Future Vehicle Propulsion Systems: Options and Implications

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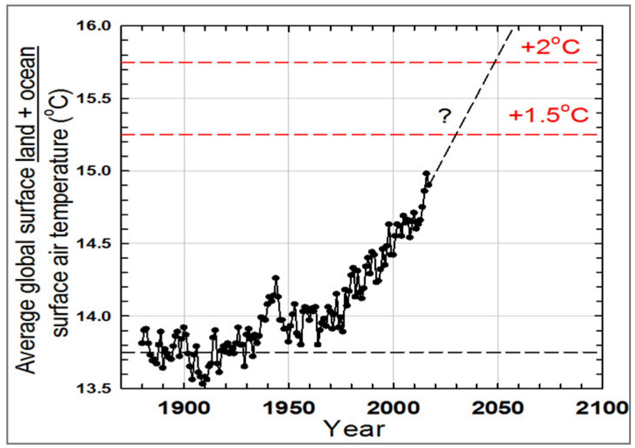
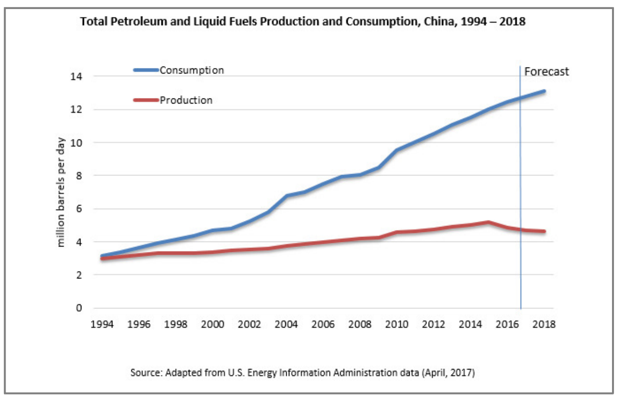
Drivers - Societal

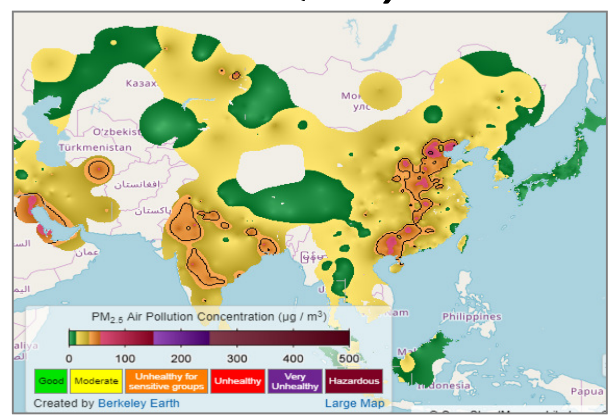
Climate Change



Energy Security

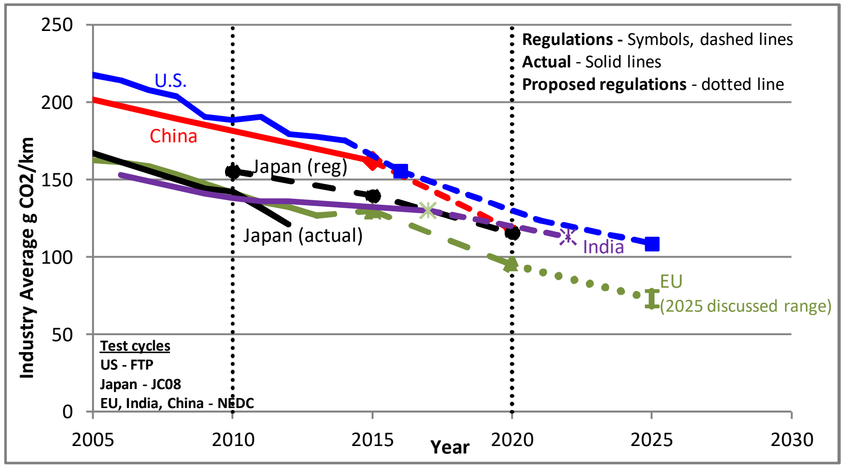


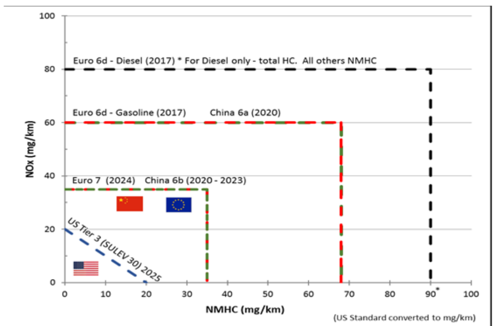
Air Quality

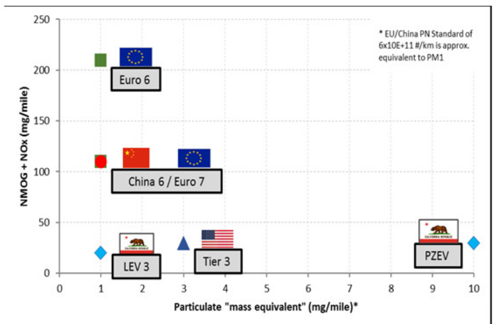


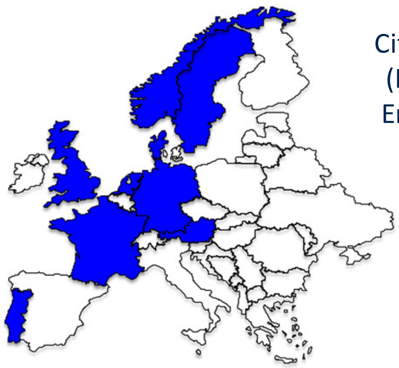
Climate change (global), energy security (regional), and air quality (local) are key factors which are driving the increased demand for environmentally sustainable transportation.

