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Implications for the floor price of oil of aggressive climate policies

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ABSTRACT

This paper identifies combinations of technical and behavioral measures that lead to progressively lower global demand for oil, culminating with a scenario that eliminates global oil demand by 2060 – in line with the broader requirement that anthropogenic CO_2 emissions reach net zero by this date in order to have a 60% chance of staying below a global mean warming of 2 °C above the pre-industrial level. The cumulative oil consumption from 2010 to the point when zero oil demand is achieved is compared with a recent oil supply-marginal cost curve. Assuming that oil is consumed in order of increasing extraction cost, the price of oil need not rise significantly above \$25–35/bbl. Even substantially less-aggressive efforts to reduce CO_2 emissions need not see oil rise substantially above \$50/bbl. Under aggressive climate policies, the peak in oil demand occurs before the supply-constrained peak in oil production would occur. This would render expensive oil (> \$50/bbl) permanently uneconomic. This includes oil from the Canadian tar sands (currently costing \$65–95/bbl for new greenfield developments) and most shale oil (with current average oil-play costs of \$48–65/bbl). This in turn implies that governments should not be promoting or permitting development of high cost oil, and also provides a clear warning to private and institutional investors.

1. Introduction

At the 21st meeting of the Conference of Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC), held in Paris in December 2015, the nations of the world adopted a target of limiting global mean warming to no more than 1.5–2.0 °C above the pre-industrial level (UNFCCC, 2015). Rogelj et al. (2015) estimate that, to have a 66% chance of staying below the 2.0 °C warming threshold, net zero anthropogenic CO_2 emissions would need to be achieved by 2060–2075. For the 1.5 °C threshold, net zero would need to be achieved a decade sooner. Net zero means that any anthropogenic emissions that remain would need to be offset by negative emissions created either through capture and geological storage of CO_2 released from combustion of biomass fuels that are replaced through new biomass growth, or direct capture and geological storage of atmospheric CO_2. It would be a monumental challenge to achieve a sink of only 1–2 GtC per year, out of a current fossil fuel emission of about 10 GtC/yr. Thus, net zero means that emissions themselves would need to be close to zero.

McGlade and Ekins (2015) have compared the amount of coal, oil and nature gas that can be consumed (releasing CO_2) while limiting warming to 2.0 °C with a 60% probability. They find that only 65% of the 2010 oil reserve of 1294 billion barrels (Gb, where G=giga) can be used, along with 48% of the natural gas reserve and just 18% of the coal reserve. As a fraction of the total (conventional + nonconventional) remaining ultimately extractable oil resource (estimated to be 5066 Gb), only 17% can be used and the other 83% will need to stay in the ground. Cost minimization implies that the least expensive oil would be consumed first, moving to progressively more expensive oil as cumulative consumption increases. The cost of the last oil consumed would then depend on the cumulative consumption reached at the point when demand falls to zero; the lower the cumulative consumption, the lower this upper limit to the price of oil. Thus, a plot of amounts of oil available at different costs, in order of increasing costs, indicates a lower bound for the price of oil as a function of increasing cumulative consumption. To the extent that supplies are not deliberately withheld, constrained by limited capital investments, or interrupted for political reasons or due to war, the market price will track this increasing lower bound.

This paper derives curves of cumulative oil consumption up to 2100 or the point where oil demand reaches zero (whichever comes first) under progressively more aggressive emission reduction scenarios, culminating in scenarios that eliminate global oil use by 2060, and compares these with updated information on the amount of remaining oil available at different costs, arranged in order of increasing cost. The impact on future oil demand of factors driving an increase in demand (growing population and GDP per person) is considered, along with a variety of technological and behavioral factors that, if implemented, would greatly reduce oil demand and, with switching of residual demand to electricity, biofuels or hydrogen, would ultimately eliminate oil demand (and related CO_2 emissions). The demand analysis is done at the scale of 10 socio-economic regions that span the entire globe, and separately considers passenger and freight transportation, residential and commercial buildings, industry, agriculture and electricity-generation demands for oil. Transportation, which accounts for 52% of global oil demand, is treated in considerable detail, based on the analysis presented in Harvey (2013). The purpose of

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this analysis is to show the plausibility of complying with the implications of the Paris targets with regard to oil use, by showing combinations of tangible (but aggressive) measures the achieve an oil phase-out by 2060–2100 in the face of growing population and wealth. This is following by a discussion of the implications of an oil phaseout by 2060–2100 in terms of potential long term prices for oil. The paper concludes with a discussion of implications for investment, strengthening of efficiency standards, cost benefit analysis and fuel taxes.

2. Methods

Energy use in a given sector in a given region depends on two activity drivers - regional population and GDP per person – and various activities (such as km travelled per person per year or m^2 of building floor area per person) that depend on GDP/P, and energy intensities (such as MJ/passenger-km or kWh/m^2yr building energy use). Global oil energy use is given by the activity times the energy intensity for each activity in a given region times the portion of the energy supplied by oil or oil products for that activity and region, summed over all activities and regions. The total end use demand must then be divided by the refining efficiency[1] to convert the demand for oil products to crude oil demand.

Fig. 1 gives the breakdown of global oil demand in 2014. Transportation accounted for 52% of oil use, industrial feedstocks 14%, industrial process energy, buildings, and electricity plus district heat about 8% each, and refinery energy use and various losses, 7%.[2] Within the transportation sector, passenger LDVs (light-duty vehicles: cars, SUVs, and light trucks) accounted for 29% and freight trucks 35%. The following sections show how the present-day activities and energy intensities in each sector and region are estimated, and how future activities and energy intensities are projected.

2.1. Scenarios for activity drivers

Historical populations and regional GDP/P in 10 world regions are used up to 2015. The low and medium projections from the 2010 United Nations Development Program forecast for population (UNPD, 2010) are used here as "low" and "high" population scenarios for the period after 2015 (adjusted as needed to exactly match 2015 data). GDP/P is assumed to increase over time toward low or high saturation values following a logistic function. Table 1 gives the 10 regions considered here, their population and GDP/P in 2015, and the two scenarios of population and GDP/P in 2100. Two composite GDP scenarios are created, combining the low population with the low GDP/P scenario in each region ("Low"), and the high population with the high GDP/P scenario ("High"). The scenarios for global population and global mean GDP/P are shown in Fig. 2a, while the resultant variation in global GDP and in the rate of growth of global mean GDP/P are shown in Fig. 2b. Note that, in both scenarios, a significant slowing in the extraordinarily rapid growth in GDP/P from 2000 to 2015 is assumed, decreasing from 3.75%/yr over 2010–2015 to 1.9%/yr (Low) or 2.4%/yr (High) over 2020–2030 and to 1.7%/yr (Low) or 2.1%/yr (High) over 2030–2050. The growth rates assumed for 2020–2030 and 2030–2050 for the High scenario are, however, comparable to those assumed in the *2015 International Transport Forum* (ITF) scenarios (ITF, 2015) (2.9%/yr and 2.2%/yr, respectively).[3] Global GDP increases from about \$114 trillion in 2015 to a peak of \$287 trillion in 2080 (a factor of 2.5 larger) in the Low scenario and to \$563 trillion (by 2100) in the High scenario (a factor of 5.0 larger). Regional population and GDP/P details are given in Online Supplement, Figs. S1 and S2.

