Is it really the end of internal combustion engines and petroleum in transport?

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Introduction - I

Globally, Transport accounts for

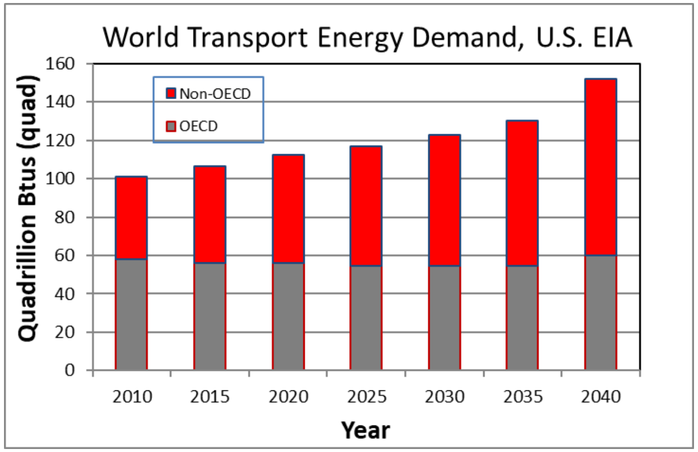
- 14% of global GHG (CO2, methane and nitrous oxide) emissions, 20% of total energy use, 23% of CO2 emissions
- Currently over 1.2 billion light duty vehicles (LDVs) and over 350 million commercial vehicles. 32 million LDVs in UK.
- LDVs account for ~44% of global transport energy demand
- Transport is essentially driven by liquid fuels – high energy density, ease of transport and storage, extensive infrastructure
- Over 4.9 billion liters each of gasoline and diesel and 1.2 billion liters of jet fuel each day. 105 TWh of fuel energy needed each day.

Demand for transport energy is growing at an average annual rate of ~1 %

- In non-OECD countries

Petroleum and transport closely linked

- 95% of transport energy from petroleum
- 60% of petroleum goes to transport fuels



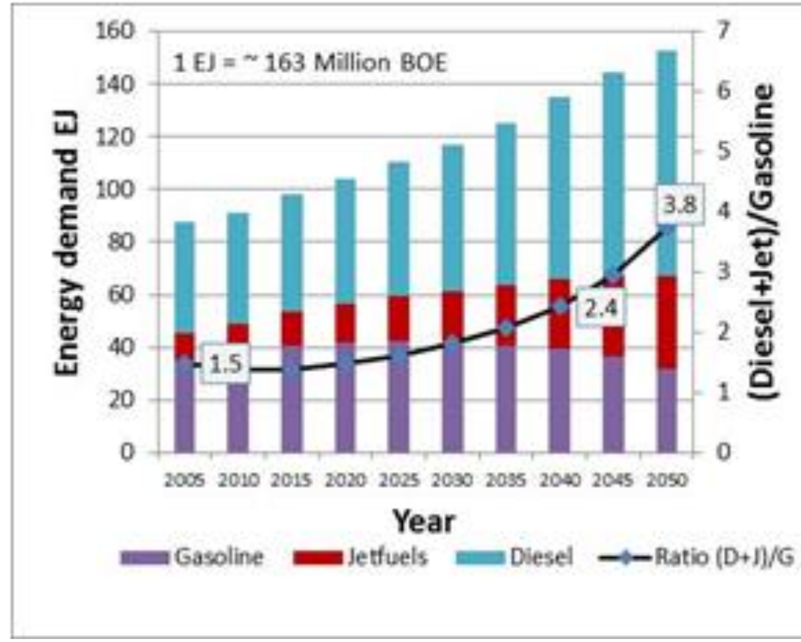
1 quad = ~172.5 million BOE - barrels of oil equivalent

