motors and generators

DC brush

rotor

armature (coil or permanent magnet)



commutator (change direction)
brushes (transfer current)

Principle of operation:

$$T = FR = Bil\cos\alpha$$

torque

force radius current length

magnetic field

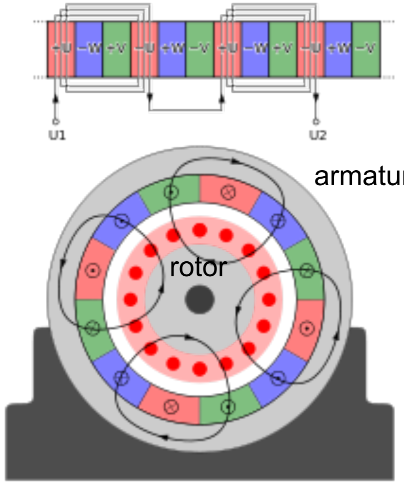
Simple
Mature technology

Brushes: low efficiency
Less reliable for high speed

AC induction

3 phase oscillating

armature



$$T = |F_s e^{i(\omega t - \pi/2)}|$$

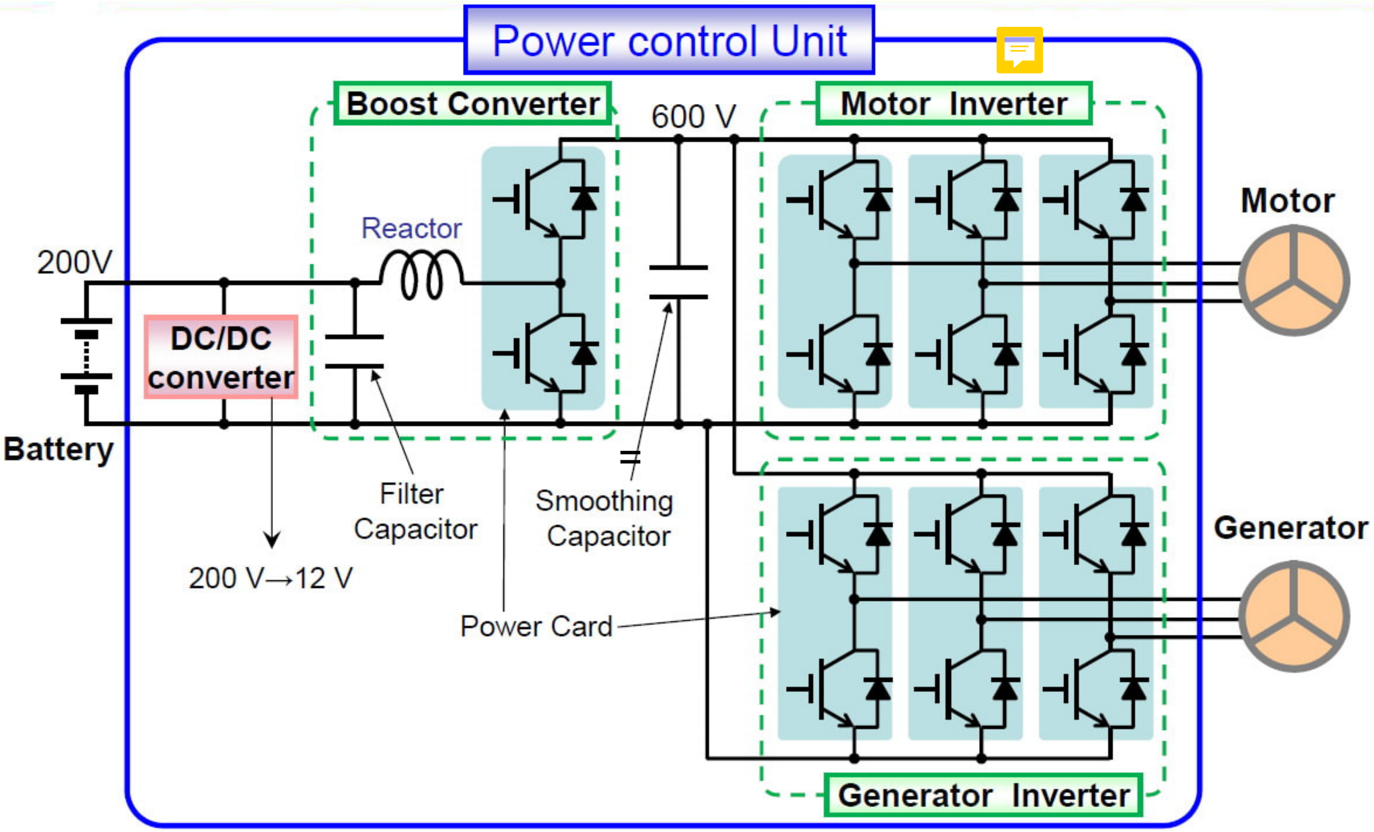
Mature technology
Efficient
Lightweight for higher power
Low cost