Drivers - Regulatory



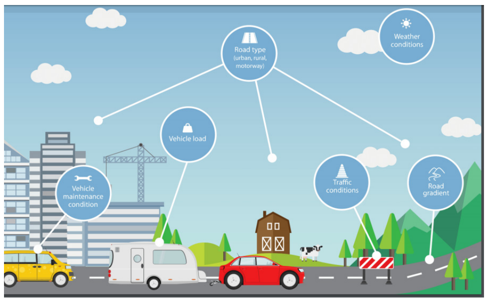






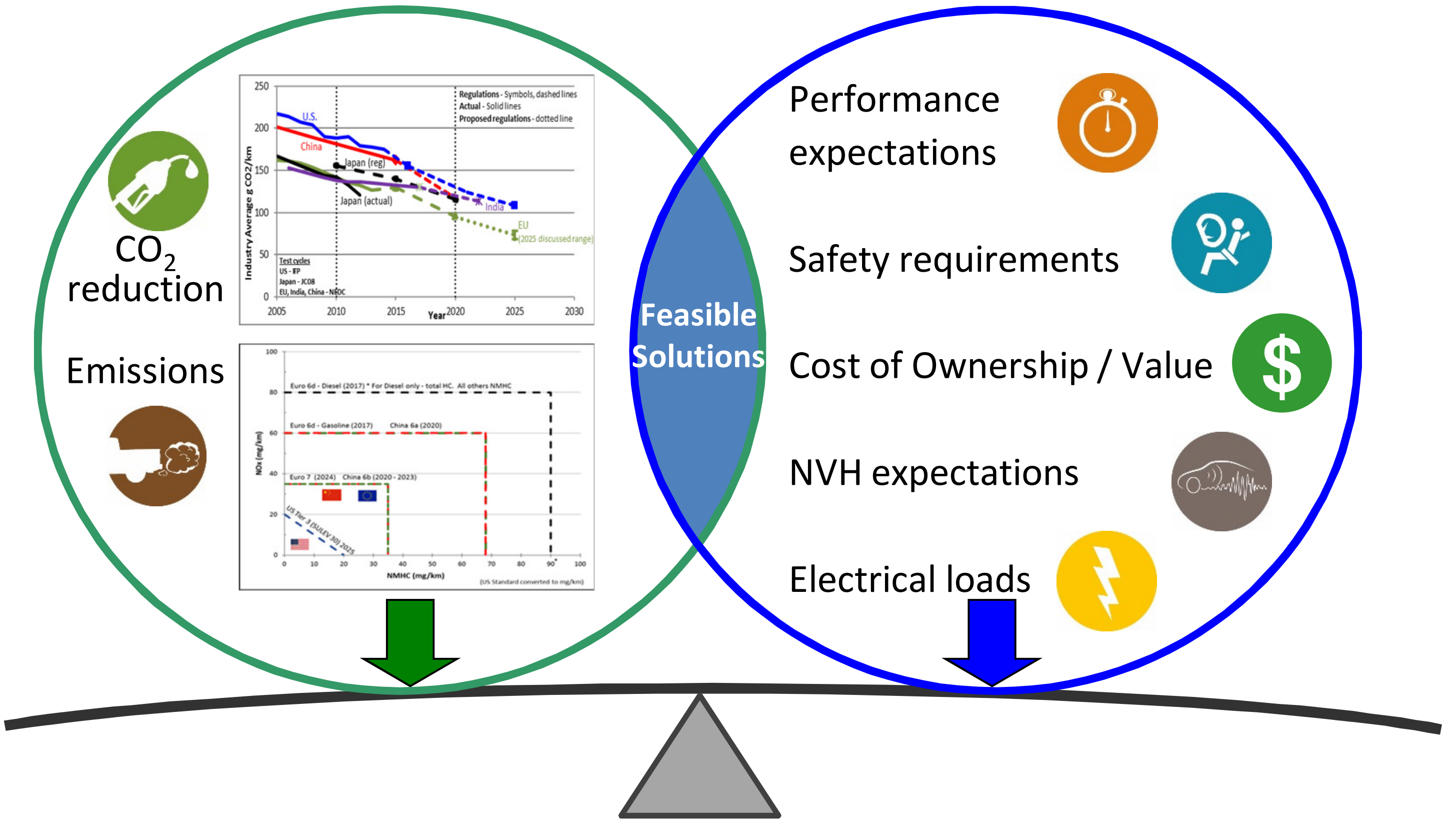
City Center Low Emission Zones (LEZs) or Internal Combustion Engine (ICE) bans are planned.

Increased emphasis on real-world driving emissions (RDE).