Introduction - II

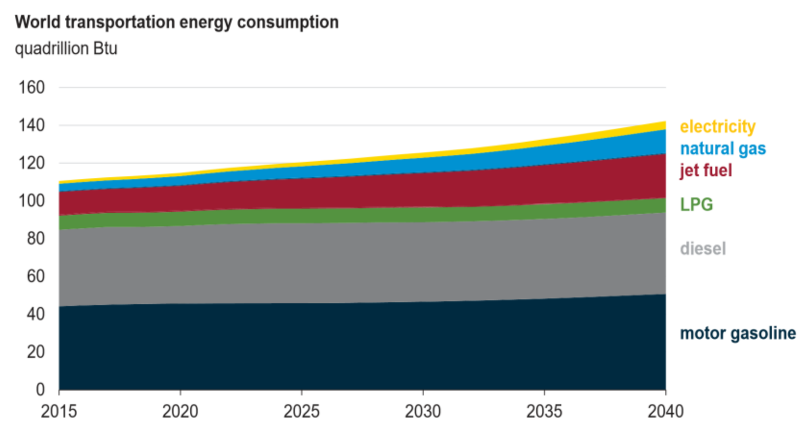
Demand growth greater in commercial transport compared to LDVs

- Greater scope for efficiency improvements in LDVs – on average, in the future, lighter and smaller, cover less distance, hybridization
- Increase in demand for diesel & jet fuel rather than gasoline
  - Will require large investments in refineries
  - Greater availability of low octane gasoline components

- Even by 2040, transport will be dominated by combustion engines 85%- 90% of transport energy will come from oil (World Energy Council, U.S. EIA)
- Imperative to improve such engines to improve the sustainability of transport



World Energy Council (WEC). Global transport scenarios 2050



U.S EIA – International Energy Outlook 2017

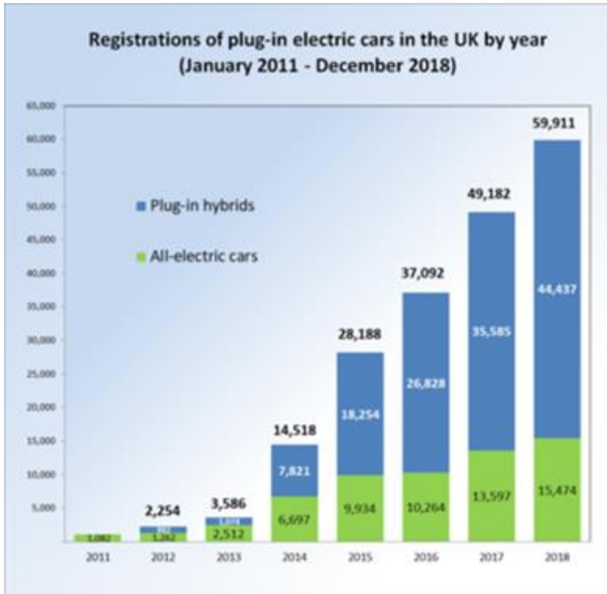
Electrification of Transport

Electric Vehicles - Different Degrees of Electrification

- Only BEVs do not have an ICE and all their energy comes from the electricity grid. Large battery
- Hybrid Electric Vehicles, HEVs (Toyota Prius) – Small battery. All their power coming from ICE but makes the ICE more efficient + Recovery of brake energy
- Plug-in HEVs, PHEVs (GM Volt) will have a larger battery but also a ICE- some to most of the energy from the ICE

Electrification of LDVs will increase significantly in the future – more in the form of HEVs

Outlook for Electrification



In 2019, around 38000 BEVs registered in the UK ~35000 PHEVs

▪Sales of plug-in EV (BEV +PHEV) rapidly increasing ~ 73000 in 2019 in UK, around 3%. [globally 2 M, 2.5%].

By End of 2019, BEV stock was, ~0.1M in U.K. ~0.3 % of passenger cars (http://insideevs.com/)

- Global stock of BEVS ~4 M
- In 2040, global LDV numbers expected to be 1.7-1.9 billion
- If ICEs are to be eliminated from LDVs by 2040, battery capacity needs to increase by a factor of over 1000. But this still addresses only 45% of transport energy demand

Such a massive increase in BEVs will have unsustainable environmental and economic impacts.

