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

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## HIGHLIGHTS

- Demand for transport is large, growing, powered by combustion of petroleum fuels.
- All alternatives start from a low base and cannot grow rapidly or without restraint.
- Forced rapid change will incur large environmental, economic and social costs.
- Transport will be powered mostly by combustion engines/petroleum for decades to come.
- Limited electrification as hybridization will help combustion engines to improve.

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ABSTRACT

Transport is almost entirely powered by internal combustion engines (ICEs) burning petroleum-derived liquid fuels and the global demand for transport energy is large and is increasing. Available battery capacity will have to increase by several hundred fold for even light duty vehicles (LDVs), which account for less than half of the global transport energy demand, to be run on electricity alone. However the greenhouse gas (GHG) impact of battery electric vehicles (BEVs) would be worse than that of conventional vehicles if electricity generation and the energy used for battery production are not sufficiently decarbonized. If coal continues to be a part of the energy mix, as it will in China and India, and if power generation is near urban centers, even local urban air quality in terms of particulates, nitrogen oxides and sulfur dioxide would get worse. The human toxicity impacts associated with the mining of metals needed for batteries are very serious and will have to be addressed. Large prior investments in charging infrastructure and electricity generation will be needed for widespread forced adoption of BEVs to occur. There will be additional costs in the short term associated with various subsidies required to promote such a change and in the longer term, the loss of revenue from fuel taxes which contribute significantly to public finances in most countries. ICEs will continue to power transport, particularly commercial transport, to a large extent for decades to come and will continue to improve. There will also be a role for low-carbon and other alternative fuels where they make sense. However such alternatives also start from a low base and face constraints on rapid and unlimited growth so that they are unlikely to make up much more than 10% of the total transport energy demand by 2040. As the energy system is decarbonized and battery technology improves there will be an increasing role for BEVs and hydrogen which could replace liquid hydrocarbons in transport and the required infrastructure will evolve. Meanwhile, there will certainly be increasing electrification, particularly of LDVs in the form of hybridization to improve ICEs.

## 1. Introduction

The transport of goods and people accounts for about 20% of the total global primary energy consumed, around 23% of $CO_2$ emissions and if other greenhouse gases (GHG) such as methane are taken into account, around 14% of the total global GHG emissions [1–3] which, at around 7 billion tonnes of $CO_2$ equivalent, is almost the same as that from livestock farming [3,4]. The world has around 1.2 billion passenger cars and 380 million commercial vehicles [5] and these numbers are expected to increase, almost entirely in non-OECD countries like China and India [5,6]. Transport is almost entirely (> 99.9%) powered by internal combustion engines (ICE) – land and marine transport primarily by reciprocating ICE and air transport by jet engines. Liquid fuels have become the fuel of choice for transport because of their high energy density and ease of transport and storage and a very large global infrastructure has been built over the past century to

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**Table 1**
Daily global demand for oil products for the latter part of 2017 [9]

| | Million Barrels of oil Equivalent (BOE) | | | Energy, exajoules | Fuel volume, billion liters |
|---|---|---|---|---|---|
| | OECD | Non-OECD | Total | | |
| Total | 47.4 | 50.7 | 98.1 | 0.601 | |
| Gasoline | 14.5 | 11.3 | 25.8 | 0.158 | 4.85 |
| Diesel/Gasoil | 13.7 | 14.6 | 28.4 | 0.174 | 4.83 |
| Jet/Kero | 4.3 | 3.2 | 7.5 | 0.046 | 1.27 |
| Residual Fuel oil | 2.1 | 5.4 | 7.5 | 0.046 | |
| Other[a] | 12.8 | 16.1 | 28.9 | 0.177 | |

[a] Other includes naphtha, LPG and ethane. 1 exajoule = $10^{18}$ Joules = 277,778 giga-watt hours = 163.4 million BOE.

support this system. Currently around 95% of transport energy comes from liquid fuels derived from petroleum and around 60% of all oil produced goes to make transport fuels [1,2,6,7,8]. Light duty vehicles (LDVs), mostly passenger cars, essentially run on gasoline and account for around 44% of the global transport energy demand [2] which is very large. Table 1 shows a snapshot of the average daily demand for oil products in the latter part of 2017 [9] in terms of million barrels of oil equivalent (BOE). The equivalent energy content, assuming 1 exajoule equals 163.4 million BOE, is shown in the penultimate column of Table 1. Then assuming a volumetric energy content of 32.5 MJ/l for gasoline and 36 MJ/l for diesel and jet fuel, the world needs over 4.8 billion liters of diesel as well as gasoline and around 1.3 billion liters of jet fuel each day. This demand is expected to grow at an average annual growth rate of around 1% [2,6], primarily in non-OECD countries, in spite of the significant improvements in transport efficiency expected in the future. Moreover, the demand for diesel and jet fuel which mostly power commercial transport is expected to grow faster than the demand for gasoline because there is much more scope to reduce fuel use in LDVs [6–8]. The supply of low-octane gasoline components such as naphtha will increase proportionately in the future as more oil is processed to meet diesel and jet fuel demand. The availability of such components will increase since they are used to make gasoline, the demand for which will not increase at the same rate. In any case, could this massive and increasing demand for transport energy be met entirely by powertrains which do not rely on combustion?

There is much current interest in electric vehicles. Many governments have announced the desire to eventually ban cars powered by ICEs, though it is often not clear if the intention is to ban *all* ICEs or ban vehicles with *only* ICEs without any electrical assistance. In any case, this has led to a belief in some quarters that all transport can and will be powered only by electricity and the ICE will quickly disappear [10] even leading to the quick demise of the oil industry [11]. The other, perhaps longer term, alternative to the ICE is the fuel cell powered by hydrogen which requires a credible global hydrogen infrastructure to be built.