More complex

https://en.wikipedia.org/wiki/Electric_motor

https://www.nidec.com/en/technology/motor/basic/00012/~/media/nidec-com/en-global/technology/motor/basic/00012/img_basic_00012_02

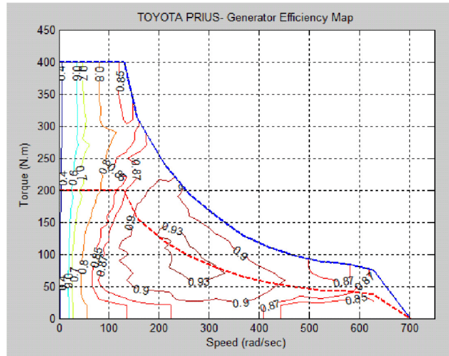
Power converters

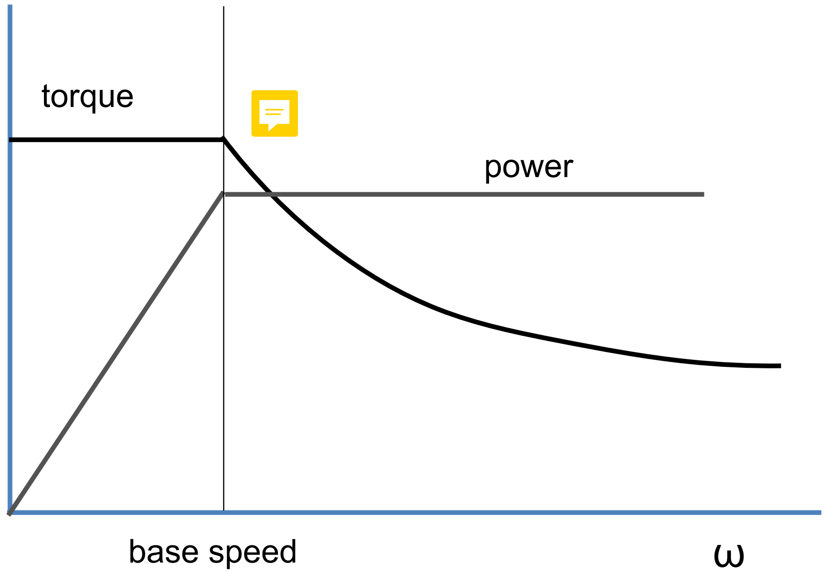


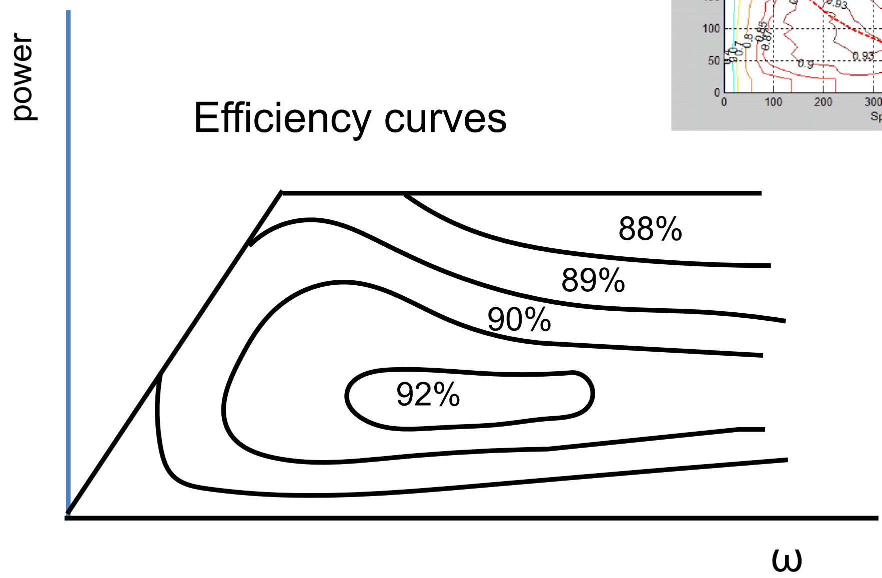
Motors and generators require oscillating current.
Batteries store DC current. The power circuitry organises the switching for maximum response and minimum losses.

