DECARBONIZATION OF MD-HD VEHICLES WITH PROPANE

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Introduction

The argument for the transition toward decarbonization of all energy sectors has hit top gear due to the spread of the COVID-19 pandemic. While it is often assumed that full electrification of these sectors will lead to their full-decarbonization, little thought on how electricity is currently generated, stored, transmitted, and consumed has been considered. The ideal scenario of 100 percent renewable power generation is widely accepted to occur in the near future and is considered as an enabler for full electrification, and, hence, full decarbonization, without a clear path for achieving it. Circular arguments are constantly being made on this topic, a common one being that renewable energy infrastructure such as wind turbines and solar panels will eventually be manufactured using renewable energy produced by several such renewable energy installations. A good possibility exists for aggressive renewable energy penetration installations to come with a penalty of increased carbon emissions in the interim by increasing our dependence on fossil energy, a ubiquitously and economically available resource. This is similar to Jevons paradox and the energy rebound effect. Once we facilitate enough renewable energy installations, our dependence on fossil energy would gradually lessen, while simultaneously promoting a shift toward renewable energy and renewable fuels, including electrofuels. However, we are still decades away from such a scenario.

Hence, the purpose of this paper is to position propane as a solution for accelerating decarbonization of the medium- and heavy-duty transportation sector and several other energy sectors. As you will see in the argument and graphics provided below, propane-fueled medium- and heavy-duty internal combustion engine vehicles provide a lower carbon footprint solution in 38 U.S. states and Washington, D.C., when compared to medium- and heavy-duty electric vehicles (EVs) that are charged using the electrical grid. When using renewable propane, the benefits go even further.

To reinforce this premise, a cursory life-cycle analysis of equivalent carbon dioxide (CO2eq) emissions was conducted between a medium-duty (Class 6-7) electric vehicle and a propane-fueled vehicle. The intent here is to evaluate the U.S. state-level difference in CO2eq emissions between the two vehicles and provide an alternate hypothesis for decarbonization using propane and its blends.

Assumptions

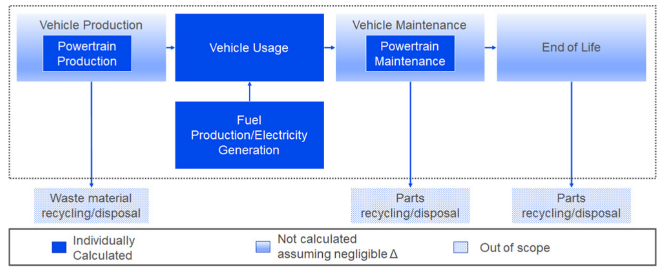
Several qualitative and quantitative assumptions of the life-cycle analysis are shown in Table 1: Assumptions of LCA, below.

Parameter	Value
Vehicle	Class 5-7 truck
State-level electricity carbon intensity (CI) – lb/MWh	Combustion emissions as per EIA data for 2018[1] and production emissions were calculated adopting CARB methodology for each state's energy mix[2,3]. Note, the carbon intensity will depend on the time of electric vehicle charging, but an average value method used by the state of California is adopted here.
Fuel well-to-wheel (WTW) CI (gCO2eq/MJ)	Propane: 83.19 for California[4]. Adopted CARB method for each state in a specific Petroleum Administration for Defense District (PADD)[5]. Renewable Propane: 45 (using Fats/Oils/Grease/Residues[6]) for all states. Renewable propane could be manufactured at one location and transported to another but the transportation emissions across states are not accounted for. Renewable Dimethyl Ether (DME): -278 (using dairy manure[7]) for all states. Renewable DME could be manufactured at one location and transported to another but the transportation emissions across states are not accounted for.
Transmission and Distribution Losses (%)	5[8] (US national average assumed for each state)
Miles per day	200
Miles driven per year	60,000
Truck life (miles/years)	300,000/5 years
Electric vehicle (EV) charging loss (%)	10%[9]

