Internal Combustion Engines, Recent Developments and Trends

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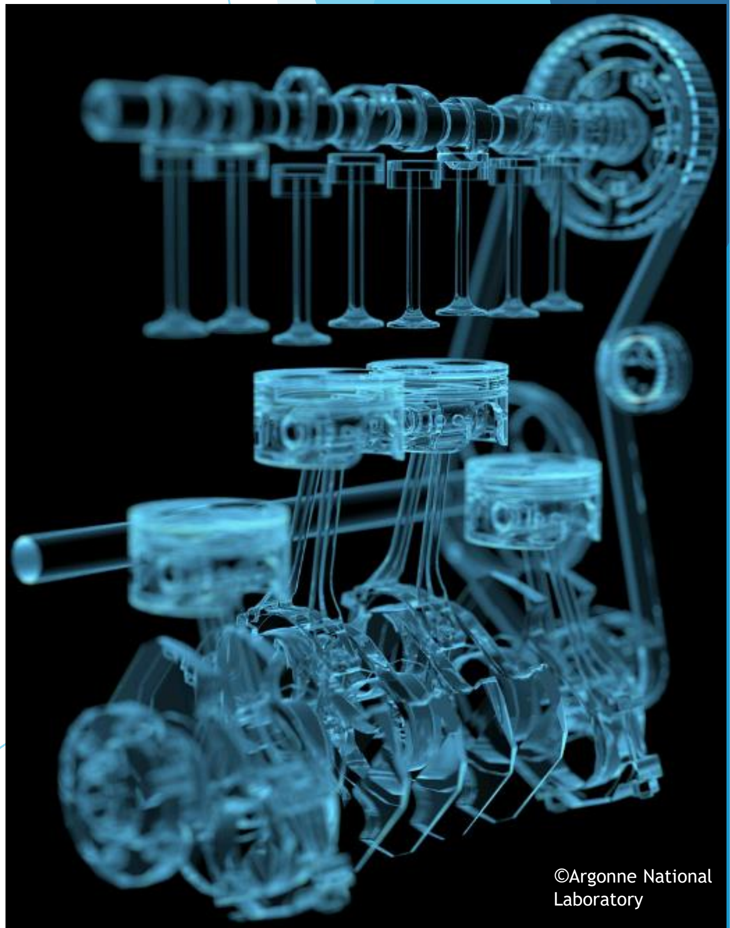
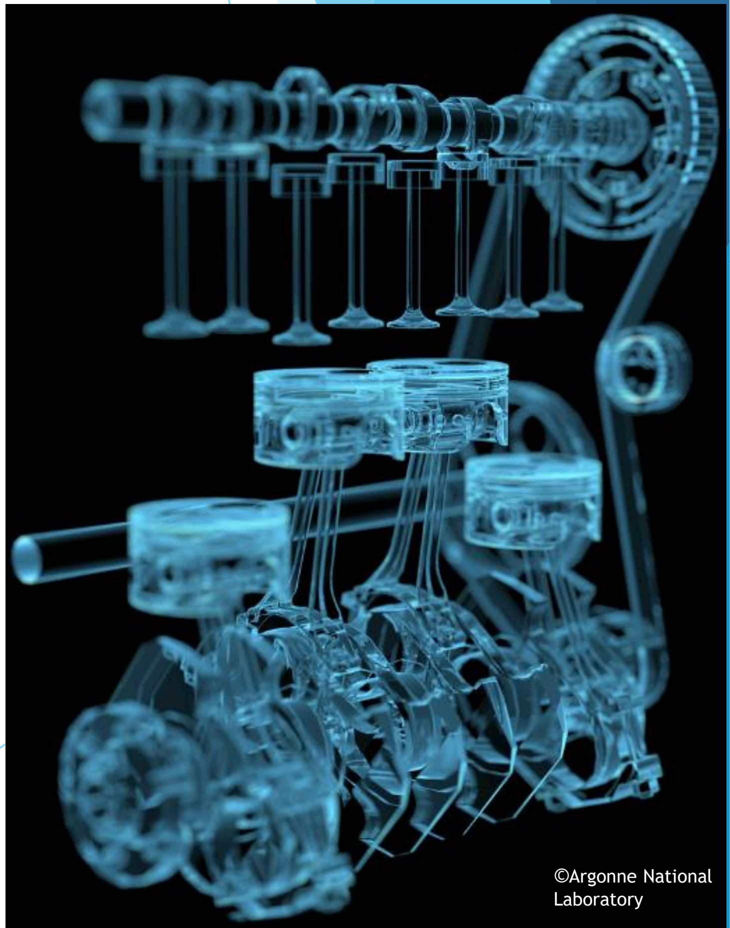
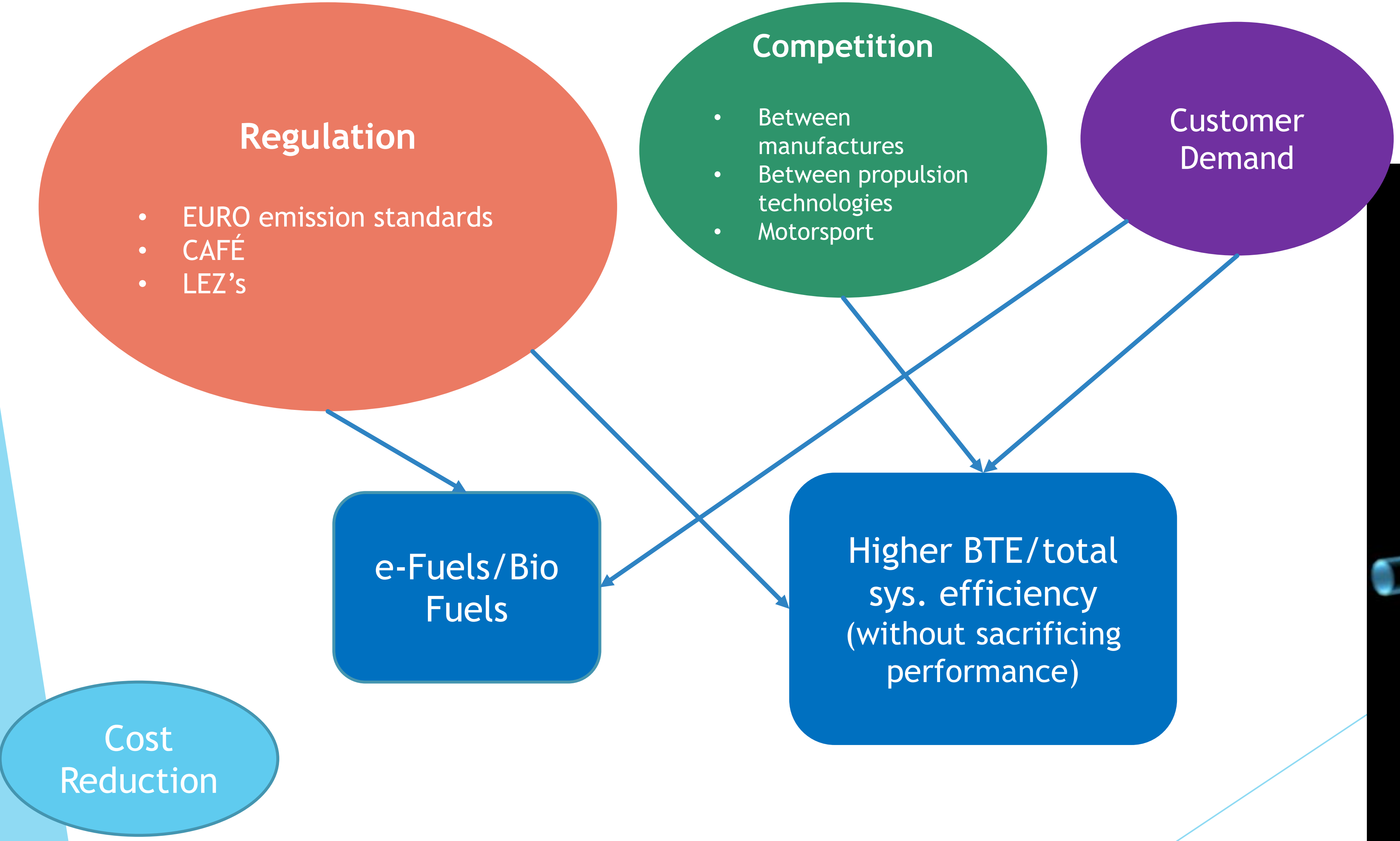