https://www.invetr.com/control-and-electronics/power-control-unit-pcu-structure

Typical characteristics of motors



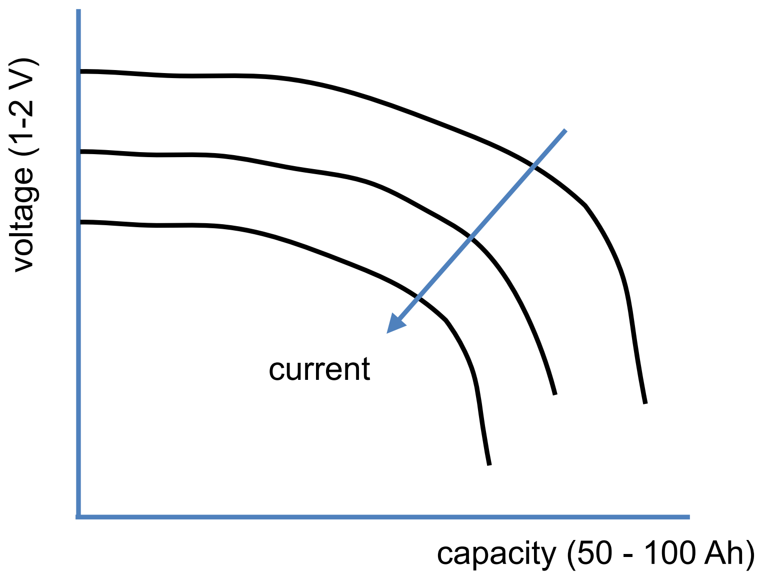


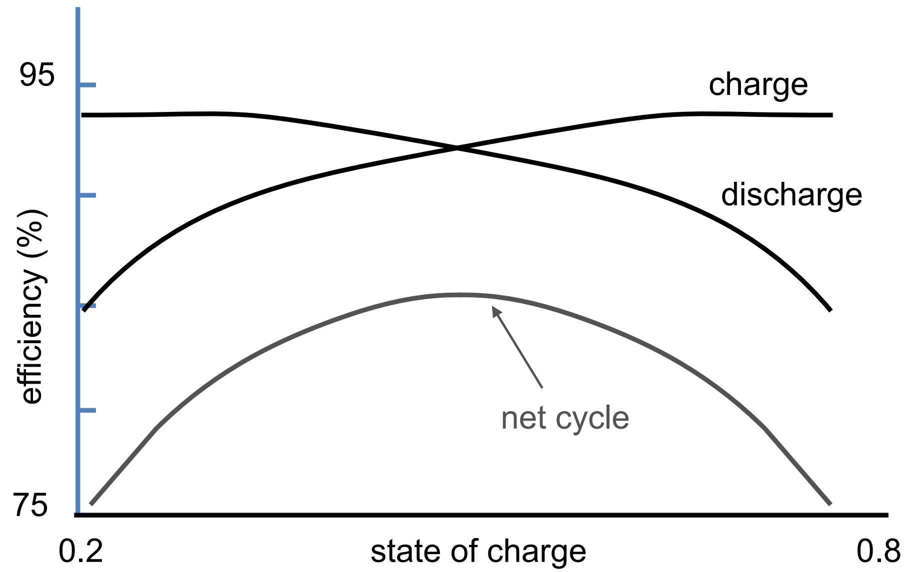


Motor characteristics depend both on the *type* of motor (AC/DC, brush/brushless, coil/PM), and the *power control system* (what kind of inverter/switching is used for AC or DC motors). But the overall characteristics are relatively similar, with a peak torque and roll-off with increasing speed.