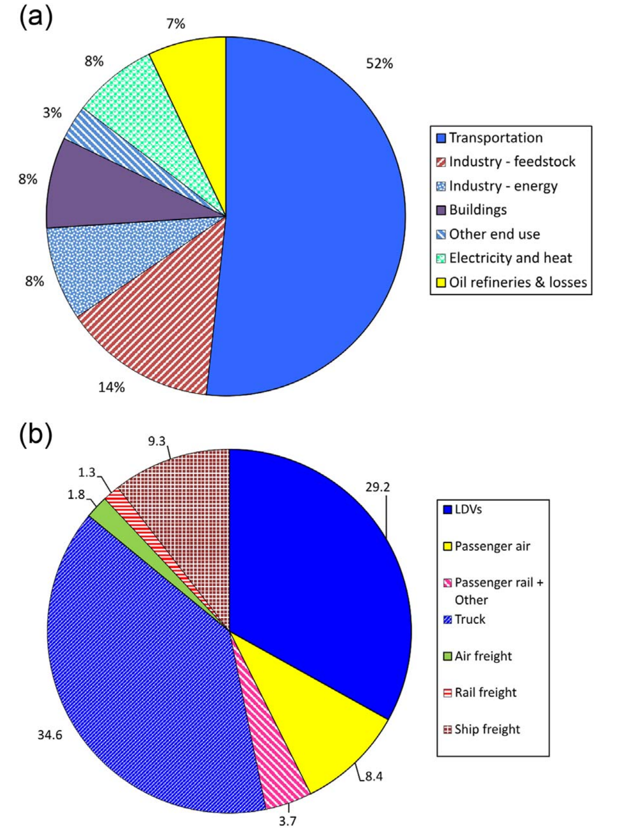

Fig. 1. (a) Relative uses of oil in 2014 on a global basis (derived from IEA (2016a, 2016b)). (b) Breakdown of transportation oil use in 2014 (as computed here).

2.2. Scenarios for transportation activity and energy intensity

The first step in constructing scenarios of future transportation activity is to estimate total per capita passenger travel in each region and the proportion of this total by each mode (LDVs, rail, air and other) for the latest year with complete data (2014), along with total regional freight transport by truck and rail and global freight transport by ship and air. Also required are average energy intensities for each mode of passenger and freight transport in each region (or in the global average for ship and air transport) for the same year. Details on how this has been done are given in Online Supplement, but an overview is presented here.

Total per capita passenger transport is assumed to increase with GDP/P following a logistic function, but asymptoting at different values in different regions, to reflect differences in population density and in present urban form. As GDP/P increases, passenger travel shifts to LDVs and air from less energy-intensive modes. Table 2 gives the regional average total per capita travel estimated for 2014 and that are assumed to be approached over time with arbitrarily large per capita income, as well as the proportions of total travel in LDVs and by rail and air, and the proportion of LDV travel by SUVs + light trucks. Two illustrative sets of scenarios are considered for the future – a business-as-usual (BAU) increase in travel with income, and a "Green" scenario. The business-as-usual scenario assumes substantial growth in per capita travel, especially in developing countries, and a significant shift toward LDV and air travel. The Green scenario assumes some moderation in the growth of per capita travel and in the LDV and air shares that could be induced through taxation to increase price of oil

[1] Based on oil inputs and outputs only.

[2] The refinery efficiency might appear to be 93%, based on 100 units of oil energy input and 93 units of output, but there are also substantial natural gas, heat and electricity inputs to oil refineries, such that the global mean oil refinery efficiency is about 83%.

[3] ITF assumes growth rates in global mean GDP/P of 2.8%/yr over 2010–2020, 2.9% over 2020–2030, and 2.1%/yr over 2030–2050 (see their Table 2.2). This gives an expected multiplication of mean GDP/P by a factor of $e^{(0.028*10+0.029*10+0.022*20)}$=2.69. They assume a population increase of 36% over this time period, which would give a multiplication of global GDP by a factor of 3.67, compared to a factor of 3.65 inferred from their Fig. 2.4. The corresponding decomposition of the overall growth factor here for the High scenario would be $e^{(0.032*10+0.024*10+0.021*20)} \times 1.34 = 3.52$

Table 1
The 10 regions considered here, population and mean per capita GDP in 2015, and peak population and asymptotic GDP/P for the Low and High scenarios.

Region	Population (millions)			GDP/P (1000 US$ PPP)		
	2015	Peak Low	High	2015	2100 Low	High
PAO (Pacific Asia OECD)	205	205	205	38.9	49	58
NAM (North America)	362	399	530	54.5	60	73
WEU (Western Europe)	495	495	526	38.4	49	57
EEU (Eastern Europe)	116	120	120	23.3	48	59
FSU (Former Soviet Union)	292	292	292	18.5	47	58
LAM (Latin America)	631	661	750	15.0	46	58
SSA (Sub-Saharan Africa)	963	2171	3230	4.8	38	52
MENA (Middle East and North Africa)	463	608	792	17.0	47	58
CPA (Centrally planned Asia)	1528	1531	1582	13.2	48	57
SPA (South and Pacific Asia)	2296	2570	3010	7.3	46	54
Global	7349	9053	11,037	15.5	44.6	55.6

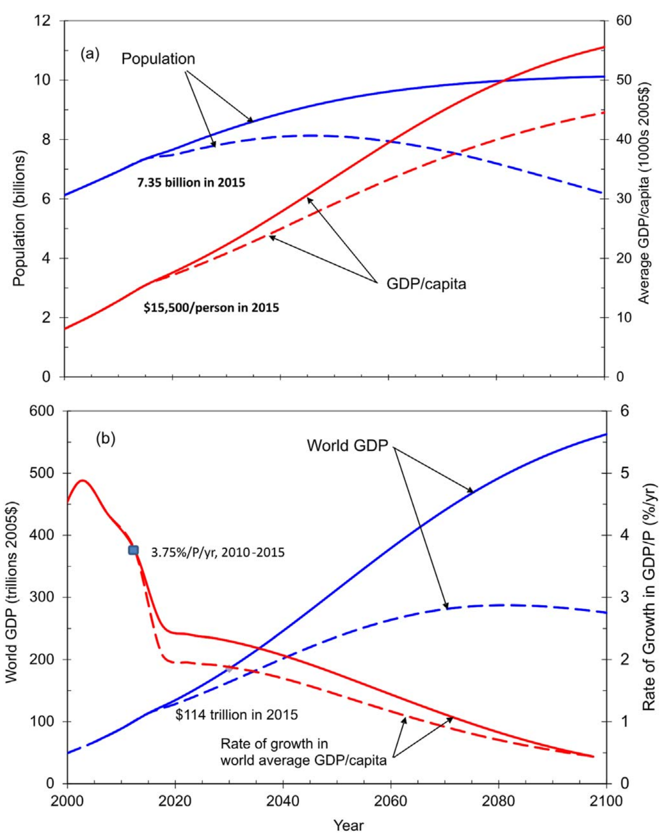

Fig. 2. Variation in (a) global population and global mean GDP/P, and (b) global GDP and rate of growth of global mean GDP/P adopted here for the Low and High scenarios. Variations up to 2015 are observed, while the post-2015 variations are illustrative scenarios derived as explained in Online Supplement.

products or through policies such as urban intensification and provision of high-quality rapid transit infrastructure.

