Future Mobility - Is it really the end of combustion engines and petroleum?

Gautam Kalghatgi

2018 Princeton-Combustion Institute Summer School On Combustion

Lecture 1

Future Mobility - Is it really the end of combustion engines and petroleum?

Gautam Kalghatgi

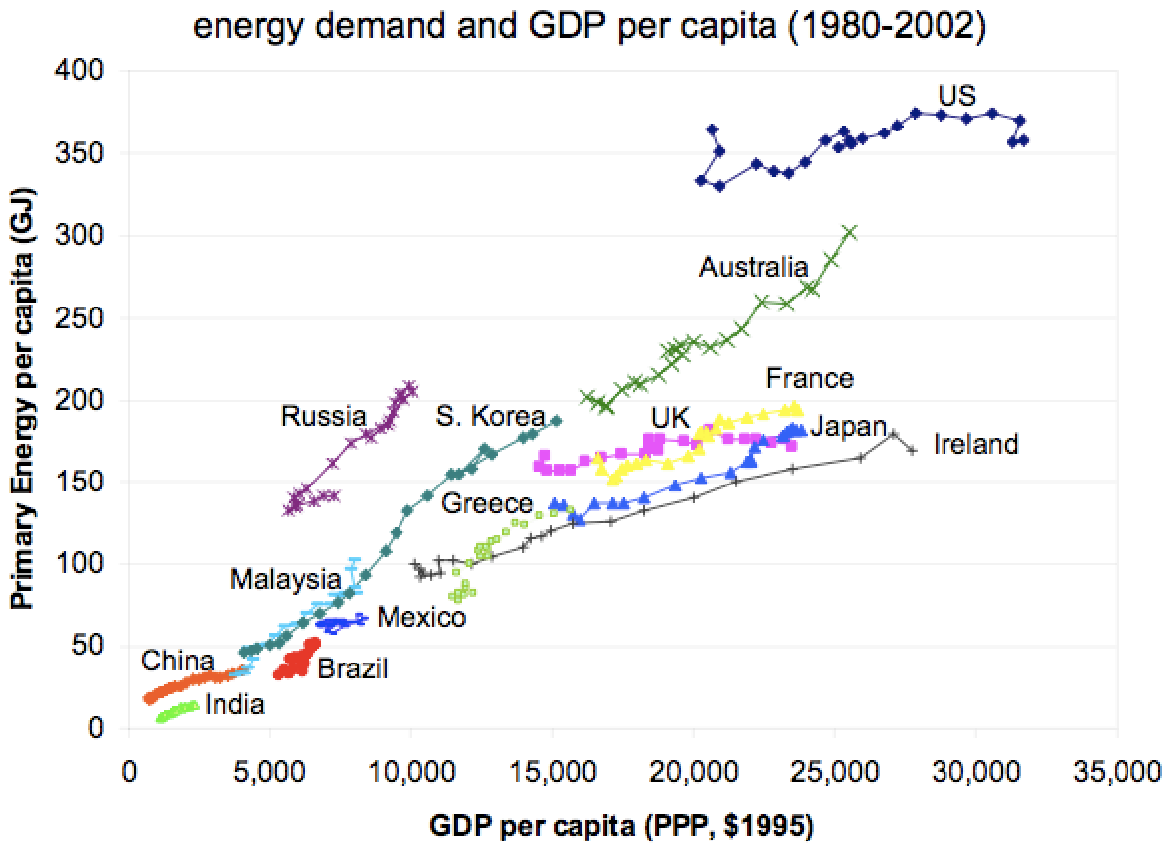
2018 Princeton-Combustion Institute Summer School On Combustion

Structure of the talk

- Long term energy supply and demand
  - Drivers
  - Constraints
  - Prospects
- Future Mobility

What drives energy demand?

- Increasing population –7 billion expected to peak to 9 billion by 2050
- Increasing prosperity