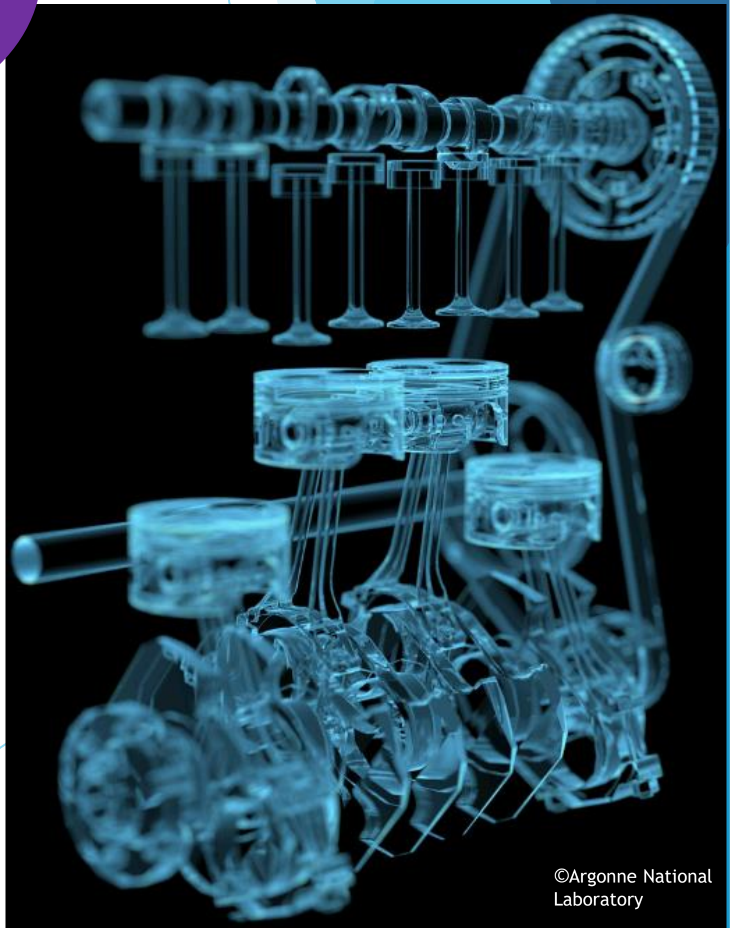
Necessity of Continued ICE Development

- Drive to reduce GHG emissions of the power generation, transportation, and mobility sectors **does not** make the ICE engine obsolete
  - No “One-fits-all” technology to replace ICE in all applications
  - Other technologies face many challenges in the short-to-medium term
- It is likely that the future will be “eclectic” with a mix of solutions (battery electric, hybrid electric, fuel cell and ICE) depending on:
  - consumer acceptance
  - country
  - specific application
- Great interest in improving the thermal efficiency of IC engines without significant increases in purchase and running costs in the short-to-medium term.
- GHG emission reduction can be achieved in current fleet (short term)

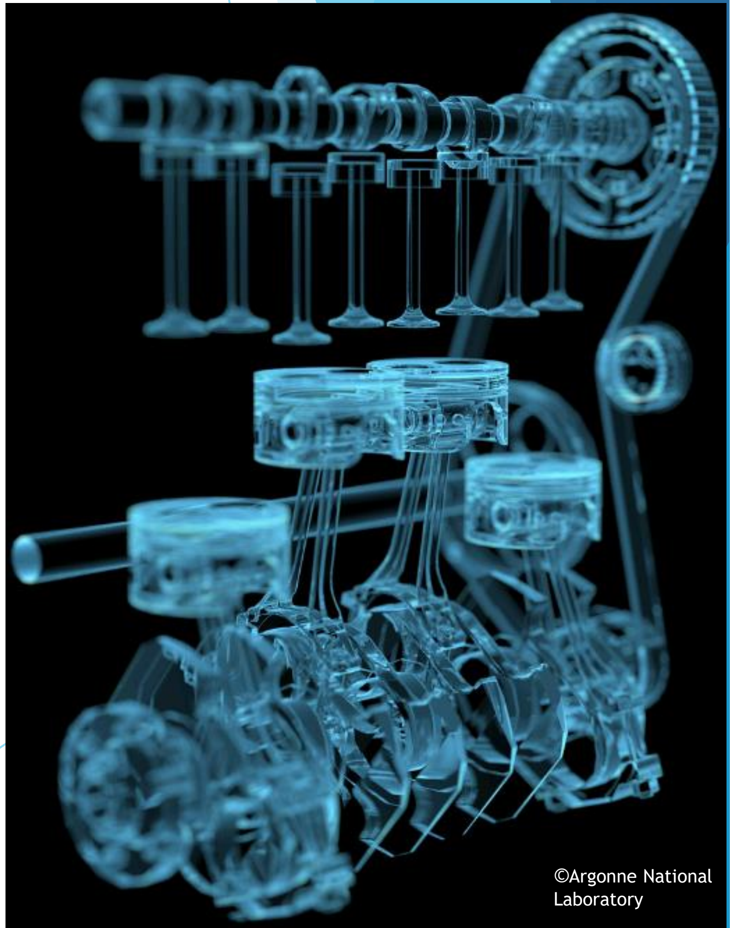


What Drives advancements in ICE?