Global freight movement is assumed to vary with global GDP but with the tkm/GDP ratio declining by 20% (Low) or 30% (High) over the period 2015–2100 as GDP/P increases, using the formulation given in ITF (2015). In the Green scenario, thetkm/GDP ratio decreases are 25% and 38%.

Fig. 3a shows the resultant variation in global people and freight transport from 2000 to 2014 (based on or estimated from observed data, as detailed in Online Supplement) and the variation from 2014 to 2100 for the Low and High scenarios with base case per capita travel assumptions and for the Green variant of the Low scenario. Fig. 3b shows the growth in LDV and passenger air travel. Total global passenger travel in 2050 is 3.5, 2.8 and 2.3 times the 2010 level in the High, Low and Low-Green scenarios, respectively, while global freight movement is 2.8, 2.2 and 2.0 times the 2010 values (and similarly for truck+rail freight). In the Green scenario, travel by LDVs and by air is disproportionately reduced relative to the 20% reduction in total travel, as rail and Other modes take up a larger share. By comparison, global surface passenger transport is 2.0–3.1 times the 2010 level by 2050 in the ITF scenarios, [4] which is a smaller increase then obtained here, while global truck+rail freight transport is 3.1–5.0 times the 2010 value – a much larger increase than obtained here in spite of similar GDP growth, for reasons partially explained in Online Supplement.

The LDV mode is broken into 5 market segments (compact and midsize car, small and midsize SUV, and pickup truck) with estimated market shares and energy intensities varying by region (Online Supplement Table S2). The proportion of urban and highway driving varies with region, with separate energy intensities for urban and rural driving that are differentiated by region (as the definition of "compact" car and of other market segments differs by region).

Argonne National Laboratory (Moawad et al., 2016; henceforth referred to as ANL) performed detailed computer simulations of the energy intensities of a wide range of present-day LDVs and of what ANL estimates could be achieved by 2030 and 2045 at the lab scale for slow and fast rates of technological improvement, with achievements at the lab scale transferred to new vehicles 5 years later. This study is an update of an earlier study (Moawad et al., 2011) and indicates about 10% larger potential reduction in fuel energy intensities by 2045 for the slow case and 20% larger for the fast case than in the earlier study. The energy intensities from the updated study for urban and highway driving with a compact car are given in Fig. 4**a** as an illustration (very similar relative energy reductions apply to other LDV market segments), while the complete set of energy intensities is given in Table S3.[5] Energy intensities are given for conventional (internal combustion engine) drive trains, and for HEVs (hybrid electric vehicles), PHEV40s (plugin hybrid electric vehicles with a 40-mile (64-km) electric range) and BEVs (battery-electric vehicles), and take into account real-world driving conditions. An advanced HEV in 2045 would require 37% of the fuel per km of a 2010 conventional vehicle with slow technological change and 24% with fast change. The PHEV, when running on fuel, requires slightly more MJ/km than the HEV because of the heavier battery. Electricity requirements (for BEVs or for PHEVs when using electricity) estimated for 2045 are about 10 times smaller than the fuel requirement with a conventional drive train today.

Fig. 4b compares the simulated energy intensity of different market

[4] The increase is a factor of 1.4–2.0 in OECD countries and a factor of 3.4–5.4 in non-OECD countries, as shown in ITF (2015, Fig. 2.17)

[5] The energy intensities shown in Fig. 4 and Table S3 are "adjusted" values that account for real world characteristics, including aggressive driving behaviour.

Table 2
Behavioral factors related to passenger travel adopted here. 2014 data were derived as explained in Online Supplement.

Region	Total Travel (km/P-yr) 2014	BAU	Green	LDV share 2014	BAU	Green	SUV+truck share of LDV 2014	BAU	Green	Air share 2014	BAU	Green	Rail share 2014	BAU	Green
PAO	17,558	20,000	12,000	0.49	0.55	0.40	0.35	0.39	0.06	0.12	0.16	0.10	0.138	0.102	0.25
NAM	20,797	22,000	16,000	0.71	0.71	0.50	0.48	0.48	0.11	0.24	0.25	0.10	0.002	0.001	0.15
WEU	13,411	15,000	12,000	0.58	0.64	0.45	0.21	0.21	0.03	0.21	0.20	0.10	0.062	0.050	0.23
EEU	6368	15,000	12,000	0.60	0.64	0.45	0.00	0.14	0.03	0.18	0.16	0.10	0.059	0.055	0.23
FSU	2692	15,000	12,000	0.36	0.64	0.40	0.16	0.26	0.05	0.15	0.16	0.10	0.360	0.151	0.25
LAM	3751	10,000	8000	0.66	0.55	0.40	0.43	0.43	0.05	0.13	0.16	0.10	0.013	0.018	0.25
SSA	406	10,000	8000	0.24	0.55	0.25	0.60	0.60	0.05	0.31	0.16	0.10	0.129	0.083	0.33
MENA	3144	10,000	8000	0.32	0.55	0.25	0.37	0.47	0.05	0.38	0.20	0.10	0.004	0.003	0.33
CPA	2601	10,000	8000	0.45	0.50	0.25	0.25	0.37	0.05	0.15	0.16	0.10	0.294	0.250	0.33
SPA	1527	10,000	8000	0.26	0.50	0.25	0.20	0.30	0.05	0.13	0.16	0.10	0.389	0.216	0.33