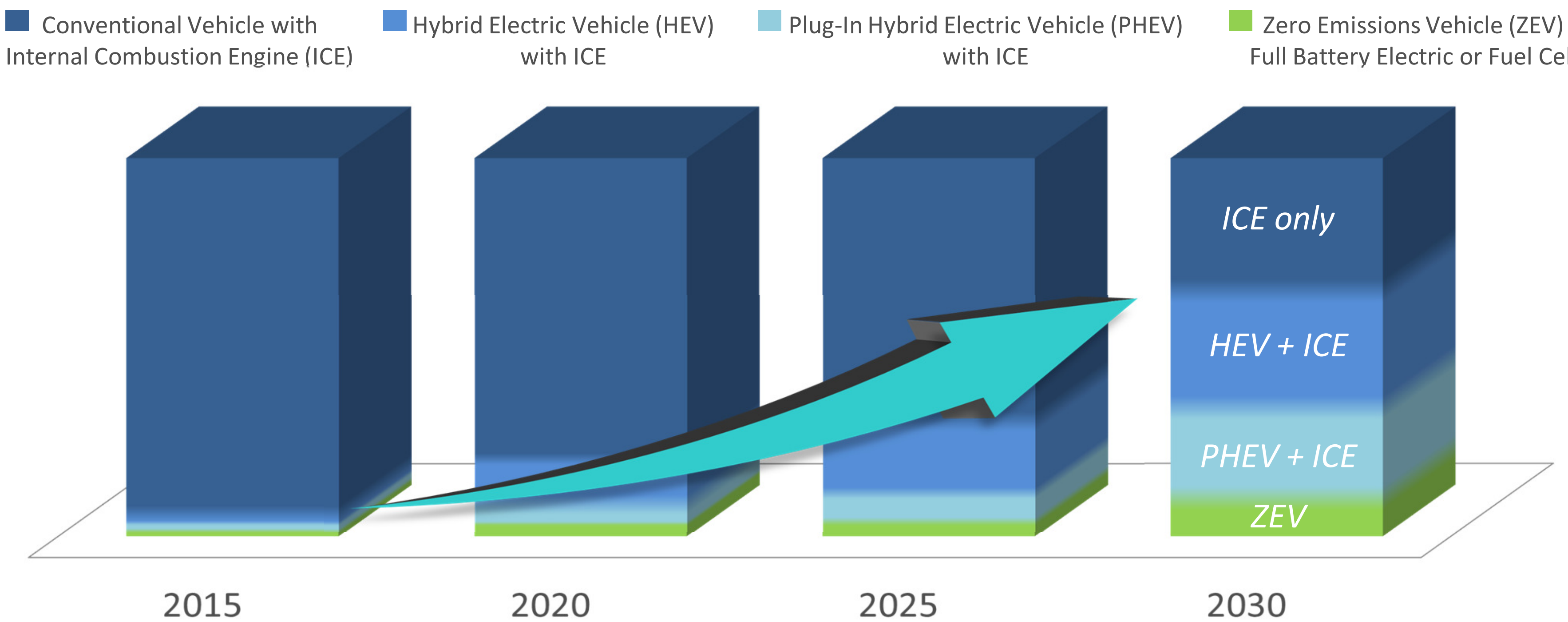
Increasingly stringent regulations, focus on RDE, City Center access bans, and LEZ / ZEV mandates are applying pressure to industry for zero-emissions propulsion alternatives globally.

Regulations & Balancing Customer Requirements



Balancing CO_2 and Criteria emissions reduction regulations and increasing customer expectations requires an integrated approach.

Global Industry Electrification Growth Projection



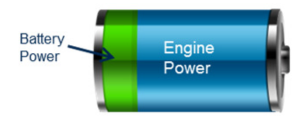
Source: Navigant, LMC, BNEF, Juniper, MIT, IHS, Accenture, KPMG, PwC, JATO, FSS, Exxon, GM, Hyundai, Honda, Nissan, Toyota, Ford

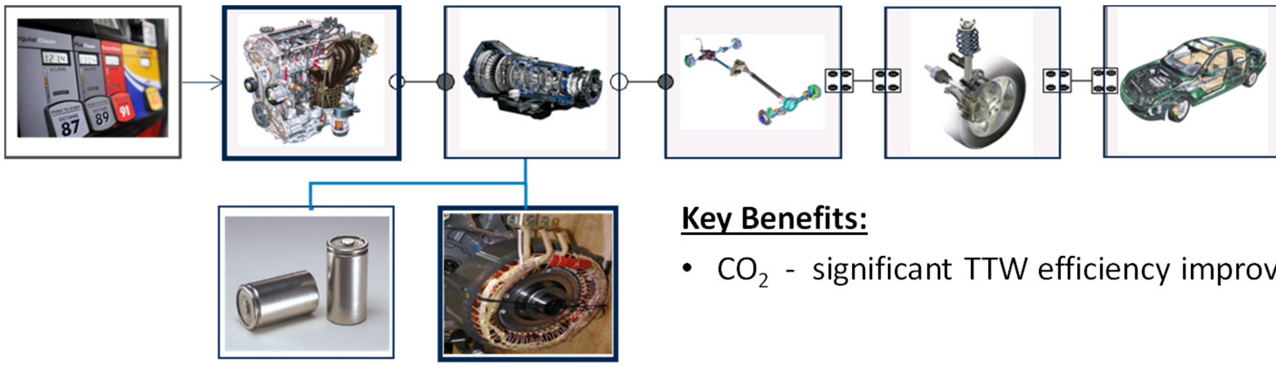
Electrification continues to expand, with significant growth expected beginning mid-next decade. A substantial portion of powertrains will still utilize internal combustion engines.