Improvements in Engine BTE/ Total System Efficiency

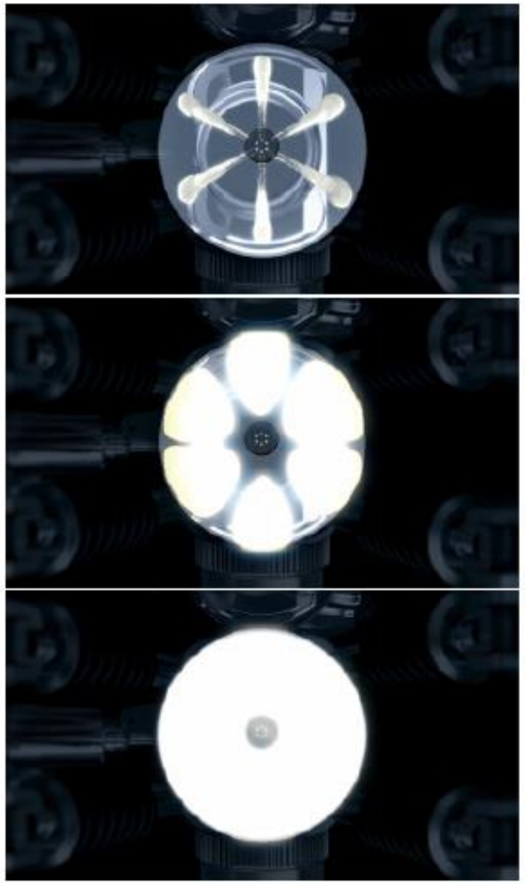


MAHLE JET IGNITION (MJI)

- Based on the concept of a pre-chamber (patented in 1918 by Harry Ricardo)
- Working principle:
  - A small volume pre-chamber is filled with a relatively rich mixture
  - At the same time, the main chamber is filled with a lean mixture
  - Both chambers are connected by small holes
  - The mixture inside the pre-chamber is ignited
  - A turbulent jet of burning mixture moves through the holes and ignites the lean mixture in the main chamber
- Advantages:
  - Enables lean mixture operation
  - Increased combustion speed and quality in the main chamber (multiple combustion sites: enables knock mitigation at high compression ratios)
  - Reduced cycle-by-cycle variation
- Disadvantages:
  - Heat loss from the pre-chamber, combustion stability issues within PC
  - Increased complexity
  - Lean operation reduces effectivity of catalytic converter

Passive MJI installation with DI fuel injector

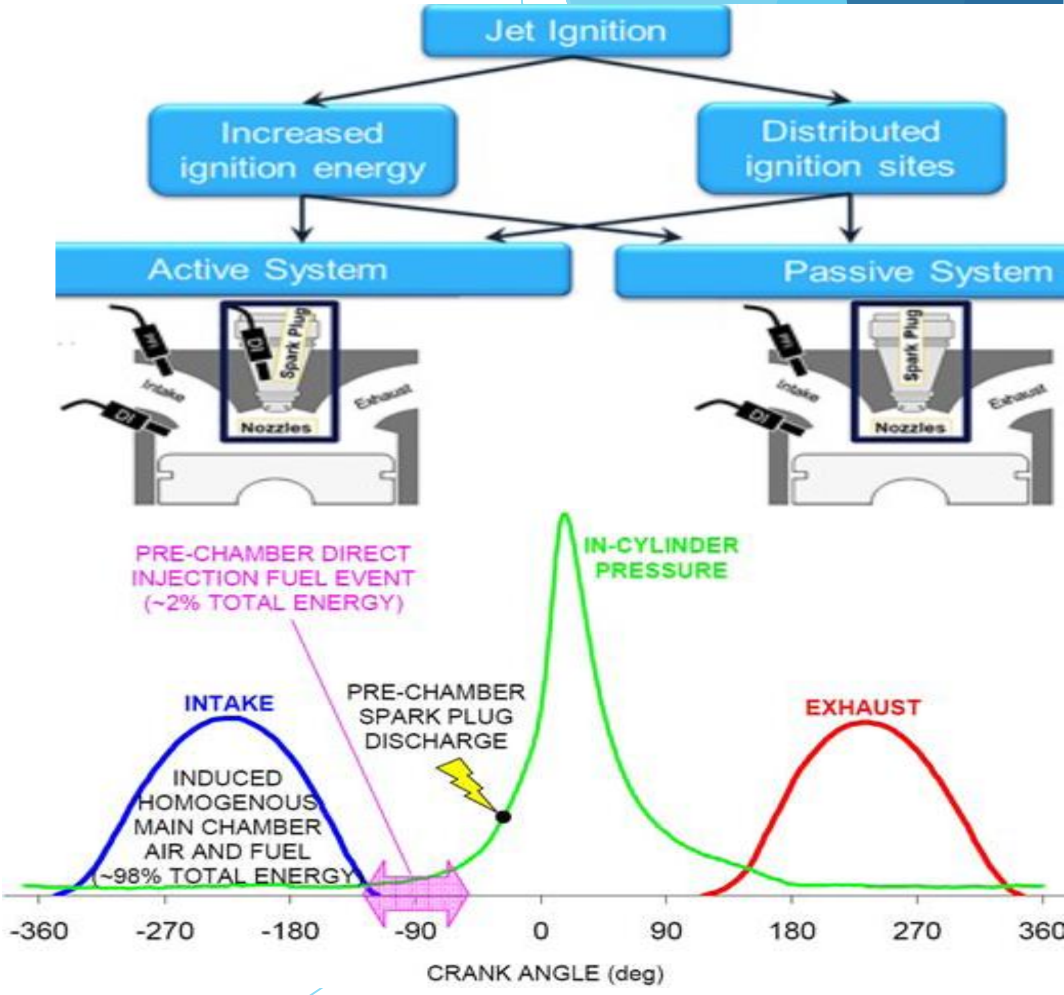
>> Injector & spark plug configuration in active system



Source: MAHLE Powertrain (Ref. 1)

MAHLE JET IGNITION (MJI), contd.