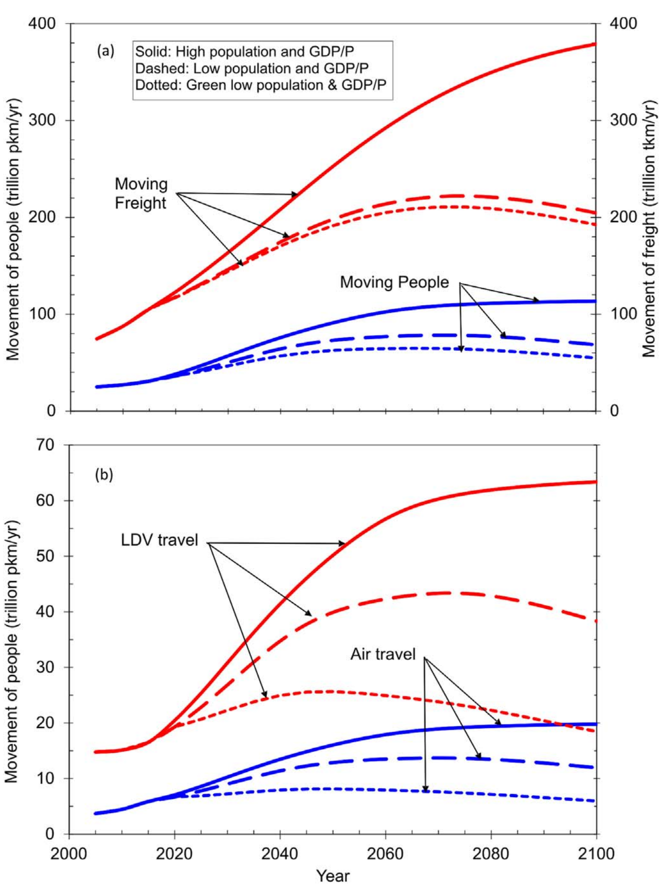

Fig. 3. (a) Variation in global transport of people and freight from 2000 to 2100 for the Low and High scenarios with base case per capita travel assumptions, and for the "Green" variant of the Low scenario. (b) Same as (a) except for LDV and passenger air travel.

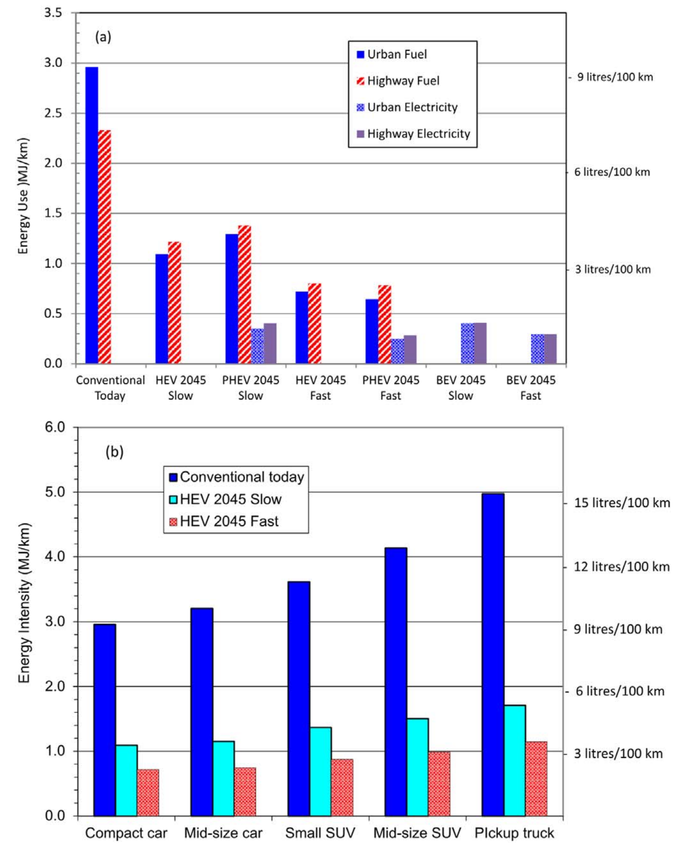

Fig. 4. (a) Fuel and or electricity energy intensity of a conventional compact car in the US in 2010 for urban and highway driving, and for an advanced HEV, a PHEV with a 40-mile (64-km) range, and for a BEV. (b) Fuel energy intensity of different market segments with a conventional 2010 drive train and for advanced (2045) HEVs. Source: Moawad et al. (2016).

segments for today's conventional drive train and for advanced HEVs. Going from today's pickup truck to the HEV 2045 Fast pickup truck reduces energy intensity by 77%, while going from today's pickup truck to the HEV 2045 Fast compact car reduces energy intensity by 86% (a factor of 7 reduction). Although this is an upper limit, it indicates the enormous potential fuel savings from a combination of market shifts and advanced technology without making the step to grid electricity.

Kliesch and Langer (2006) indicate that 60% of fuel otherwise used in urban driving could be displaced by electricity using a PHEV with a 64-km (40-mile) range for US driving patterns, assuming recharging at night only and operation in charge-depleting mode. For the same assumptions, the fuel savings would be 80% for German driving patterns (Plötz et al., 2015). Given a PHEV requirement using fuel of ¼ to 1/3 that of today's conventional LDV, then if 2/3 of urban driving is powered by grid electricity, the average fuel requirement per km of urban driving is reduced by a factor of 9–12. With a modest shift away from SUVs and pickup trucks, and less aggressive driving behaviour, a reduction substantially greater than a factor of 10 is possible. In highway driving, the energy requirement of an advanced PHEV using fuel is about half that of a conventional vehicle, and the energy intensity using battery energy is just over ¼ of that using fuel, although the proportion of driving using battery energy would be much smaller than in urban driving.[6]

We consider two energy efficiency scenarios: Slow, in which the higher ANL energy intensities for 2045 labs are achieved in new vehicles by 2050, and Fast, in which the lower energy intensities given in ANL are achieved by 2050. About 85% of the reduction at the lab scale that is thought to be achievable from 2010 to 2045 in the ANL study is achieved by 2030. A stock turnover model, described in Online Supplement, was used to assess the impact on stock average energy intensity of a linear reduction in the energy intensity of new vehicles by 85% of the 2010–2045 lab reduction from 2010 to 2035, followed by a linear variation for the remaining 15% from 2035 to 2050. As shown in Online Supplement, the resulting variation in stock energy intensity can be accurately fitted with a logistic function, which is used here. As the assumptions underlying the ANL study are somewhat conservative, and because technological advances beyond those foreseen in the ANL study are likely, energy intensities are assumed to decrease by a further 0.33%/yr after 2050 for the Fast scenario and by a further 1.0%/yr in the Slow scenario, which causes the energy intensities under the two scenarios to converge by about 2100. At the same time that energy intensities decrease for each drive train, a transition from conventional vehicles toward HEVs and later to a mixture of PHEVs and BEVs for new vehicles is assumed. This transition continues from the 2014 market shares in PAO, NAM, WEU and CPA (where HEV, PHEV and BEV are already non-zero), but does not begin until 2020 in other regions. Once the transition begins, it proceeds at the same rate in all regions. Fig. 5 shows the combined HEV+PHEV+BEV market share for the Slow and Fast scenarios in various regions, while Fig. S5 shows the separate HEV, PHEV and BEV shares (for a case where the BEV share plateaus at 1.0) in WEU for the Slow and Fast scenarios. The shares of each drive train in the total vehicle stock are assumed to lag the new-market shares by 5 years.[7]