Motors are significantly more efficient than ICEs. However, when the relatively high efficiencies of power switching, battery storage and motors, the roundtrip efficiencies can become relatively low, e.g. $(0.9)^2 = 0.8$. A balance between hybridisation and efficiency needs to be reached for optimisation.

Typical characteristics of batteries





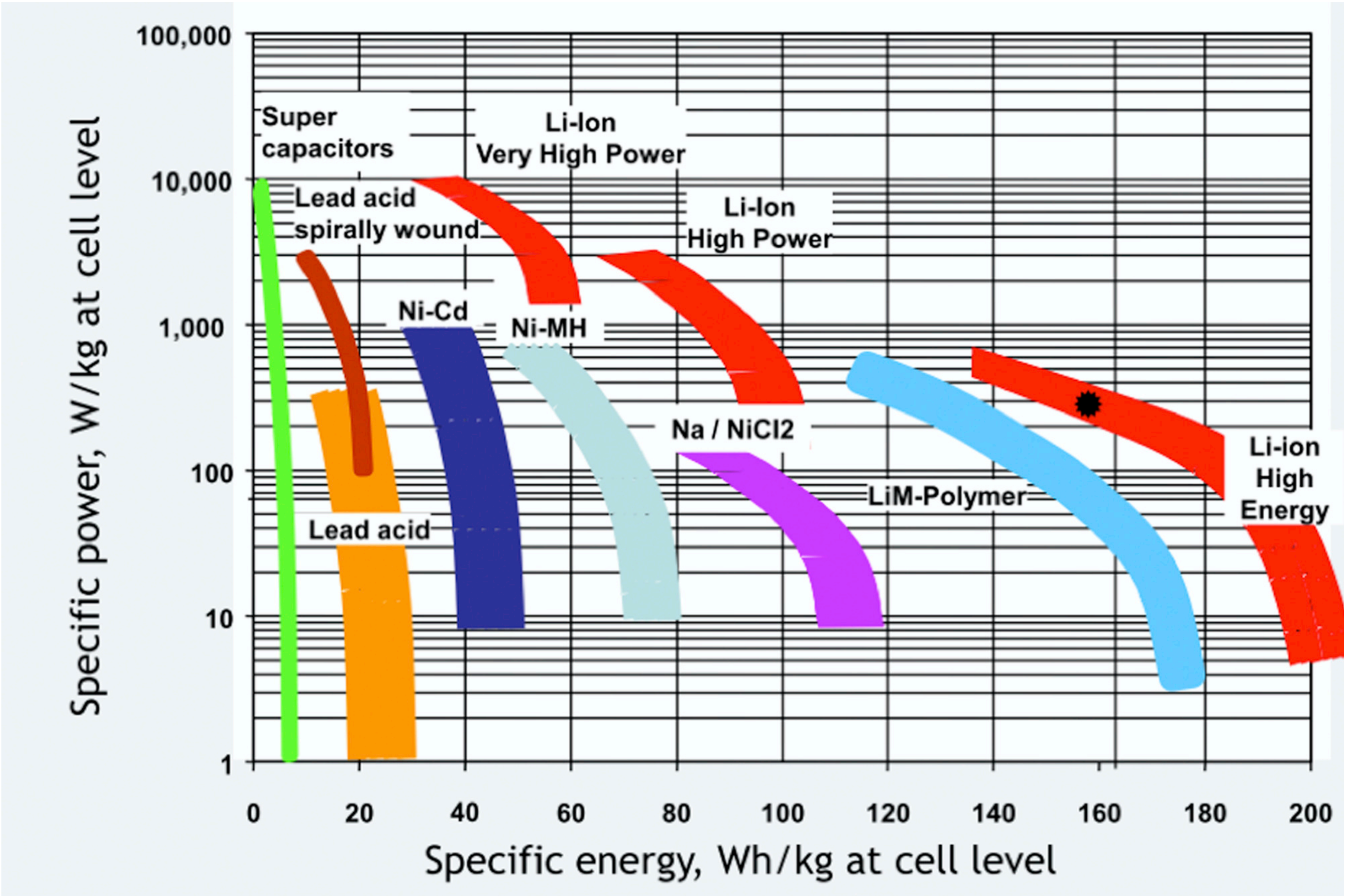
Battery specifications:
- specific energy capacity, cycle life, peak power
- current-voltage characteristics depend on type of battery, and state of charge
- state of charge (SOC) usually kept at 60-70% for maximum efficiency
- engines turn on/off to maintain SOC