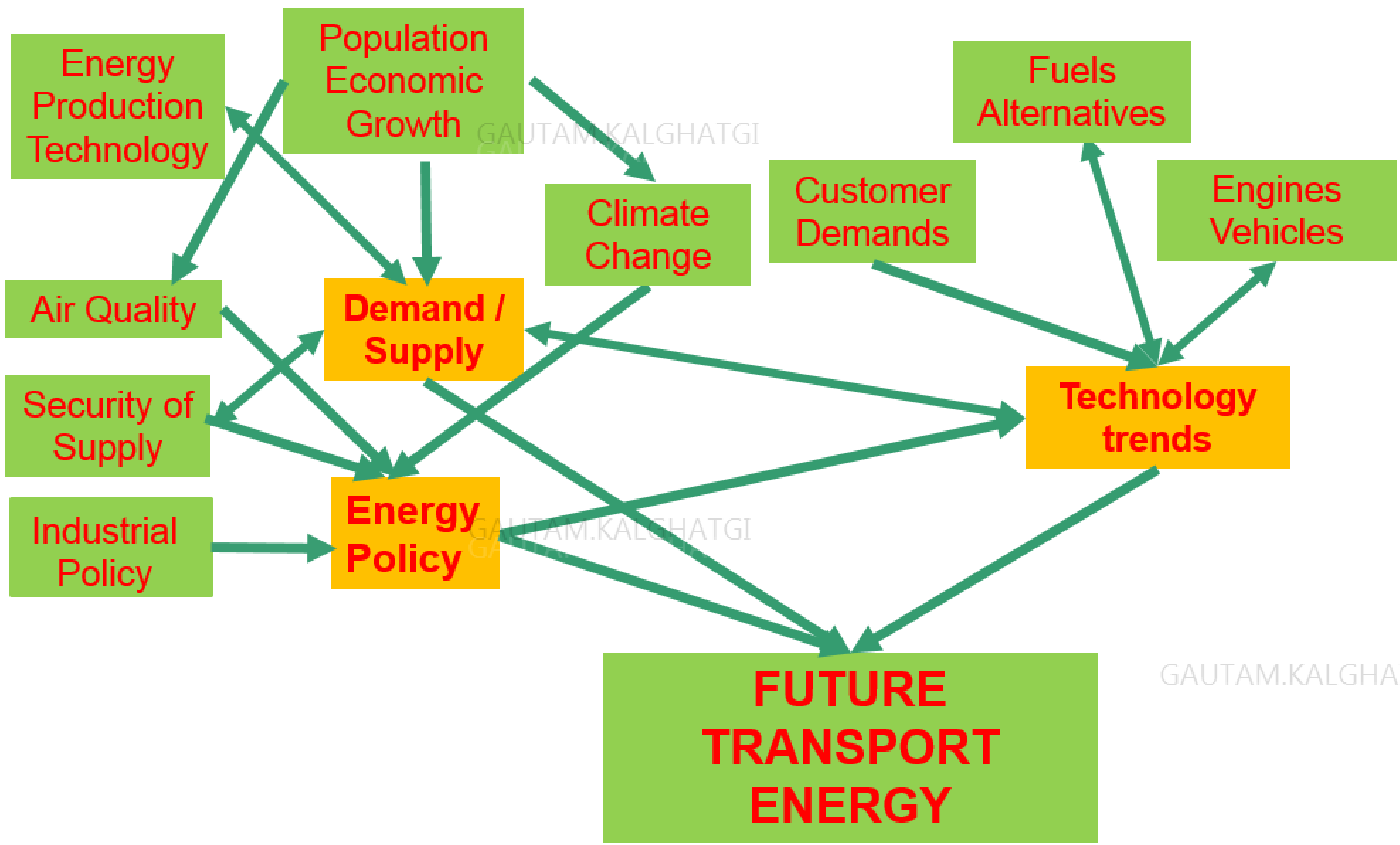


Source: UN and DOE EIA

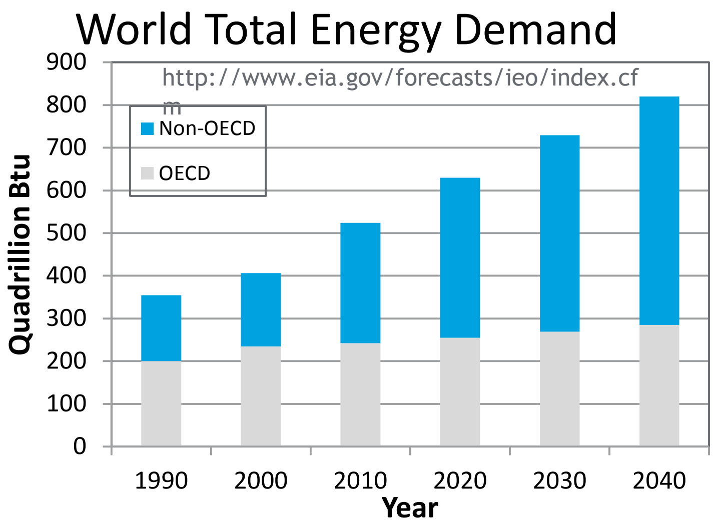
http://notable.files.wordpress.com/2007/04/energy-per-capita.png

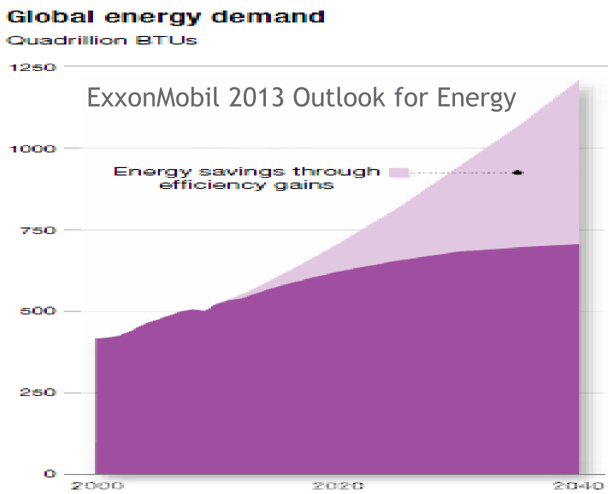
- Other drivers – increasing urbanisation, local and global pollution concerns, energy security, improved efficiency