Fig. 6 gives the global average LDV fuel (and electricity) requirement per km driven. For the Frozen case, average energy intensity rises as regions with relatively high energy intensity today increase in relative importance. For the other scenarios, the declining average takes into account the reductions in energy intensity illustrated in Fig. 4, a shift to an HEV drive train as shown by the curves shown in Fig. 5 followed by a subsequent shift to PHEVs for the Green+PHEV scenario (with electric shares as given in Table 4), a small shift away from SUVs and light trucks to compact and midsize cars, and a 5–10% reduction in energy use by 2100 due to less aggressive driving behaviour. The net result is that average fuel use per km drops by 60–80% by 2050. The early rapid drop in energy use is largely due to the shift from conventional to HEV drive trains, rather than to a rapid early reduction in the energy intensity of either drive train. The average fuel use per km times global LDV vkm (regional pkm divided by regional average number of passengers per vehicle, summed over all regions) gives the total LDV fuel requirement.

The energy intensity improvements assumed for passenger transport by other modes (largely buses and mini-buses), rail and passenger air, as well as for freight transport by truck, rail and ship, are given in Table 3 along with summary LDV results. The non-LDV energy

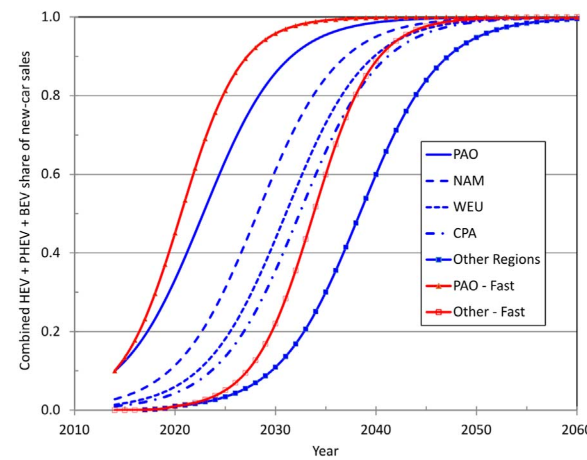

Fig. 5. Slow (blue lines) and fast (red lines) scenarios for the transition from conventional to HEV+PHEV+BEV drive trains for LDVs in various regions (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

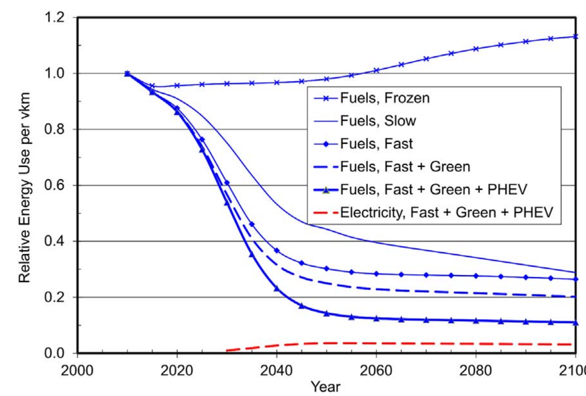

Fig. 6. Global average LDV fuel (and electricity) requirement per km driven.

Table 3
For LDVs: energy intensities assumed to be achieved by new vehicles by 2030 (Fast) or 2045 (Slow) relative to the energy intensities of new vehicles in 2010 with conventional drive trains. For all other modes of passenger or freight transportation: fleet average energy intensities achieved after 2050 relative to the corresponding energy intensity in 2010.

LDVs				
Drive train	Urban		Highway	
	2010	Mid century	2010	Mid century
Conventional	1.000	0.539	1.000	0.492
HEV	0.570	0.243	0.870	0.344
PHEV	0.667	0.218	0.850	0.336
Other passenger modes and freight transport				
Passenger mode		*Freight mode*		
Diesel passenger rail	0.650	Diesel rail freight	0.650	
Passenger air	0.350	Air freight	0.350	
Other passenger	0.500	Truck freight	0.500	
		Ship	0.250	
Other uses of oil				
		Oil Share		
Agriculture	0.75	0.623		
Industry fuel process energy	0.75	0.149		
Industry feedstock energy	0.25	0.736		

[6] As seen in Fig. 4, conventional vehicles are more fuel efficient in highway driving than in urban driving, while the reverse is the case for advanced HEVs. This is because energy consumption per km driven depends on the engine load (energy that must be supplied to the wheels to overcome aerodynamic and rolling resistance, and for acceleration and hill climbing) divided by the drive-train efficiency. Aerodynamic resistance increases with speed to the third power, so load/km is smaller in urban driving. For conventional vehicles, this is more than offset by the lower drive train efficiency at low loads and losses during braking, resulting in greater MJ/km energy use in urban driving. In HEVs, the efficiency losses at low load are much smaller, and some of the energy lost during breaking is captured (and used to charge the battery). Thus, in HEVs the aerodynamic resistance factor dominates, and MJ/km energy use is larger for highway driving than in urban driving (although still about 25% smaller than for advanced conventional vehicles, as seen in Table S3).

[7] Seven years would be more accurate, based on the stock-turnover model, but the scenarios use 5-year time steps.

Table 4
The energy scenarios considered here for both Low and High GDP scenarios. x=L (Low GDP scenario) or H (High GDP scenario).

Scenario	Brief description
xFz (Frozen)	All energy intensities for new transportation equipment and buildings fixed at 2010–2015 levels
xS (Slow)	Slow attainment of maximum efficiency assumptions, transition to HEVs only for LDVs, no heat pumps in buildings
xF (Fast)	Fast attainment of maximum efficiency assumptions, transition to HEVs only for LDVs, no heat pumps in buildings
xFG	xF + Green behavioral assumptions
xFG-E	Same as xFG except shift to 100% PHEVs for LDVs, 100% electrification of rail, 15% electric share for trucks, some use of heat pumps in buildings. Grid electricity is assumed to supply 65% of urban and 10% of highway PHEV driving in NAM, and 80% of urban and 20% of highway PHEV driving in other regions.
xFG-E-SC	Same as xFG-E + slow (by 2100) transition to C-free fuel replacement
xFG-E-FC	Same as xFG-E + fast (by 2060) transition to C-free fuel replacement

intensities given in Table 3 are the higher energy intensities estimated by Vyas et al. (2013) to be achievable by 2050. In the Fast scenario, these energy intensities are achieved by roughly 2050, while in the Slow scenario they are achieved somewhat later. An additional energy intensity reduction of 0.5%/yr is applied after 2050, as any present estimate of energy saving potential surely does not exhaust the possibilities with further technological advance. The time variation in these energy intensities, relative to 2015, is given in Fig. S5. For most transport modes, the potential energy intensity reduction is thought to be much less than for LDVs. All starting (2014) energy intensities have been slightly adjusted from the *a priori* values so that the calculated amounts of oil used for road, rail, air and ship travel in 2014 exactly match the IEA oil energy use by region for each of these end uses in 2014.