1. https://www.eia.gov/electricity/state/unitedstates/
2. https://www.nei.org/resources/statistics/state-electricity-generation-fuel-shares
3. https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/comments/tier2/elec_update.pdf
4. https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities
5. https://www.eia.gov/todayinenergy/detail.php?id=4890#:~:text=The%20Petroleum%20Administration%20for%20Defense,PADD%205%20the%20West%20Coast.
6. https://ww2.arb.ca.gov/sites/default/files/classic//fuels/lcfs/fuelpathways/comments/tier2/rpane_temp.pdf
7. https://www.greencarcongress.com/2020/02/20200212-oberon.html
8. https://www.eia.gov/tools/faqs/faq.php?id=105&t=3#:~:text=The%20U.S.%20Energy%20Information%20Administration,annually%20in%20the%20United%20States.&text=EIA%20has%20estimates%20for%20total,in%20the%20State%20Electricity%20Profiles.
9. https://www.fueleconomy.gov/feg/atv-ev.shtml

Battery capacity (kWh/mi)	2.6[10] (Note, the average annual efficiency of Proterra buses deployed by Foothill Transit has been around 2.2 kWh/mile[11]).
Battery size (kWh)	520
Li-ion cycle life (-)	1,000[12] (Currently, typical EV battery warranty lasts for 100,000 miles or 8 years). 5,000[13] (typically needed for a million-mile battery with 200 miles of EV range)
Battery manufacturing CO2eq emissions (kgCO-2eq/kWh)	140[14] (as per the International Council on Clean Transportation report, this is a value based on a study of a Ford Focus battery EV using real factory data). 61[15] (energy used for battery manufacturing is from zero-carbon sources). Batteries are manufactured at various locations (predominantly outside U.S.) and transported, but the transportation emissions are not accounted for.
Recuperated energy by regenerative braking (%)	20
Propane vehicle fuel economy (mpg)	5.5 for propane and renewable propane 5.3 when propane is blended with renewable DME due to DME's lower energy content. These fuel economies are nominal and current generation propane vehicles demonstrate on par performance with diesel[16].
Specific power of engine powertrain with after-treatment and transmission (kW/kg)	0.47[17]
Engine peak power (kW)	260
Carbon footprint of Internal combustion engine vehicle (ICEV) and EV common fluids (KgCO2eq per maintenance interval)	26.5[18] (40% inflation factor for medium-duty vehicle over light-duty vehicle value).
Carbon footprint of EV motor, inverter, controller, transmission, and cooling system (kgCO2eq)	2989[13] (10 percent inflation factor for medium-duty vehicle over light-duty vehicle value).
EV service interval (miles)	40,000
Carbon footprint of ICE with after-treatment and transmission (kgCO2eq/kg)	5.3[13]
Carbon footprint of ICEV oil and radiator coolant per maintenance interval (kgCO2eq)	4.5 and 9.8[14] (40 percent inflation factor for medium-duty vehicle over light-duty vehicle value)
ICEV service interval (miles)	5,000 for oil change, 15,000 for radiator coolant change, and 40,000 for all other maintenances.

In addition to the assumptions listed above, the CO2eq emissions from the vehicle body, doors, chassis, tires, tire replacement, wheels, wheel replacement, final assembly, interior and exterior, and lead-acid battery were all assumed to be similar between the two vehicles such that the difference between them is negligible. EVs are heavier than internal combustion engine vehicles (predominantly due to battery mass) and hence may need additional material "padding" but incremental emissions attributed to those are considered negligible. Furthermore, no credit was assumed for the Lithium-ion battery second life, i.e. for its use in utility scale grid applications after its end-of-life for transportation applications. In addition, no credits for recycling the components of the Lithium-ion battery were assumed as this is still an active topic of research[19]. Similarly, CO2eq emissions from end-of-life were assumed to be similar for the two vehicles such that the difference between the two is negligible (even though the EV is heavier than the conventional vehicle). Finally, electricity that is generated in a state is assumed to be used for charging the EV even though electricity is imported from neighboring states (and sometimes countries outside the U.S.) in several states i.e. the net carbon intensity could be computed based on emissions attributed to electricity generation or electricity consumption[20]. It is also assumed that the medium-duty vehicle is charged only in the state to which it belongs to or operates most of the time. It is reiterated here that the purpose of this analysis is to evaluate the difference between total-life cycle CO2eq emissions between a medium-duty propane vehicle and EV but not to accurately quantify their individual carbon footprint. Figure 1 shows the boundary diagram of the life-cycle analysis, below.