Future Energy - Many Drivers for Change



Energy demand increasing - scope for efficiency





- World energy demand is increasing (40-60 % higher in 2040 than in 2010) in spite of improved efficiency
- Most of the growth in non-OECD countries

The amount of energy used per unit of GDP at world level is decreasing steadily: 1.4% p.a. between 1990 and 2008, with an acceleration since 2004 (1.9% p.a)

http://www.worldenergy.org/documents/fdeneff_v2.pdf

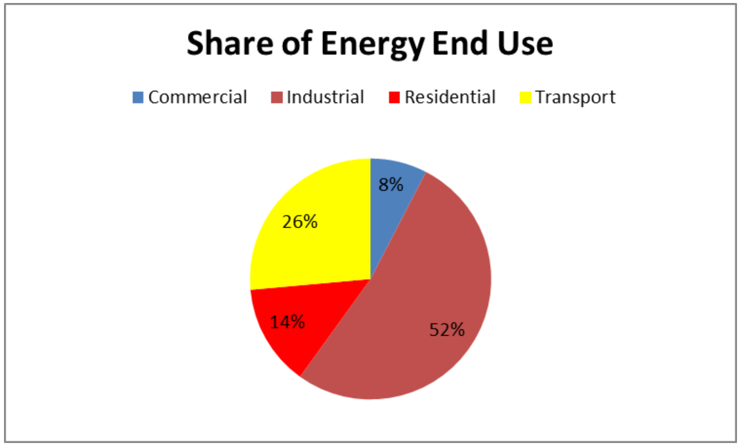
- 20-30% of residential energy use can be saved e.g. energysavers.gov
- World average efficiency for thermal power generation is ~35% while in Europe it is ~40% . Best in class ~48% . China ~32% , India ~27 %

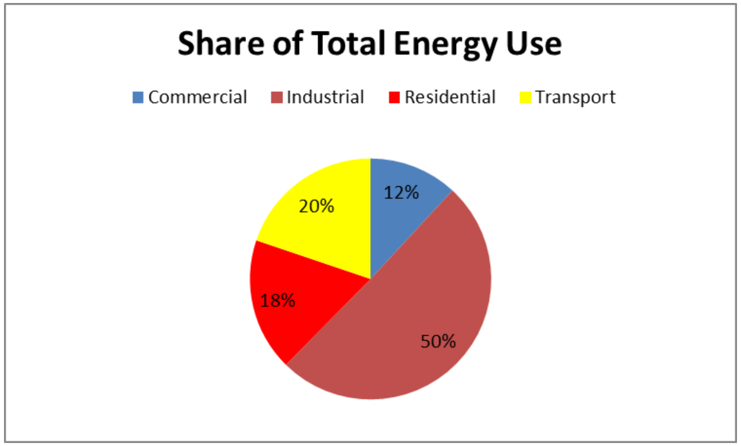
Global Energy Consumption by Sector (2011 in quads)

	Energy EndUse[2]	Electricity Losses[3]	Total Energy Use[4]	Share of Total Energy Use
End-Use Sectors				
Commercial	29	34	62	12%
Industrial	200	66	266	51%
Residential	52	40	92	18%
Transportation	101	2	103	20%
Total End-Use Sectors	382		524	
Electric Power Sector[4]	204			39%
Total Electricity losses[3]	142			

[1]This is the most recent year for which data are available at the time of update.
[2]Energy end-use includes end-use of electricity but excludes losses.
[3]Electricity losses includes generation, transmission, and distribution losses.
[4]Total energy use includes electricity losses.