Greenhouse gas (GHG) and other pollutants

- GHG impact depends on how electricity used is generated.
- Battery production could generate up to 200 kg/kWh of CO2 GHG than ICEV production.
- In many parts of the world, certainly India and China BEVs will cause more CO2
- PM2.5, NOx and SO2 also will be worse if coal is a source of power.
- Human Toxicity Potential (HTP) - With ICEs, associated with NOx, particulates and other pollutants. With BEVs, HTP is associated with mining of metals, particularly cobalt, and 3-5 times worse.

  http://www.adlittle.de/sites/default/files/viewpoints/ADL_BEVs_vs_ICEVs_FINAL

BEVs ARE NOT GREEN OR CLEAN AND REPLACING ALL LDVs BY BEVS REQUIRES ~1000 TIMES INCREASE IN BATTERY CAPACITY

Full electrification not relevant to most commercial transport

- 36 tonne 500 mile range lorry – ~ 1000 kWh battery, 6.4 tons weight, cost over $180,000. Charging time around 12 hours.
- A320 Neo carries 266 MWh of fuel energy. A battery pack carrying the same energy would weigh 1640 tons – 19 times the max take off weight. At 1 MW, would require 11 days to charge.
- Container ship Benjamin Franklin carries 4.5 million gallons of fuel, 170 million kWh. The battery pack would weigh over a million tons – 5.8 times the dead weight tonnage.

Moore's Law for batteries?

- Not applicable. Electrons in a microprocessor do not take up space but ions in a battery do. Only new battery chemistry will bring major changes
- Gains in performance and reduction in cost typically 1.5-3% per year outside the microchip world (Smil, https://spectrum.ieee.org/energy/renewables/moores-curse)

Autonomous cars accelerate spread of BEVs? No!

- Level 5 autonomy requires 1.5 -3.75 kW of extra power + 1- 5 kW for heating and cooling. A minimum of 2.5 KW
- A car on call for 24 hours with a 50 kWh battery cannot go very far!

Economic and Other Implications of Forced Electrification of LDVs

- cost/availability of new infrastructure such as charging points - https://www.wsj.com/articles/the-problem-with-electric-cars-not-enough-chargers-1502017202 , £ 30-80 billion estimated for the UK - http://uk.reuters.com/article/us-britain-power-autos-analysis/britain-faces-huge-costs-to-avoid-power-shortages-with-electric-car-plan-idUKKCN1BC3VU
- Incentives to persuade motorists to buy them
- lost government revenue from fuel tax (£ 35 billion a year for the UK),
- cost/availability of extra electricity needed. Up to 8 GW (three nuclear power stations) needed in the UK if BEVs increase to 9 million (30% of total) by 2030 http://fes.nationalgrid.com/media/1281/forecourt-thoughts-v12.pdf
- Eventually, the problem of recycling the batteries http://www.sciencedirect.com/science/article/pii/S2214993714000037 and Olivetti et al. 2017, Joule 1:229-243
- Availability of cobalt and other materials – prices are increasing
- Ethical issues associated with mining of metals - https://www.amnesty.org/en/latest/news/2017/09/the-dark-side-of-electric-cars-exploitative-labor-practices/

Alternatives to Petroleum Based Liquid Fuels (electrification, biofuels, natural gas, LPG, DME, methanol, hydrogen..) not expected to take much more than 10% -20% share of transport energy by 2040

- Start from a very low base
- Significant barriers to unlimited growth
- Generally relevant to light-duty vehicles (LDVs)

Alternatives - Biofuels

Made from biomass - Sugar, starch, vegetable oils, residues to ethanol, bio-esters, diesel ….

- Current share – around 2.0 % of transport energy demand. Primarily ethanol in gasoline (~100 billion liters per year)
- Main Drivers –
  - Import substitution/self reliance/security of supply
  - Use for agricultural surpluses
  - Bio-waste management
  - Greenhouse gas credit (depends on assumptions)
- Challenges –
  - Food vs Fuel - availability of land
  - Higher costs per unit of energy
  - Sustainability – deforestation, water and fertiliser use

Second Generation Biofuels

Actual production in the U.S. in 2015 was 2.2 million gallons of gasoline equivalent – the original requirement (RFS2) was 3 billion gallons by 2015

[http://www.dovetailinc.org/report_pdfs/2017/dovetailbiofuels0117.pdf/]

Alternatives - Natural Gas

- Exists naturally, is cheap and abundant (shale gas revolution)
- Normally used for heating and electricity generation but can be used in IC engines. Is a gas – contains 800 times less energy compared to gasoline. Needs to be compressed to 200 atm (CNG) or liquefied (LNG)
- Desirable properties – high octane. Reduction in particulates. Lower CO_2
- Commonly used in cars in some countries . In 2012 there were 17 million NG vehicles but the share of transport energy is still only 1%

BARRIERS

- Infrastructure
- Initial cost. Extra cost for dedicated CNG cars -~$8000, trucks -~$30,000. LNG trucks -~$90,000. Actually with oil price below $64/ barrel, not economic
- Lower driving range
- Safety and environment – methane 40 times more potent than CO_2 as a greenhouse gas. Conversions are not always safe.