It is also assumed that the battery size is sufficient to provide the required cabin heating for the EV, though some medium- and heavy-duty vehicles also employ auxiliary diesel and propane generators for supplemental heating[21]. As such, the carbon footprint of any auxiliary heating device is not accounted for in this analysis. Finally, no land-use modification and its impact on carbon footprint for proliferating the production of renewable fuels is considered.

The State of the U.S. Electrical Grid

Figure 2(a-i) shows the state-level energy mix for electricity generation for all fifty U.S. states and Washington, D.C., using coal, natural gas, petroleum, biomass and other, nuclear, geothermal, solar-photovoltaic (PV), wind, and hydroelectricity. It is very clear from the charts, the magnitude of effort needed

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12. https://batteryuniversity.com/learn/article/bu_1003a_battery_aging_in_an_electric_vehicle_ev
13. https://silanano.com/wp-content/uploads/2020/09/The-Future-of-Energy-Storage.pdf
14. Hall, D. and Lutsey, N., 2018. Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions.
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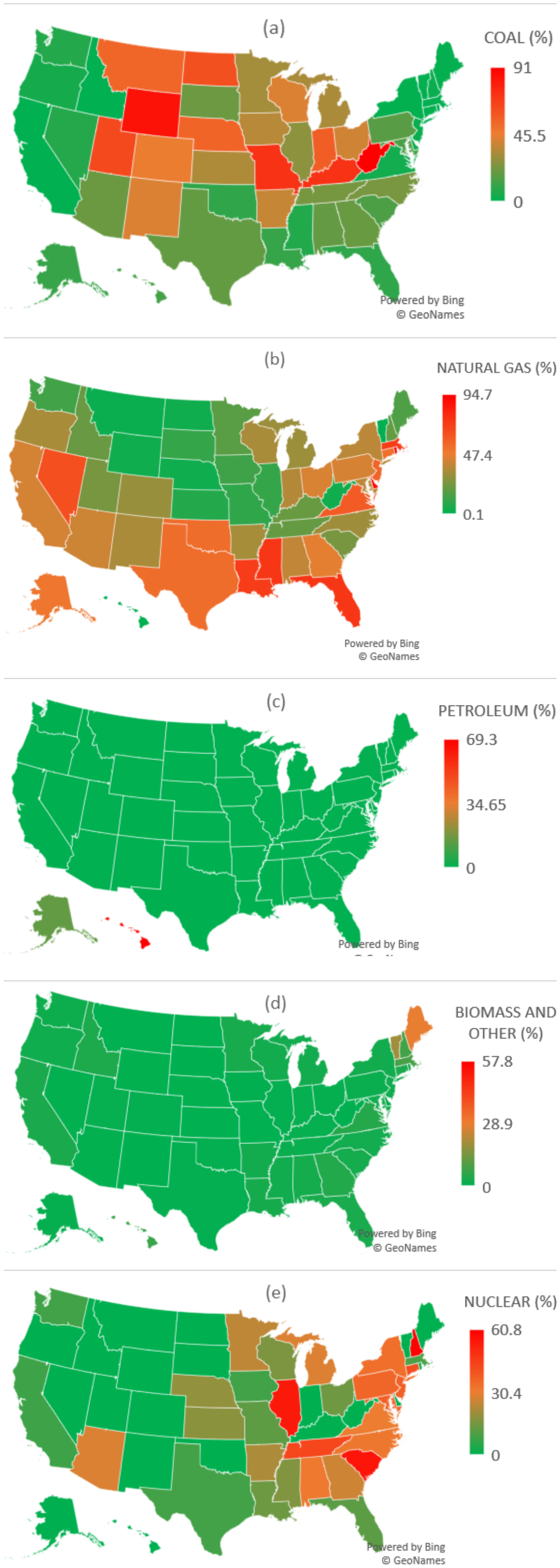
16. Rengarajan, S., Liu, Z., Lerin, C., Stetter, J., Narang, V. and Lana, C., 2020. LPG Direct Injection Engine for Medium Duty Trucks (No. 2020-01-5008). SAE Technical Paper.
17. Kawamoto, R., Mochizuki, H., Moriguchi, Y., Nakano, T., Motohashi, M., Sakai, Y. and Inaba, A., 2019. Estimation of CO2 Emissions of internal combustion engine vehicle and battery electric vehicle using LCA. Sustainability, 11(9), p.2690.
18. Hawkins, T.R., Singh, B., Majeau- Bettez, G. and Strømman, A.H., 2013. Comparative environmental life cycle assessment of conventional and electric vehicles. Journal of Industrial Ecology, 17(1), pp.53-64.
19. https://www.anl.gov/article/doe-launches-its-first-lithiumion-battery-recycling-rd-center-recell
20. de Chalendar, J.A., Taggart, J. and Benson, S.M., 2019. Tracking emissions in the US electricity system. Proceedings of the National Academy of Sciences, 116(51), pp.25497-25502
21. https://www.lpgasmagazine.com/doe-funding-for-vehicle-technology-shows-parity-for-propane/