Hybrid Electric Vehicle (HEV)

Internal combustion engine (ICE) powertrain combined with electric drive and energy storage systems

- Scheduling engine operation
- Vehicle energy recuperation



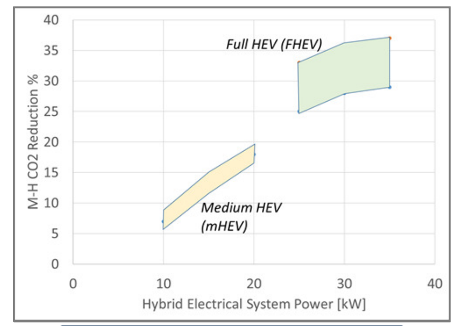


Key Benefits:

- CO_2 - significant TTW efficiency improvement

Key Challenges:

- Cost - substantial incremental cost for electric machines, power-electronics, and batteries
- Package - additional electrification components make it difficult to package



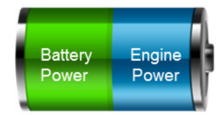
CO_2 benefit is a function of system electrical power

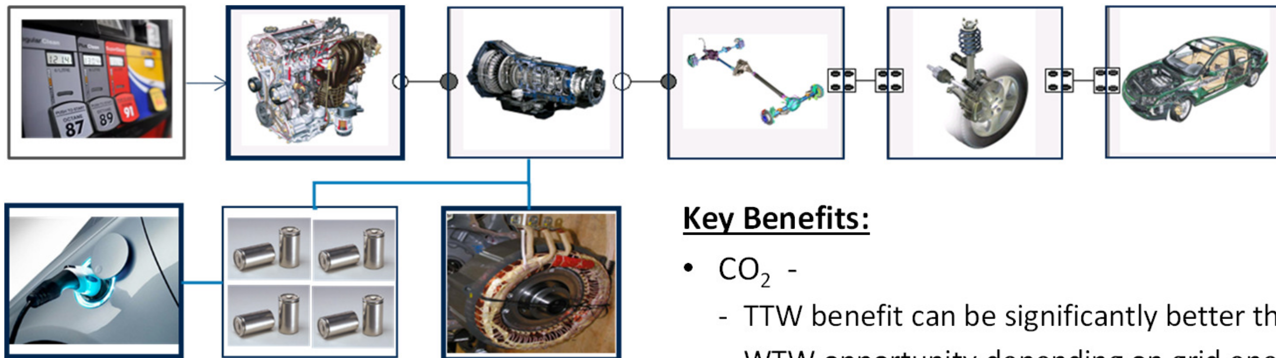
Full HEVs offer significant CO_2 / fuel economy improvement over conventional powertrains, but cost remains a significant challenge.

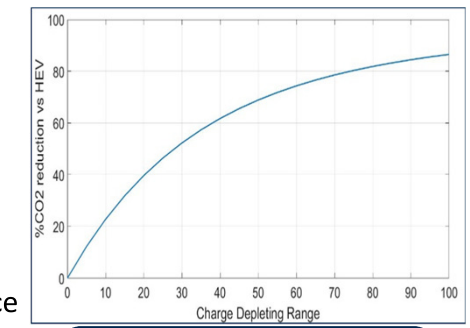
Plug-In Hybrid Electric Vehicle (PHEV)

Hybrid electric powertrain with increased battery energy capacity (vs. HEV) and external charging capability

- Sustained electric drive capability
- Displace fuel use with grid energy







Tank-to-Wheel CO_2 benefit is a function of battery energy capacity

Key Benefits:

- CO_2 -
  - TTW benefit can be significantly better than HEV
  - WTW opportunity depending on grid energy source

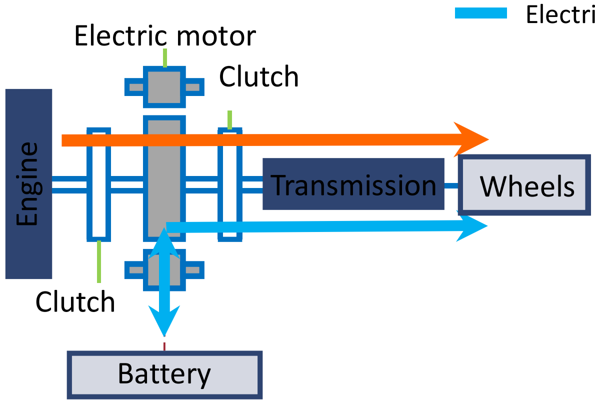
Key Challenges:

- Cost
- Technical complexity
- Package

Plug-in HEVs offer an even greater CO_2 opportunity than Full HEVs due to the electrified-only miles, but cost and package are even greater challenges.

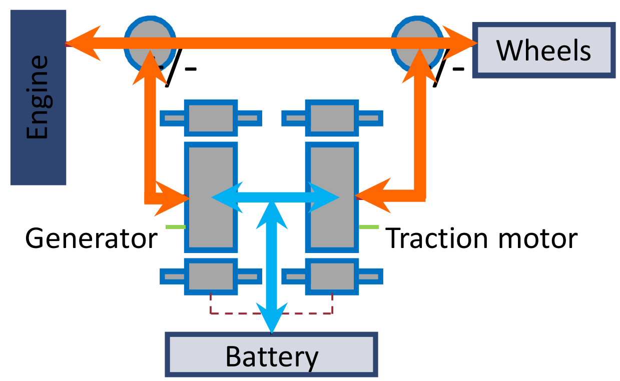
Hybrid Electric Powertrain - Architectures

Parallel Hybrid



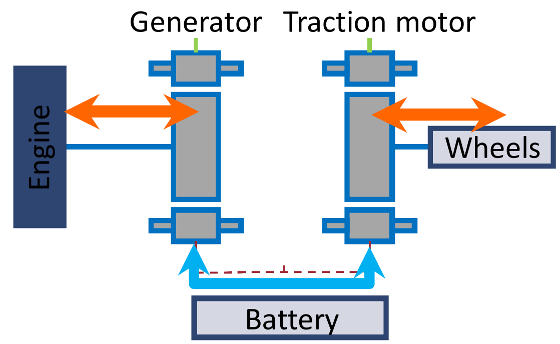
- *Leverages existing conventional transmission architectures*
- *Retains mechanical path of conventional powertrain*
- *Enhances base conventional powertrain performance*