2.3. Building floor area and energy intensity scenarios

Buildings accounted for only 8% of global oil use in 2010, while oil accounted for only 11% of global building energy use. Building energy demand by end use, energy source (fuels or electricity), sector (residential or commercial), and region is projected as in Harvey (2014). Increasing per capita income leads to an increase in residential and commercial floor areas per capita and in per capita energy use for cooking, hot water and for consumer goods and office equipment. The tendency for increasing per capita income to increase indoor winter temperatures and associated heating energy uses in regions (such as northern China) where winter indoor temperatures are uncomfortable is accounted for here. Reductions in energy use per unit floor area or per person (depending on the end use) are applied through a gradual improvement in building code standards for new buildings and renovations, and account for gradual building stock turnover through replacement or renovation. Some shift from fuels to electric heat pumps is allowed and, optionally, a complete shift away from oil (and coal) to some combination of natural gas, biofuels and hydrogen. Online Table S8 gives per capita residential and commercial floor areas in 2010 and assumed to be reached with arbitrarily large income, as well as estimated stock average heating energy intensities in 2010, the heating energy intensity for new buildings in 2010, and the heating energy intensity for new buildings that is assumed to be reached by 2025 or 2035. Building floor areas and energy intensities have been adjusted such that total fuel and electricity use for residential and commercial buildings match the IEA totals on a regional basis. Full justification for the heating energy intensity reductions assumed for the mitigation scenarios is given in Harvey (2014).

The growth in building floor area – a key driver of energy demand – is shown in Fig. S6 for the Low and High scenarios. By 2050, global residential floor area has grown to 2.1 and 2.5 times the 2010 level for the Low and High scenarios, respectively, while global commercial floor area has grown to 2.9–3.6 times the 2010 level by 2050 (this rapid growth underlines the importance of rapid near-term improvements in the energy performance of new buildings in high-growth areas).

2.4. Other oil uses

Detailed accounting models have not been developed for other sectors. Instead, oil energy demand is computed as follows: agricultural energy use varies with global population times an energy intensity factor times the fraction of energy supplied as oil products, while industrial process and feedstock energy use varies with global GDP times an energy intensity factor and oil fraction. For the BAU scenario, the energy intensity factors are held constant at 1.0, while in the mitigation scenarios they decrease from unity in 2010 toward the asymptotic values given in Table 3 following a logistic function. Justification for the asymptotic values for agricultural and industrial process energy is given in the Online Supplement. Feedstock energy is the energy value of the oil material that becomes part of material products such as plastics. The feedstock energy input per unit of plastics produced can be reduced through greater use of secondary (recycled) plastics, and in the mitigation scenarios it is assumed that the proportion of plastics not recycled decreases in half over time. Biofuels or hydrogen are assumed to eventually replace all oil process energy in the zero-emission scenarios, while biomaterials are assumed to eventually replace all oil feedstock use.

3. Yearly-demand results

The impact on daily and cumulative oil demand is computed here for a sequence of progressively more stringent technical and behavioral scenarios for both the Low and High GDP scenarios. These techno-behavioral scenarios are outlined in Table 4. In the first two efficiency scenarios, new LDVs are assumed to achieve either the larger (Slow improvement) or smaller (Fast improvement) energy intensities given in Table S3 for each drive train and market segment, combined with a 100% shift from conventional vehicles to HEVs. The third scenario assumes the Green activity levels and behavioral factors, and so represents the assumed limit to what can be achieved without reliance on batteries. The next scenario assumes a 100% shift to PHEVs for LDVs, a 15% shift for truck freight, full electrification of rail transport, and partial displacement of heating fuel use in buildings with electric heat pumps, but no deployment of BEVs. The oil demand remaining in this scenario thus represents that amount of oil that would need to be displaced through some combination of uptake of BEVs, battery swapping in PHEVs, or use of biofuels or hydrogen for LDVs, use of biofuels or hydrogen in all other end-use sectors, and through replacement of existing oil-powered electricity generation with a range of carbon-free alternatives. (Elsewhere (Harvey, L.D.D., "Cost, Environmental and Resource Implications of Alternative Strategies for Achieving Zero Greenhouse Gas Emissions from Light-duty Vehicles by 2060", manuscript in preparation), the cost and resource implications of these alternatives are analyzed).

Fig. 7 shows the variation in daily oil demand for land passenger transport (largely LDV transport), passenger air, domestic freight, and international freight for the High and Low Frozen cases, and for the other scenarios for the Low case. The most dramatic reduction relative to the Frozen scenario – a factor of 6 by 2100 without green

