On the Pursuit of Emissions-free Clean Mobility – Electric Vehicles versus E-Fuels

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Abstract: With the passing of every second we get closer to a society that is more cognizant of the effect carbon dioxide emissions are having on our planet, and that is more willing to take part in sustainable efforts to combat this and ever more interested in investing in cleaner technologies like electric vehicles (EVs). EVs are marching strongly into a market that is currently dominated by internal combustion engine vehicles, the current main fuel of which is a known contributor to most of the emission related climate problems that we now find ourselves in. Moving ahead, it is important that any move from internal combustion engines to more nascent technologies like EVs is sustainable and not detrimental to the environment. There is an ongoing debate between proponents of so-called e-fuels (being synthetic fuels

made from atmospheric carbon dioxide, water, and renewable energy) and EVs wherein e-fuels are largely accused of being a half-measure while EVs are thought to contribute more in terms of brake and tire emissions than the ICE vehicles. This raises the question of whether there should even be a complete replacement of the combustion engine vehicle fleet or that should there be a 'mobility mix' similar to how we currently refer to an energy mix with power grids. This article offers some perspectives by critically analyzing and diving deeper into these pressing concerns to answer some of these questions.

Keywords: *electric vehicles; e-fuels; emission-free; air quality; brake and tire emissions; indirect emissions*

Introduction:

Ever since the early 1960s, there has been enough observational evidence to suggest that growing concentrations of carbon dioxide (CO_2) in the atmosphere correlates to climate change across the globe [1]. Ever since then, efforts to tackle this issue have evolved in many directions. After identifying the role of emissions from internal combustion engines (ICEs) [2-4], tremendous efforts have been made to mitigate these by modifying engine technology, searching for more optimum and cleaner fuels, and also rethinking the prime mover used for mobility as exemplified by how electric vehicles (EVs) are now penetrating the global vehicle market [5-7]. EVs provide a convenient way to shift the emissions from the

tailpipe to the power plants although such power plants might use non-renewable sources that still cause emissions. These are often termed as indirect emissions and with an increasingly diversifying energy mix across the world with a growing contribution from the renewable energy systems, these indirect emissions will also fall [8-10]. Since most nations across the world are now moving towards using renewables and clean energy, governments everywhere acknowledge electric vehicles as a clean alternative to mobility [11]. At the other end of the spectrum, reducing CO_2 emissions can be looked at a bit differently by using e-fuels made from CO_2 extracted from the atmosphere or from another CO_2 emissions source (for example a gas-fired power plant), hydrogen electrolyzed from water, and renewable energy throughout. These feedstocks are then converted into synthetic hydrocarbons that can be utilized with our existing infrastructure and, in the form of "drop-in" fuels, existing ICE vehicles [12, 13]. Using power to drive this conversion of CO_2 to fuels is what is often termed as Power-to-X, where X is usually the end product (e-fuel in this case) that is obtained [14, 15]. Energy vectors like ammonia or hydrogen that do not contain carbon in them, but in turn utilize fossil-powered electricity, require us to think in terms of embedded CO_2 in them and are also considered e-fuels/ carbon-neutral synthetic fuels in some contexts. E-fuels can also be thought of as a convenient option considering how they do not require society to make changes to the existing mobility infrastructure while only having to modify with the energy vector as opposed to electric vehicles, which require us to make simultaneous wholesale changes to both the energy and prime mover vectors. Moreover, such e-fuels can be blended in as they become available, whereas the EV path requires what is effectively a binary switchover. Since the current grid infrastructure is not prepared to meet the energy demand if the entire ICE vehicle fleet is to be replaced with electric vehicles, this has given rise to many novel concepts such as vehicle-to-grid and smart grid integration technologies [5]. However, e-fuels are not without limitations. On a commercial scale the economic feasibility of e-fuels is largely unknown and the energetic efficiency of this route in comparison with direct electrification is very low. Also, since e-fuels basically utilize CO_2 from an existing gaseous source, be it