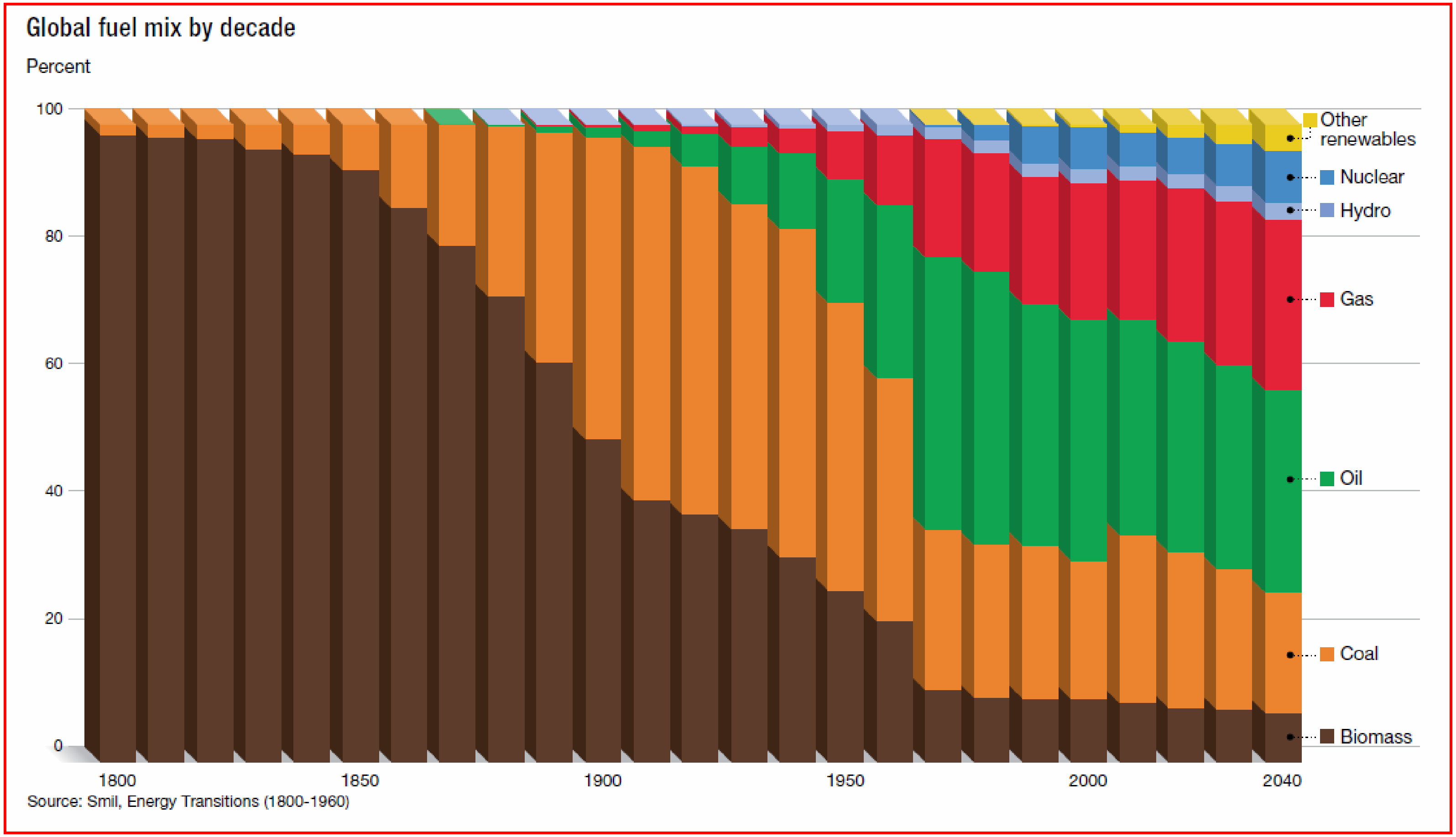
http://www.eia.gov/tools/faqs/faq.cfm?id=447&t=1





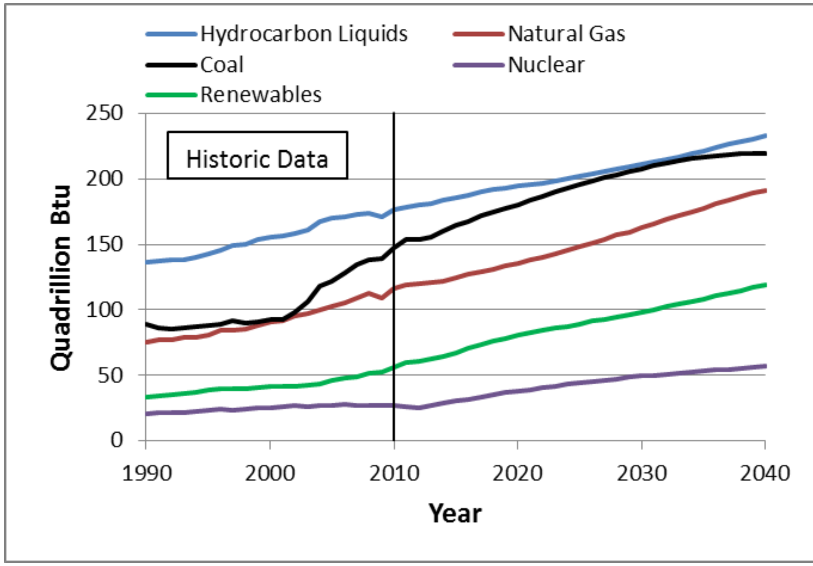
1 quad (quadrillion BTU) = 1.055×10^{18} joules = 172.4 million BOE (barrel oil equivalent)= 277.8 TWh