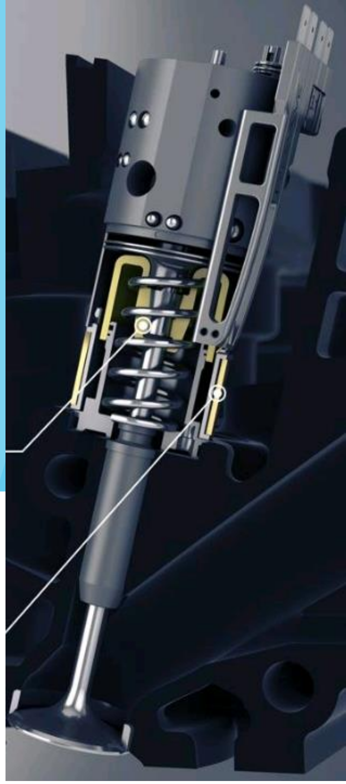
- Two systems developed as a bolt-on option using COTS parts
  - Active
    - Injection and ignition inside pre-chamber
    - Claimed BTE improvement of up to 25%
  - Passive
    - Ignition only inside pre-chamber
    - Claimed BTE improvement of up to 10%
  - Pre chamber challenges overcome by:
    - A very low pre-chamber volume (2% of clearance volume)
    - Advanced control strategies to allow for fast catalyst heat-up and lambda stability
  - First limited production implementation in the Maserati Nettuno engine (passive)
    - 630 HP @ 7500 RPM
    - 43% maximum BTE



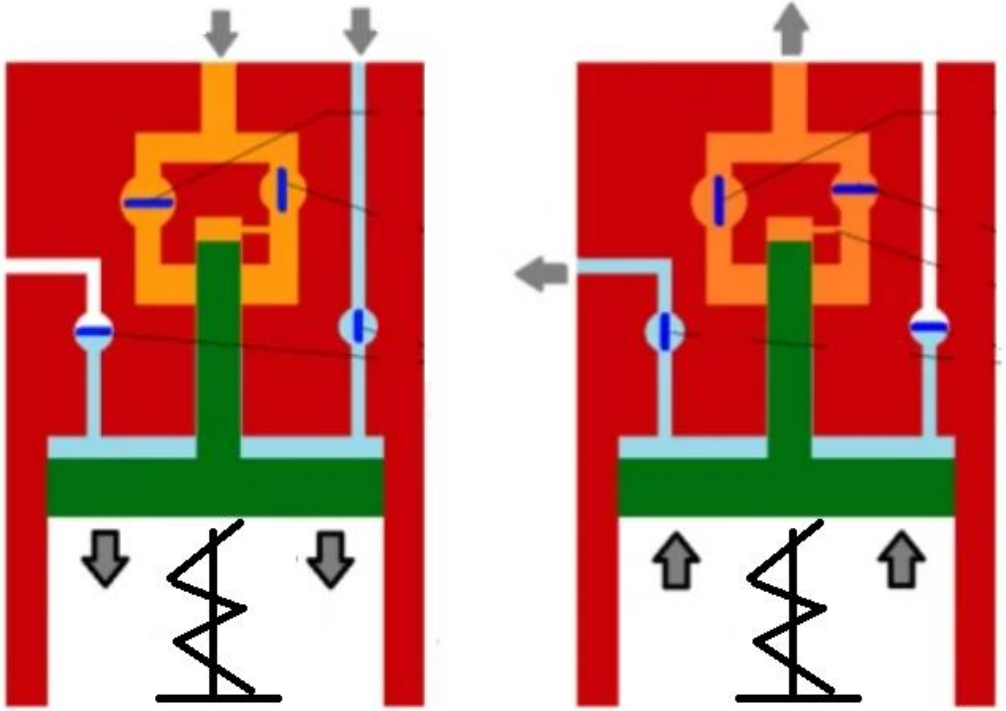
Source: Green car congress (Ref. 2)

Camless Valvetrain (Freevalve)

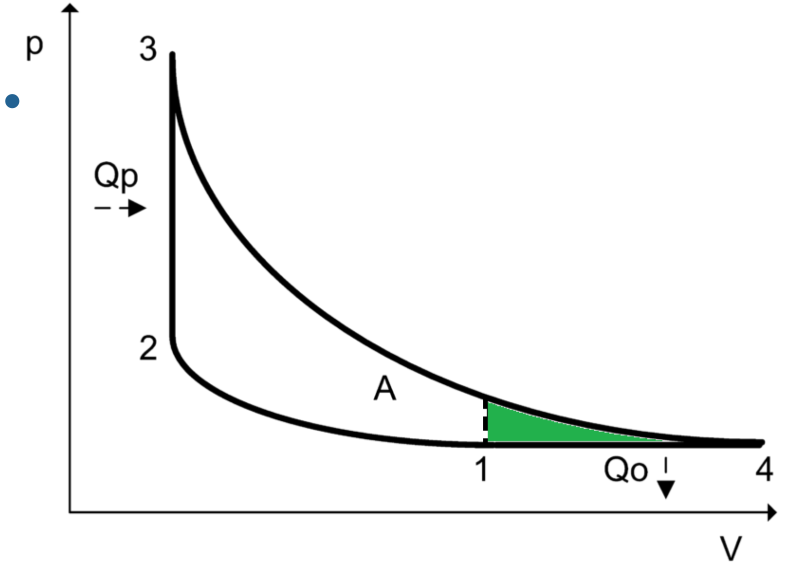
- Fully variable valve actuation using electro-hydrolic-pneumatic actuators combined with advanced sensor techniques
- Valve actuation and control is completely independent from engine
- One actuator per valve, consisting of an actuator piston, a cylinder, two solenoids, two spool valves, two port valves and a hydraulic latch
- To open: high pressure air forces down the actuator piston while oil enters into the compartment above to form a hydraulic lock
- To close: valves open releasing air and oil pressure, valve returns to seat via spring



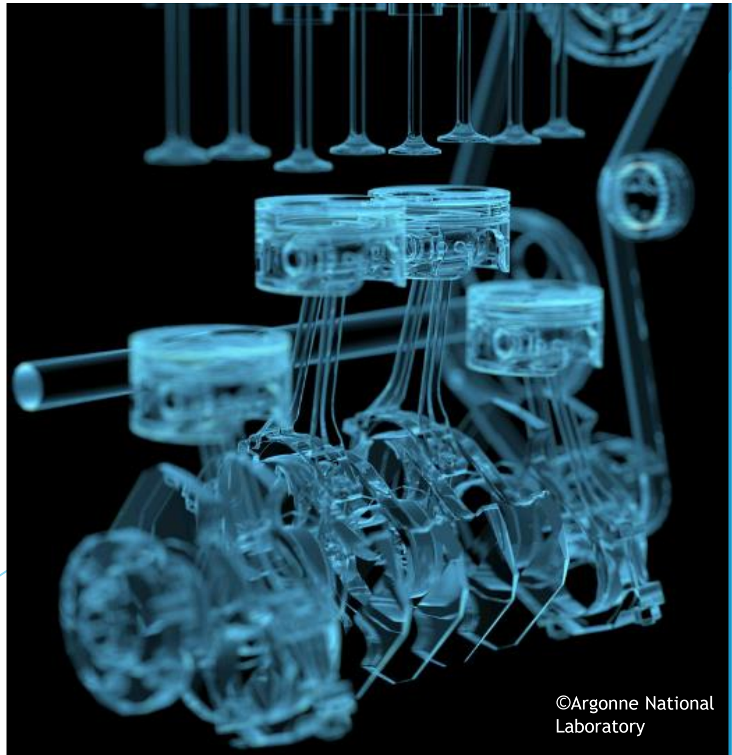
Source: Freevalve (Ref. 3)



Camless Valvetrain (Freevalve) contd.