OUTLOOK

Renewed interest because of shale gas. Ultimately limited by infrastructure. More suited to heavy duty fleet. LNG for marine. Share increasing to 5% by 2040 in some projections but depends on oil price.

Alternatives - LPG, DME, Methanol

LPG (Liquid Petroleum Gas) – By product of oil refining and NG processing. Over 17 million cars (Turkey, Korea). 1% share of transport energy.

Dimethyl Ether (DME) – Can be made from coal, biomass or NG. High cetane, low soot.

Methanol – High octane but half the energy content of gasoline. Very aggressive to fuel system components. Can be made from coal, biomass or NG. Commonly used in China. Much interest in India

Synthetic Fuels – Made using the Fischer Tropsch processing of syngas. Very high capital cost.

- GTL – Gas to liquid
- CTL- coal to liquid
- BTL – Biomass to liquid

Use of such fuels makes sense somewhere, some time . Will continue to be used as niche fuels. Some, like methanol could find increasing use in some countries.

Alternatives - Hydrogen

PRODUCTION

- Energy carrier, like electricity and will need to be manufactured
- Production is energy intensive.
- Production from natural gas or coal , produces CO2. Electrolysis of water using electricity from renewable (at the moment < 0.5% of total energy use) or nuclear (waste disposal, proliferation issues). Hydrogen production must use CO2-free primary energy if CO2 mitigation is the concern
- Why convert electricity to H2? Much greater reduction in CO2 if renewable energy is used to replace coal-generated electricity.

STORAGE and TRANSPORT

Volumetric energy content ~ 3200 times lower than liquid fuels at room temperature/pressure . Liquid hydrogen 5 times lower than gasoline -

- Compression (~ 25% energy lost). Liquefaction (~40% of energy lost).
- Extensive infrastructure investment needed for distribution. Costs ~15x of liquid hydrocarbons, 4x natural gas (IEA). Liquid H2 transport too risky.
- **Significant safety issues**

Not a viable transport fuel over the next few decades. Some niche potential

- Even in 2040, ~90% of transport energy will come from petroleum-based fuels powering ICE
- Improvement of such systems is imperative to ensure sustainability of transport

Ensuring the sustainability of transport

Stage 1 – Conventional engines using known fuels e.g. gasoline, diesel, CNG, LNG, LPG, biofuels improve to reduce GHG and other pollutants. Better combustion, control and after-treatment coupled with partial electrification (HEVs). Will also require some changes to fuels – e.g. gasoline anti-knock quality needs to be increased to enable higher efficiency in SI engines

Stage 2 – Developing new fuel/engine systems allows greater scope. Unconventional engines e.g. Opposed Piston 2 stroke using 'new' fuels (not limited by existing specifications) might offer further flexibility. Such approaches will also help mitigate future supply/demand issues which are likely to arise under Stage 1.

Stage 3 – Longer term. As overall energy system is decarbonized, and battery technology develops, increasing role for BEVs, Hydrogen

Changes need to be assessed on a cradle-to-grave, LCA basis though some changes may be forced

Scope for improving ICE with existing fuels

Significant scope for improving efficiency of SI engines- Lean burn, downsizing/turbocharging, compression ignition, better control

- In the U.S., best-in-class efficiency is 16% better than average for cars of similar size and performance
- GDCI with market gasoline (Delphi) shows ~ 25% improvement
- Compared to 2015 fleet average, 30% improvement in the U.S. market is possible with combustion system improvements alone

Further improvements (up to 50%) possible with light-weight materials, vehicle down-sizing and partial electrification, demand reduction

Improved after-treatment – e.g. with particle filters, zero particles. With modern catalysts and intelligent control, exhaust could be cleaner than intake in many parts of the world

Some additional scope with "low-carbon" fuels if they make sense – proper life cycle assessment necessary

Examples of fuel/engine system development

- Gasoline Compression Ignition (GCI) – run CI engines on low-octane gasoline rather than diesel fuel

Overall GHG/Efficiency benefits - ~ 25 - 30%% wrt SI and ~5% wrt Diesel

Engine – Low injection pressures (< 500 bar). After treatment focus on HC/CO control rather than NOx and soot. A simpler and cheaper diesel engine

Fuel- Low Octane (70-85 RON, DCN < ~22), no stringent requirement on volatility. "Less processed" fuel.