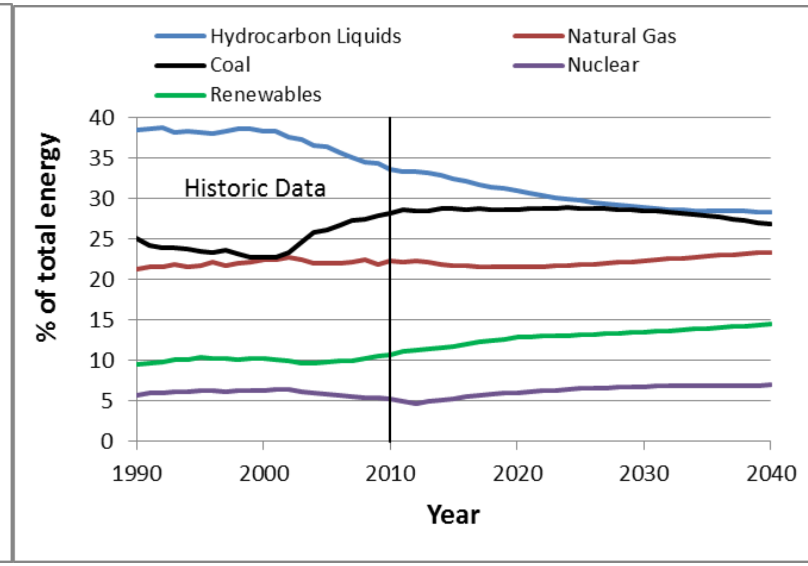
Evolution of the energy mix



- Transition of energy systems takes a long time
- Often sparked by evolution of technology e.g. steam engine (coal), IC engine and chemicals (oil)

Global Energy Consumption by Fuel Type

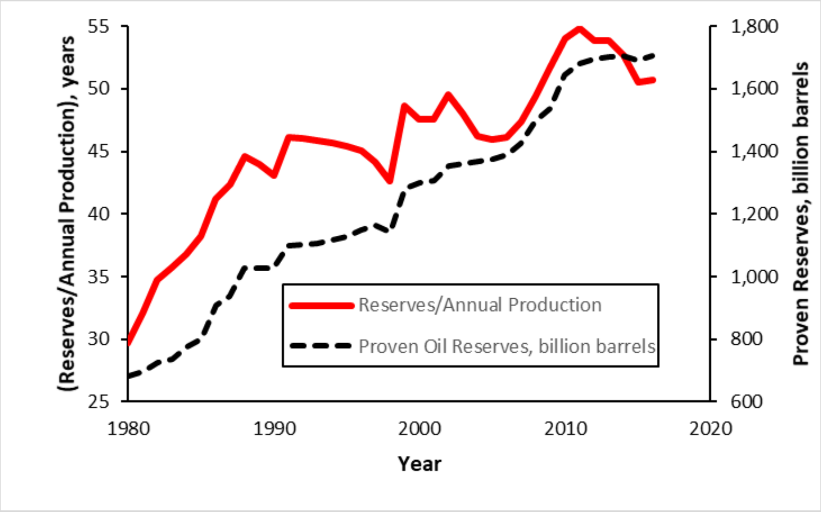


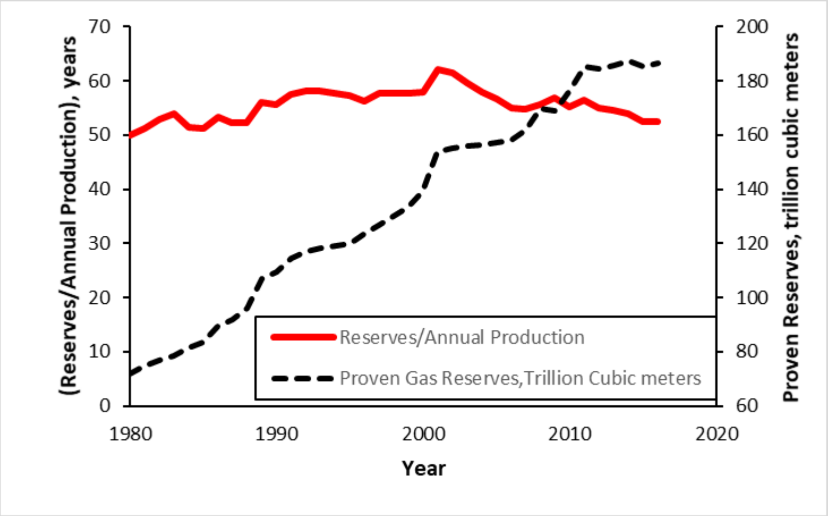


2013 International Energy Outlook, U.S. EIA
http://www.eia.gov/forecasts/ieo/index.cfm

- Share of hydrocarbons (oil, gas, coal) 83% in 2016, 79% in 2040
- Global per capita consumption of hydrocarbons is ~1.5 tons/y
- End of 2016, wind ~ 1.6 %, solar ~ 0.56%, Nuclear ~ 4.5 %, Hydro ~ 6.8 % of total energy demand (13276 million BOE) – BP Statistical Survey 2017
- Coal produces 40% of electricity globally (http://www.iea.org/topics/coal/)
- Still 2.6 billion people rely on biomass for their energy and 1.3 billion people have no access to electricity (Exxonmobil 2014 and 2013 Energy outlook)