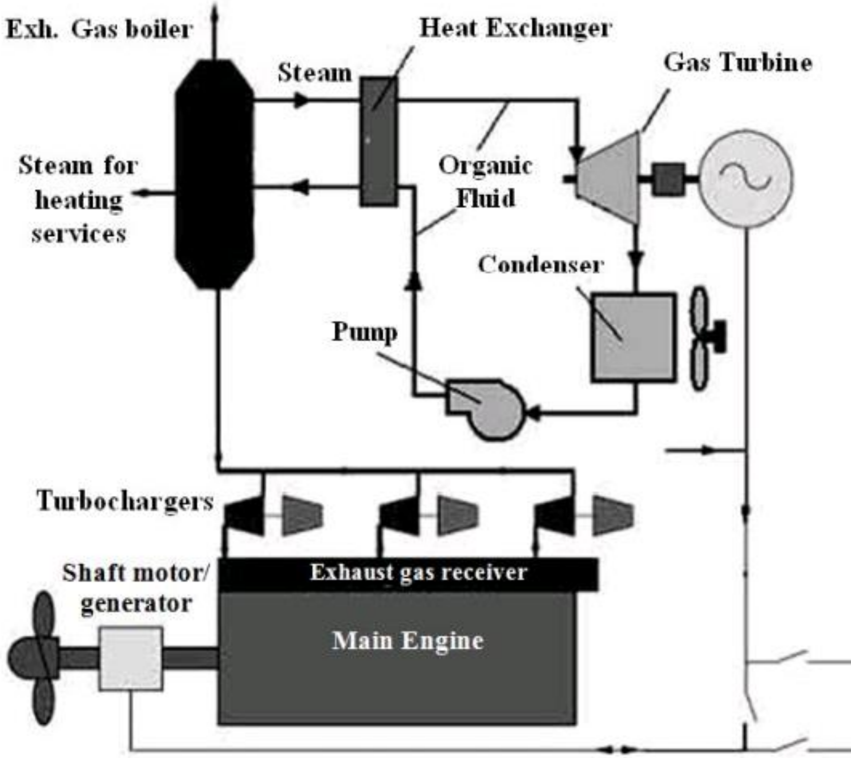


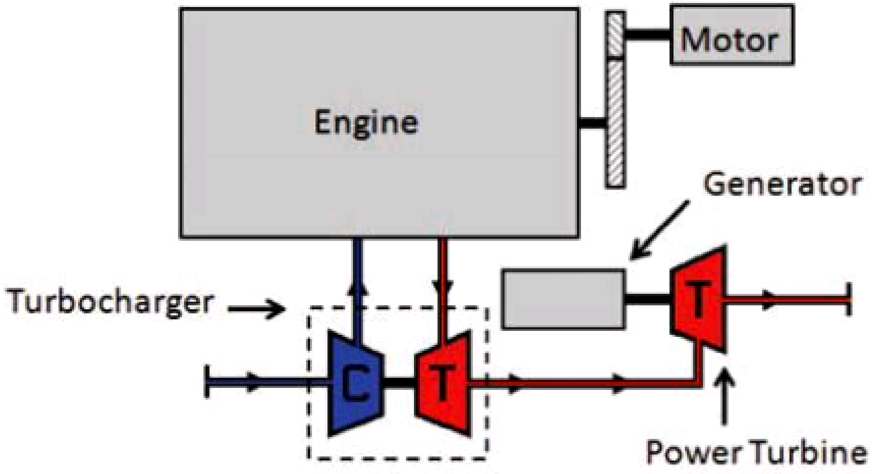
- Allows implementation of various concepts
  - Over-expansion ("Miller Cycle")
  - Temporary valve (And cylinder) deactivation
  - Two and four stroke operation in the same engine
  - Use of intake runner inertia at engine speeds
  - Elimination of Throttle losses (the valve opening regulates air intake)
  - Allows for turbocharging without a wastegate
  - Simple implementation of EGR internally (I-EGR)
  - improve atomization of heavier fuels (pre-heat, delayed intake valve opening)
  - Allows for optimization across entire engine operating range (machine learning)
  - Quick heating of catalytic converter, reducing emissions in "heat up" period
- Freevalve claims "targeting 50% BTE" (Koenigsegg Gemera 600HP, 3 cyl.)
- Disadvantages: cost, additional pneumatic pump required, competition from variable cam lobe technologies (i.e. Hyundai CVVD)



