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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

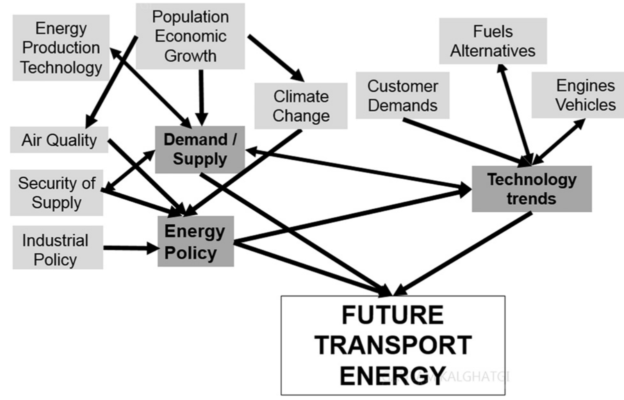

Fig. 1. The evolution of transport energy is determined by the complex interplay between many drivers.

(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