What is the Appropriate Power Source for Large Prime Movers within Decarbonised Transportation?

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It is abundantly clear, to most, that the world is becoming increasingly distressed by pollutants, many of which arise from fossil fuel combustion within transport. A primary area of concern is emissions that enhance global warming (these are also known as greenhouse gasses). The most well known is CO_2 *or carbon dioxide, however this is by no means the only emission of significance and, in terms of radiation impact on warming, it is only about 50% of the total with other gasses and soot or black carbon aerosols being very important too*[1]. *Further a range of toxic emissions, especially soot and nitrogen oxides, are of concern in regard of their impact on human health*[2]. *In response many societies have deemed electrification of transport as essential. To date electrification has focused mainly on rail and an accelerated move towards battery electric vehicles mostly foe personal transport. I discuss the technical issues surrounding this essential transformation and consider the options for supply and use of energy in particular in large transportation vehicles in both the near (5-15 years) and mid-term (15-35 years).*

INTRODUCTION

A very strong case for reducing, indeed essentially eliminating combustion emissions, has been made by both climate scientists[1-4] and health professionals[5]. The desired timescale for substantive reduction in greenhouse gasses has been proposed to be around a single generation (e.g. 25 to 30 years). It is the norm to talk about greenhouse gasses as purely CO_2, however this is not correct[1] because many other gasses also contribute; however to first order it is assumed that these other gasses and particulates track CO_2 emissions. The timescale for reducing toxic emissions is likely shorter due to their immediate health impacts. These aggressive timescales will drive a substantial number of technology changes with, most likely, some unexpected and, so far, under estimated impacts.

This paper is aimed at a UK context, however its generalised conclusions should be scalable to other counties. This article firstly considers, in depth, key issues surrounding electrification of transport. It is argued that, now, this is the preferred route for the majority of transport in that it delivers zero emissions at the point of use and, will, deliver zero or near zero emissions as and when but not before, the electrical supply is substantially decarbonised. This gives rise to the key question that are large prime movers, defined here as modes of transport to carry substantial loads of goods and/or people and typically greater than 5 tonnes, suitable or appropriate for battery electric power? This paper excludes specifically excludes air transportation and very large marine applications which have specific issues.. The aim of the paper is to address the issue of o-board energy source and the likely technology to utilises this stored energy. .

THE ELECTRIFICATION CASE AND ARRISING ISSUES

Current thinking is that environmental clean-up can be best met by a substantive electrification of transportation. Apart from rail, where electrification is already extensive[A], it is widely assumed that the single biggest transformation will be in small passenger cars and equivalent sized commercial vehicles used in urban settings. Various targets have been set: the IEA advocating on the part of OECD nations has suggested 30% electric vehicles EVs by 2030[6], the UK Government is targeting all such vehicles to be zero emission by 2050[7] and the Scottish government has the most ambitious target of all such vehicles being zero emission by 2040[8]. A key question is how far it is practical for electrification to encompass transportation technology and what areas might suit alternative clean technologies?

EVs (electric vehicles) include hybrids; the later are very effective for short journeys and/or in urban settings. Indeed any situation that imposes substantial speed modulation and start/stop use would benefit fromsuch. However, hybrids are not effective on long journeys involving a steady load; indeed they are likely to be more polluting than a simple optimised i.c. engine system because of the substantial extra mass involved in the electric motor and battery. Plug-in Hybrids (PHEVS) are an important improvement, but only where they offer a pure electric battery range of 30 miles or greater; this inevitably increases vehicle mass which is often counterproductive. PHEVs, together with pure battery electric vehicles (BEV) can realise near total emission reduction but, crucially, only if we both have a fully decarbonised power generation system and the fuels for PHEVs are carbon neutral.

As argued in Kalgahti[9], these targets for EVs and especially BEVs are very ambitious and do not appear to have fully addressed all essential issues. Kalgahti[9] highlights several points: a) if the electricity generation system is not fully decarbonised, spontaneous extra or marginal demand is likely to be met by fossil fuel generation (most likely gas or diesel) with the unintended consequence that EV vehicles would then emit more CO_2 than the equivalent low emission combustion powered vehicles; b) that the whole life cost of batteries contributes to CO_2 emissions; c) even if the power generation requirement is met, the infrastructure to charge all vehicles is largely absent. Therefore it is hard to find truly balanced reporting of these impacts simply because advocates of electrification frequently neglect these and other issues. I will go on to evidence these issues next.