syngas from a cement plant for instance or from CO_2 from atmosphere using Direct Air Capture (DAC), these fuels upon combustion emit CO_2 back into the atmosphere making them carbon-neutral and not zero-carbon emission fuels [16, 17]. A comparison of the CO_2 emissions from these different technologies is shown in Figure 1 (a). A life-cycle study by Garcia et al [18], as depicted in Figure 1 (b) and (c), reveals that compared to conventional diesel ICE powertrains, electric, e-fuel, and hybrid e-fuel powertrains exhibit a nearly 50% reduction in WTW emissions during the use phase. The results indicate that during the complete use phase of a vehicle, e-fuels and EVs have similar CO_2 emissions reduction potential, while hybrids provide a 10% further decrement. Hence, EVs are not completely emission-free vehicles, as their operation leads to emissions due to the high WTT emissions caused by the high CO_2 emission intensity of electricity generation for EV charging or fueling. This emphasizes the importance of renewable electricity production in any sustainability action or policy aimed at decarbonizing any sector, including the use of EVs for transportation sector decarbonization. Due to higher emissions during the production phase of a battery car compared to diesel and hybrid vehicles, the CO_2 emission reduction potential of EVs is lower from a life cycle perspective. It is also interesting to note that e-fuels offer higher life cycle emission reductions in the US, whereas in the EU, the EV option is more efficient than e-fuels for life cycle CO_2 emission reduction, owing to its relatively cleaner electricity generation mix [19].

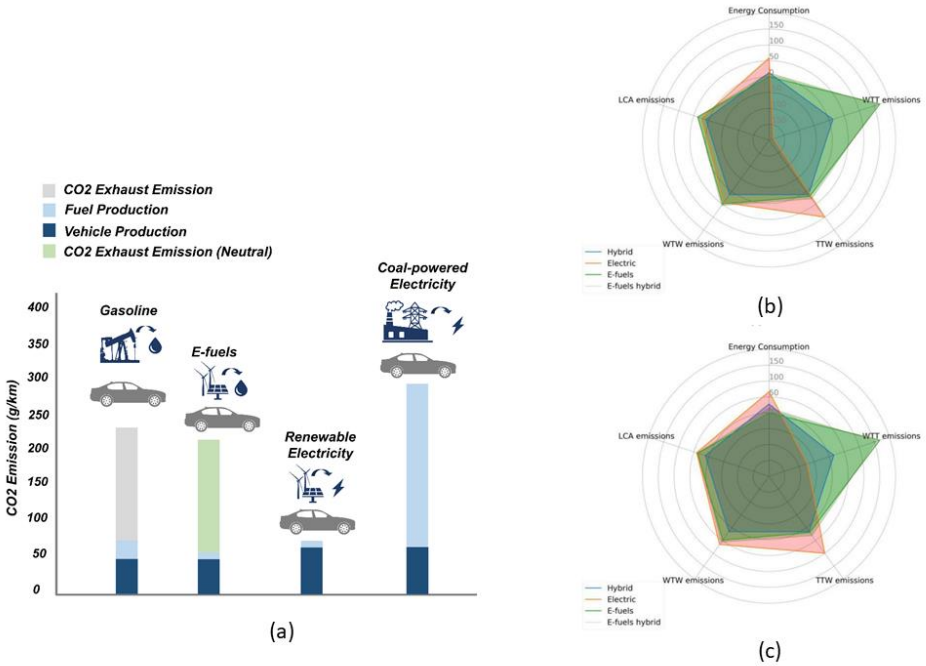


Figure 1: (a) A comparison of life-cycle CO_2 emissions from conventional and electric vehicles and their fuel/power sources. Data in the plot based on [20] (b) Overall life-cycle emissions and energy consumption from hybrid, electric, e-fuels and e-fuels hybrid vehicles in the Europe (c) Overall life-cycle emissions and energy consumption from hybrid, electric, e-fuels and e-fuels hybrid vehicles in the US. LCA over a lifetime of 150000 kilometers.

Rising above the notion of just CO_2 emissions and looking at the other emissions in general that might come from an EV and a conventional ICE vehicle operated on e-fuel, it is thought that both types of vehicles, contribute to particulate matter (PM) emissions from tires and brakes as well as from road wear. Since these emissions are usually functions of the mass of the vehicle, and EVs are generally heavier than ICE vehicles, these PM emissions tend to be higher with EVs [21-23]. With competing advantages and disadvantages between these technologies, that are both aimed at promoting sustainable mobility, it becomes imperative to understand and comprehend what the future of mobility could or rather should look like to meet the climate goals.