for enabling a 100 percent renewable energy electrical grid in the U.S. Currently, the U.S. renewable energy penetration stands at approximately 18 percent[22].



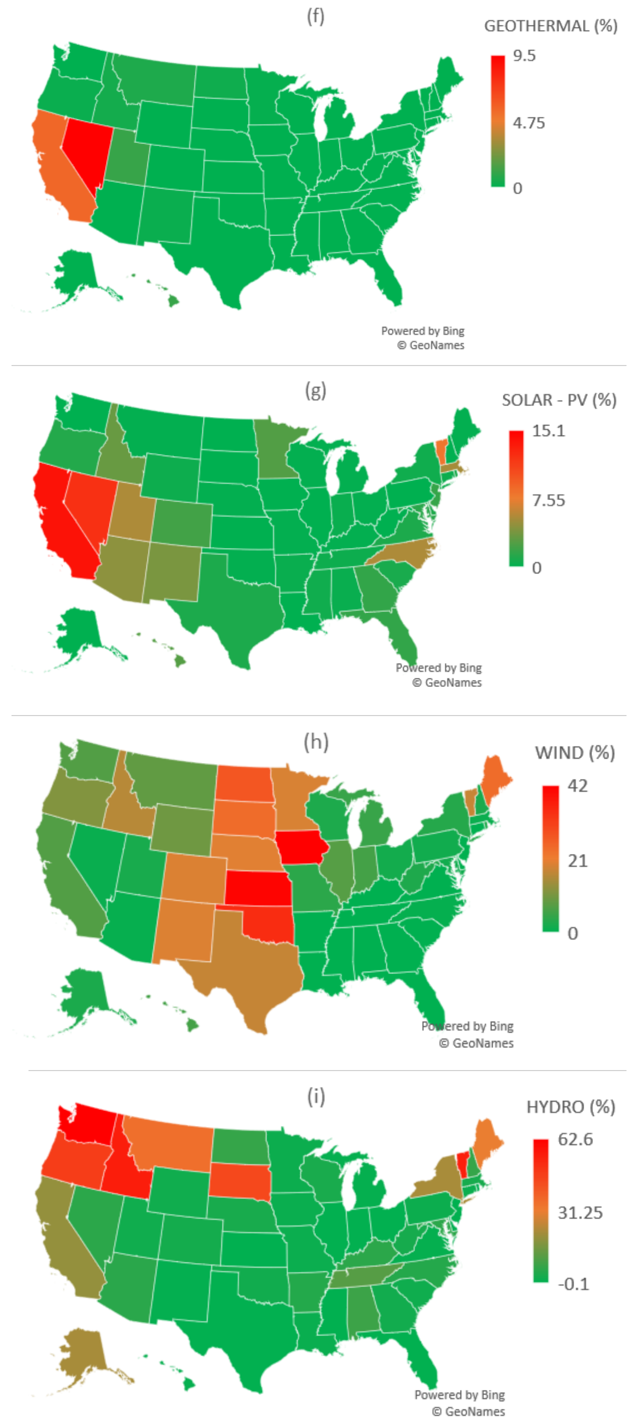


Figure 2: State-level energy mix for electricity generation from (a) coal, (b) natural gas, (c) petroleum, (d) biomass and other sources, (e) nuclear, (f) geothermal, (g) solar-PV, (h) wind, and (i) hydroelectricity.

Simulated Scenarios

Table 2 outlines the five scenarios that were simulated in this study. It is to be noted that DME and renewable DME are similar to propane in terms of their physical properties. DME has been long considered as a replacement for diesel fuel for medium- and heavy-duty transportation sectors due to its high cetane rating and low soot formation tendency. Renewable DME can be blended with conventional or renewable propane

22. https://www.eia.gov/outlooks/aeo/section_issue_renewables.php2.

further reducing the blended fuel's carbon footprint. In this study, a 20 percent-80percent (by mass) renewable DME-propane (or renewable propane) blend was assumed (Note, the Propane Education & Research Council is collaborating with Oberon Fuels to study the impact of this fuel blend on ICEV performance and emissions).

Furthermore, renewable fuel and vehicle component production carbon intensities were assumed the same as status-quo even under a decarbonized electric grid scenario (Case V). The carbon intensity of renewable fuels and component production carbon intensities will be much lower due to cleaner electricity generation. Projections are out-of-scope for the current analysis. In addition, propane vehicle fuel economy has been assumed the same as status-quo even for Case V. In reality, the fuel economy will improve significantly due to the evolution of propane engine technologies over the next 20 to 30 years.