Currently, the main alternatives to petroleum based fuels are biofuels, compressed natural gas (CNG) and liquid petroleum gas (LPG), which together contribute around 5% of total global transport energy. The share of electricity is small and of hydrogen or synthetic fuels, negligible. There are many initiatives across the world to develop such alternatives – particularly electricity. Amongst the drivers for change, which will be of different importance at different times in different countries, for such policies are–

(a) Energy security concerns/reduction of oil imports.
(b) Growing local air quality concerns – in many urban centers transport is a major source of pollution
(c) Climate change concerns – decarbonizing transport energy to reduce $CO_2$ emissions

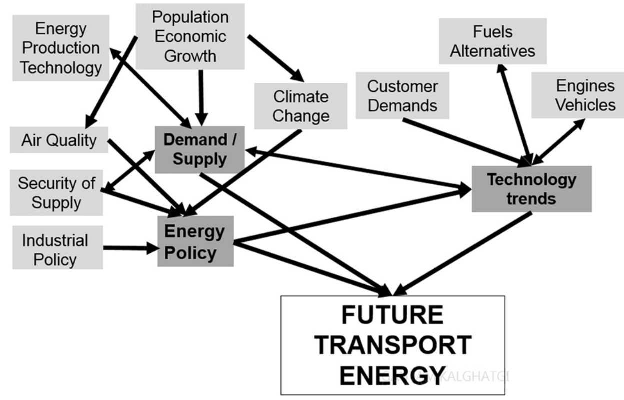


**Fig. 1.** The evolution of transport energy is determined by the complex interplay between many drivers.

(d) To support farmers and increase rural employment by finding a use for agricultural surpluses e.g., in biofuels and bio waste management
(e) Desire for leadership in new technology e.g., the Chinese government policy on "new energy" vehicles

The evolution of transport energy, like all energy, depends on the complex interplay between many such drivers as illustrated in Fig. 1 and will be very different in different parts of the world. As discussed in this review, all the alternatives start from a very low base and have constraints on rapid and unlimited growth. Hence credible projections suggest that even by 2040 around 90% of transport energy will come from combustion engines powered by petroleum [2,6–8].

## 2. Electrification of transport

There are different degrees of electrification, currently based on the lithium ion battery [12] which, along with the associated power electronics, is the single most expensive component and its size and cost depend on the degree of electrification.

Only pure electric or battery electric vehicles (BEVs) derive all their energy from electricity. All other 'electric' vehicles have hybrid powertrains and derive some or all of their power from an ICE. Different degrees of hybridization ranging from simple start/stop systems to full hybrids enable fuel saving to different degrees. In full Hybrid Electric Vehicles (HEVs), such as the Toyota Prius, all the energy comes from the ICE; a battery and an electric motor manage the energy flow through the system to enable the ICE to run more efficiently and also to recover energy lost in braking. HEV technology is primarily relevant to SI engines in stop/start city driving. Diesel engines, which are already very efficient, will not benefit as much as SI engines from hybridization though hybridization could enable recovery of energy lost in braking and downsizing to some extent. HEV technology is expected to become very widespread since it offers car manufacturers a proven way to reduce fuel consumption and $CO_2$ emissions to meet the stringent targets set by many governments. In series hybrids, the ICE is not connected to the wheels but simply serves to charge the battery which provides the energy to the motor/s which drive the vehicle. Thus even in a series hybrid, all the energy comes from the ICE. Diesel-electric series hybrids are commonly used in locomotives and ships.

BEVs such as the Nissan Leaf, require much larger batteries and power electronics and hence are much more expensive. Plug-in hybrid electric vehicles (PHEVs) carry an ICE which extends the vehicle range and will use conventional fuel if they travel beyond the battery-powered range of around 40 km. A PHEV has a smaller battery compared to a BEV but also has a parallel hybrid transmission system. If the battery-enabled range in a PHEV is small, there might not be much incentive for PHEV owners to actually plug in their cars to the electricity grid and the cars will run as a normal HEV on the ICE.

There are many constraints on the rapid and large expansion in the number of BEVs as discussed below but electrification in the form of hybridization is expected to spread very rapidly in the future.

### 2.1. Environmental impacts of BEVs

BEVs produce no pollutants such as particulates, nitrogen oxides (NOx), carbon monoxide (CO) and unburned hydrocarbons (UHC), at the tailpipe. However, the impact of BEVs on greenhouse gases (GHG) depends entirely on how the electricity used to power the BEV is produced [13–31]. In addition, high levels of GHG emissions are associated with battery manufacture depending on the GHG intensity of the energy used and could be as high as 200 kg $CO_2$ eq/kWh [27] and for a BEV with a large battery, could constitute a significant portion of the GHG emissions over its life [23–29].

In China and India where transport energy demand is growing faster than elsewhere, the share of coal in electricity generation and hence its carbon intensity is very high. In fact India has reiterated recently that coal will continue to produce roughly three-quarters of India's electricity for decades to come [32]. In China, with the current energy mix, GHG emission associated with the production of BEVs is around 50% higher than that for a comparable ICEV [29]. In areas using significant amounts of coal for power generation such as India and China, on a life cycle basis, BEVs can actually have higher total $CO_2$ impact than similar ICE vehicles [16,19,20,25,31] and it is counterproductive to promote BEVs until the power sector is sufficiently decarbonized [19,25]. The HEV is a better option to reduce GHG emissions rather than the BEV in such areas [17,20,22,25,31].

The extra demand for electricity from BEVs is often met from marginal generation which can quickly respond to changing demand and usually comes from fossil fuels – solar is not available at night and like wind and hydro power, its output cannot be changed at will [15,31]. The carbon intensity as well as other emission impacts of this marginal electricity generation are higher compared to the average value even when renewables are a part of the electricity generation mix. In the U.S., since coal is still used in power generation, the extra emissions ($CO_2$ and $SO_2$) released as a result of charging BEVs at night can cause 50 percent higher costs to human health and the environment compared to using "average" electricity [31].