Powersplit



- *Simplified dedicated hybrid transmission design*
- *Engine power is split between electric and mechanical paths*
- *CVT functionality*
- *Efficient e-drive and regen power flows*

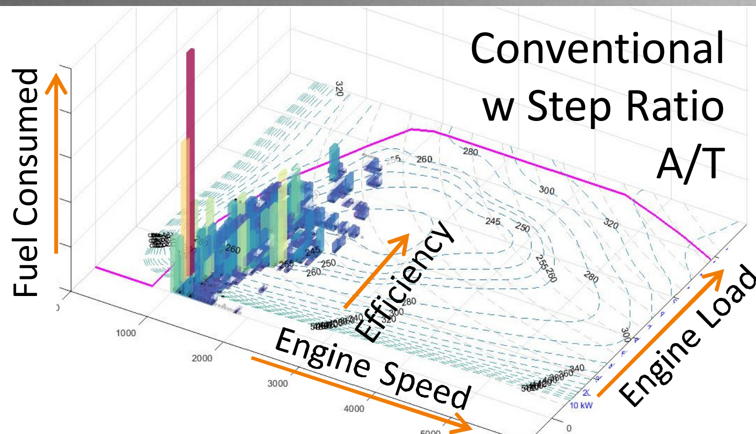
Series Hybrid



- *Engine mechanically de-coupled from wheels – IVT functionality*
- *High degree of modularity*
- *Most efficient e-drive and regen power flows*

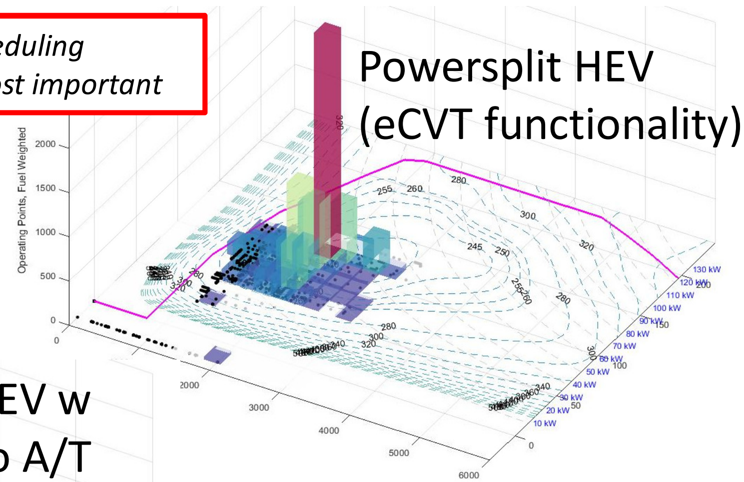
Hybrid electric powertrains can be classified according to these main architecture types which drive different engine requirements.