Table 2: Simulated Scenarios

Case	Detail	Li-ion battery cycle life (-)	Li-ion battery manufacturing emissions (kgCO2eq/kWh)	State-level electricity CI	ICEV fuel economy (MPG)
I	Comparison between conventional propane vehicle vs. EV	1,000	140	Status-quo	5.5
II	Comparison between renewable propane vehicle vs. EV	1,000	140	Status-quo	5.5
III	Comparison between conventional propane/renewable DME blend vehicle vs. EV	1,000	140	Status-quo	5.3
IV	Comparison between renewable propane/renewable DME blend vehicle vs. EV	1,000	140	Status-quo	5.3
V	Comparison between renewable propane/renewable DME blend vehicle vs. EV	5,000	61	95% lower carbon emissions than status-quo	5.3

Well-to-Wheels Carbon Intensity of "Fuel"

Figure 3(a) and Figure 3(b) show the well-to-wheels carbon intensity of propane and grid electricity over the U.S., respectively. Note, the carbon intensities are plotted on the same scale for both energy types. As mentioned before, the CARB methodology was adopted to calculate the well-to-wheels carbon intensity of propane for each state in a specific PADD region. Since the fifty U.S. states and the district are divided into five different PADD regions, five different values of propane are obtained[5]. Differences in the propane carbon intensities predominantly arise from the percentage of propane obtained from natural gas processing and that obtained from oil refining, which varies for each PADD region.