Moreover, if electricity generation is near urban centers, as in Beijing, and if coal is part of the energy mix, the impact of PM2.5 (fine particulate matter less than 2.5 μm in diameter), sulfur dioxide ($SO_2$) and NOx on urban air quality is much worse for BEVs compared to ICEVs [30]. Even after the very significant cleaning up of power generation near Beijing that is anticipated in the coming years, for instance by reducing the use of coal and the use of NOx after-treatment, PM2.5, NOx and $SO_2$ are still expected to be worse for BEVs compared to HEVs in 2030 [30]. A study centered on the U.S. [24] concluded that depending on where the vehicle is driven – driving a BEV may actually cause more widely-dispersed and damaging emissions (of NOx, SO2 and PM2.5) associated with electricity generation than driving a similar ICEV, though there could be benefits for GHG emissions.

BEVs have a very significant impact on human toxicity, freshwater eco-toxicity and freshwater eutrophication, primarily caused by the production of metals required for batteries [24–26] even if the energy system supporting BEVs is completely clean and green. In one study [26], the human toxicity potential (HTP) of a BEV has been estimated to be three to five times worse compared to a similar sized ICEV which impacts human health via exhaust pollutants. These issues have probably not attracted the attention they deserve because all this serious pollution is exported to faraway places such as the Democratic Republic of Congo (DRC) where the metals like cobalt are mined and BEV numbers are currently small.

### 2.2. Full electrification is relevant primarily to the small passenger car sector

The limitations on the battery size, because of energy density and cost, currently limit the use of electrification essentially to the small passenger car sector. Full battery electrification is not practical or desirable for commercial transport as discussed below.

For reference, in the Tesla S series, the 85 kWh battery pack weighs 1200 lb (544 kg) and takes around an hour to charge fully on the 120 kW Tesla Supercharger [33]. So the battery pack energy density is 155 Wh/kg and current battery costs are around $190/kWh [34]. There is expectation, sometimes invoking Moore's law for microchip development, of a significant improvement in the energy density and the cost of batteries in the future. However, battery capacity cannot improve very much more unless some new battery chemistry, other than lithium ion, is invented and commercially deployed [35]. This is because ions in a battery do take up space, unlike electrons in a microchip, and battery performance is dictated by the thermodynamics of the relevant chemical reactions [35]. Outside the microchip-dominated world, innovation does not obey Moore's Law and gains in performance and reductions in cost in the fields of materials, energy and transportation range from 1.5 to 3 percent a year [36]. We will assume values of 180 Wh/kg and $125/kWh for the energy density and cost of the battery pack in the discussion below.

Consider a heavy duty 80,000 lb (36 metric ton, MT) Class 8 truck in the U.S. with a 500 mile range, like the Tesla Semi truck. The average, real-world fuel consumption of Class 8 U.S. trucks is 35.3 l/100 km [37]. So over 500 miles, the truck would use 282 l of fuel or 2820 kWh of fuel energy. Assuming a brake thermal efficiency of 42% [38] for the diesel engine, around 1180 kWh would be transferred to the wheels. However, power demand can be reduced by a further 20% by better aerodynamics and so on as demonstrated by the SuperTruck program [38]. These technologies would be available to the electric truck as well so that the energy demand could be reduced to around 950 kWh. Assuming a battery to motor efficiency of 95%, the battery will have to store at least 1000 kWh of energy and weigh at least 5.5 MT compared to around 1.3 MT for a typical diesel engine for such a truck; cost at least $125,000 while an entire Class 8 truck costs around $100,000; and with the Tesla Supercharger would take around 12 h to charge. A recent paper [39] calculating the energy requirement from first principles suggests a minimum battery pack capacity of at least 1100 kWh for such a truck with higher weight and cost than calculated above. Figures as low as 800 kWh for the battery pack can also be found on the internet for the Tesla Semi truck but seem unrealistically low. So even though a battery electric long-distance heavy duty truck is technically feasible it may not be practical – the capacity of the truck to carry goods will be reduced, the cost will be high and the charging time will be too long. Energy consumption per unit of load carried will increase because of the reduced payload capacity. If deployed in large numbers on a global scale, there would be very serious environmental impacts associated with battery manufacture. In contrast, electrification via the e-highway concept where the truck draws electricity while in motion [40] might be an option for commercial transport in the future if and when the required infrastructure is built. Of course, "e-highways" already exist in the form of existing railway lines which have been electrified. Electric city buses and delivery vans with shorter ranges and easier access to recharging would be practically feasible and address urban air quality concerns, though very expensive.

Suggestions about purely electric air and bulk long-range marine transport are also not credible. Table 2 lists, for illustration, the maximum take-off weight and the volume of fuel carried by three different types of commercial aircraft – a small commuter jet (Embraer 135 [41]), a medium-haul jet (Airbus A320 [42]) and a long-haul jet (Airbus A380 [43]). Assuming the density and energy content of jet fuel to be 0.81 kg/l and 44.3 MJ (12.3 kWh)/kg respectively, the weight and energy content of the fuel is calculated and shown in the next two columns of Table 2. With the energy density of the battery pack at 0.18 kWh/kg,

**Table 2**
Fuel capacity and equivalent battery pack size for three different types of aircraft.

| | Maximum Take-off Weight (MTOW), kg | Volume of fuel, liters | Weight of fuel[a], kg | Energy content of fuel (ECF)[a], MWh | Weight of battery pack with the same ECF[b] (WBP), kg | WBP/MTOW |
|---|---|---|---|---|---|---|
| Embraer 135 [41] | 20,000 | 5146 | 4168 | 51 | 284,831 | 14 |
| Airbus A320 Neo [42] | 76,000 | 26,730 | 21,651 | 266 | 1,479,506 | 19 |
| Airbus A380-800 [43] | 576,000 | 323,545 | 262,071 | 3223 | 17,908,216 | 31 |

[a] Assuming density of 0.81 kg/l, Energy content of 12.3 kWh (44.3 MJ)/kg for jet fuel.
[b] Assuming 0.18 kWh/kg for battery pack energy density.

about 68 times lower than that of jet fuel, the weight of the battery pack alone would be 14, 19 and 31 times the maximum take-off weight for the three aircraft types considered as shown in the last column of Table 2. Even if some new battery chemistry is invented in the future to make the energy density of the battery pack comparable to that of jet fuel, the charging times would be prohibitively long. For instance, even at an improbable 10 MW charging rate (the Tesla Supercharger works at 0.12 MW), the Airbus A320 would need over a day to acquire the electrical energy equivalent to that in the fuel.