Waste Heat Recovery

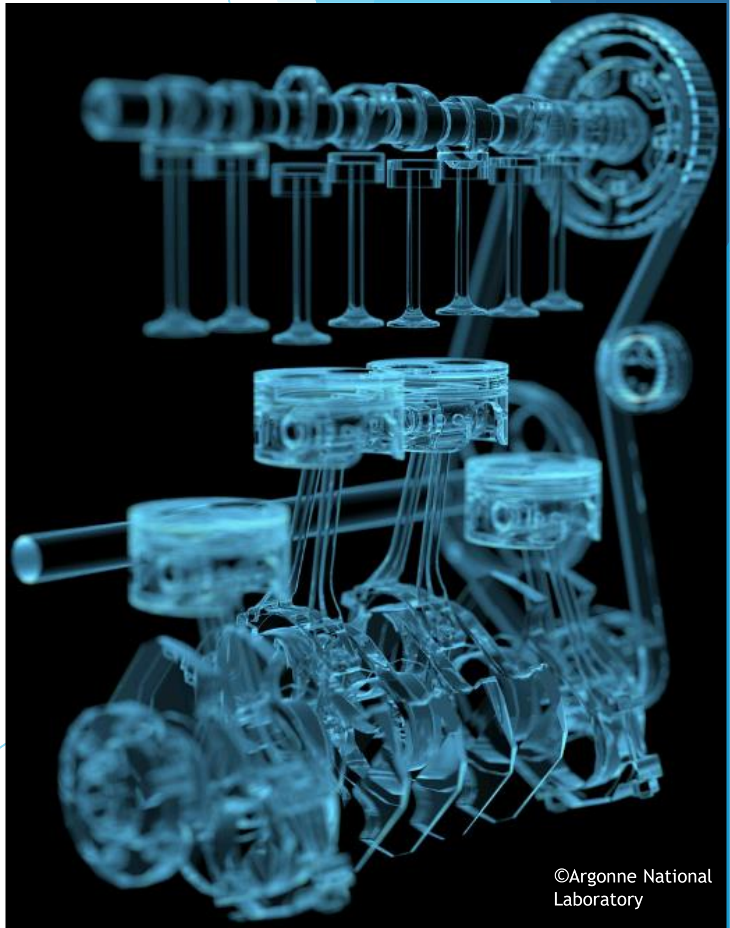
- All ICE's reject a large amount of heat via exhaust gases (20-30% of fuel energy)
- This waste heat can be recovered to extract work and increase total system efficiency
- The most prevalent type of heat recovery system employed in ICE's today is turbocharging: using exhaust gases to force more air into the engine
- Other promising technologies not yet commercial:
  - Electric turbo-compounding
    - Efficiency gains in the region of 5% reported
    - Main challenge- overheating of the electrical machine on turbo-shaft
  - Organic Rankine cycle
    - Efficiency gains in the region of 15% reported
    - Large size and weight limit usage to marine or large truck applications





Source: Technologies for Waste Heat Energy Recovery (Ref. 4)

e-Fuels/Bio fuels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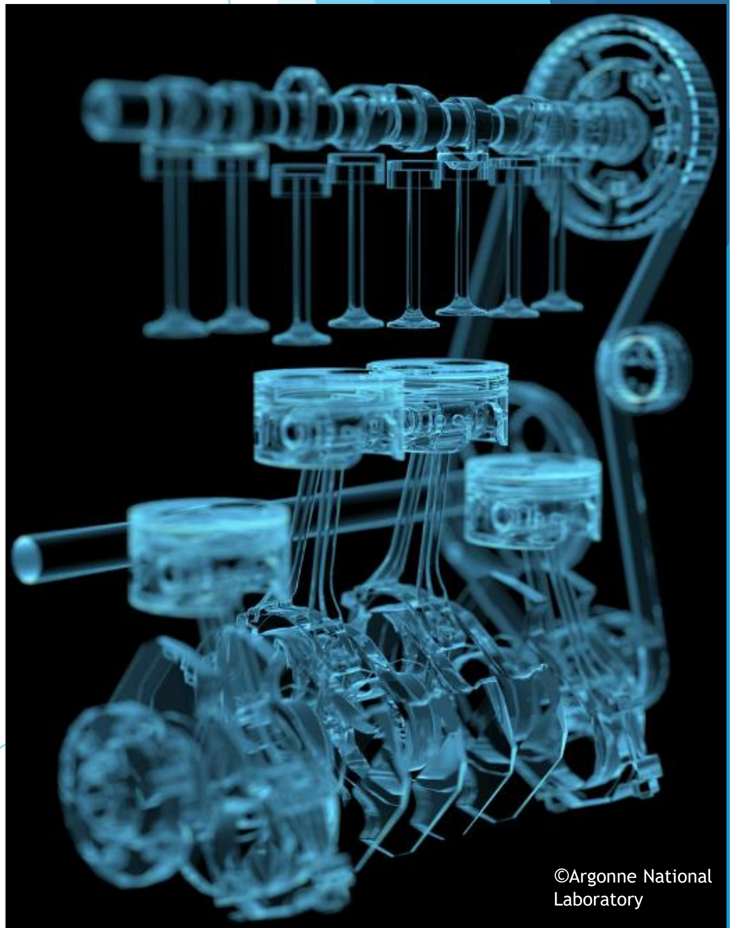
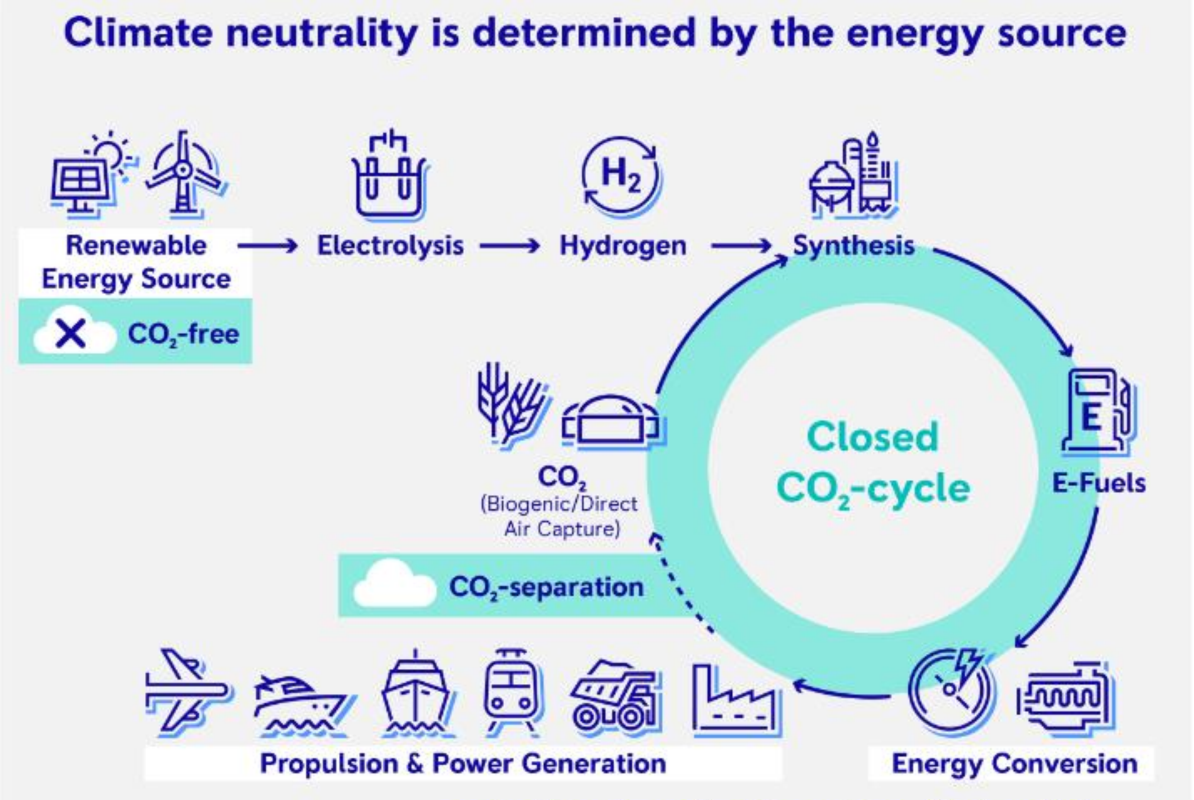
Bio Fuel Generations