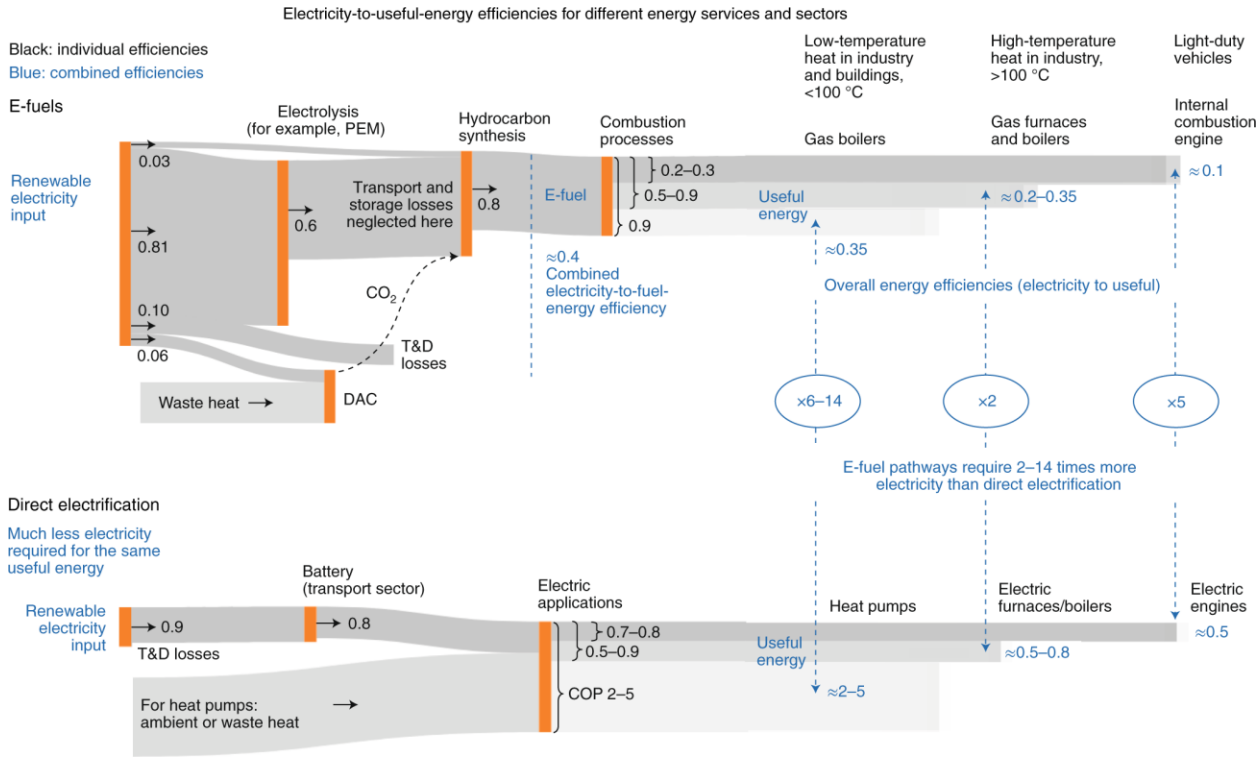
Are e-fuels just a half-measure?

Ueckerdt et al [12] make a direct comparison of direct electrification (using electric motors to drive vehicles) and indirect electrification (using e-fuels to drive internal combustion vehicles). While e-fuel has multiple energy conversion steps such as electrolysis, hydrocarbon synthesis and the combustion process that powers the internal combustion engine (with loss of efficiency at each step), direct electrification in contrast does not have multiple conversion steps (except for conversion to chemical energy in batteries for the transportation sector). These energy conversion steps account for a major difference in the overall well-to-wheel energetic efficiency, which is about 10% for e-gasoline in a light duty vehicle and about 50% for a vehicle running on an electric motor (see figure 2). The study by Ueckerdt et. al.,[12] also suggests that this difference in the overall efficiency, would need a 2-14 time increase in the renewable electricity production for the e-fuel production. While the well-to-wheel energetic efficiency of e-fuels may be worse than direct electrification [12], it is important to remember that globally there is no shortage of renewable energy. Furthermore, since an e-fuel packages this in a readily-transportable form it can be argued that, because all of the feedstocks for their synthesis are free and a product with a high value is made, there are could be significant economic possibilities from their adoption, provided the production of these fuels is cheap. However, even if the inefficiencies of e-fuel synthesis when compared with direct electrification[12] can be overlooked, the investment costs involved with e-fuels present a significant challenge to implement them on a larger scale [24]; these, of course, *are* tied to the efficiency. At the moment e-fuels are thought of as the only means to effectively decarbonize hard-to-decarbonize parts of the transportation sector like the aviation industry providing as they do a way to power an aircraft on a carbon neutral basis, without having to attempt to mount a heavy battery pack on-board [25, 26]. While e-fuels might sound like an inevitable option when it comes to aviation industry where vehicle-based carbon neutral options are difficult, this is not the case with road transportation which is currently in transition. Here we have sufficient solutions that are near commercial viability for zero-carbon pathways