The large container ship, Benjamin Franklin carries 4.5 million gallons of fuel [44] i.e. around 170 million kWh of fuel energy – a battery pack to hold that much energy would weigh over a million MT, around 5.8 times the dead weight tonnage [45] of the ship and would take nearly two years to charge at a rate of 10 MW.

### 2.3. Impact on the power sector and charging infrastructure of full electrification

Changes to electricity generation and distribution will also be required if the aim is to replace conventional cars by BEVs. Smil [46] estimated that to convert the whole U.S. passenger car sector to electricity would require 25% additional electricity generation. The implication for peak power are more serious. For instance, currently there are 32 million or so cars and vans registered in the U.K. [47] and the National Grid in the U.K. estimates that by 2030, if the number of BEVs increased to 9 million and if they all decided to charge at once, the peak electricity demand would be around 8 GW higher [48]; for comparison, the new Hinkley Point power station has a capacity of 3.3 GW and is expected to cost around £20 billion. In any case too many domestic charging points would overstress the electricity network [48]. For instance even one electric vehicle charging in a residential distribution network of six households could raise peak loads enough to reduce the expected transformer life [49]. Such high power demand can be mitigated by developing a smarter grid which does not allow all the cars to charge at the same time but this will also need large investments. Moreover, in the U.K., 43% of car owners have to park on the road [48] and would need access to public charging points. Some estimates suggest that the U.K. could need up to 2.5 million new public charging points costing up to 87 billion Euros [50]. Even if BEVs become comparable in cost to ICEVs, quick and convenient charging facilities will be essential to persuade people to buy them. A 350 kW charger would charge a comparatively small 30 kWh battery to 75% capacity in 5 min which is comparable to refueling times for ICEVs. However, with current Li-ion battery technology, such fast charging rates over many charging cycles reduce the battery life and increase the risks of fire [12]. Thus, any significant forced penetration of electricity in the transport sector would require large prior investments in additional power generation and charging infrastructure and new approaches to grid management [48,51].

### 2.4. Other economic consequences of full electrification

Currently BEVs are subsidized by the tax payer in many ways [51]. Such incentives will be needed till BEVs become competitive with ICEVs on cost and convenience but will not be affordable as BEV numbers grow. In many countries, fuel tax is a major contributor to public finances. Governments will have to find ways of recouping these taxes, perhaps by taxing electricity or imposing a mileage tax, increasing the total cost of ownership of the BEV [51].

### 2.5. Security of supply of materials needed for battery production

There is some concern about the security of supply of lithium needed for the batteries. The extraction process is laborious and the reserves, though abundant, are concentrated in a few countries like Australia, Chile and Argentina and the current production is mostly in China. These countries might be unable or unwilling to ramp up the production rates sufficiently to meet increasing global demand [52]. Lithium prices have been increasing – the price of lithium in April 2018 was $16.5/kg compared to the average price in 2016 of $7.5/kg [53]. The Democratic Republic of Congo (DRC), which faces political instability and has questionable mining practices, is the main source of cobalt and the refining focus is in China [52]. There have already been stories in the mass media connecting the plight of children working in cobalt mines in the DRC to EVs [54]. Compared to its average price of around $24/kg in 2016, the price of cobalt in April 2018 was $93/kg [53]. Such price increases of materials, which account for around 80% of the battery pack cost [52], will make it more difficult for battery pack costs to come down. Serious issues associated with the social, ethical, economic and environmental impacts of production of these metals will also loom much larger as the number of BEVs increases.

### 2.6. Recycling batteries

As the number and size of batteries grows with the number of BEVs, recycling of the batteries will become increasingly important to salvage material to reduce the impact on the supply chain and safely dispose of waste. Li-ion battery recycling is particularly complicated because of the way they are assembled and because the battery packs will vary in shape and will be large and heavy and contain many different materials. Very many details need to be worked out to set up a viable recycling system [52,55]. Since even a small car like the Nissan Leaf with a short range has a battery pack weighing 218 kg, the weight of materials to be handled will be exceptionally large.

### 2.7. Autonomous driving and BEVs

It is also believed that autonomous (driverless) car technology will help the deployment of BEVs [11]. However, the sensors, additional computing and data processing needed by fully autonomous cars will require an additional 1.5 kW to 2.75 kW of power [56]. Also, the car will need heating in the winter and air-conditioning in the summer, which would require 1–5 kW of power depending on the ambient temperature and the size of the vehicle. If an autonomous car being used for taxi service/ride sharing in a city is expected to be on call for 24 h a day and has a 50 kWh battery, the additional energy requirement over 24 h would be more than its battery capacity before it travels any distance at all. In fact a more sensible option for autonomous driving, even if this technology were to become practical in the future, would be an HEV or a PHEV with regenerative braking, not a BEV [56].

### 2.8. Deployment and outlook for BEVs

There has been a very rapid growth in the numbers of BEVs and PHEVs over the past few years as more manufacturers have introduced more choice and governments have tried to promote the technology. However, this growth has been from a very low base and the estimated number of BEVs and PHEVs worldwide was around 3 million, accounting for less than 0.25% of the global LDV numbers at the end of 2017 [51,57]. The number of LDVs across the world is expected to be 1.7–1.9 billion by 2040 [6,7]. So to replace all LDVs by BEVs across the world by 2040 would require a 600 fold increase in their number. If these future LDVs also include larger cars with longer ranges compared to today's BEVs, the battery capacity and the raw materials required will have to grow even more. As discussed above, such a rapid and enormous increase in global BEV numbers will increase the demand for materials used in batteries to unsupportable levels, have significant detrimental environmental impacts and will require large investments in charging infrastructure and additional clean electricity generation.