Based on the state average energy mix for electricity generation and assuming a 10 percent charging loss, the carbon intensity of the electricity used for charging the EV was obtained. For validating the carbon intensity of the grid electricity, consider the state of California where the current analysis provides a carbon intensity of 87.5 gCO2eq/MJ of consumed electricity. This value includes 10 percent charging loss and hence the actual electrical grid carbon intensity would be 78.75 gCO2eq/MJ, including the electrical transmission loss. Earlier this year, CARB published a carbon intensity value of 82.92 gCO2eq/MJ for average grid electricity used for charging EVs[3]. This value is 5 percent higher than the value deduced from the current analysis. **Hence, this analysis may indeed underestimate the carbon footprint of EVs.** Nonetheless, no further correction to electrical grid carbon intensities was considered in this analysis.

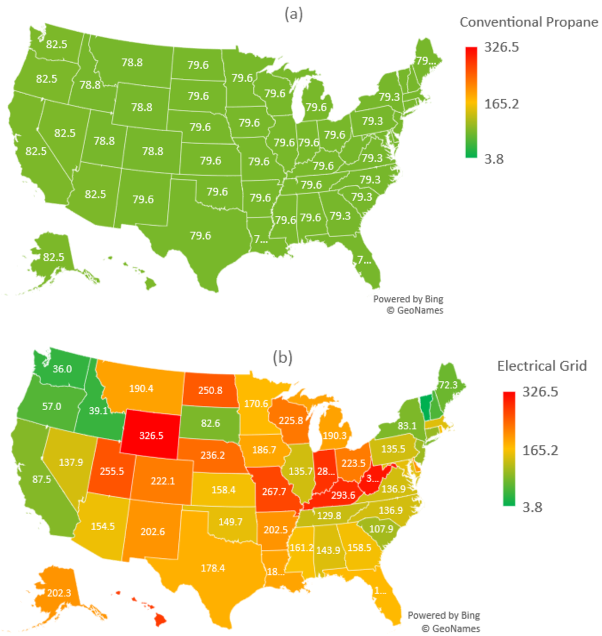


Figure 3: WTW CI (gCO2eq/MJ) of (a) propane and (b) grid electricity.

However, the carbon intensity of the energy by itself does not provide the entire picture of the total carbon footprint of vehicles as the EV powertrain efficiency is far superior (>70 percent efficient[10]) than that of the internal combustion engine vehicle (~35-40% efficient) i.e. converting electrical energy to mechanical work is more efficient as compared to converting fuel chemical or internal energy to mechanical work due to higher second-law of thermodynamic irreversibility and energy losses. Hence, the powertrain efficiency should be considered for a rational comparison of carbon footprint between the two vehicles, the results of which are discussed in the next section.

Results and Observations

Figure 4(a-e) shows the total difference in life-cycle CO2eq emissions between a single medium-duty propane vehicle and EV for all five cases. The results are shown in a two-color scale with the color green highlighting locations where a medium-duty propane vehicle is better than an EV from a total CO2eq life-cycle emissions and the color red highlighting locations where EVs are better suited than propane vehicles. The numbers on the chart for each location represent the difference in total CO2eq life-cycle emissions in U.S. tons when compared for a single medium-duty vehicle.

See graphs on next page.