such EVs which also seem to have an increasingly firmer grip on the automotive market. However, it must be remembered that the attraction of EVs and hydrogen-powered fuel cell vehicles to the vehicle manufacturers (the original equipment manufacturers, or OEMs) is essentially engineered by the dictation by governments of the measurement of tailpipe CO_2 emissions as the metric of compliance. This framework takes no account of the origin of the carbon in the fuel, essentially ruling out the use of biofuels or e-fuels. While a collective EU stance on the matter seems to effectively mean no new ICEV can be sold in the bloc starting from 2035. This debate has been met with some resistance, especially by Germany, the biggest car market in the bloc, which backed the EU decision on the condition that new ICEVs run on carbon-neutral fuels can still be sold in the future. [27-29]. This has essentially sparked the debate between the two technologies where it is asserted by some that utilizing e-fuels in road transport, a sector that accounts for almost one fifth of the global greenhouse gas emission[30], would just be a half-measure since there are ready alternatives that could achieve carbon-free mobility.

The current global mobility fleet is dominated by ICEs, with about a 99.8% of the vehicles using them; simultaneously almost 95% of the transportation energy comes from liquid fuels [31]. While taking efforts to mitigate carbon emissions by moving towards a technology much like EVs, and phasing out ICEs, we must do so in a way that the shift is gradual and sensible while not having to compromise on the goal of mitigating carbon emissions and thereby exacerbating the climate crisis[32, 33]. The complete electrification of mobility, assuming that we want to replace the entire ICE vehicle fleet with EVs, would mean huge and interrelated changes both along the prime mover vector and the energy vector [33] which will take a considerable length of time to complete, given the increasing longevity of vehicles sold. From a consumer point of view, even though not much emphasis is given on the total cost of ownership (TCO), when it comes light duty vehicles, it is worth to note that the TCO for EVs are in general less than that of ICE vehicles, when comparing similar segments. For example, Kia Niro 64 kWh (EV) has a TCO of 0.32 USD/km while Kia Sportage utilizing gasoline has a TCO of 0.53 USD/km [34]. This TCO can be expected to

rise a bit higher, if the same vehicle were to be run using e-gasoline, which can be more expensive than regular fossil-based gasoline. A Transport and Environment (T&E) study estimates that the TCO for running a synthetic-fuelled car can be 43% higher than that of electric vehicles [35]. So EVs are clearly better in giving us a way to move away from carbon emissions (assuming they are powered by renewable electricity throughout), e-fuels seem to have some merit for the different reason that they are more practical to implement and suitable for the decarbonization of the legacy fleet, which cannot be achieved via the complete electrification route [36]. Choosing to decarbonize the transportation sector by dumping the existing internal combustion engine fleet could present significant challenges on its own both in terms of economics considering the scale of it, and environment, since 25% of the generated waste from these parts cannot be recycled and are often dumped in a landfill, which might cause severe land degradation [37, 38]. While most cars to do end up in a land fill at the end of their lifespan, factors that might lead propel the a complete shift to an alternative prime mover away from internal combustion engines, will worsen the problem of land degration. These factors could be direct (a legislation that restricts ICE use in the future) or indirect (by incentivizing other non-ICE run vehicles, and taxing ICE-run vehicles) and would exacerbate the issue of land degradation, while taking into consideration that lifespan of an average light duty vehicle has improved (more than doubled) since 1960 [39].So, as we produce highly engineered fossil fuel run vehicles that have a longer span, the only way to sustainably run them would be decarbonize the fuel source.