This raises the question, how much extra electrical power do we need? The UK National Grid has estimated that its transport electrification will require only another 5GW of power generation[10] by 2040, however this figure is considered a low estimate[9]. A basic analysis from the RAC based published figures[11] (this is in turn taken directly derived from official UK Government figures) suggests we currently have 31.31[11,12] million cars with an average mileage of 7,800 miles per

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[A] For populated regions electrification is the widely preferred solution, for long distance, remote and/or infrequent train traffic diesel is likely to continue to play a significant role.

year[11,13]. If I assume a fleet average of 10 miles per litre of fuel consumption (~45 mpg equivalent), and that, compared to gasoline, a pure electric vehicle is twice as efficient (i.e. 90 mph equivalent) and driving habits do not change, then a 30% adoption of EVs (substantially below the UK's 2040 goal) this requires an additional average electricity generation of 9.3 GW. This estimate is consistent with the UK government's estimate of 8-11GW[7] though clearly at odds with that of the UK National Grid[10,] however the later[10] does make clear that it assumes the Government targets will not be achieved. The same source[10] then goes on to state that building say and extra 10 nuclear stations is not realistic and, further, that marginal peak load would be better achieved by gas fired power. This approach will have substantial impacts on the net carbon emissions of transport and on EVs as will be argued. From a short-term financial investment standpoint this position[10] is not wholly unreasonable. However, several authors[9,14], including one financial analyst[15], have concluded that using gas fired power to charge EVs produces CO_2 emissions in excess of an efficient hybrid or similar small i.c. engine car. Therefore there is either some 'magical thinking', an overt scepticism by the power industry or, as yet, no proper holistic strategy for carbon free power generation of electricity. Without major new build of, non-intermittent, zero CO_2 emission power plant or intermittent sources with sufficient on-grid energy storage, a rapid expansion of EVs will actually increase, not decrease CO_2 emissions[9,14].. On a cold winter's day, when say the bulk of the UK is subject to an anticyclone leading to very light winds with hazy cloud and/or fog, both solar and, hence, minimal wind power charging of a mass fleet of EVs will self-evidently be highly compromised. Not least because the preferred charging hours for EVs will be night-time [14],. for night-time EV charging there would be major problems of supply. Given the current predicated UK Government strategy for new power plant[16] major issues appear to be inevitable.

To further emphasises the above issues, it is important to acknowledge not just the overall security of supply in total power production, but also to recognise the sensitivity of the electricity grid to marginal demand at the point where demand matches exceeds supply. If the electricity grid is operating near its marginal limit the possibility of demand exceeding supply[17] exists. Management of the grid then becomes critical because it is essential to maintain the stability of the AC frequency. Indeed, to avoid the dangerous situation of differing supply frequencies on the grid from different generators, the grid frequency stability has to be kept within 1%[18]. Some have argued that this is not a significant issue in a carbon minimised generation system[19] but others have raised significant concerns[20]. Indeed, battery storage systems are now being actively used to augment frequency stability[21] and not just as a buffer for total power[14]. Certainly batteries can facilitate frequency stability; this leads then to the question how much electricity has to be stored? The issue of total power reserve to ensure on-demand EV charging when such vehicles are ubiquitous is more difficult to envisage. A basic estimate suggest at least 100GWhr of storage, equating to about 8-12 hours of EV charging, would be required to match anticipated demand by 2030 if transportation targets, 30% EV cars by 2030, are to be met. This equates to 9.3 GW or 223 GWhr; thus a figure of 100 GWhr is which is less than 50% of the anticipated demand could well be the minimum required storage to cover the scenario of a large winter anticyclone severely limiting solar and wind for night-time charging. . Current plans are for 7 GWhr[22], a number that clearly will have to grow rapidly and by over an order of magnitude to meet a minimum estimate to cover 50% of the anticipated daily requirement. One benefit of such large amounts of battery storage is that the frequency control issues and power security issues would be substantially mitigated though not eliminated; this conclusion thus supports the apparently diverse views of both[19] and[20].

The key importance of the above, is that there are only two ways of solving this issue: a) build more CO_2 free electricity generation which is not intermittent, unless it in itself is backed-up with >100 GWhr of extra electrical storage; or control the demand-side aggressively. Ultimately, battery storage is seen as a key component of a smart electricity grid. One example of might be where the charging rate of an electric vehicle's battery is modulated, by the UK Grid operator, to control both the grid stability, and overall demand. This would typically be by contractual consent of the vehicle user through a contract between the power supplier (and/or national grid) and the user. However, it is likely to be unpopular with users and therefore this approach is unlikely to be extensively adopted. Current government strategies, and the above arguments, are based solely around cars and not trucking and transport in a wider sense. With trucking a further major issues arises in the form of stored energy density and this is dealt with later. One consequence of this for, say a PHEV user, might well be a low battery charge in the morning and therefore a polluting journey to follow; thus exacerbating all the problems of charging full battery electric vehicles with marginal power[10,14]. For a BEV user the contract would need to ensure a minimum useable charge to ensure essential journeys are practical. Here, the consequence is that the battery capacity available to the grid would be substantially less than the total capacity of the vehicles. Further when vehicles are mobile or not near any charging infrastructure they would have no value to the grid operator. This is important because if a large proportion of the fleet is mobile and thus disconnect from the grid, they remove a substantial power reserve. Indeed, this scenario is implicit in[14].

The above arguments produce three clear conclusions:

1. If government targets for electrification of vehicles are to be met they must be accompanied by a commensurate policies to supply the grid with electricity that is generated totally free of CO_2. Indeed, the use of combustion powered electricity generation, at marginal load, whilst financially expedient, will not lead to significant CO_2 reduction and, indeed, is far more likely to increase CO_2 emissions.

2. Sufficient street furniture for both daytime and night-time charging is essential if the essential benefits of demand side management and spare battery capacity of EVs for the grid are to be realised.