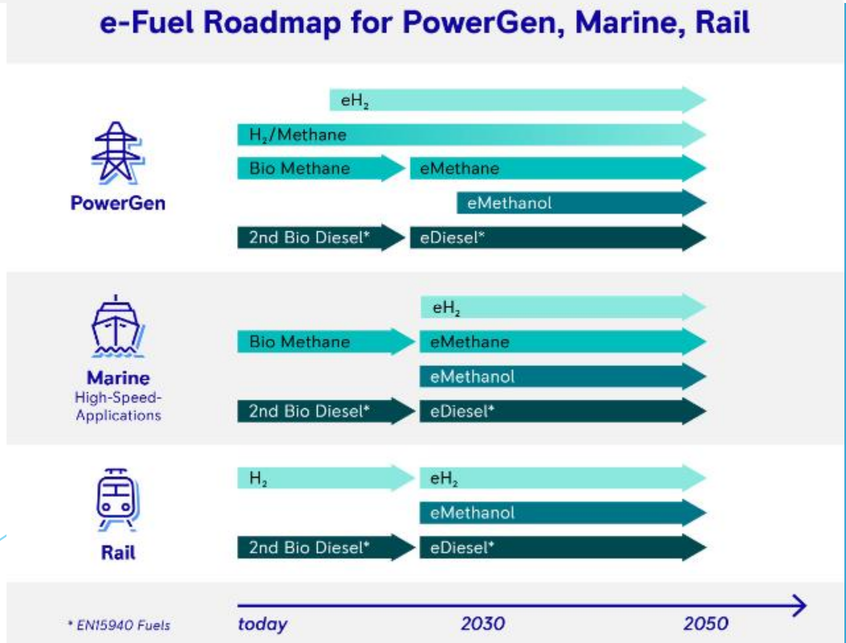
- Bio Fuel is a fuel produced over a short time (in contrast to the very long process involved in creation of fossil fuels)
- It can be made of biomass or by storing electrical energy in the chemical bonds of gasses and liquids (in the case of e-fuels)
- Most Bio-fuels can be used in ICE's with little to no modifications
- The Four generations of Bio-Fuels:
  - First Generation: Made of food crops by transesterification, or yeast fermentation examples: bio diesel from soybean oil, Ethanol from sugar cane
  - Second Generation: Made of dry plant/wood biomass or agricultural waste. More environmentally friendly than using food crops, but requires more energy to produce
  - Third Generation: Made of Alge that can be grown with salt or waste water. High energy requirement, cost and fast degradation of the product. In development.
  - Fourth Generation: electro-fuels and solar fuels. Hydrogen is produced from water by electrolysis or by sunlight (photochemical or thermochemical reactions). The hydrogen can be used directly as a fuel or turned into liquid fuel



e-Fuels

- The e-fuel life-cycle
  - Electrolysis of water to produce Hydrogen
  - Separation of CO2 from the atmosphere or other sources (water, biomass, flue gas)
  - Chemical synthesis of the desired fuel
  - Oxidation in ICE or fuel-cell releasing water and CO2 into the atmosphere
- Fuels explored
  - Hydrogen: no further energy to produce, but hard to store and a low volumetric energy density
  - Methane
  - Methanol
  - Dimethyl Ether
  - Fischer-Tropsch gasoline, Diesel and other fuels

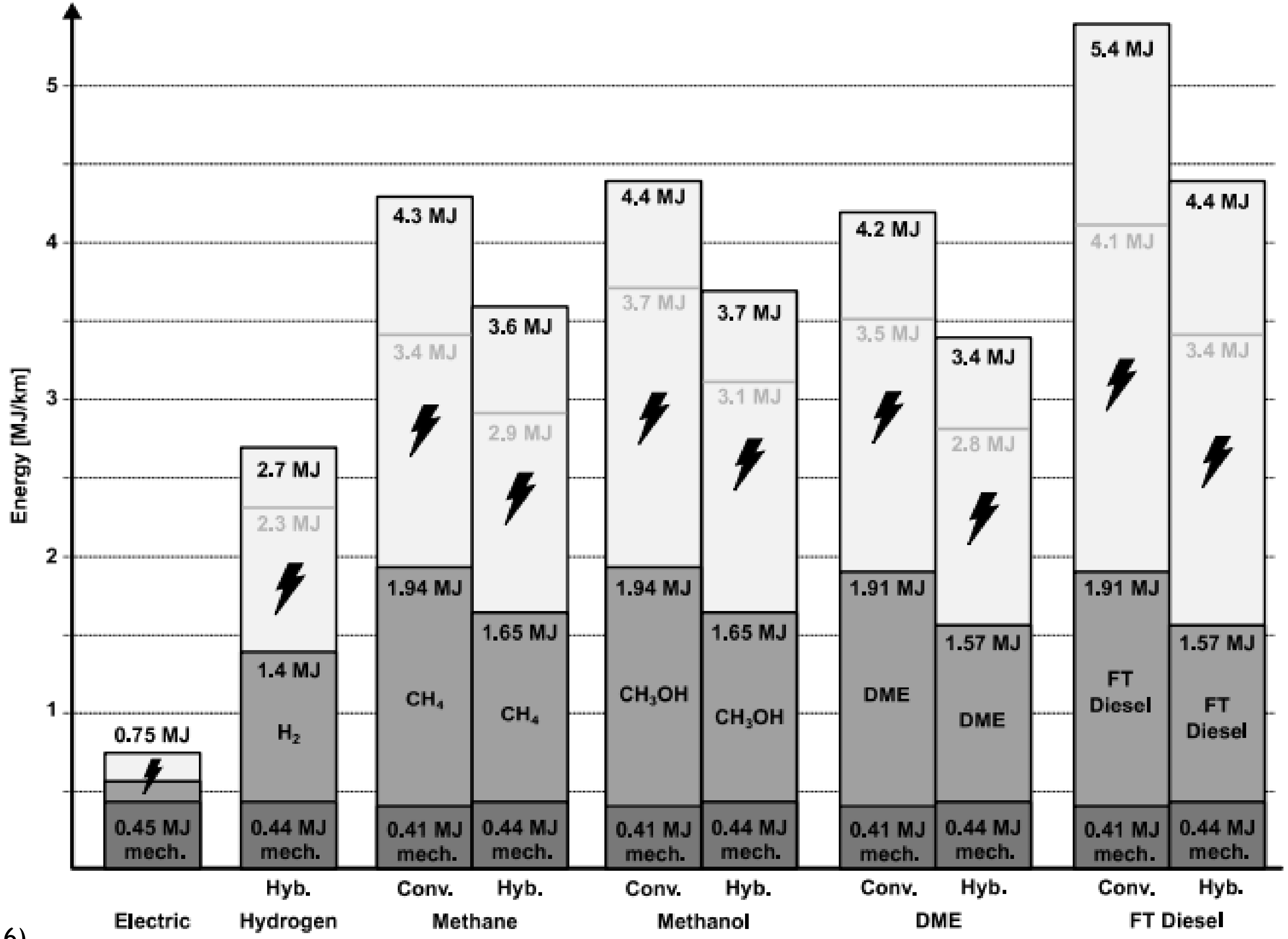




Source: MTU-Rolls Royce (Ref. 5)