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165

166 **Figure 2 – A sankey diagram comparing the well-to-wheel energetic efficiency comparison of e-fuel**

167 **(indirect electrification) and direct electrification alternatives. Reproduced from [12]**

168 **Comparing indirect emissions**

169 Indirect emissions are emissions that are associated with the mobility but have its origin in the way they

170 are powered. The term gained popularity when EVs were initially claimed to be emission-free and the

171 claim was moderated by pointing out that there were emissions associated with the nature of the

172 electricity that was used to power it [8]. However it is largely ignored that, by this rationale, it is the case

173 that internal combustion engines also have associated emissions if the emissions that arise from the

174 refineries that produce and transport the fuels are accounted for [40]. The indirect emission sources,

175 namely the power plants and refineries today, when compared for their overall GHG emissions show that

176 the conventional power plants that we have today, when run on fossil resources contribute significantly

177 to global GHG emissions. It is estimated that petroleum refineries have the second highest GHG emissions
178 as a sector with 1.22 MMT CO_2e, being only second to the power plant sector[41]. This trend could very
179 well change in the coming years, considering the increased investments in Renewable Energy Systems
180 (RES) which also contribute to the electricity mix bringing down the sectoral GHG emissions. This trend is
181 evident from Figure 3 (a). Since almost 60% of the petroleum products produced by refining of fossil fuels
182 are used as transport fuels, we could associate that proportion of greenhouse emissions as indirect
183 emissions associated with the conventional ICE-run vehicles [42, 43]. On the other hand, it has been noted
184 that about only 0.03% of the electricity produced was utilized by the EVs in the Europe in 2014 and it has
185 been estimated that about 4-5% of the electricity generated in Europe might be utilized for powering EVs
186 in 2030 and about 9.5% by 2050 [44]. These can be assumed to be conservative estimates of the global
187 electricity consumption of electric vehicles since the shift towards EVs is likely to be much slower in
188 developing markets. The indirect emissions from transportation can be seen in Figure 3 (b) wherein it is
189 clear that even in terms of indirect emissions we would be better off with electric vehicles at the moment
190 but it is also fair to note that the indirect emission data comparison is drawn between a prime mover that
191 constitutes the 99.8% of the transportation needs [31] with a growing, but nevertheless small, number of
192 vehicles utilizing electricity for transportation when compared with ICE vehicles. With a higher
193 contribution from renewable energy systems (RES), we could hope that the indirect emissions from the
194 electric vehicles can be brought down as, in terms of operational emissions, EVs are only as good as their
195 electricity source. Different countries have different sources of electricity and hence very different carbon
196 footprints. Figure 3 (c) shows the grams of CO_2e/km from electric vehicles depending on the electricity
197 mix used in the country [45]. It is currently estimated that the social cost of carbon, which is a measure of
198 the economic harm (in terms of dollars) from the impacts of emitting one ton of CO_2 into the atmosphere
199 is over 50 USD/ton [46]. However, considering that currently 95% of our transportation needs are being
200 powered by liquid fuels for a variety of reasons such as high energy density and convenience of storage

and transportation, we can safely assume that we will have, even in the foreseeable future (at least until 2040), a clear demarcation between electricity/energy demand and fuel demand [31]. This has also been acknowledged by the scientific community working on artificial photosynthesis [47] and the production of solar-fuels [48, 49]. These works, despite having a very low technological readiness level (TRL) when compared to e-fuels produced by Fischer-Tropsch [50-52] or Methanol-to-Gasoline (MTG) processes [53-56], show how there is a wide range of efforts across the scientific community to address the need for a clean and renewable fuel and not *just* clean electricity.