## 3. Hydrogen fuel cells

If hydrogen is used to power transport, it will most likely be used in a fuel cell because of its higher efficiency. Refueling is expected to be quicker and the range will be longer for a fuel cell vehicle (FCV) compared to a BEV. Hydrogen can be made from many different sources (biomass, natural gas, coal) and could contribute to energy security and diversity. However, currently FCVs, which also need to be full hybrids, are very expensive. The storage tank on the vehicle alone costs \$3000–\$4000 [58].Though hydrogen fuel cell cars such as the Toyota Mirai are commercially available, their numbers are negligible. The true cost of a Mirai, including losses absorbed by Toyota and the subsidies given by governments is probably well over \$125,000 though the car is sold to the customers in Europe at around \$75,000 [59]. The main barrier to any significant and quick growth of FCV numbers is the development of a hydrogen infrastructure.

Hydrogen, like electricity, is an energy carrier. Its production requires a lot of energy [58,60–62]. If this energy is not renewable or $CO_2$–free (e.g. nuclear) the $CO_2$ emissions from a hydrogen car will be higher than for a conventional car [23,60]. The cheapest sources of hydrogen are natural gas and coal but using these will produce $CO_2$ and will require $CO_2$ capture and storage to reduce $CO_2$ emissions. It can also be made from water using electricity. Decentralized hydrogen production is the best choice for market uptake and for avoiding a costly distribution infrastructure but is less efficient and costs more than large-scale, centralized production [58,61]. Biological means of production have not progressed beyond the research phase.

The volumetric energy content of Hydrogen gas is around 3100 times lower compared to gasoline at normal pressure and temperature. It has to be compressed to very high pressures (up to 700 atmospheres) or liquefied by bringing its temperature down to $-253^{\circ}$ C in order to carry enough mass on a vehicle to get a reasonable range. This requires a lot of energy e.g, liquefaction might consume up to 40% of the energy contained in the hydrogen in the first place. Both approaches pose big problems for carrying it on a vehicle [58,61,62].

Transporting, storing, and delivering hydrogen to the point of end-use is costly because of the high pressure or very low temperature (for liquid hydrogen) needed. Global investment to supply hydrogen for transport has been estimated [58] to be in the range of several hundred billion dollars over several decades (\$0.1–\$1.0 trillion for pipelines and \$0.2–\$0.7 trillion for refueling stations). Substantial research and investment in transport infrastructure design and implementation, running to hundreds of billions of dollars over several decades [58,61] will be needed before commercial hydrogen supply may become a reality. There are also some concerns associated with the wide flammability limit of hydrogen.

It is highly unlikely that hydrogen will become a viable fuel for transport in the next two or three decades. It has to overcome very significant barriers in production, storage, distribution and cost.

## 4. Further development of ice and new fuel engine systems

ICEs continue to improve as better combustion, after-treatment and control systems are developed. However, there is even more scope to develop highly efficient, affordable, safe engines to meet increasingly stringent requirements on local air quality and GHG emissions if the fuel and engine are co-developed as a system rather than focus on engine development using market fuels.

For instance modern diesel engines are compression ignition (CI) engines and are very efficient but expensive and complicated because they have to control particulates and NOx while using diesel fuel because this requires very high injection pressures and complicated after-treatment systems. In Gasoline Compression Ignition (GCI) a CI engine is run on low-octane gasoline. This makes it significantly easier to control particulates and NOx [63] because the fuel does not ignite as quickly as diesel and will have more time to mix with oxygen in the cylinder before combustion starts thereby almost eliminating soot formation. NOx can then be controlled by using exhaust gas recirculation (EGR). Such a low-octane fuel would need much less processing in the refinery compared to conventional diesel or gasoline and is expected to be more easily available in the future. The GHG impact of a GCI engine, on a well-to-wheel basis, could be around 30% lower compared to an equivalent SI engine and around 5% lower, mostly originating from fuels manufacture, compared to an equivalent conventional diesel engine [63]. However, the engine would be simpler and cheaper than the modern diesel engine because of lower injection pressures and simpler after-treatment. The GCI concept has been well-demonstrated in research engines but development is needed to make it feasible on practical vehicles e.g. on cold start, high pressure rise rates at high loads, transients and UHC and CO emissions. Such development is likely to be easier compared to what has already been required to overcome the difficulties presented by using diesel fuel in diesel engines. In the longer term it will also require the availability in the market of a new, albeit a simpler fuel. The recently announced Mazda SkyAktiv engine [64] follows a similar principle.

Reactivity Controlled CI (RCCI) is another technology that is being developed to get high, diesel-like, efficiency but with very low soot and NOx [65] while using fuels currently available in the market. A fuel that is resistant to autoignition such as gasoline or ethanol or natural gas is injected in the port and the mixture is ignited by directly injecting diesel into the cylinder. The ratio of gasoline to diesel used changes according to the requirements of the engine. The amount of diesel used is higher at low loads where ignition is more difficult but lower at higher loads. However, over a normal operating cycle, the amount of diesel used is less than 20% of the total fuel consumption and this would help mitigate the expected future demand imbalance between diesel and gasoline [6,7].

Octane on Demand (OOD) is aimed at improving the overall GHG footprint of spark ignition (SI) engines whose efficiency is limited by knock. Higher octane fuel allows the SI engine to avoid knock and run at higher efficiency but such fuel is required only at high loads where knock might be a problem. In OOD the engine has two fuel injection systems and will carry a high and low octane fuel. It could run on low octane fuel, which has a low carbon footprint for most of the operating regime without compromising engine efficiency [66]. New ICEs such as opposed piston engines are also being developed and show much promise [67] and could also use less-processed fuels.

## 5. Other alternatives to petroleum-based transport fuels for IC engines

Currently these alternatives account for around 5% of total transport energy demand. Some of them, such as natural gas (NG) are expected to grow fast and take a much greater share of global transport energy. However there are constraints on the unlimited and fast growth of such alternatives and they are not expected to take more than about 10% share of transport energy by 2040 [2,6].