3. An increase in electricity storage of over an order of magnitude beyond immediate plans to >100GWhr is essential.

Perhaps a key reason that only small passenger cars and small commercial vehicles are expected to become electrified is simply a practical one of energy storage density on the vehicle. To examine this on a levellised approach, Table 1 below shows the 'on-vehicle' storage mass ratio relative to gasoline that I simply use as a baseline.

Table 1. Comparison of weight to effectively match the stored and mechanically extractable energy equivalent to 50 litres of Gasoline.

Fuel	**Conversion Eff. to Mechanical Energy (%)**	**Stored Energy Density (MJ/kg)**	**Required Fuel Tank Mass (kg)**	**Available (MWh/kg)**	**Energy Storage Mass Ratio relative to Gasoline**
Gasoline	35%	44.4	20	0.02815	1.00
Diesel	43%	48	20	0.34013	1.19
Electricity (Tesla now)	82%	-	-	0.000157	0.216
Electricity (Tesla 3 claim)	*82%*	-	-	*0.000207*	*0.284*
LPG (DF) (**Green LPG** assumed the same)	43%	46	25	0.03009	1.06
CNG (DF) (Biomethane assumed the same)	43%	43	116	0.01103	0.39
LNG (DF) (scaled to large truck tank(	43%	54.4	116	0.01395	0.742
H_2 700 bar (FCV)	60%	120	300	0.00525	0.187
H_2 700 bar (DF)	43%	120	300	0.00520	0.185
Ethanol (DF)	43%	26.8	25	0.02038	0.761
Hydrous (5% H2O) (DF)	43%	25.5	25	0.01936	0.725
Methanol (DF)	43%	19.9	30	0.01594	0.586

Note: Electricity in italics represents an optimistic future estimate. LPG=Liquefied Petroleum Gas, CNG = Compressed Natural Gas, LNG = Liquefied Natural Gas, DF= Dual Fuel, FCV = Fuel Cell Vehicle. Electricity assumes a battery electric vehicle (BEV); hybrids are not considered because they are combustion vehicles with little CO_2 advantage other than in purely urban use. See Appendix for all the assumptions used in the above table.

Table 1 compares a number of fuels in terms of storage energy to mass density compared to 50 litres of gasoline (which is approximately 11 gallons UK or Imperial gallons). This is a typical fuel load of a small to medium size car. Energy storage mass, for a lightly laden passenger car at low speed is a modest concern. For a high-speed vehicle it is a significant concern. For say a goods vehicle, limited by axel load this is a major concern as it directly trades-off laden goods weight with fuel. To understand the impact my analysis I assess the equivalent mass that matches 50l of gasoline including tank or equivalent. Since large tanks have a lower tank mass to fuel ratio, for large prime movers, the fuel to tank mass ratio for liquid fuels, is likely to be >5:1. Thus my figures must be considered as 'generous' in favour of battery electrification.

Note that in Table I have deliberately avoided hybrid systems. Whilst these have a clear utility, especially in urban settings and for other short journeys, they are much less relevant to large prime movers operating over large distances where a high percentage of power is continuously being used and power modulation is low. Further, over long distances, the importance of a high relative energy source becomes paramount. In any case these are seen as an intermediate case for a transition to cleaner systems. In practice they would improve efficiency but they would substantially increase mass (by adding electric engines and batteries to the i.c. engine system). Hence any potential gain in efficiency would be lost out with an urban setting. There may be a special case for the use of hybrids, especially PHEVs for urban delivery vehicles and to use the pure EV power mode for movements in zero congestion areas.

Now I consider the implications of electrification for medium and large goods vehicles. Table 1 clearly shows that, for goods transport applications where weight is an issue, diesel and LPG are easily the best fuels and that ethanol and methanol are sensible alternatives. All hydrogen solutions are unattractive due to storage mass including the fuel cell vehicle (FCV). Hydrogen storage in lightweight systems is therefore a pre-requirement of all hydrogen transport systems but, as yet, is not available. Indeed, the energy to mass figures of Table 1 clearly show the disadvantage of any compressed gas system.

The weight of battery electric storage is high, even if the most optimistic estimate for the Tesla 3 is taken (see Appendix 1) the ratio to diesel is over 4.2 times higher compared to diesel. This is a substantial weight penalty. It is tempting to imagine that something like Mores law could apply to battery development. However this cannot apply because in electronic chips it is the flow path that limits you, which has been continuously improved by every increasing miniaturisation. In a battery you are limited by the space an electron can occupy around say a lithium atom and this limit is nearly exhausted. A 400 Whr/kg has been suggested as the physiochemical limit for current Li-ion batteries[23]. Thus the optimistic figure I have used in Table 1 of 70% of this number looks to be realistic and optimistic because batteries capacities degrade with charge-discharge cycling. Even with improved technology, which may achieve only 20% degradation over 4,500 cycles[24] this estimate is unlikely to improve significantly.

4. Electrification of small and medium vehicles with low load carrying requirements is consistent with the analysis of this paper, give that the clean power infrastructure required is provided. There are important limitations in battery lifetimes and battery capacity but these are practically manageable for such applications.