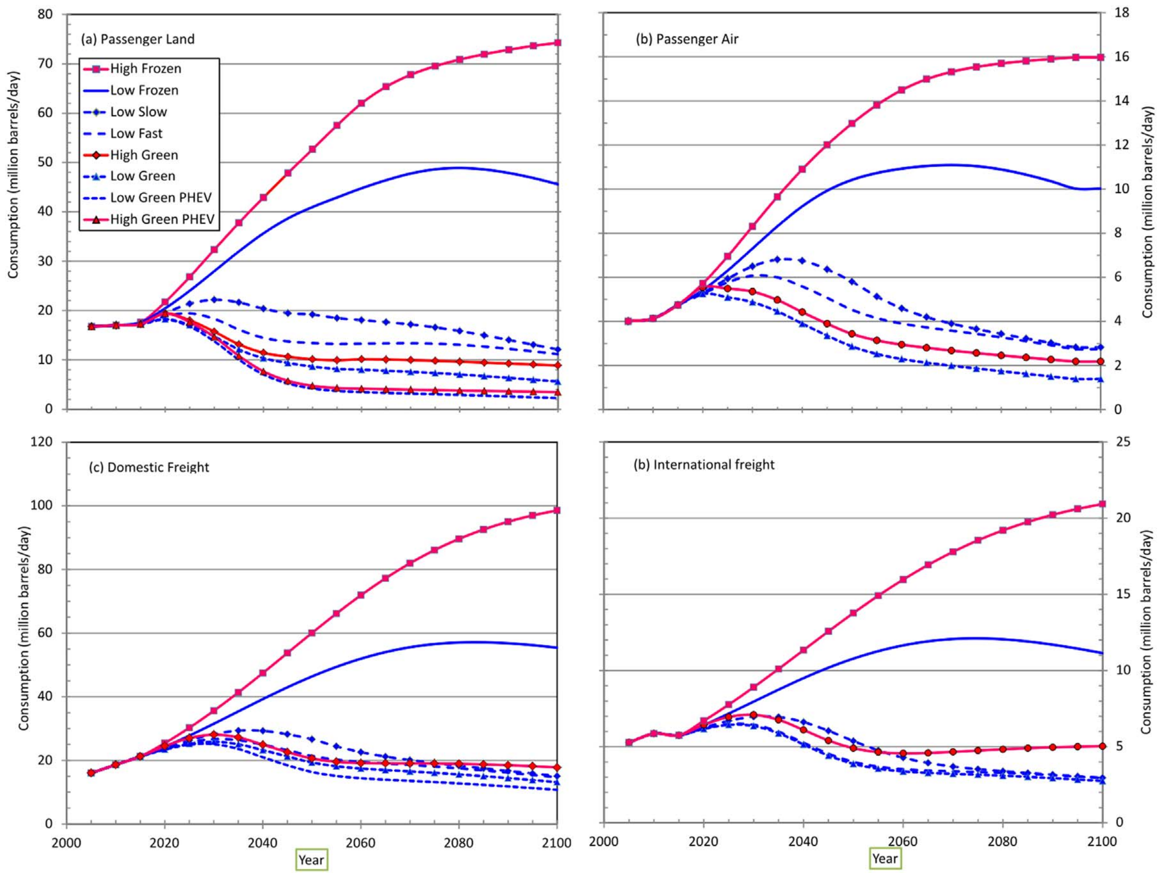

Fig. 7. Variation in daily oil demand for land passenger transport, passenger air, domestic freight, and international freight for selected High (red) and Low (blue) GDP scenarios (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Table 5
Global amounts of remaining oil resources of various types and their cost ranges (2010US$), as estimated by McGlade and Ekins (2015).

	Amount (Gb)	Cost Range ($/bbl)
Current conventional	822	12–50
Reserve growth	847	27–72
Undiscovered conventional	303	17–99
Natural gas liquids	279	12–108
Total conventional	**2250**	
Arctic	66	51–108
Light tight oil	299	40–78
Mineable bitumen	101	65–80
In situ bitumen	841	47–57
Extra heavy oil	440	47–57
Kerogen	1069	69–98
Total unconventional	**2815**	
Overall total	5066	

assumptions - occurs for passenger land, due to the large fuel-saving potential for LDVs even without introduction of BEVs. Smaller reductions occur for passenger air (40%), domestic freight (factor of 4) and international freight (factor of 2.3). Relative to 2010, oil use is held roughly constant or falls slightly even for the High scenario (and even without PHEVs for LDVs).

4. Cumulative consumption and supply-cost curves

As noted earlier, McGlade and Ekins (2015) estimate the total remaining (as of 2010) recoverable oil resource to be 5066 Gb. They have broken this total into amounts (of various types) thought to be available at different extraction costs (based on then-present technologies), as shown in Table 5. They indicate that there are about 300 Gb of light tight oil (shale oil) available at $40–78/bbl, 840 Gb of in situ bitumen available at $47–57/bbl, and 100 Gb of mineable bitumen available at $65–80/bbl, among others (all costs are as 2010US$).[8] Similar costs and amounts are given in Fig. 8.3 of IEA (2013) and Fig. 3 of Aguilera (2014), the latter representing a synthesis of several sources. When cumulative consumption to 2010 of about 1200 Gb of conventional oil is added to the remaining conventional oil of 2250 Gb given in Table 5, the total (3250 Gb) falls in the upper part of the range of 2400–3600 Gb ultimately recoverable conventional oil given by 9 studies that are compared in Sorrell et al. (2010).

Fig. 8 is a plot of the McGlade-Ekins data in terms of marginal cost of production (the cost of the next increment of production, assumed to be in order of increasing cost) versus cumulative consumption after 2010. The marginal costs for cumulative consumption after 2010 of 1, 2, 4, and 5 trillion barrels of oil are estimated to be $27, $47, $70 and $96 per barrel, respectively. According to the McGlade-Ekins dataset, 1700 Gb of conventional oil and natural gas liquids (NGLs) could be provided at a cost of $40/bbl or less, while Aguilera (2014) indicates that 4000 Gb of conventional oil and NGLs could be provided at a cost of $40/bbl or less. The costs shown in Fig. 8 are extraction costs, including a return on investment of around 10%/yr. Market costs would be higher, due to additional costs associated with transport of oil and restrictions in supply due to political instability or insufficient investment in the lowest-cost oil fields offset by investment in (and production from) more expensive oil fields. If demand were to continuously fall due to stringent climate policies worldwide, any excess of supply would drive price down, forcing decreases in output

[8] bbl, the standard shortform for "barrel", means "blue barrel", because barrels of oil were originally blue.

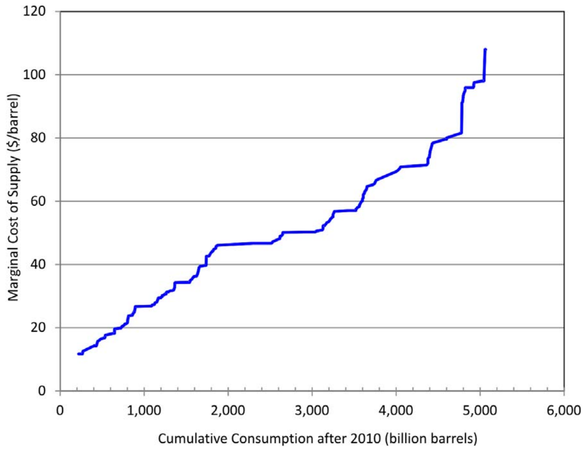

Fig. 8. Amount of remaining oil (as of 2010) available at different costs, arranged in order of increasing cost. Source: McGlade and Ekins (2015).

from oil sources with costs greater than the market price (either through bankruptcy or voluntary reductions). Thus, with falling demand and barring geopolitical considerations (including deliberate reductions in output from low-cost producers), prices after a given cumulative demand would not greatly exceed the corresponding price shown in Fig. 8.

Fig. 9 shows the variation in total daily oil demand for each of the techno-behavioral scenarios listed in Table 4 for the Low and High GDP scenarios along with the corresponding cumulative oil consumption. Shown adjacent to the right axis are the marginal costs associated with last barrel of oil consumed for selected scenarios, taken from Fig. 8. For the most stringent efficiency and behavioral scenarios but with no fuel switching, the marginal cost of oil has risen to only about $47/bbl for the Low GDP scenario and to $50/bbl for the High scenario. With a phase-out of the remaining oil requirements by 2060 (i.e., assuming an effort to comply with the Paris Agreement), the marginal cost of the last consumed oil is about $30/bbl for both GDP scenarios.