Efficiency
- efficiency depends on state of charge, and rate of charging/discharging
- Peak net cycle efficiencies can be relatively low (80%)

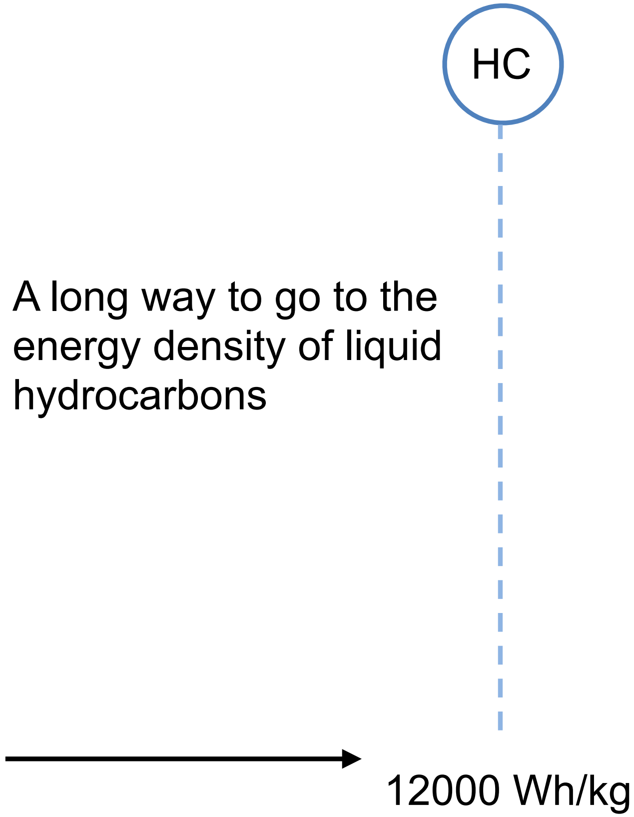
Typical battery characteristics

	Specific Energy (Wh/kg)	Peak Power (W/kg)	Energy efficiency (%)	Cycle life
Lead/acid	35-50	150-400	>80	500-1000
Ni-Cd	50-60	80-150	75	800
Ni-MH	70-95	200-300	70	750-1200
Li—ion	80-130	200-300	>95	1000

Battery specific power and energy



A long way to go to the energy density of liquid hydrocarbons



Summary

- HEVs offer higher efficiencies (typically 30-50% better):
  - more favourable operating point
  - regenerative braking
  - stop/start
  - no throttling
- Care must be taken with system design
  - multiple roundtrip efficiency losses (esp. series)
  - additional weight
  - complexity of management
  - stop/start can create problems for emissions system

Hybrid quiz

https://www.vle.cam.ac.uk/mod/quiz/view.php?id=11966362 http://to.eng.cam.ac.uk/teaching/surveys/4A13_Lent.html