Where vehicles need to have a high power to weight ratio and operate away from large electric infra structure, clearly other fuels have clear advantages.

A number of solutions are being explored for the electric powering of trucks. One practical truck which has been proposed, is the Tesla Semi[25,26] with anticipated range of 300 and maybe 500miles. This unit requires a new generation of electric charger the Tesla Megacharger [who's exact specification is yet to be released]; the expected power for this unit is least 1MW[27] or 1,000kVA. Volvo have also proposed a truck but with a much smaller range of 200km or 120 miles[28] and hence a much lower charging requirement. The Volvo approach may be suitable for local distribution of goods.

To understand the amount of power involved, a typical UK house is limited to circa 25kVA. A single phase a supply will not typically exceed typically 100kVA or 1/10th of the requirement for a Tesla Semi Megacharger. Therefore these charging points are likely to be highly restricted in their initial locations. Therefore unless and until there is a major upgrade of our power networks, especially street furniture, this technology will most likely be limited to large conurbations with access to large MVA cables.

Siemens has proposed an alternative approach in which electricity is distributed using overhead wires to pantographs[29]. Such an approach is feasible in limited urban and near urban areas simply due to the large cost of installing street furniture; additionally it is highly likely that there would be considerable public unhappiness with the visual impact.

Transport demand in terms of HGVs for diesel is currently about 8 MTOE[30] (MTOE = million tonnes of oil equivalent). Assuming that all transport energy was electrified and that say there is a two-fold increase in efficiency due to this change (see efficiency ratios in Table 1) this points to an additional 2 GW of generation in addition to my estimate of 11GW previously (for just 30% of cars). Of course if a large number of trucks choose to charge at night or in short window of time this figure of 2 GW would increase and battery storage to manage the adverse demand timing would increase[14]. Were all transport to be electric the power generation demand increase would have a potential peak of an extra 38GW. Assuming phased charging this could be reduced to say 15-20GW equating to an extra 50% increase in generation and a consequent increase in electric distribution capacity. My estimate should be compared with a similar estimate for Japan[14] where a figure of 7.5 GW is postulated for circa 30% EVs. Further note that this analysis is specific to cars, as they are the only vehicles planned to become EVs in the near or medium term. Japan has a population of circa 126M[31] and has 61M[32] vehicles each averaging 4.3Kmiles based on an average of two sources[33,34]. Whereas the UK has a population of 66M[35], with 38M vehicles (cars)[36] and an average mileage of 7.8kmiles[37] so the UK's proportionate power demand for EVs would be 68% of Japan or 5GW. However Japan, by dint of its much larger population, has a much larger amount of generation capacity, varying from peaks of demand of circa 130GW down to 89 GW[38] compared to the UK's range 40-25GW[39]. Consequently Japan has greater surplus at non-peak demand periods which will account in large part for my minimum estimate of an extra 15GW for the UK being compared to Japan's of 7.5 GW[14]. This extra capacity, likely solar, is presumed to be then stored in large battery plant for EV night-time charging[14]. This analysis further re-enforces the very large figure of >100GWhr grid storage requirement, The scale of the margin is crucial because it means that frequency control of the supply, which is critical at marginal[17,18] supply over demand dictates the likely use of fossil and thermal generation for EV charging[9,14]. The UK has less additional surplus and its declared plans for storage are currently an order of magnitude too low[22] and, additionally, nuclear new build, apart from Hinkley C (scheduled 2025), is yet to be confirmed[16]. Nuclear has a lead-time of 10-15 years hence there remains considerable uncertainty in the availability of sufficient power for car EVs. Additionally, issues of network distribution to both home and workplace, to ensure EV charging can be day and/or night is as yet, unclear. If EV vehicles lead the power generation and grid storage issues, we will experience the bizarre situation where by using marginal gas and coal thermal power[14] we substantially increases their CO_2 emissions compared to gasoline vehicles[9,14,15].

Battery technology also has environmental and economic concerns. Kalgahti[9] highlights supply issues for Li, Co and Ni all of which are essential. There are also considerable toxicity issues if the scale of Co and Ni extraction ramps up[40] to meet anticipated demand.

Finally there is an intriguing issue of taxation currently the exchequer takes £28.2billion in fuel duty[41]; clearly this would not happen in a highly electrified transport scenario and therefore revenues would need to be generated elsewhere or by a change in taxation. Obviously therefore, once EVs operate at scale, this must become a major issue.

5. Penalties of weight of batteries, availability of numerous very high power charging points and a further requirement for additional 11 GW of grid power and >100GWhr of grid storage will have a significant impact on the uptake of electrification of heavy goods vehicles.

