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Resource implications of alternative strategies for achieving zero greenhouse gas emissions from light-duty vehicles by 2060

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HIGHLIGHTS

- Implications for land, renewable electricity, and precious metals are assessed.
- Minimal conditions for sustainability of automobile transportation are identified.
- Under strict conditions, a global all-electric LDV fleet could be sustainable.

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ABSTRACT

This paper examines alternative strategies for eliminating the use of oil for passenger transportation in light duty vehicles (LDVs: cars, SUVs and light trucks) by 2060, namely, deep reductions in the energy intensity (MJ/vkm) of LDVs combined with a shift to hybrid and/or all-electric vehicles, or combined with a shift of the residual fuel requirements to C-free fuels (either renewable biofuels or hydrogen produced from C-free energy sources, and used in a fuel cell). Different combinations of these measures have dramatically different implications concerning land area requirements (for biofuels), additional electricity requirements (for electric vehicles or to produce hydrogen electrolytically), and in the demand for potentially limiting metals (Pt, Ru, Li and Nd in particular). Recent estimates of battery, fuel cell and motor sizes in advanced vehicles, and corresponding material loadings, are combined with scenarios for the growth of the global vehicle fleet and recycling potential to estimate future material requirements. For any of the alternative to fossil fuels to be sustainable over the next century, it is essential that LDV energy intensity be pushed to the lowest technically achievable potential, that significant reductions in precious metal loadings be achieved, and that 90% or better recycling efficiency be achieved. Even then, longer term sustainability is not guaranteed, which implies that the primary emphasis in urban development and redevelopment over the next century should be to create cities with little to no dependence on the private automobile for transportation.

1. Introduction

This paper examines the implications for land use and the consumption of precious and rare metals of alternative strategies for eliminating the use of oil for light-duty vehicles LDVs: cars, SUVs, and light trucks). It complements a parallel paper [1] that focuses on a cost comparison. Under the 2015 Paris climate accord [2], the nations of the world agreed to a target of limiting global mean warming to no more than 2.0 °C above pre-industrial levels. To have only a 66% chance of staying below the 2.0 °C threshold, it is estimated that global CO_2 emissions would need to reach net zero by about 2060-75 [3]; any delay beyond this date reduces the probability of achieving the agreed goal. Harvey [4] developed scenarios that eliminate global oil demand across all sectors by 2060-2100, and assessed the implications for the long-term price of oil. The measures pertaining to LDV oil use considered in Harvey [4] are: (i) reductions in the growth of travel demand relative to an income-driven business-as-usual (BAU) scenario, (ii) a reduction of the share of LDV (and other energy-intensive modes) in meeting travel demand compared to a BAU scenario, (iii) some shift from large (light truck and SUV) LDV market segments to smaller segments compared to a BAU scenario; (iv) reductions in the energy-intensity (MJ per vehicle-km driven, MJ/vkm) of all drive trains (conventional vehicles (CVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), fuel-cell vehicles (FCVs), and battery-electric vehicles (BEVs, having an all-electric drive train)); (v) shifts from conventional to any of the alternative drive trains; and (vi) shifts from oil products to biofuels or hydrogen to satisfy any remaining fuel requirements after various combinations of the preceding options have

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Nomenclature

BAU	business as usual
BEV	battery electric vehicle
CV	conventional vehicle
EV	electric vehicle (PHEVs and BEVs)
FC	fuel cell
FCV	fuel cell vehicle

GDP	gross domestic product
HEV	hybrid electric vehicle
LDV	light duty vehicle
PGM	platinum group metal
PHEV	plugin hybrid electric vehicle
REE	rare earth element
SUV	sport utility vehicle
URR	ultimately recoverable resource

been implemented.

In this paper we take as our starting point the BAU scenarios for LDV travel developed by Harvey [4], combined with LDV energy intensities and market segment and drive-train shares fixed at the 2015 levels. We then consider energy intensity improvements and shifting entirely to HEV drive trains as minimal measures, which by 2050 could reduce fuel requirement per km driven by a factor of 3–4 for urban driving and by a factor of 2–3 for highway driving compared to 2010 CVs. A shift to PHEV drive trains, in which 2/3 or more of urban driving could be powered by grid electricity, would greatly reduce but not entirely eliminate the need for oil while minimizing the required size of batteries and vehicle charging power draw. The final elimination of oil demand for LDVs could be achieved through some combination of (i) utilization of biofuel to meet the residual oil demand, (ii) utilization of hydrogen fuel, (iii) reliance on battery swapping to get the necessary range for inter-urban travel using PHEVs, or (iv) transitioning to fully electric LDVs with a sufficiently dense network of fast-recharging stations.