### 5.1. Biofuels

Biofuels can be made from sugar and starch from food crops such as corn, vegetable oils, sugarcane and sugar beet. Such biofuels are known as first-generation biofuels. Next generation biofuels could be made from non-food crops such as Jatropha, wastes and agricultural and forestry residues such as straw and corn stover and novel feed stocks, such as algae [68–70].The most common biofuel is ethanol which is used as a gasoline component and is made from corn and sugarcane. In 2016, the global production of ethanol was 26.6 billion U.S. gallons (around 100 billion liters) [71] Ethanol has excellent anti-knock properties but a liter of ethanol contains only around 66% of the energy of a liter of gasoline without any oxygenate. The other major biofuel is biodiesel made from esterification of vegetable oils. In 2016, the world biofuels production was 1.54 million BOE per day [72] amounting to about 2.5% of total transport energy requirements.

The cost of production of biofuels depends very much on feedstock, process, land type and crop yield. [71,73] and they are in general, more expensive to produce compared to conventional fuels for the same energy content. There are increasing concerns about the sustainability of biofuels associated with land and water use, deforestation and possibility of GHG deficit [74–78]. Around 80% of the biofuel used in the EU is biodiesel made from edible oil seeds and on average EU food-based biodiesel produces 80% more CO2 emissions than the fossil diesel it replaces [78]. Biodiesel made from palm oil is even worse – on average three times worse for the climate than fossil diesel and the EU has ended support for such fuels [78]. In the U.S. around 46% of corn production goes to make ethanol [79] which supplies less than 3% of total transport energy used. Even dedicating all U.S. corn and soybean production to biofuels would meet only 12% of gasoline demand and 6% of diesel demand in the U.S. [76]. In a world with increased need of food for a growing population, a large allocation of land to produce fuels is unlikely.

Much faith was invested in second-generation biofuels which can be produced from non-food cellulosic bio-materials such as straw to provide sustainable biofuels. However actual production of such biofuels has very much failed to meet the targets. For instance, the initial RFS (Renewable Fuels Standard) target in the U.S. for 2015 for cellulosic ethanol was 3 billion gallons which was subsequently revised down to 120 million gallons by the EPA (Environmental Protection Agency) whereas the actual production was 2.2 million gallons [78]. Research is being done on producing biofuels from algae [79,80]. However currently they are very expensive to make. There are also other important barriers to overcome [79,80] and the commercialization of such fuels in the next 25 years is very unlikely.

### 5.2. Natural gas (NG) [81–85]

Natural gas (NG), primarily made up of methane, is normally used for electricity generation and heating. However it can be burned in an IC engine to power transport. Indeed it is commonly used in some countries (Pakistan, Iran, Argentina and Brazil) in passenger cars and currently there are around 24 million natural gas vehicles across the world [81] though its share of global transport energy is less than 1%. There is increasing interest in NG in some countries because of the availability of cheap and abundant shale gas e.g., in the U.S., particularly for heavy duty vehicles. Vehicles can be dedicated to the use of NG only or could be "bi-fuel", capable of running both on NG and a conventional fuel such as gasoline and diesel. Existing gasoline engines can be converted to use NG by installing the gas cylinder, usually in the trunk, and the compressed natural gas (CNG) injection system and electronic controls. The range of forecasts and other issues which will affect the use of natural gas in transport are discussed in [83,84].

Natural gas is usually much cheaper than conventional fuels. It is also a cleaner fuel than gasoline or diesel – the exhaust emissions of particulates, CO and NOx will be lower. It also has a better $CO_2$ footprint compared to conventional fuels because of its higher hydrogen content as long as emissions of methane from the supply chain or the engine exhaust, are adequately controlled because methane is a much more potent GHG compared to $CO_2$. In one experimental study [85], five after-market conversions which enabled two heavy duty trucks to run on NG as well as diesel were compared to the diesel-only baseline. Methane emissions due to incomplete combustion were found to lead to CO2e emissions that were 50–127% higher than the equivalent diesel vehicle. Oxidation catalysts evaluated on the vehicles at steady state reduced methane emissions by at most 15% and this study highlights that control of methane emissions and improved control of in-cylinder methane combustion are required to reduce total GHG emissions of natural gas vehicles. NG also has high resistance to knock. Dedicated spark ignition engines can be designed to take advantage of this to have higher efficiency. The use of NG in transport has been promoted for reasons of energy security in some countries and local air quality (India) in others.

However, at normal temperatures and pressures a liter of natural gas contains around 800 times less energy compared to a liter of gasoline. It has to be compressed or liquefied to increase the weight and hence the total amount of energy that is carried in a limited volume on the vehicle. In CNG vehicles, NG is stored in containers at pressures of around 200 atmospheres. If liquefied natural gas (LNG) is used it has to be stored at $-162^{\circ}$ C. Such containers take up more space and are much more expensive than the fuel tanks for conventional vehicles. CNG cars also have up to 40% lower driving range because of the limitations on the size of the fuel tank. Conversions which also allow the car to also run on gasoline can be cheaper because the CNG fuel tank can be smaller. The higher cost increase for heavy duty CNG trucks can be more easily recovered through savings in fuel costs because of their higher fuel consumption.

Conversion to LNG is significantly more expensive. Hence LNG is much more feasible where fuel consumption is very large, the additional capital costs can be more easily absorbed and fueling infrastructure installed e.g., long-haul road fleets, rail and marine applications.

The global share of transport energy taken by natural gas is expected to increase to around 5% by 2040 in some projections [2,6] primarily in the commercial sector – heavy duty road fleets, rail and marine. There are likely to be wide regional variations depending on many factors like the relative cost and availability of NG. The main barrier to growth is the lack of fueling infrastructure.

### 5.3. Liquid Petroleum Gas (LPG)

LPG (Liquid Petroleum Gas), also known as Autogas is a by-product of oil refining and natural gas processing [86,87]. Once the temperature is increased above ambient temperature during distillation of petroleum, dissolved gases in the crude are released and make up LPG which consists primarily of propane, with some butane, and could be up to 2% of the weight of crude oil. LPG is usually used for cooking but can also be used as a transport fuel. With a moderate increase in pressure it can be liquefied and stored as a liquid on the vehicle. About 9% of all LPG is used in transport [87]. The number of LPG vehicles across the world was estimated to be around 17 million in 2010 and the global consumption for transport was around 23 million tons of LPG [87] which translates to around 1% of total global transport energy demand. There are good supplies of LPG because it originates both from natural gas processing and crude oil refining. However, the share of LPG in transport applications is not expected to increase substantially.