Kalghati[9 & 42] has argued very clearly that it is impractical to electrify air transport where required battery weights massively exceed take-off weights of typical aircraft. Also that a larger container ship could take circa 2 years to charge up at 10 MW. Similar arguments can be deployed readily to dismiss the case for say the electrification of trains by battery in remote areas where overhead wiring is impractical or simply not economic. Thus there is little prospect of replacing the gas turbine for air transport in the medium term. Likewise, with no other changes the diesel engine represents the most practical and efficient technology for large prime movers. There is a strong possibility that some small level of hybridisation of ships and trains for operation over limited range in say urban and near urban areas. However, in the case of trucking the swapping of tractor units from diesel to electric in an extra urban hub area may prove more cost effective and practicable. A similar scenario could exist for shipping using tugs and for aircraft using electric tractors. An exception to this could be medium sized delivery vehicles that operate in an urban and limited extra urban environment; here a PHEV solution could well prove attractive and practicable

7. Electrification is, currently, very far from practical for large prime movers such as air transport, shipping or remote rail freight. Indeed, at this point of time this scenario must be considered highly improbable. It's most likely role is via hybridisation and generator sets to smooth transients and permit clean operation over small distances such as in clean-air zones.

WHAT ARE THE ALTERNATIVES IN THE SHORT AND MEDIUM TERM?

If electrification is not the current answer, the question arises as to how should power large prime movers be powered and with what fuels? Without doubt since its design and realisation the Diesel engine has developed enormously; but its true potential was evident to its inventor, Rudolph Diesel[43,44,]. The later realising that, in an over simplistic estimate, it could operate with a compression ratio in excess of 200[44]. The importance of compression ratio lies not in the work required to compress the gasses, but in the benefits of a consequent large expansion ratio. It is the lack of the later that limits current gasoline engines and renders them unsuitable for high efficiency transportation power. Whilst 200:1 is not achievable, because the temperatures would literally cause the fuel an air to be literally atomised into neutral atoms and charged ions or a weak plasma. This would negate the release of the chemical energy. However the Diesel does deliver very high expansion ratios and thermal efficiencies up to and, in future, beyond 50%[45]. No other power system can match this on a single cycle operation; certainly combined cycle (e.g. a steam plant recovering waste heat) can deliver 60% or above has very large mass and size.. In my considered view, therefore, the diesel engine will retain is position as the primary power unit of choice. Quite simply there is no other foreseeable technology that offers the efficiency, usability, flexibility compact package size and power of the diesel. However, as argued above, CO_2, NO_x and particulates must be significantly reduced. The later two can and are being ameliorated by appropriate exhaust after treatment, but the former requires a fundamental switch away from mineral based diesel fuel. Kalghati[42], has argued such in a similarly in a very recent paper.

Thus, if diesel is the most efficient engine, how can it be made clean? Obviously bio diesel is now available, albeit in limit quantities. This fuel can be blended into traditional mineral diesel and will continue to bring progressive benefits in CO_2 reduction. However biodiesel is unlikely to meet anything like total global demand. One-way forwards, with diesel technology is to utilise a much broader range of bio[46-52] or electro fuels[53-55]. This would open up access to a very board sweep of biofuels as well as zero carbon (e.g. H_2) and low carbon (e.g. LPG, bio LPG, Natural Gas, Bio Methane, Alcohols etc.) fuels.

To achieve this the most logical approach, which needs only modest adjustment to both existing and new diesel engines, is to employ a high quality dual-fuelling[55-57] technology. There are alternates that use the so-called homogeneous charge compression ignition (HCCI) technology[58-60], however these are usually implemented in a partially premixed mode[61,62] to control the rate of in-cylinder pressure rise which can become noisy and also damaging to the engine. These 'advanced' combustion modes markedly reduce NOx and particulates but at the expense of total power output and a higher premium on engine control it should be noted that multi-fuel capability and a pilot fuel injection, as in dual-fuelling is common[58,59,61].

What is Dual-Fuelling?

The conventional diesel engine gains its high efficiency through a high compression ratio and its use of a turbo-charger to further utilise the energy in the exhaust gases by further compressing the inlet gasses. The combination of the two allows for a very high expansion ratio on the power stroke enabling the engine to utilise most of the available energy of the fuel as mechanical power. Uniquely the diesel can do this because, unlike gasoline where the fuel will detonate at high temperature and pressure, seriously limiting the expansion ratio, the diesel engine burns the fuel slowly thereby avoiding detonation.

In a dual-fuel diesel the diesel fuel is substituted by introducing a second fuel fed into the air intake. As long as this fuel has a high octane number and is therefore resistant to autoignition, a small amount of injected diesel fuel acts as a controlled and smooth ignition source. The second fuel, which can be 70% or higher of the total then ignites to provide most of the power. The important step in this technology is that it enables fuels with a low cetane number (cetane number characterises autoignition flammability at high temperature and pressure,) to be used. Convectional diesel fuels must ignite readily at high pressure and temperature otherwise the fuel would not or only partially burn. However many alternate bio-fuels and electro-fuels[B] that do not posses this property do exist such as methane, hydrogen, LPG and alcohols. All of these fuels are available from bio or electro fuel production routes.

Today technologies have been developed which can convert both existing diesels and new engines to dual fuelling[55]. This brings forwards the opportunity to utilise a very wide range of low carbon and zero carbon fuels in, arguably, the most efficient engine known. Given that these second fuels are lighter and lower carbon they burn easily and usually at a lower combustion temperature that lowers NOx. Lighter fuels, and especially those with oxygen like alcohols, are very also good a reducing particulates as well. These advantages are important but they do not measure mitigate against using additional exhaust emission technologies for particulates such as diesel particulate filters[64] nor the latest selective catalytic technologies to largely eliminate NOx[65].