These alternatives have quite different implications for land requirements for biomass or solar power plants, and for potentially limiting metals (Li for batteries, platinum group metals (PGMs, primarily Pt, Pd and Ru) for catalytic converters and fuel cells (in which Pt and Pd are partly substitutable for one another), and Nd and Dy for permanent-magnet motors that would be used in HEVs, PHEVs and BEVs, as well as in wind turbines that might be added to meet the additional electricity demand arising from electric LDVs). In the biofuel case there would be competition with food production for land, and continued use of PGMs in catalytic converters for pollution control, but with minimal need for critical metals for batteries and motors using HEV drive trains. Biofuel land requirements would be smaller with PHEVs than with HEVs, but the demand for critical metals for batteries, motors and possibly wind turbines would increase. Use of hydrogen fuel cells, either in an HEV or PHEV, would eliminate land requirements for biofuels, but there would be a need for PGMs as fuel cell catalysts (probably exceeding the demand for PGMs in the catalytic converters of CVs) and for Li in batteries. Given the constraint that the transportation system be C-free, hydrogen would most likely be produced through electrolysis of water using (C-free) electricity. This would represent a far less efficient use of C-free electricity than using such electricity to charge vehicle batteries, but would address problems of vehicle range associated with BEVs without the need for fast charging. Conversely, hydrogen could be produced from water directly from solar thermal energy, through thermo-chemical splitting.

This paper differs from previous work in several important respects. First, although previous studies have individually addressed the resource requirements of each of the drive train-fuel combinations discussed above, none has intercompared the implications of the alternatives side-by-side in the context of scenarios that achieve the near-elimination of oil use by 2060. This study does. Second, this study makes use of the latest analysis by Argonne National Laboratory of the potential future performance and cost of advanced LDVs [5]. The ANL analysis provides internally-consistent estimates of vehicle energy intensity and the sizing of fuel cell, motor and battery components, which permits determining material resource requirements of in the context of a scenarios with a strong emphasis on energy efficiency, an essential element of any comprehensive effort to address global warming. Third, the growth in travel demand (affecting biofuel or electricity requirements and vehicle lifespan) and vehicle stocks is explicitly modelled in 10 different socio-economic regions, with allowance for differences in the timing and rates of transition to various alternative drive trains. Fourth, this paper examines the solar and/or wind generation capacity that would be needed to produce H_2 fuel or recharge batteries, alongside material requirements, for alternative scenarios.

2. Composition of batteries

Most HEVs and all PHEVs and BEVs marketed today use Li-ion batteries. Li-ion batteries differ in the chemical composition of the cathode and anode; among the cathode choices are $LiCoO_2$ (LCO), $LiNi_xCo_yAl_zO_2$ (NCA, typically with x = 0.8, y = 0.15 and z = 0.05), $LiNi_xCo_yMn_zO_2$ (NCM, where x + y + z = 1), $LiMn_2O_4$ (LMO), and $LiFePO_4$ (LFP), while the anode choices are graphite and $Li_4Ti_5O_{12}$ (lithium titanate, referred to as LTO). Li-ion batteries have an electrolyte (an ion-conducting material between the cathode and anode) consisting of $LiPF_6$. Table 1 compares the energy density, cost and lifetimes of the different cathode and anode chemistries, which affect their market shares, as well as present-day and projected future market shares. LMO is the oldest cathode chemistry and has a falling market share because of its limited lifespan, LCO has safety concerns and so is not expected to play any role, NCA may be limited by safety concerns, LFP can be combined with an LTO anode to give a long overall battery lifespan, and NCM is a new chemistry with a growing market share [6]. Simon et al. [8] project that the market shares of NCA and NCM cathodes will grow at the expense of LFP cathodes in family cars, but that LFP will capture 100% of the small-delivery-truck market by 2020. The Ni:Mn:Co ratios in NCM cathodes can vary, ranging from 1:1:1 to 6:2:2, with a higher proportion of Ni giving a higher energy density

Table 1
Characteristics of different cathodes and anodes that can be used in Li-ion batteries, and proportional share of different chemistries today and as projected in the future by two different research teams. Source: cathode and anode characteristics, Berckmans et al. [6]; market shares for different types of EV, Pehlken et al. [7]; market shares for family cars, Simon et al. [8].

Chemistry	Characteristics			Market shares			
	Energy Density (Wh/kg)	Cost	Lifetime	Today and in the future		Family cars	
				HEVs	PHEVs and BEVs	2010	2020
Cathodes							
LMO	410–492	Low	Low	10%	30%		
LFP	518–587	Medium	High	80%	35%	70%	25%
LCO	546	Medium	Medium				
NMC	610–650	High	High	10%	35%	35%	40%
NCA	680–760	High	Medium				40%
Anodes							
Graphite	372[a]	Medium	Medium				
LTO	175[1]	High	High				

[a] mA h/g.