e-Fuels, contd.

- The mechanical energy at the vehicle wheels, the chemical energy in the vehicle tank and the electric energy for production, storage and distribution are illustrated for conventional as well as hybrid vehicles
- e-Fuel production is energy intensive, but by using renewable power sources, can allow for de-carbonization of all ICE based applications



Source: A review of synthetic fuels for passenger vehicles (Ref. 6)

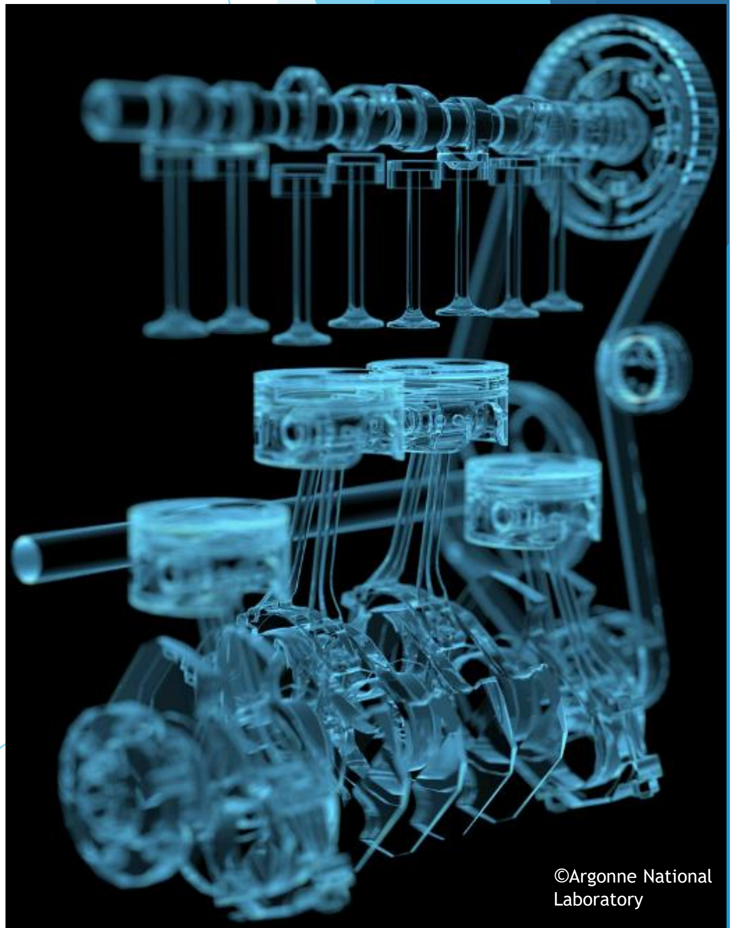
e-Fuels, contd.

- Proof of concept implementation: Haru Oni, Chile
  - HIF
  - Siemens Energy
  - Porsche

Source: Siemens Energy (Ref. 7)

Summary

- Continued development of the ICE is beneficial and necessary to achieve de-carbonization/zero impact emissions from power generation, transportation, and mobility applications dependent on it
- This is especially important in the short-to-medium-term
- Regulation, competition and customer demand drive innovation and lead to the two trends presented:
  - Improvement of engine BTE/ total system efficiency
  - Development of e-Fuels/Bio fuels
- The technologies presented make industry target of 50% BTE seem closer than ever before
- e-Fuels are a promising prospect for full de-carbonization of all ICE dependent applications



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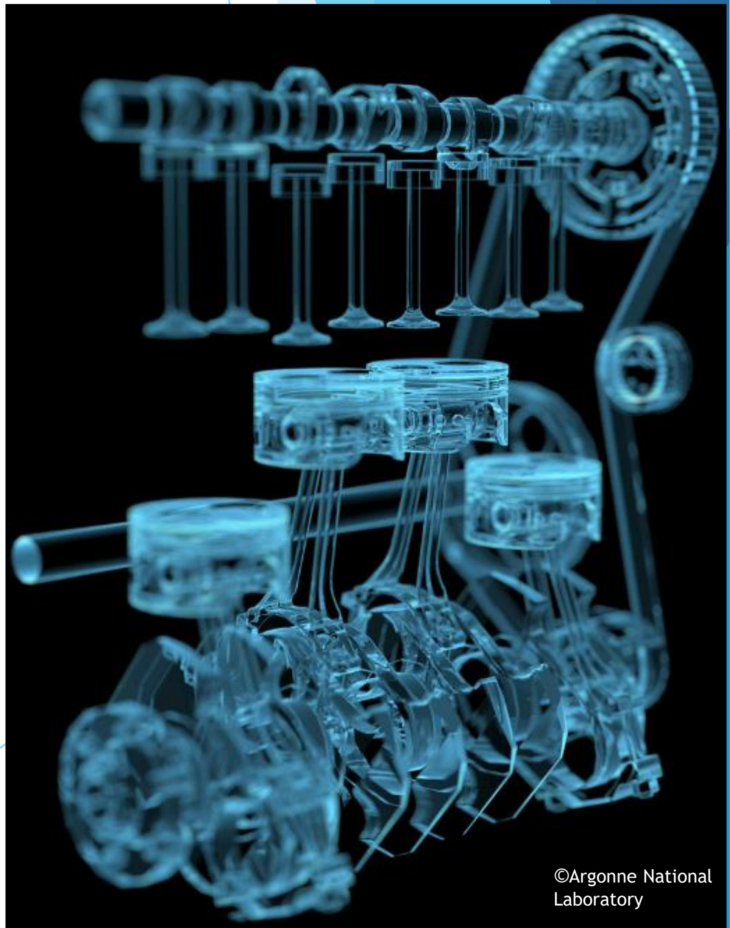

Questions?