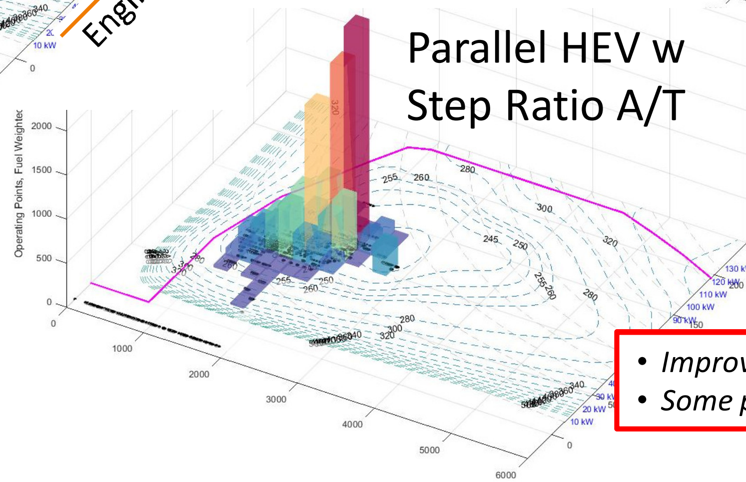
Engine Efficiency Optimization



- *High frequency of Low Load operation*
- *Wide dynamic range required*

- *Optimal scheduling*
- *Peak BTE most important*

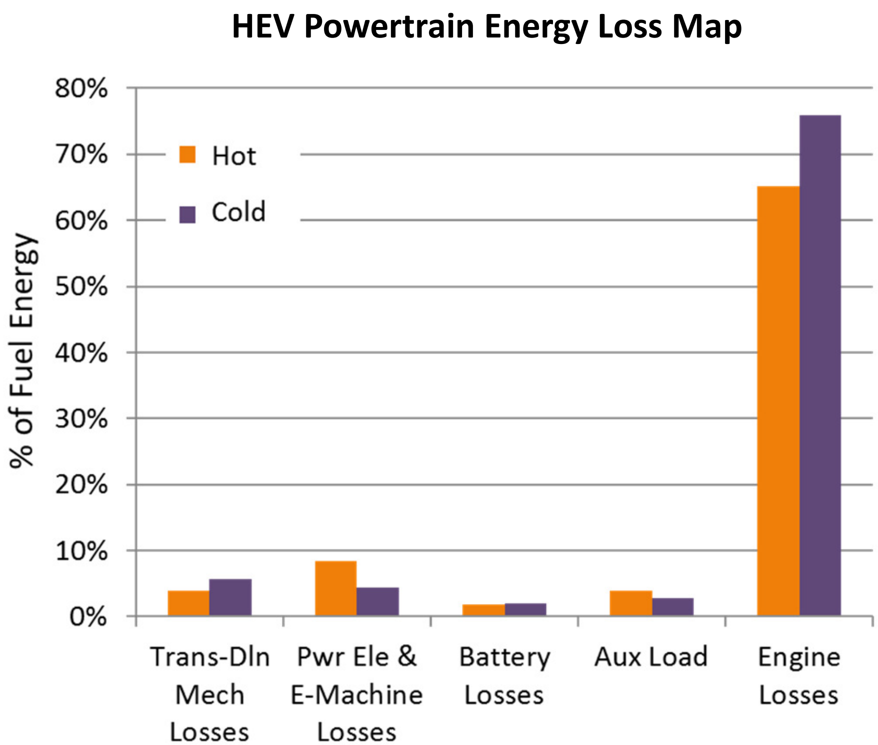


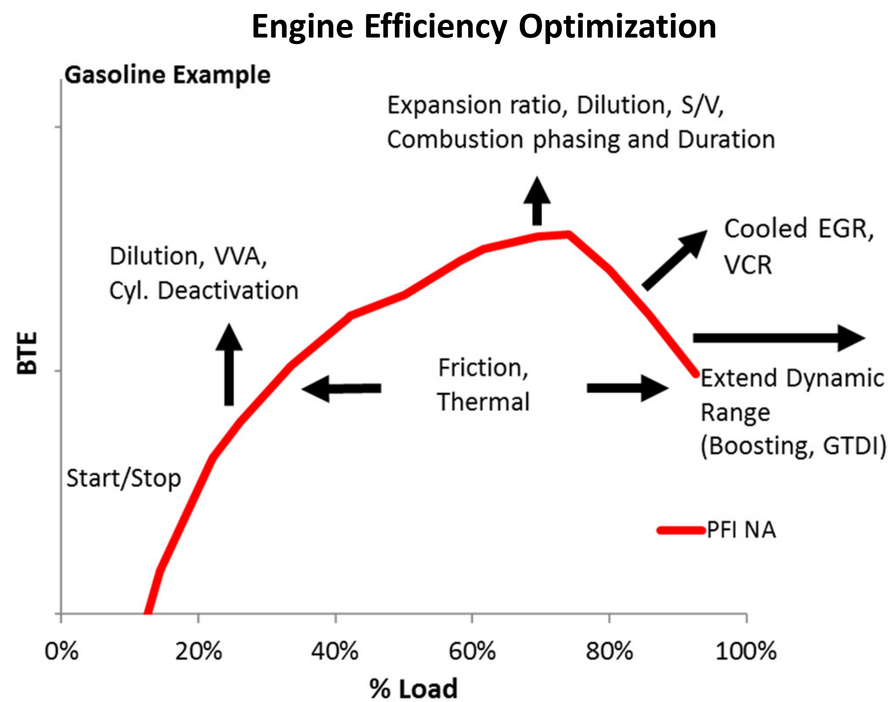


- *Improved scheduling*
- *Some part load operation*

Different transmission architectures produce differences in engine speed & load scheduling. Consequently, the engine needs to be optimized in the context of the powertrain system.

Powertrain Efficiency – HEV Subsystem Losses





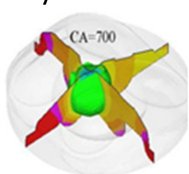
Engine losses dominate and are the largest lever for increasing HEV efficiency. Industry trends are toward continued development in I.C.E. technology for improved thermal efficiency.

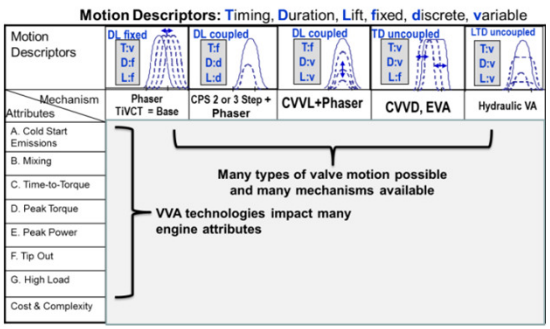
Advanced I.C. Engine Technologies

Go Further

Combustion

- Advanced direct injection systems
- Improved fuel economy
- Reduced NOx emissions

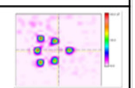
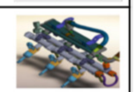


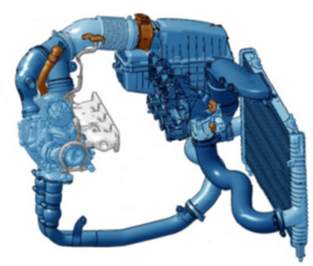


Variable Valvetrain

- Variable timing, lift and duration
- Improved breathing efficiency
- Improved transient response

Fuel Injection

Advanced Fuel Injector Design and Manufacturing	
Multi-Hole Solenoid Direct Injector at Increased Fuel Pressure	
PFI + Solenoid DI	