Demand/Supply - Will help mitigate demand imbalance between diesel and gasoline that is otherwise expected

Improve Sustainability of Refining

- Octane on Demand (OOD) – Supply high octane fuel to SI engines only when needed – enables SI engines to run on low-octane gasoline but achieve high efficiency. Up to 5% GHG benefit. Requires two fuel systems on board.

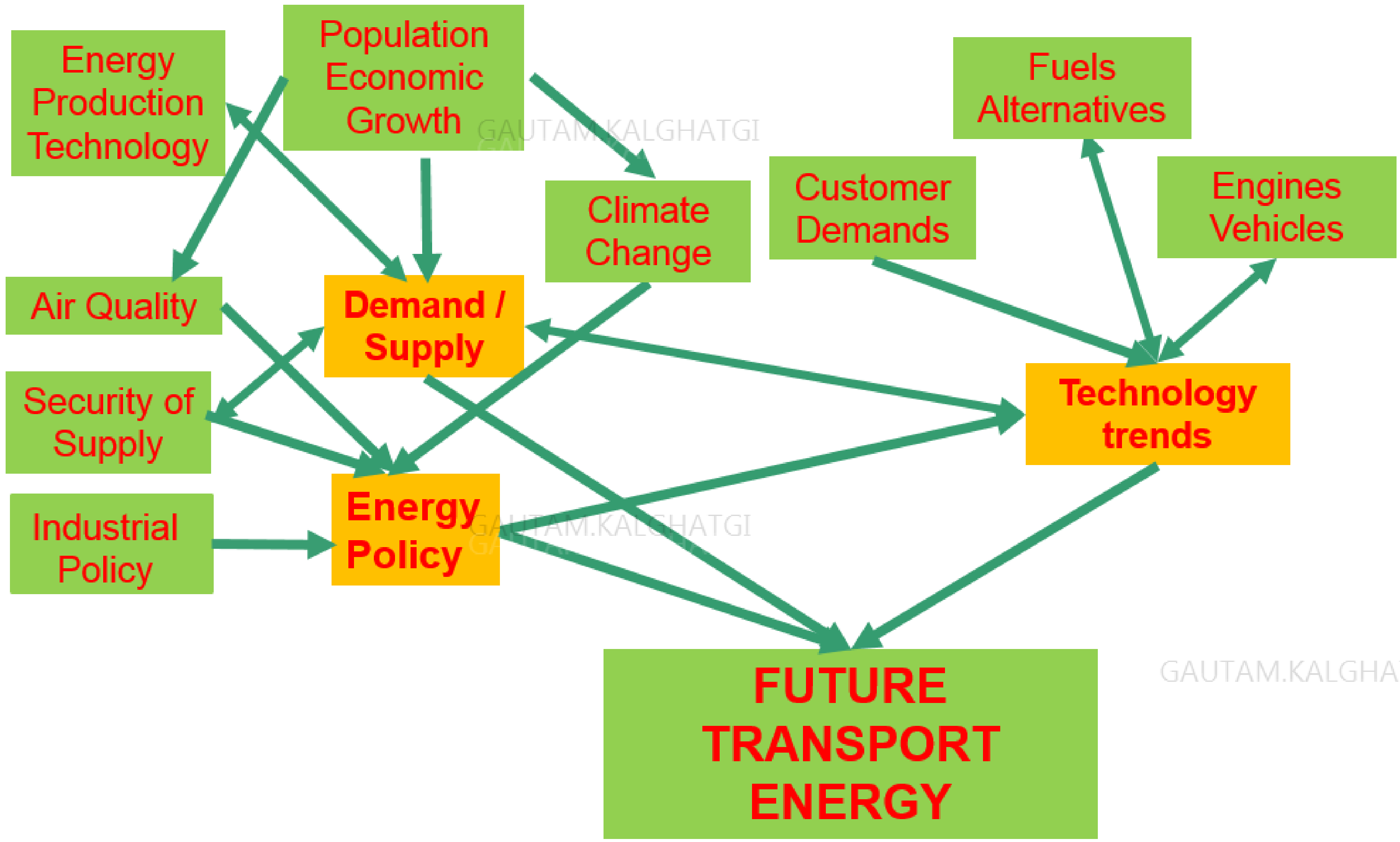
Concepts proven in labs/demo vehicles. All stakeholders need to work together to bring such optimized fuel/engine systems to the market. Will become commercially attractive when price of low-octane gasoline drops