### 5.4. Synthetic fuels

Liquid fuels can be made from syngas, a mixture of carbon monoxide and hydrogen which can be produced form a variety of sources, using the Fischer Tropsch (FT) process [88]. When gas is the source, the acronym GTL, for gas to liquids, is used; with biomass as the source the acronym used is BTL, biomass to liquids; with coal as the source the acronym used is CTL, for coal-to-liquids. Depending on the catalyst and the process used, the FT process can produce diesel fuel (e.g., Shell Middle Distillate Synthesis) or gasoline (Sasol process) along with other products like waxes. GTL diesel has very high cetane number, no aromatics or sulfur and hence is a very clean fuel (e.g. in terms of particulate emissions) for conventional diesel engines. The capital costs involved are extremely high and it is almost always more sensible to burn the primary hydrocarbons to make electricity rather than liquid fuels. A study by the National Petroleum Council (NPC) [88] projected that there could be 0.5 million BOED (barrels of oil equivalent) of GTL by 2030 but concludes that GTL is unlikely to be a major component of global transport fuel supply by 2020. The availability of cheap natural gas (e.g., in the U.S.) may cause increased interest in GTL.

### 5.5. Methanol

Methanol can be produced from coal, natural gas or biomass [89,90] at low cost. It has high octane and can be used as a gasoline blending component. However, it has only about half the energy content of gasoline on a volume basis. It is also toxic and is very aggressive to fuel system components and currently not favored by most vehicle manufacturers at high concentrations. However, it is commonly used in China [89]. Methanol can also be used to make MTBE (Methyl Tertiary Butyl Ether), which is a better gasoline component and is used extensively in many countries such as Saudi Arabia. It can also be used in the production of dimethyl ether and FAME (Fatty Acid Methyl Ester), a biodiesel. In countries which have to import petroleum and have a lot of coal, there is increasing interest in the use of methanol, made from low-grade coal, in the transport sector e.g. in India and China.

### 5.6. Dimethyl ether (DME)

DME can also be made from coal, natural gas and biomass [91]. It is a gas at normal pressure and temperature but, like LPG, can be liquefied with moderate increase in pressure and cooling. This makes transport, storage and distribution of DME easier. It has a high cetane number and burns cleanly with low levels of particulate and is well suited for use in conventional diesel engines. Several heavy duty manufacturers are developing vehicles to run on DME but its use in transport is still limited because of the extra infrastructure needed for distribution.

### 5.7. Electro fuels or e-fuels

Renewable energy could be used to produce hydrogen which could be used in fuel cells or to make liquid fuels, known as e-fuels or electrofuels, which can then be used in ICEs. There is significant interest in such e-fuels which will have a very low GHG footprint. However they are very expensive and e-fuel generation cannot realistically be scaled up to the levels needed to fuel the global vehicle fleet in the short to medium term [92,93]. For instance the EU would have to generate one and a half times more than its current total electricity production, and all of this electricity would have to be renewable, in order to power its road transport by this route. Such an approach to decarbonizing the road transport sector would need massive investments from governments in expanding renewable electricity generation. Moreover, for road transport, it is far more efficient to use renewable electricity directly to power battery electric vehicles rather than use e-fuels. In one study [93], the well-to-wheel efficiency for a passenger car is estimated to be 73% for a BEV approach compared to 13% via the e-fuel route. Hence e-fuels are best used to power aviation where batteries are not a viable option but to supply 50% of EU aviation fuel from e-fuels in 2050 would require a quarter as much electricity as is currently generated in the whole of the EU [92].

However, as the overall energy system is decarbonized and the share of wind and solar electricity in electricity generation increases, more and more electricity will be produced when it is not needed. E-fuels offer a route to utilize this excess electricity particularly to make aviation fuels and help reduce the GHG footprint of the aviation sector to a certain extent.

## 6. Supply of petroleum

It is clear that transport will largely be powered by petroleum based liquid fuels in the foreseeable future. The question then is whether there will be sufficient supply of oil to meet this demand. Global crude oil supply capacity has been growing faster than demand in the last several decades. Fig. 2 shows the evolution of oil reserves between 1980 and 2010; the data are from the B.P. statistical survey [72]. Also plotted in the figure is the ratio of the reserves to the annual production level-solid line. In 1980 there was enough oil to last for around 29 years at the then production level while by the end of 2016 there was enough oil to last around 50 years. Oil reserves have gone up because each year there are new discoveries and the recovery rates have been improving. It is impossible to recover and produce all of the oil in a known oil deposit – in 2007 the average world-wide recovery factor, the fraction of the in-place oil discovered that is technically recoverable, was estimated to be only 27% [94]. Oil recovery factors can vary very widely – the best recovery factors could approach 70% though such efficient recovery is rare [94]. However, enhanced oil recovery (EOR) techniques such as injecting fluids or gas (e.g. $CO_2$) to force oil out, can significantly improve recovery rates. For instance, in the U.S. the average recovery rate improved from ~22% in 1979 to ~39% in 2007 [94]. Unconventional oil resources such as shale oil are increasingly coming on stream and will significantly increase the availability of oil in the future. Hence the growth in transport will not be constrained by the supply of oil in the foreseeable future.