Global Hydrocarbon Resources

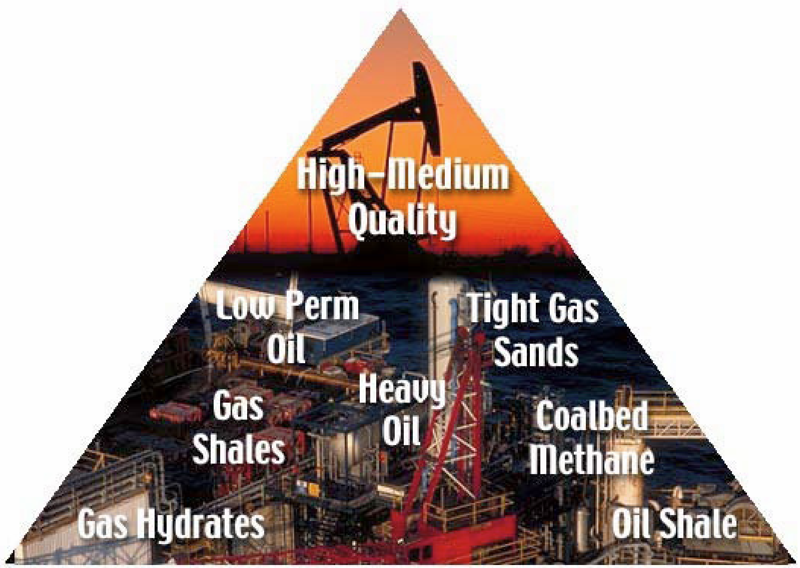




Source: BP Statistical Survey 2017

- EIA estimate of global shale gas reserves in 2013 – 207 trillion cubic meters (http://www.eia.gov/analysis/studies/worldshalegas/)
- Global coal reserves will last 110-132 years at current consumption rates (http://www.worldcoal.org/resources/coal-statistics/)
- Unconventional hydrocarbons

Conventional and Unconventional Hydrocarbons



Conventional – High quality, easy to recover, small volumes
Unconventional – Low quality, difficult to recover, very large volumes. Improved technology, higher price for conventional needed. Environmental issues.

http://www.npc.org/Study_Topic_Papers/29-TTG-Unconventional-Gas.pdf

Oil sands (sand+clay+water+ bitumen) – Canada ~170 billion barrels -98% - of total reserves (http://www.eia.gov/countries/cab.cfm?fips=CA), [Saudi Arabia (265 bb)]

Heavy oil – Venezuela, Russia

Oil Shale – China, U.S.

Coal Bed Methane (CBM) – methane held in coal by water pressure (~7% of NG prod in US)

Known deposits are 3-4 times bigger than known deposits of conventional oil and gas (excluding gas hydrates).

Climate Change and COP 21

- Most countries have put in their voluntary INDCs (Intended Nationally Determined Contributions)
- A few countries (e.g. EU) have targets to reduce CO2 below historic levels.
- Many countries explicitly reject CO2 caps(e.g. India, China, Saudi Arabia),intend to use energy more efficiently and increase investments in renewables
- There will be a review in 2020 to make the targets more ambitious.
- Commitments are non-binding and no independent verification
- Climate fund ($100 billion per year by 2020) issue not clearly resolved
- Even if current INDCs are fully honored, the 2° C target will not be met by a long way
- Other signs also not promising – low fossil fuel prices, "climate justice", development priorities, politics (U.S., EU) and legal issues….

How will the world manage energy in the future? - An optimistic view

Technology and human ingenuity will ensure that future energy demands will be met fairly, cleanly and peacefully

- Conservation of energy and resources /efficiency improvements
- Development of renewables and sustainable biomass
- Conservation of forests
- CO2 sequestration (?)