Summary

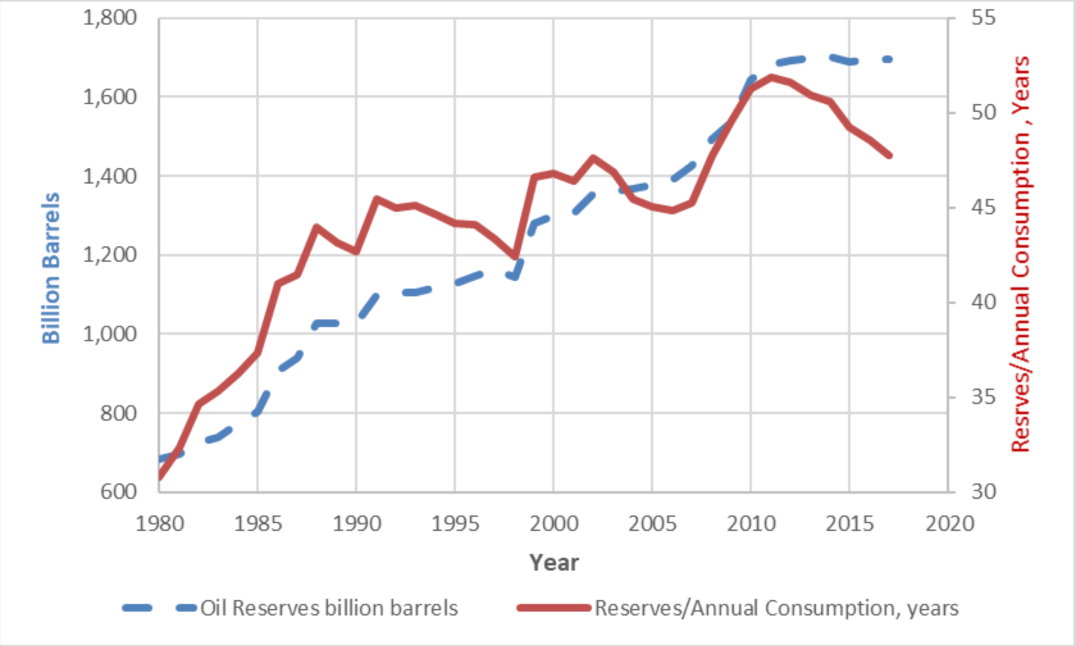
- Global transport energy demand is large and increasing
- Different motivations for change in different places
- Alternatives start from a very low base, are costly/inconvenient and cannot grow without constraint
- Even by 2040, most (~ 90%) of transport energy will come from petroleum powering ICEs
- Alternatives need to be assessed on a life cycle basis
- GHG and other impacts of transport can be reduced by improving ICEs
- More diesel and jet fuel needed compared to gasoline AND surplus of "low-octane gasoline"
- Great scope for developing highly efficient engines running on such fuels
- Gasoline Compression Ignition (GCI) or Octane on Demand (OOD) engines offer such a prospect
- All stakeholders need to work together to bring such optimized fuel/engine systems to the market rather than only developing engines for existing market fuels
- Meanwhile there will be increasing electrification – mostly hybridization which will help ICE improve

THANK YOU FOR YOUR ATTENTION

Future Transport Energy - Many Drivers for Change. Difference between different countries



Supply of Oil



Data from BP Statistical Review of World Energy

- Reserves have increased faster than demand
- Current reserves will last for over 50 years without any further addition
- Large increases from shale oil in the past couple of years

Supply will not be a constraint for any future growth in transport energy demand