## 7. Concluding discussion

The existing transport system, built around internal combustion engines powered by petroleum-derived liquid fuels, meets an essential need and supports a large number of jobs. The global demand for transport energy is very large at around 105 Terawatt hours (TWh) of

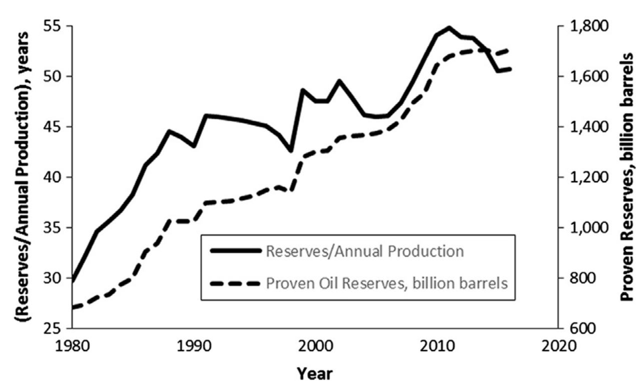


**Fig. 2.** Evolution of proven oil reserves and the reserves to annual production ratio. Data from [72].

liquid fuel energy *each day* (Table 1) and is growing; for comparison, in 2016, for the *whole year*, the consumption of wind and solar energy together amounted to 1292 TWh [72]. Dismantling such a system abruptly, say by banning the production of internal combustion engines (ICEs), as some politicians suggest, will have extreme economic, social, environmental and political impacts and is highly unlikely. Every alternative to this system starts from a very low base and faces significant environmental and economic barriers to fast and unrestrained growth. The forced building of an alternative system either entirely around battery electric vehicles (BEVs) or hydrogen fuel cell vehicles (FCVs) will be hugely expensive and be environmentally damaging if the primary energy system is not sufficiently decarbonized and toxicity impacts associated with the battery supply chain are not properly addressed.

For instance, the available battery capacity will have to increase by many hundred fold, perhaps over a thousand fold, if all light duty vehicles (LDVs) in the world are to be fully electric by 2040 but this will only address less than half of the transport energy demand since commercial transport cannot realistically be run on electricity alone on this time scale. More importantly, BEVs are not 'zero emission' vehicles – they simply shift their emissions impact from the tailpipe to somewhere else. Electricity generation needs to be sufficiently decarbonized for BEVs to have an advantage over ICEVs on a life cycle basis in terms of GHG emissions. While this is true in some areas of the world, it will not happen for decades in rapidly growing markets like China and India because coal will remain an important part of the electricity generation mix. Also in such areas, if electricity generation is not sufficiently distant from urban traffic centers even the impact on urban air quality of pollutants like particulates, NOx and $SO_2$ would be worse for BEVs compared to ICEVs. The very serious environmental/human toxicity problems associated with mining of metals needed for batteries will also have to be addressed as BEV numbers grow. Large prior investments in charging infrastructure and continuing subsidies to persuade people to buy BEVs and in extra electricity generation and grid management will be required if governments wish to force such changes.

Transport will be essentially powered by combustion engines till these barriers are overcome and this could take decades. There will be increasing electrification, particularly of LDVs but it will be mostly in the form of hybridization to improve the efficiency and performance of vehicles carrying internal combustion engines (ICEs). As the overall energy system is decarbonized and battery technology improves there will be an increasing role for BEVs and hydrogen which could replace liquid hydrocarbons in the long run and the required infrastructure will evolve. Alternatives to petroleum based liquid fuels such as biofuels, natural gas, LPG, DME, methanol and hydrogen will grow but have their own constraints on fast and/or unlimited growth but could increase their share of transport energy from the current 5% to around 10% by 2040. Future transport will not be limited by the supply of petroleum which has been growing faster than consumption over the past 35 years – current reserves are enough to last the next 50 years at current production/consumption rates.

Many technologies have gone through a hype cycle [95] including alternative fuels [96,97] in transport. Currently, BEVs appear to be near the top of the first phase of the hype cycle where expectations are raised by overly positive and irrational enthusiasm for a new technology. The hype is promoted by the media which tends to focus on potentially big stories and decision makers follow the trend rather than carefully assessing the potential of the technology or all the consequences of forcibly implementing it. Quite often, once the difficulties of widespread commercial adoption of the technology and the true consequences become clearer, the hype will suddenly ebb and collapse [95].

Incidentally, if BEV numbers indeed grow fast, the global demand for gasoline which mostly powers LDVs will be further reduced and the expected gap (see Section 1) in demand for middle distillates (jet fuel and diesel) on the one hand and gasoline on the other, will only widen. More oil will need to be processed to meet the increasing demand for middle distillates. There will be a proportionate increase in the supply of low-octane gasoline components, mostly from the initial distillation of oil, which are used for gasoline production. Such components are best suited for GCI and anything that suppresses gasoline demand, such as a rapid increase in BEVs, will suppress demand for them and make them more easily available.

Transport policy should be based on a balanced approach using all available technologies, taking into account local and global environmental and GHG impacts, security of supply and social, economic, political and ethical impacts. The best chance of significantly mitigating GHG and other impacts of transport lies in improving combustion engines assisted by partial electrification and better control and after-treatment systems. An even better approach is to develop new fuel/engine combustion systems like gasoline compression ignition (GCI). This will require collaboration between the oil and auto industry and governments. It would be very short sighted indeed not to invest in improving ICEs since they will inevitably be powering the transport sector, particularly the commercial transport sector, to a large extent for decades to come.

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## Glossary

*BEV:* Battery Electric Vehicle
*BOE:* Barrels of Oil Equivalent
*BOED:* BOE per day
*BTL:* Biomass to Liquid
*CI:* Compression Ignition
*CNG:* Compressed Natural Gas
*CO:* Carbon Monoxide
*CTL:* Coal to lLiquid
*DME:* Dimethyl Ether
*FAME:* Fatty Acid Methyl Ester
*FCV:* Fuel Cell Vehicle
*GCI:* Gasoline Compression Ignition
*GHG:* Greenhouse Gas
*GTL:* Gas to Liquid
*HEV:* Hybrid Electric Vehicle
*HTP:* Human Toxicity Potential
*ICE:* Internal Combustion Engine
*ICEV:* ICE Vehicle
*LDV:* Light Duty Vehicle
*LNG:* Liquefied Natural Gas
*LPG:* Liquid Petroleum Gas
*MTBE:* Methyl Tertiary Butyl Ether
*NG:* Natural Gas
*NG:* Natural Gas
*NOx:* Nitrogen Oxides
*OOD:* Octane on Demand
*PHEV:* Plug-in HEV
*PM2.5:* Particulates less 2.5 micrometer diameter
*RCCI:* Reactivity Controlled CI
*SO2:* Sulfur Dioxide
*UHC:* Unburned hydrocarbons