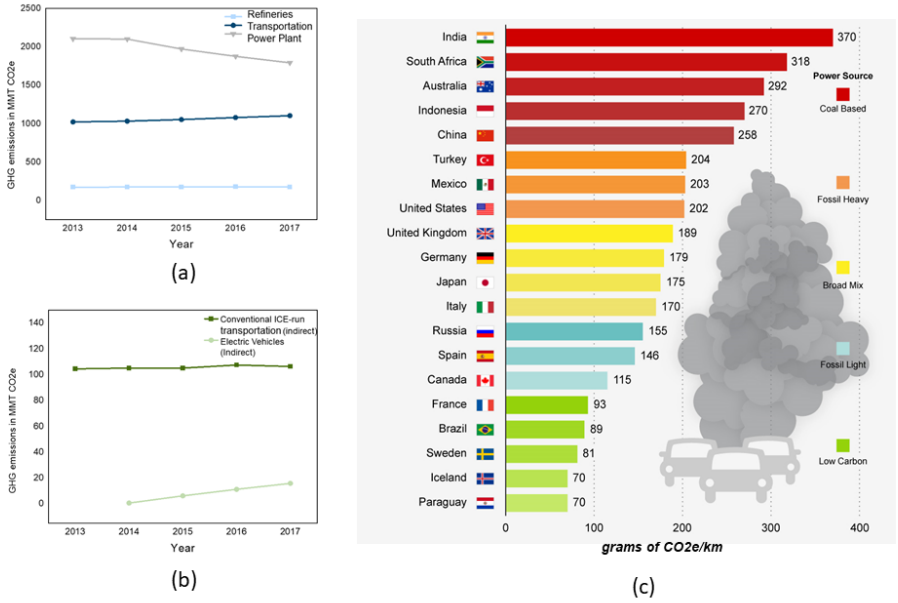


Figure 3 (a): A comparison of the greenhouse gas emitted by refineries, transportation and the power plant sectors as a whole [57-59], (b) A comparison of the indirect emissions associated with conventional and electric vehicles [31, 44], (MMT – Million Metric Tons), [c] Carbon emissions of grid-powered electric vehicles by country (g CO_2e/km) (reproduced from [45])

Non-Combustion Emissions

More recently, concerns have been raised over the non-combustion emissions from vehicles. A positive correlation between the weight of the vehicle and non-exhaust particulate emissions which are emitted

from the tires and brakes has been identified [23, 60]. Tire and brake emissions are not regulated at the moment, despite evidence suggesting a link between particulate emissions and a plethora of health issues ranging from respiratory diseases to even death [61]. Concerns over these emissions have been sparked recently largely because of the difference in mass between EVs and their conventionally-powered counterparts. Figure 4 shows the average mass of vehicles in different segments with electric, gasoline and diesel-fuelled ICE vehicles [60]. From the figure, it is clear that EVs when compared with their conventional ICE counterparts are significantly heavier. This could mean that EVs, despite helping overcome the challenge of mitigating CO_2, might exacerbate local air pollution by increasing emissions of particulate matter (PM). PM emissions, especially range of 2.5 nm to 10 nm ($PM_{2.5}$ to PM_{10}), have been an issue even for conventional ICEs but an increasing number of EVs could exacerbate the problem and directly have an effect on air quality and urban life-style [21, 22] despite widespread belief that all emissions from transport are associated with combustion only. Non-combustion emissions pose a serious threat but cannot be avoided since most of our road transportation depends on the traction wheels generate from the road surface. There could be scope for improving the materials of tires which would emit fewer particulates as the vehicle moves but it is also possible that we may have to rethink the way we move about fundamentally. In a bid to counter-act the two main factors that slow down conventional means of transport, friction and air resistance, one such futuristic way of thinking about transportation was introduced – the Hyperloop [62, 63]. Virgin Hyperloop One, has devised a test Hyperloop track in France, which involves magnetic levitation that would lift passenger pods off the rails while moving them through a near-vacuum low-pressure tube thereby enabling mobility with almost no resistance [64]. A technology like this could completely avoid non-combustion emissions. The virtue of moving inside of a tube, also enables us to move in almost any weather or geographic conditions. Comparing this with either EVs or ICE vehicles, windshield wipers employ a hydrocarbon-based windshield washer fluid which during bad weather also introduce volatile organic compounds (VOC) emissions [65] into atmosphere. This

shows that emissions from transportation needs some revisiting holistically and that the need for emission-free mobility needs to be emphasized rather than ad-hoc partially clean solutions

While a technology such as Hyperloop is not currently mature, it is perhaps better to think of future mobility in terms of a mobility-mix where that mobility is powered by different technologies that co-exist rather than looking for a one-size-fits-all solution (the so-called “silver bullet”, which is what the ICE operating on fossil fuels has been up until now).