Energy Requirement and Security cannot be ignored

- Unconventional fossil fuels – heavy oil, oil sands, shale, coal bed methane
- New oil production techniques
- More oil fields
- Development of clean coal technology
- Nuclear energy

Transport

Introduction - I

Transport is central to modern society and demand for transport energy is very large

Globally, it accounts for

- 14% of global GHG (CO_2, methane and nitrous oxide) emissions, 20% of total energy use, 23% of CO_2 emissions
- Currently over 1.1 billion light duty vehicles (LDVs) and 255 million commercial vehicles
- Over 4.8 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.
- LDVs account for ~44% of global transport energy demand

Petroleum and transport closely linked

- Transport is essentially driven by liquid fuels – high energy density, ease of transport and storage, extensive infrastructure
- 95% of transport energy from petroleum
- 60% of petroleum goes to transport fuels

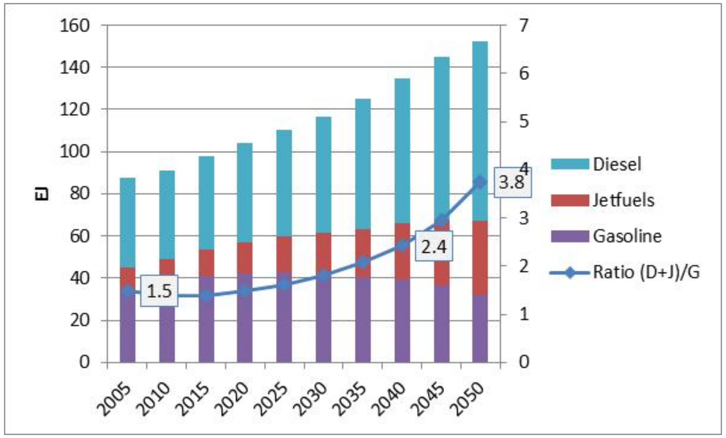
Demand for transport energy is growing at an average annual rate of ~1 %

- In non-OECD countries

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



WEC Freeway Scenario (http://www.worldenergy.org/wp-content/uploads/2012/09/wec_transport_scenarios_2050.pdf

- Will require large investments in refineries
- Greater availability of low octane gasoline components

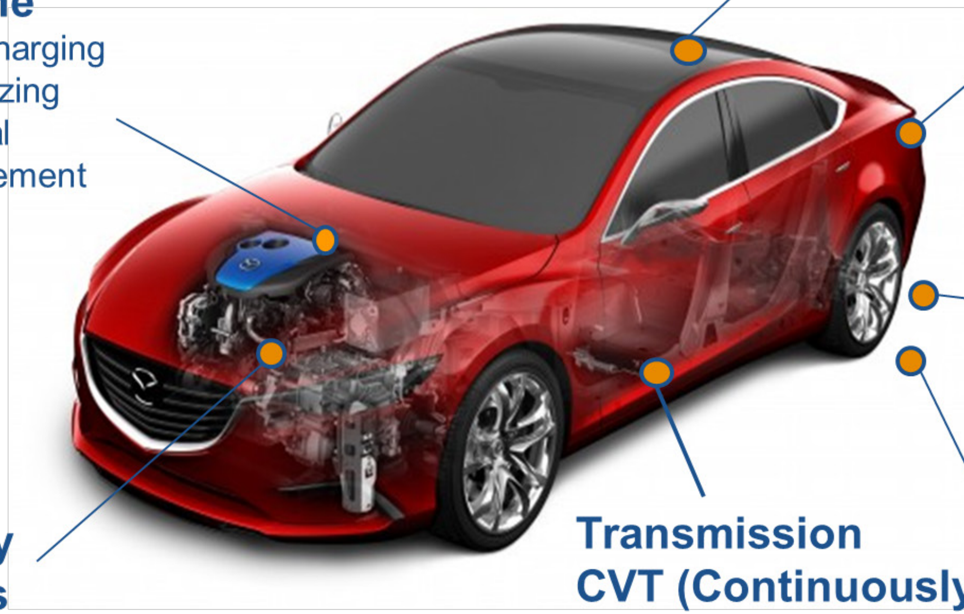
- Even by 2040, transport will be dominated by combustion engines85%- 90% of transport energy will come from oil (World Energy Council, U.S. EIA)\
- Imperative to improve such engines to improve the sustainability of transport

Technology Trends - Vehicles

Engine
Turbocharging
Downsizing
Thermal management

Improved Aerodynamics

Vehicle Weight Reduction



Hybridization
Regenerative Braking

Auxiliary Systems Efficiency
Air Con
Lighting

Transmission
CVT (Continuously Variable Transmission)
Down speeding

Improved Tires

Technology Trends - Engines

SI Engines - Main trend towards improving efficiency

Minimize throttling, improve knock resistance

- Downsizing/turbo charging
- Electric Hybridization
- Pressure to increase octane quality of gasolines

CI Engines – Main trend towards reducing soot/NOx at high efficiency

- Increased cost and complexity

Enabling technologies

- Battery technology
- Weight reduction/new materials
- Low temperature oxidation catalysts
- Lean NOx catalysts

Great potential for co-optimizing engine/fuel systems simultaneously

- Gasoline Compression Ignition (GCI) - Run CI engines on low-octane gasoline
- Octane on Demand (OOD) – Best use of available fuel octane quality