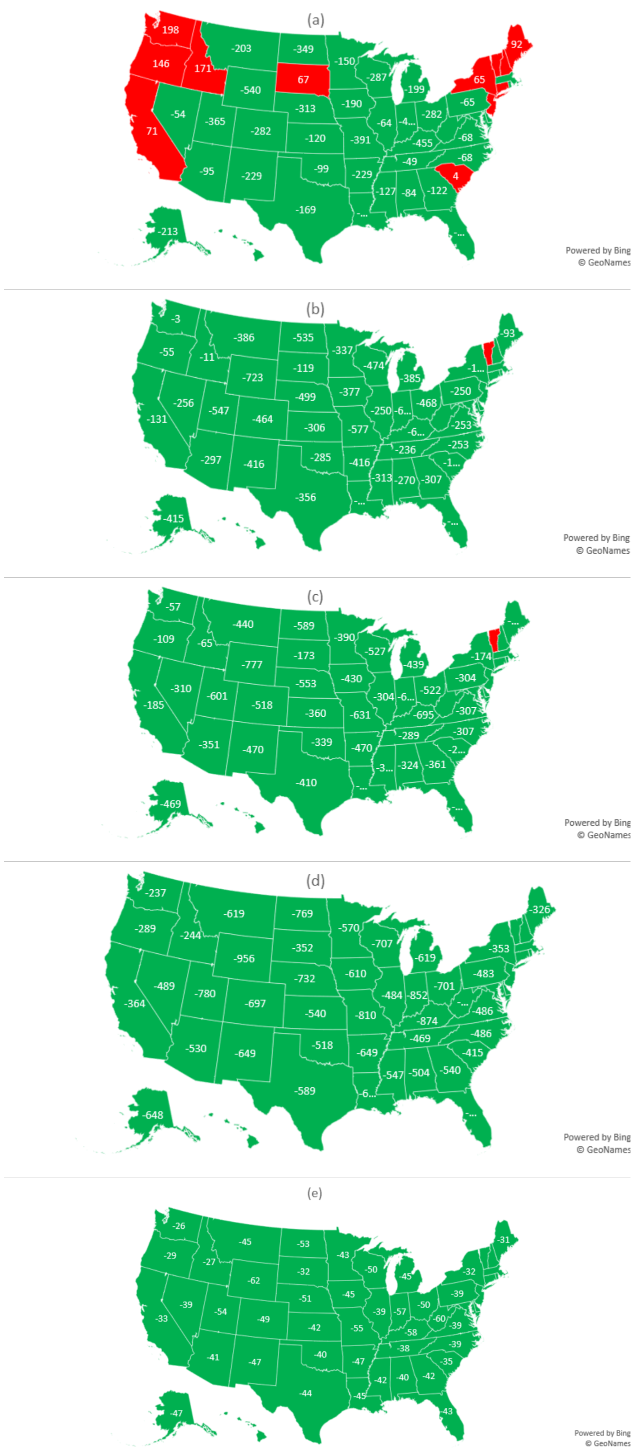


Figure 4: Difference in life-cycle CO2eq emissions (U.S. tons) between a medium-duty propane vehicle and an EV for (a) case I, (b) case II, (c) case III, (d) case IV and (e) case V.

Some key observations from the above infographics:

- Currently, propane fueled medium- and heavy-duty vehicles provide a lower carbon footprint solution in 38 U.S. states and the district when compared to medium- and heavy-duty EVs that are charged using the electrical grid. This is evident from the results of case I as seen in Figure 4(a). Evaluation of carbon intensity for a microgrid charging infrastructure that is powered by solar-PVs and supplemental battery energy storage is out-of-scope of this analysis. Grid-scale Lithium-ion energy storage batteries also contribute to significant CO2eq emissions akin to their transportation counterparts, but have a longer usable life.
- Currently, renewable propane-fueled vehicles provide a lower carbon footprint solution in all 50 U.S. states except Vermont when compared to medium-duty EVs that are charged using the electrical grid. This is evident from case II results as seen in Figure 4(b). Vermont is a special case where electric power is generated predominantly from clean hydroelectric power plants with additional hydroelectric power imported from Canada. Vermont has the following energy mix: 55 percent hydroelectricity, 17.6 percent wind energy, 8 percent solar-PV, and 19.4 percent biomass.
- As seen from Figure 4(c), currently, vehicles with a fuel blend of propane and renewable DME (80 percent-20 percent by mass) can enable a lower carbon footprint solution in every state except Vermont when compared to medium-duty EVs that are charged using the electrical grid.
- As seen from Figure 4(d), currently, vehicles with a fuel blend of renewable propane and renewable DME (80 percent-20 percent by mass) can enable a lower carbon footprint solution in all 50 states when compared to medium-duty EVs that are charged using the electrical grid.
- Finally, as seen from Figure 4(e), even in an ideal scenario of a decarbonized grid with 95 percent carbon intensity reduction and with Lithium-ion batteries manufactured with zero-carbon energy sources (61 kgCO2eq/kWh) and lasting for a million miles (5,000 cycles), vehicles fueled with a blend of renewable propane and renewable DME enable a lower carbon footprint solution in all 50 states compared to medium-duty EVs.