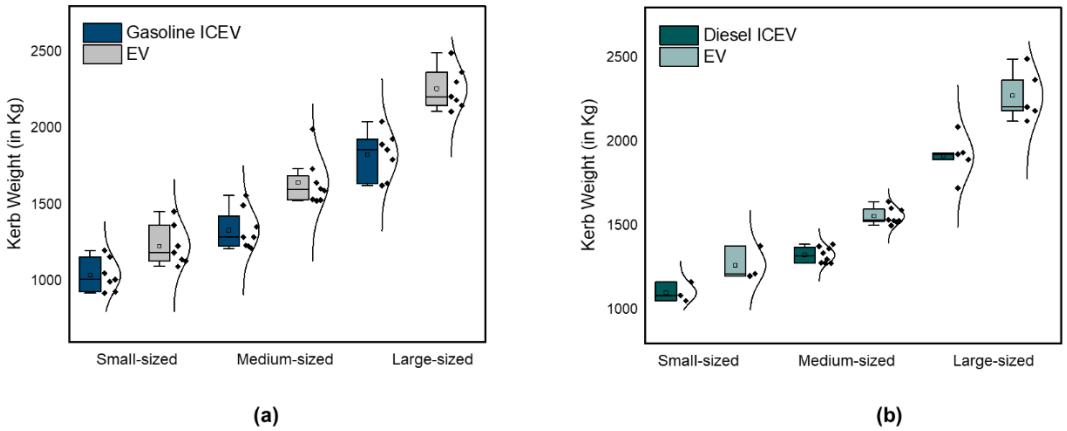


Figure 4: Comparison of the kerb weights of conventional vehicles with comparable electrified counterparts (a) Kerb weights of gasoline-powered internal combustion engine vehicles against that of electric vehicles (b) Kerb weights of diesel-powered internal combustion engine vehicles against that of electric vehicles. Data in the plot taken from [60]

Need for Policy Action

Policy adoption within the transportation sector has favored EVs for zero direct emissions [66]. Recent policy changes have also moved the automotive OEMs to pursue the idea of EVs via a forced phase-out of ICEs, with the current policy measures seeming imminent [67]. While EVs do in fact reduce CO_2 emissions as we move towards renewable energy, and thereby will help to avoid global warming and the climate

crisis, speculations on the non-combustion emissions and the feasibility of utilizing intermittent renewable resources for large-scale implementation cannot be ignored. With non-combustion emissions being unavoidable from all forms of road vehicles, it becomes imperative for us to rethink the way we move. This also emphasizes the need for a comprehensive cradle-to-grave life cycle assessment of e-fuels and electric vehicles to fully assess the environmental impact of the two technologies, which also directly implies the need for accurately measuring non-combustion emissions like brake and tire emissions from vehicles[68, 69]. A comprehensive LCA would allow us to more objectively assess the impact of these technologies and help policy makers plan for a cleaner future. Policy makers that wish to take a step in this direction should perhaps choose to promote public transportation. Moving towards public transportation, of course, is not without its challenges. Policy changes aside, discouraging the use of personal vehicles would need a very effective public transportation system in place that overcomes the past spatial planning decisions. Public transport systems, usually state-owned or controlled, require a huge subsidy from the public purse to be run and hence a push towards using them would mean a huge subsidy from governments. Traffic rationing schemes, that have been used in the past to reduce vehicular emissions can cause legal problems and severely undermine the economy [70, 71]. Imposing a 'personal mileage budget', wherein a limit is set on the number of miles driven by individuals driving combustion vehicles utilizing fossil fuels could promote the use of public transportation networks. Another possible approach could be to perhaps set a limit on the amount of fossil fuel that could be purchased by an individual which would drive the public to drive more efficient vehicles or to drive the less efficient vehicles less. Brake and tyre emissions aside, a positive correlation between the effect of weight of the vehicle on road wear would suggest a need for higher road tax on EVs than on conventional ICE vehicle. Futuristic technologies for transportation including Hyperloops and ionic flights [62, 63, 72] might have very low negative environmental impact when they become feasible but in the interim, considering how the transportation sector is in flux, it is perhaps better to think of mobility in terms of a 'mobility-mix'

allowing for the merits from each of these technologies to be incorporated in a more holistic way. Emission-free mobility in absolute terms with the current mobility infrastructure might be an unreasonable target to achieve and cleaner mobility will largely be a function of offsetting the emissions with negative emission technologies (NETs)[73, 74] which again will have to come from direct or indirect taxation or some form of voluntary contribution. Climate action in transportation needs strong policy measures on different levels, right from the production of vehicles to recycling them, considering all the steps in the life cycle. While technical issues like battery degradation can be addressed by scientific research, issues associated with, for example, the mining of materials for batteries [75] and subsequently recycling them sustainably needs stronger policy changes and public outreach [76].

Conflict of Interest:

There are no conflicts of interest to declare

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