Kalghati[42] has drawn similar conclusions to those of this paper, also in a study aimed at looking at the fuelling of commercial vehicles, though his case including

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[B] Electrofuels are created using excess electricity to typically for hydrogen by electrolysis of water and then process this with such as CO_2 captured from a process or direct from air.

aircraft. One of his conclusions is, that given a sufficiency of CO_2 neutral electricity, that e-fuels make sense albeit he concludes that the emphasis of these fuels should be on powering air transport. These conclusions are within a context of considering non-OECD countries where dependence on fossil fuel power generation may persist longer than within the OECD communities because countries have declared a much more aggressive approach to decarbonisation of transport[5-7].

8. Currently only diesel and LPG provide good energy to weight ratios for on-vehicle storage of energy where weight is a significant issue. Bio fuels, such as Bio LPG, Bio Ethanol, Bio Methanol and Bio Methane (e.g. CNG) are not just practical alternatives, but provide an enormous opportunity to reduce both greenhouse and toxic emissions. CNG suffers from a, currently, high tank mass, but is likely to be widely available and can be produced sustainably. Dual-Fuel Diesel technology provides the obvious route to access these sustainable fuels for transport applications.

Comments on Fuels Suitable for Dual Fuel Diesel engines.

A wide range of fuels can now be generated that are either very low or zero carbon emitters; these include:

H_2 when it is produced from non-fossil fuel sources such as electrolysis using excess wind or solar power or nuclear power.

Advantages: Easy to generate from excess renewable electricity. Disadvantages: Storage requires heavy systems, energy density is low, combustion at high density results in high temperatures leading to significant NOx. Conclusion: Likely to be utilised only when there is a plentiful and cheap source of H_2,

Compressed Natural Gas (CNG), which, very importantly, can be produced as bio-Methane from anaerobic processing of waste[28].

Advantages: Can be transported via a well-established gas network, has a reasonable energy density when stored at high pressure, can be produced from waste biological and other materials by anaerobic digestion. Bio-methane can be easily incorporated in the existing gas grid. Disadvantages: has to be burnt lean to avoid NOx & particulates. Has significant weight penalty though about a factor of 2 less than batteries. Likely to be used where it is readily available, for instance in vehicles and ships used to transport the gas and storage weight is less important. Conclusion: Will be used in specific applications.

Liquefied Natural Gas (LNG), this fuel; is both of current and growing importance.

Advantages: The current supply chain for LNG is already established and it is shipped in huge quantities. Even as a mineral fuel it offers significant advantages in reducing both CO_2 and particulate emissions, both achieved throngh the virtue of its high H to C ratio. Of greater importance is that this fuel can be produced both from waste, by anaerobic digestion of organics, and as an electro-fuel (E-fuel). Therefore it has a clear trajectory to sustainability and being carbon neutral.

Ethanol & Hydrous Ethanol, which can be produced by fermentation of high sugar crops and also waste cellulosic material (e.g. wheat stalks etc.)[28,29]. Ethanol is a very good potential future bio-fuel, in particular it has been shown that using it admixed with water in modest quantities brings marked benefits to combustion emissions[56,61].

Advantages: Good energy density, easily produced from sugar rich biomass by well-established techniques, can be burnt at relatively high loads with much lower NOx because it is an oxygenate. Can be utilised even if diluted with water to say 10%; this asset potentially reduces the cost of ethanol production. Disadvantages: Not yet available in high volume for mass applications. Conclusion: Will be used and uptake will likely be limited by availability.

Methanol that can be produces as part of CO_2 capture from the atmosphere[34] or as an electrofuel[35]. (An electrofuel is a fuel that is produced from excess electricity by say hydrolysis or electro or electro-thermal processing; preferably it is produced by a CO_2 neutral cycle. Electro-fuels include fuels synthesised from CO_2 captured from the atmosphere). Methanol is currently widely available as a major chemical industry feedstock.

Advantages: Good energy density and can be produced by a variety of established methods; in particular it is a strong candidate as an electrofuel. Can be burnt at relatively high loads with near zero NOx and particulates because it is an oxygenate. Disadvantages: Not yet available in high volume for mass applications. Conclusion: Will be used and uptake will likely be limited by availability.

LPG including ***Bio LPG***[31,32].

Advantages: LPG is readily used as a dual-fuel and its use is proven and established, it has good energy density and it is widely available. Further, it has a much lower carbon footprint than pure diesel. Routes for its production from renewable bio sources are emerging. Disadvantages: Not strictly a "green fuel' unless it is produced from bio-sources and cannot be used at very high-load without producing NOx and particulates. Conclusion: Will be used and uptake will likely be limited by availability.

Biodiesel. Biodiesel is now well established[33,40] and already blended into pump diesel. References 33 & 40 give a number of sources for its production largely from vegetable oils and recycled cooking oils. It has an important role to play in future transportation, not least because dual-fuel diesel requires approximately 20% diesel fuel.