It is noted here that the current supply of renewable fuels does not meet the fuel demand. However, the Western Propane Gas Association is targeting a 100 percent replacement of conventional propane with renewable propane by the year 2030 in California, while the entire U.S. propane industry is targeting at least a 50 percent replacement of conventional propane with renewable propane by 2050. In addition, investments into renewable diesel facilities by companies such as Marathon Petroleum[23] and Phillips 66[24] should help address the fuel supply issue as renewable propane is a byproduct of renewable diesel and sustainable aviation fuel (~5-10% of off-gas is renewable propane). Furthermore, recent advancements in carbon capture technology[25] and tapping captured CO2 from power plants (plus industrial facilities and marine sector) for synthetic DME production are also very encouraging[26].

Conclusions and Recommendations

- 15 states (California, Connecticut, Colorado, Hawaii, Maine, Maryland, Massachusetts, New Jersey, New York, North Carolina, Oregon, Pennsylvania, Rhode Island, Vermont, and Washington) and Washington, D.C. have proposed full electrification of medium- and heavy-duty trucks[27] by 2050 with a target of 30 percent "zero-emission"[28] vehicle sales by 2030. The rationale behind the decision needs to be revisited as it largely hinges on the fact that the electrical grid will be fully decarbonized by that time.
- All 50 states should aggressively invest resources in incentivizing renewable fuels. Currently, propane vehicles are being certified for the California low NOx (0.05 g/hp-hr) and Ultra-low NOx (0.02 g/hp-hr) vehicle standards. Propane, renewable propane, DME, and renewable DME do not contain aromatics or polycyclic aromatic hydrocarbons and lead to very low tail-pipe particulate matter. In addition, along with CO2eq emissions, the U.S. electrical grid can also lead to higher NOx and particulate matter emissions than the regulated internal combustion engine vehicles tail-pipe

Ultra-low NOx emissions, which should all be considered for evaluating EV life-cycle NOx and particulate matter emissions.

- Federal government agencies, particularly the Department of Energy, should aggressively invest in various parallel pathways (e.g. biomass and carbon capture) for renewable and synthetic fuel production, not only for liquid fuels but also for alternative fuels such as propane, to address the supply demand.
- **Propane vehicles enable a low carbon society today.** All U.S. states and the district should aggressively pursue decarbonization efforts immediately using alternative fuels such as propane and DME rather than wait on grid infrastructure improvements that are decades away from realization. Prematurely investing in full electrification, as a means for decarbonization for all sectors, without improving the state of the U.S. electrical grid in the near term will be counter-productive. Hence, full electrification is not tantamount to decarbonization.
- Even in the distant future, blended renewable fueled vehicles (propane and DME) offer a better solution than medium- and heavy-duty EVs (e.g. with 95 percent reduction in the carbon intensity of the electric grid plus Lithium-ion battery manufactured with zero-carbon sources and lasting for 1 million miles).
- Imposing a carbon tax purely based on exhaust CO2eq emissions (and not based on life-cycle analysis) results is a perverse incentive. This will be a missed opportunity to leverage other low-carbon solutions like propane that are available immediately. **There is a critical need for accurately accounting emissions on a life-cycle basis.** Hence, best practices must be developed for accurately capturing life-cycle emissions.

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26. http://www.alignccus.eu/news/align-ccus-alchemy-synthetic-fuel-produced-flue-gas
27. https://www.reuters.com/article/us-autos-emissions-trucks/15-u-s-states-to-jointly-work-to-advance-electric-heavy-duty-trucks-idUSKCN24F1EC
28. Note, the author does not subscribe to the term, Zero Emissions Vehicles (ZEVs) as vehicle manufacturing emissions are neglected in the terminology. In addition, EVs also lead to particulate matter (PM) emissions due to brake wear, tire wear, and resuspension.