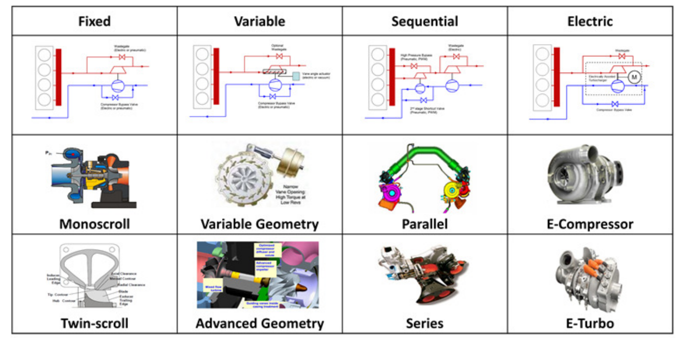


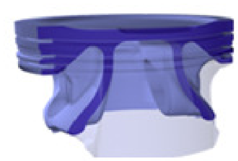
Cooled EGR

- Improved combustion efficiency
- Decreased pumping work
- Knock mitigation

Boosting Systems

- Improved power density
- Improved transient response
- Boost requirements to drive wide range Cooled EGR





Power Cylinder Systems

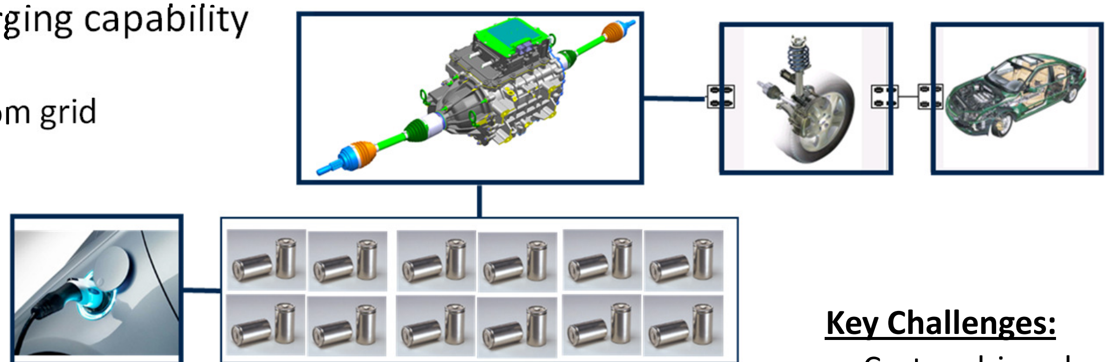
- Reduced mass and inertia
- Advanced coatings
- Low tension ring packs

Advanced engine technologies will continue to be developed and implemented to improve thermal efficiency, reduce emissions and minimize energy losses.

Battery Electric Vehicle (BEV)

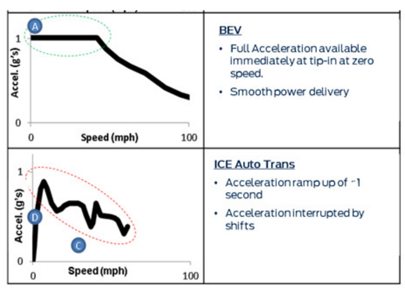
Fully electric propulsion system – electric drive system (e-machine & gear box) with high energy capacity battery and external charging capability

- All electric drive
- Vehicle energy supplied from grid



Key Benefits:

- CO_2 -
  - TTW efficiency >90%
  - WTW opportunity depending on grid
- Zero Criteria Emissions
- P/T Simplicity -
  - fewer parts; easier optimization
- Electric Driving Experience -
  - Instant torque + Smooth acceleration



Smooth power delivery
creates a unique driving experience

Key Challenges:

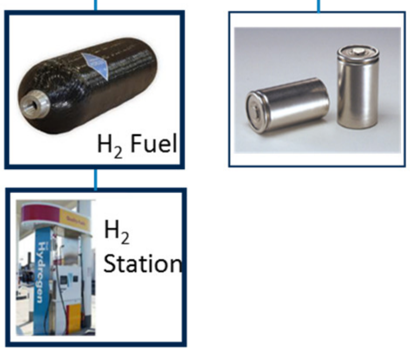
- Cost - driven by high capacity battery
- Weight
- CO_2 Impact - dependent on grid energy
- Recharge Time
  - charge rate vs. cell life trade-off
- Range

Battery Electric Vehicles can offer many advantages over F- / P-HEVs, but meeting customer requirements with respect to cost, recharge time, and range are key to broad acceptance.

Fuel Cell Electric Vehicle (FCEV)

Fuel cell powertrain generates electrical power using hydrogen and oxygen within a fuel cell stack – system includes an electric drive system, on-board H2 fuel storage and high voltage battery.

- Electric drive
- Vehicle energy recuperation



Key Benefits:

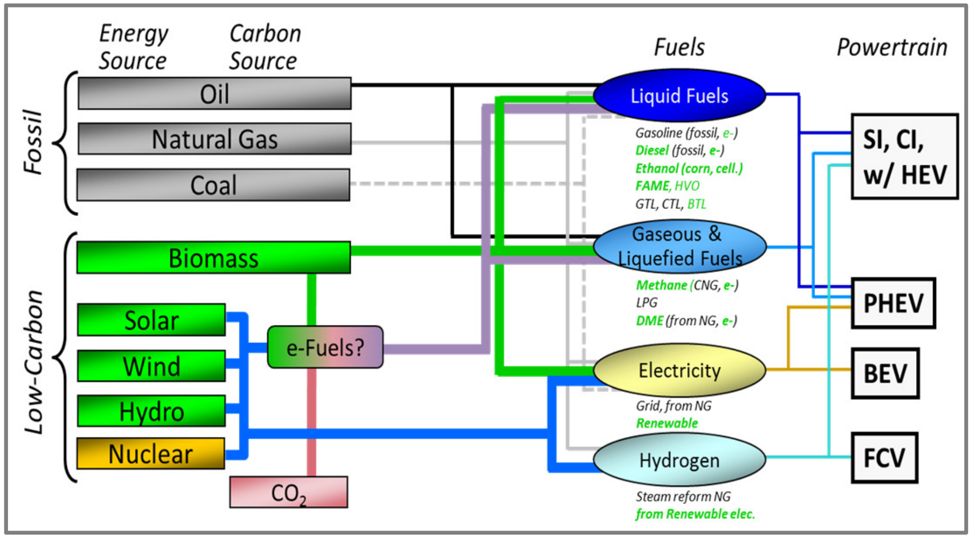
- CO_2 -
  - TTW efficiency >50%
  - WTW opportunity depending on H2 source
- Zero Criteria Emissions
- Electric Driving Experience -
  - Instant torque + Smooth acceleration
- Faster refuel (approaching liquid fuels)
- Longer range capability than BEV
- Greater potential for high energy demand vehicles

Key Challenges:

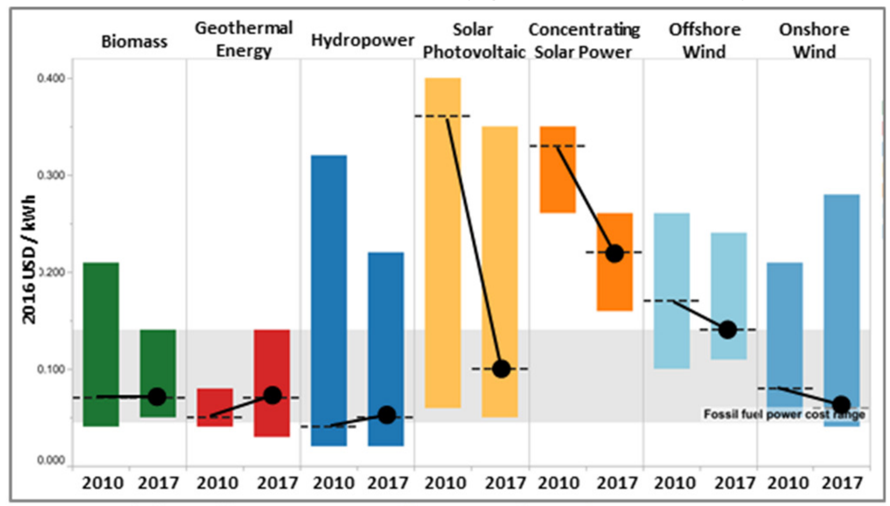
- Cost
- Package (onboard H2 Storage)
- CO_2 Impact
  - dependent on CO_2 intensity of H2 energy generation
- H2 Infrastructure

Fuel Cell EVs, with more range and faster refueling than BEVs, may be a viable ZEV option in certain applications, but high cost and lack of infrastructure limit implementation.

Sustainable Energy Options



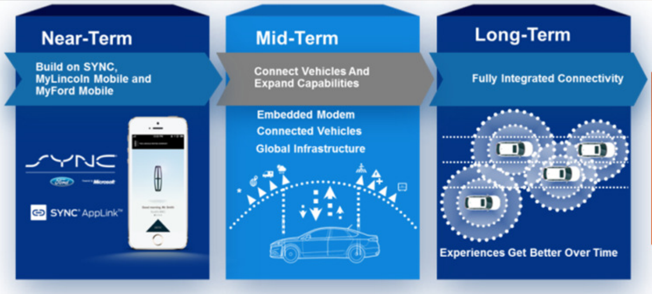
Costs of renewables for electricity generation are competitive



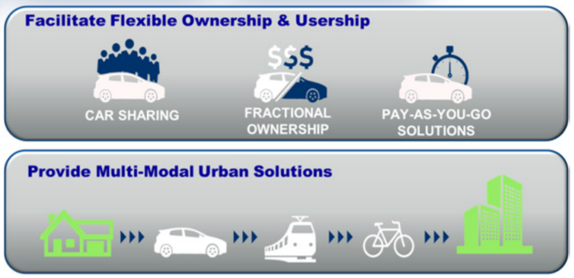
Source: International Renewable Energy Agency – Renewable Power Generation Costs in 2017

Low-carbon fuel and renewable electricity options can be developed to greatly reduce WTT CO_2 emissions, but they must be cost effective and integrated into the energy infrastructure.

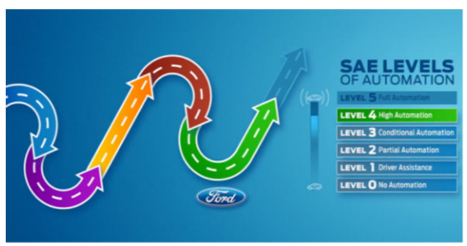
Mobility – Impact on Propulsion System

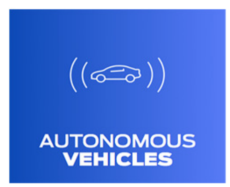


- Up front knowledge of vehicle route
- Look ahead interaction with other vehicles & infrastructure



- Increased utilization improves "customer value"
- Centralized deployment - efficient management of energy infrastructure
- Revised durability requirements





- Complete knowledge & control of driver behavior
- Auxiliary load management (AV technologies)

Connectivity, Mobility, and Autonomy offer many new degrees of freedom for the propulsion system – a broader transportation systems view is needed to fully realize the benefits.