<u>Advantages</u>: Reduces CO_2 emissions and can be readily used in existing diesel engines, has an excellent energy density. <u>Disadvantages</u>: does not impact NOx and particulate reduction directly.

The above list is not intended to be exhaustive; rather it identifies those fuels that are available and accessible today. Undoubtedly new fuels and other fuels will be considered and likely used, the driving force for this will be bulk availability, cost and being sustainably low carbon.

It is instructive to consider the relative energy storage destiny of various potential dual-fuels and compare those to gasoline (as abase case) as well as the key alternative technologies namely compressed hydrogen and electric batteries. Using the data of table 1 this is illustrated for the key fuels for dual-fuel which are capable of being CO_2 neutral as either being produced from waste, derived from bio-mass or synthesised as an electro-fuel following CO_2 atmospheric capture. Figure 1 illustrates the potential, based on energy storage.

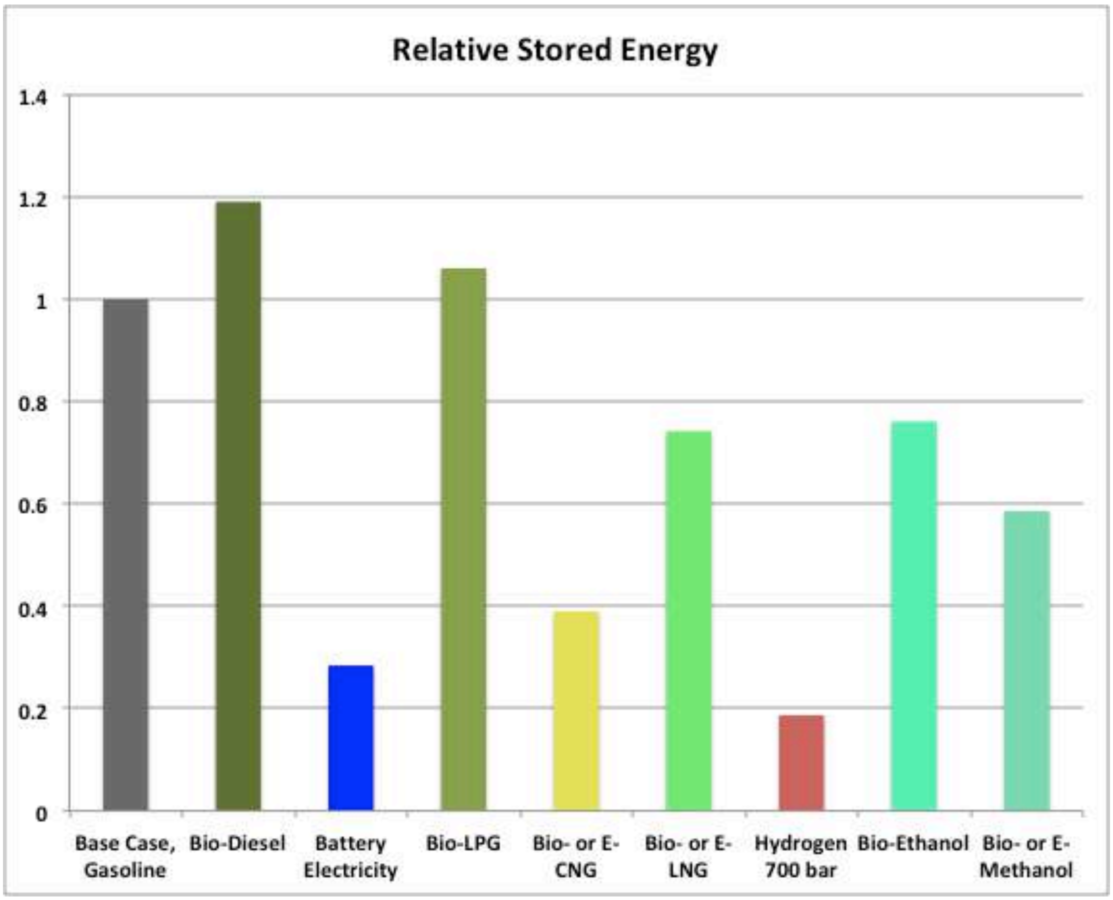

Figure 1

The disadvantages of compressed gasses (CNG or Hydrogen) are abundantly clear, indeed it is hard to imagine that those with an energy storage fraction less than 0.5 can or will prove to be practical in the medium term and almost certainly not in the long term, especially for large prime movers where weight is critical and trades-off directly with load capacity..

The advantages off all those materials marked in a shade of green, is that they are available now, have a good energy to mass storage ratio and they can be produced, going forwards, as sustainable bio- or electro- fuels.

CONCLUSIONS

There is no doubt that electrification of transport is a preferred option, it will progressively assume ascendency in power for transport over the next 50 years. However big technological problems and commercial barriers have to be overcome. Not just batteries but the commissioning and realisation of far greater electric power generation and its deployment in high power cables, substations and charging points to the average street. The likely timescale to realise this may well be 30+ years.