+ Demand Management

Electrification of Transport

Electric Vehicles - Different Degrees of Electrification

	Conventional Car	Hybrid TOYOTA *Prius*	Plug-In Hybrid CHEVROLET *Bolt*	Electric Vehicle NISSAN *Leaf*
Total Range	350 miles	450 – 550 miles	330 – 370 miles	100 miles
Electric Range	None	< 2 miles	30 – 70 miles	100 miles
Gasoline Range	350 miles	450 – 550 miles	300 miles	None
Re-fueling	Fill-up	Fill-up	Plug-In (daily use) Fill-up (long trips)	Plug-In
Price Premium	Base	\$2,000 - \$5,000	> \$8,000	> \$15,000

- Batteries and associated electronics are expensive
- HEVs have all their power coming from ICEs and gasoline and PHEVs some to most of the energy from gasoline
- Only BEVs do not have an ICE and all their energy comes from the electricity grid

Electrification of LDVs will increase very significantly in the future – in the form of HEVs and maybe PHEVs but unlikely to be BEVs

Outlook for Electrification

▪Global sales of EV (BEV +PHEV) rapidly increasing ~ 1.2 M in 2017 (less than 1.5%)
By the end of 2017, global stock was, 3 M, 0.25% of total passenger cars (http://insideevs.com/)

- In 2040, LDV numbers expected to be 1.7-1.9 billion
- If 20% of these are to be EVs, their number needs to increase by a factor of over 120. But this still addresses less than 8% of transport energy demand
- What will be the environmental consequences?
- Will there be supply issues – for cobalt and lithium?
- Will people buy BEVs even if they are more expensive, difficult and slow to charge, have shorter range?
- Will governments put in the large prior investments needed if they want to force such a change?
- Other economic, social, ethical consequences?

Greenhouse gas (GHG) and other pollutants

- GHG impact depends on how electricity is generated. In many parts of the world, certainly India and most of China BEVs will cause more (50% more in China) GHG than ICEV.
- India has reiterated that 75% of its electricity will come from coal for decades to come.
- If BEVs are charged at night, no solar - fossil fuel electricity used
- PM2.5, NOx and SO2 also will be worse if coal is a source of power.
- Human Toxicity Potential –"All other secondary environmental measures pale in comparison with the potential impact BEVs have on human health. … the decision to drive a BEV instead of an ICEV essentially shifts the damage to human life caused by car ownership, from a relatively small impact more localized to the vehicle in the case of an ICEV, to a relatively large impact localized to the mineral mine tailings in the case of a BEV…." http://www.adlittle.de/sites/default/files/viewpoints/ADL_BEVs_vs_ICEVs_FINAL_November_292016.pdf

Full electrification not relevant to most commercial transport

- Tesla S – 85 kWh battery pack weighing 544 kg. Cost $180/ kWh. With the 120 kW Tesla supercharger charging time 60-75 minutes
- 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 26,370 liters of fuel. A battery pack carrying the same energy would weigh 1640 tons – 21 times the max take off weight
- 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 car on call for 24 hours with a 50 kWh battery cannot not go anywhere!

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 and they all wanted to charge at the same time 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 ethanol 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

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. 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 many of these constraints to be broken. 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 basis though some changes may be forced

Gasoline Compression Ignition (GCI) – an example of fuel/engine system development

- CI engines are the most efficient IC engines but use diesel fuel
- Particulates and NOx emissions causing more concern and standards are getting more stringent
- Conventional diesel fuel ignites easily, before it has a chance to mix with oxygen in the cylinder giving high particulates and NOx
- Advanced diesel engines are expensive and complicated because they are trying to control particulates and NOx while using conventional diesel fuel
- Control of particulates and NOx much easier with fuels with high ignition delay - “Gasoline-like” Fuels

Gasoline Compression Ignition (GCI) – Inject “gasoline” in a “diesel” engine much earlier in the cycle compared to diesel fuel

- Higher ignition delay allows more time for mixing before combustion
- But optimum fuel is lower octane (70-80 RON) than current gasoline and requires much less processing and has a lower GHG footprint

GCI – Advantages and Outlook

- Gasoline Compression Ignition (GCI) has following advantages

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

- Initially GCI has to run on market fuels but later on less-processed fuels
- Development work needed – starting, optimisation of injectors and injector strategy, transients, sufficient boost pressures at high EGR levels, lower temperature oxidation catalysts …
- Maybe particularly suited to countries like India and China – rapid increase in demand for diesel and jet fuel; less investment in existing diesel technology…
- All stakeholders need to work together to bring such optimized fuel/engine systems to the market

Summary

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 only by improving ICEs
- More diesel and jet fuel needed compared to gasoline AND increase in octane of gasoline pool
- Great challenge to the refining industry – huge investments (100s of billions of $) 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