Therefore in the medium-term, low to zero carbon alternates are need, especially for larger transport systems operating over a longer range. Additionally, electric power in transportation comes with significant weight penalties. As previously pointed out, for short-range applications battery vehicles are a logical choice where the excessive weight and/or size of storage can be managed by limited range. It is therefore clear that solutions need to be sought from accessible, efficient technologies that can be realised today for longer-range vehicles. I believe this paper makes a clear case for the use of dual-fuel diesel technology that, in combination with a diverse portfolio of biofuels and low carbon fuels, has clear potential to deliver sustainable power for prime movers. Based on likely availabilities, current infrastructure for such fuels, energy storage density, and a pathway to efficiently create these fuels as either E-fuels or as biofuels the following appear to be the logical way forwards: LNG, LPG and Methanol & Ethanol appear to be excellent choices; further all can be produced with either v low or zero CO_2 emissions for the future. Additionally CNG should be considered where its additional on-vehicle weight storage penalty is acceptable. It should be taken as read, that biodiesel is a preferred pilot fuel.

Given that dual-fuel technology is relatively mature, it is therefore a considerable surprise that, to date, its uptake has been minimal to modest.

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Appendix: Assumptions and Sources for Table 1.

All storage is based on a tank of 50l of gasoline and matching the equivalent range for such a tank:
A typical mild-steel 20kg tank containing 50l of gasoline has 1665 MJ of energy and weighs (including the tank) 57.5 kg. Therefore the storage mass for other fuels is calculated based on them having 1665 MJ of energy equivalent once the fuel is adjusted for calorific value and the efficiency of conversion; thus a high efficiency of conversion as it electric requires proportionally less storage,

Gasoline density assumed at 0.75 kg/l, diesel 0.83 kg/l,; Ethanol 0.79; Methanol 0.79; liquefied LPG 0.55 kg/l; hydrogen 0.063 kg/l @ 700 bar; NG at 250 bar storage.

Note all i.c. engines are assumed to have circa 10% transmission losses at reasonable rpm.:
Irimescu, A., Mihon, L. & Pãdure, G. Int.J Automot. Technol. (2011) 12: 555. https://doi.org/10.1007/s12239-011-0065-1

Gasoline engines are now targeting 56% thermal efficiency:
https://jalopnik.com/mazdas-skyactiv-3-engine-could-be-as-clean-as-some-elec-1822516318
Assuming 40% is realised (a poor estimate) with 10% loss 35% conversion efficiency is reasonable for an advanced modern engine.

Diesel engines are targeting 50% thermal efficiency:
https://www.theicct.org/publications/advanced-tractor-trailer-efficiency-technology-potential-2020–2030-timeframe
Very large slow speed marine engines may well exceed this figure by 10%; a realistic estimate including power train losses is 43%. This is consistent with the US Supertruck programme: Chp. 8 of the Super Truck Programme 2015: https://www.nap.edu/read/21784/chapter/10#131

An LPG equivalent tank is assumed to be heavier (25kg) as it requires higher pressure; new materials could easily mitigate this.

Bio LPG assumed the same as LPG:
https://www.calor.co.uk/home-energy/biolpg

Total efficiency is then BEVs are assumed 92% each way charge-discharge efficiency that is consistent with real world practice[8]. Powertrain loses are low at around 3% so the overall 82%:

http://www.roperld.com/science/TeslaModelS.htm
85Kw weighs 1200lbs this gives 0.00157 MWh.kg

Tesla 3 battery claimed at 0.000207MWh/kg:

https://insideevs.com/tesla-claims-model-3-battery-has-highest-energy-density-of-any-electric-car/

Dual Fuel (DF) use assumes the same efficiency as diesel efficiency.

Hydrogen is say 50 kg based on:
http://www.mahytec.com/en/our-solutions/ 38kg for 37L @ 700bar. 224.4 L @ STP is 2g so 2.3Kg stored. 0.005254083 MWh/Kg

Also see:
http://www.fuelcellstore.com/ultra-light-composite-storage-cylinder-e-series gives max of 0.000712695 MWh/kg

Compressed NG:
http://www.qtww.com/product/q-lite-lightest-cng-tanks/
Lightweight tanks for gas & liquid to 3600psi or 248 bar.
3.78541 litres per US Gallon.

FCV 60% conversion efficiency from H_2:
https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf
https://web.archive.org/web/20070221185632/http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/storage.pdf

LNG:
https://www.api.org/~/media/Files/EHS/climate-change/api-lng-ghg-emissions-guidelines-05-2015.pdf

https://www.cryodiffusion.com/products-and-services/cryogenic-cylinder-for-lng/cryogenic-cylinder-for-lng-for-taxis-buses-and-trucks/

The tank equivalent mass is scaled to match the 50l gasoline norm from a tank suitable for a truck, the figure of 0.742 decreases to 0.45 if LNG were used on a car, which is much less likely and not relevant to large prime movers.

Bio methane:
http://european-biogas.eu/wp-content/uploads/files/2013/10/eba_biomethane_factsheet.pdf assumed ~75%CH4;24%CO2;1%N2

Energy Storage:
https://www.thegwpf.org/content/uploads/2019/02/GridStorageWeb-1.pdf
https://www.carboncommentary.com/blog/2018/8/23/the-economics-of-power-to-fuels