Oil consumption in this analysis is purely demand driven, and plateaus at 275 Mb/day in the High Frozen scenario and peaks at 180 Mb/day in the Low Frozen scenario. The available oil resource is fully consumed by 2065 in the High scenario and by 2100 in the Low scenario. In reality, oil supply would not increase at an ever-increasing rate to meet continuously growing demand and then suddenly drop to zero when it is exhausted. Rather, it would peak while some portion, generally estimated at 50% of the ultimately recoverable resource (URR), is consumed. As cumulative oil consumption to 2010 was about 1200 Gb, the URR is about 6300 Gb here, meaning that peak supply would occur after cumulative consumption of about 3150 Gb since the first oil use, or after about 2000 Gb since 2010. This would result in the slope of the curve of cumulative consumption vs time in Fig. 9b,d decreasing at the 2000 Gb point, and becoming horizontal as cumulative consumption approaches 5066 Gb. At this point, the market price for oil would rise (likely far) above the sum of production and other costs, and this price increase would drive down demand so as to match the declining supply (while stimulating earlier exploitation of resources further up the cost curve). In scenarios where oil consumption falls to zero by 2060–2100, cumulative consumption after 2010 remains below 2000 Gb, so price increases triggered by physical (as opposed to political or economic) constraints on the rate supply would not be expected.

5. Discussion and policy implications

In this section the implications of the above analysis for oil sector investments are discussed, the fuel economy targets assumed here for LDVs and trucks are compared with presently-existing national

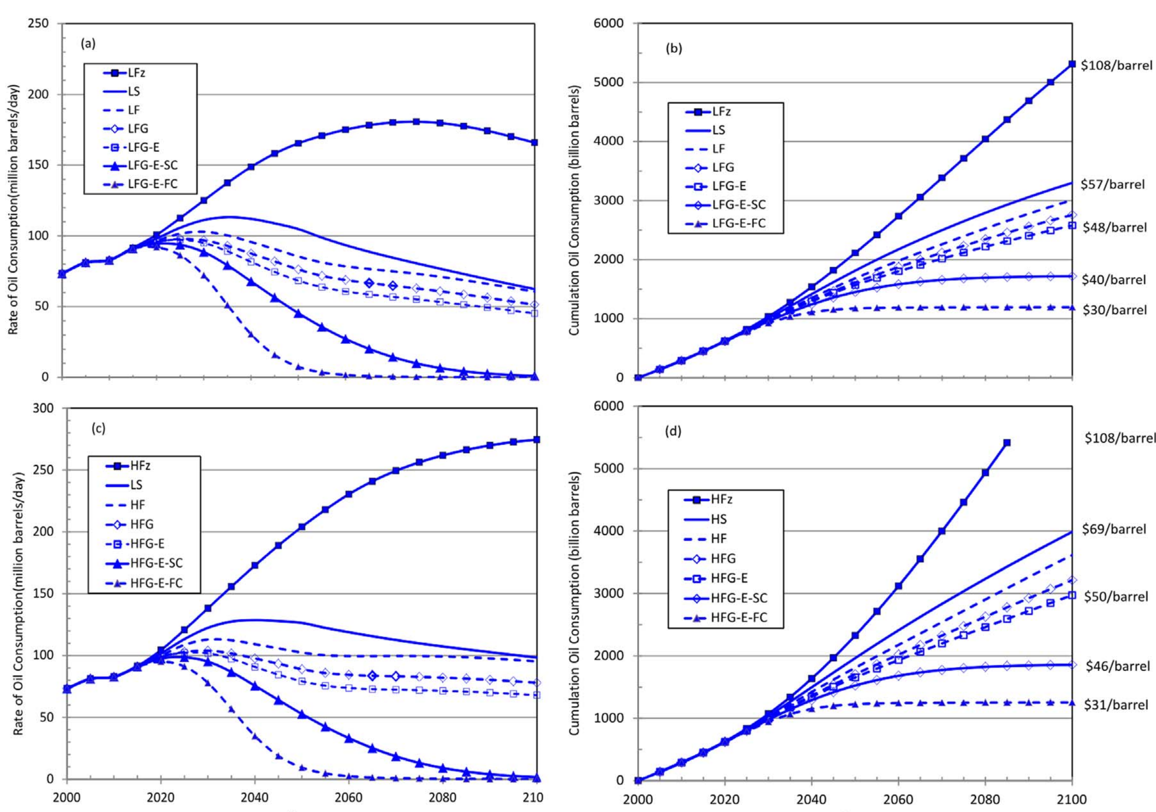

Fig. 9. (a) Variation in daily oil consumption and (b) growth in cumulative oil consumption over time for the Low GDP scenario and various energy scenarios. Shown next to the right axis in (b) is the marginal cost of the last barrel of oil consumed for selected scenarios. (c) and (d): Same as (a) and (b) except for the High GDP scenario.

standards for the 2020–2030 time frame, and some implications for fuel efficiency cost-benefit analysis, and required taxes on oil products are presented.

5.1. Implications for oil sector investments

The analysis presented here indicates that there is sufficient oil available at extraction costs of $30/bbl or less to meet cumulative oil demand between new and a total-oil phaseout date of 2060, and sufficient oil at a cost of $40/bbl or less to meet the demand up to a phaseout date of 2100. This implies that, if the nations of the world follow through with their Paris goal of limiting global mean warming to 2ºC, there will be strong downward pressure on international oil prices toward these levels. Even with only partial movement toward the Paris goals (scenarios LFG-E and HFG-E here), oil at $50/bbl or less would be sufficient to supply cumulative demand to 2100. By comparison, costs of recent shale oil production in the US ranged from $30–90/bbl, with mean costs by share-oil play ranging from $48–65/bbl (Avedele, 2016), while a new bitumen mine in Canada in 2015 without an upgrader would have cost US$85–95/bbl (with a 10% real return on investment), a new in situ (SAGD, steam-assisted gravity drainage) operation would have cost $55–65/bbl, and the cost of expanding an existing SAGD operation would have cost $50–60/bbl (Birn, 2016). Taking into account inflation, these costs are comparable to the cost range assumed by McGlade and Ekins (2015), given above.

Millington and Murillo (2015) carried out an extensive analysis of the sensitivity of the cost of oil production from the Canadian tar sands; they indicate crude bitumen costs (in 2014 Cdn$) of $53–65/bbl for SAGD projects and $61–79/bbl for mine projects, with most-likely costs of $59/bbl and $70/bbl, respectively. These central estimates increase to $80/bbl and $90/bbl when the cost of transporting diluted bitumen to the oil hub at Cushing, Oklahoma are included. However, Millington and Murillo (2015) expect such oil to continue to sell at a discount of $15/bbl over the long term relative to the price of WTI (West Texas Intermediate), which is more aligned with the international market price, because of the lower quality of tar sands oil. Thus, profitable expansion of the tar sands operations requires an international oil price of Cdn$95–105/bbl or US$70–80/bbl. Although some reduction in production costs for new operations can be expected through learning-by-doing, this will be offset to some extent by the fact that the least costly resources are exploited first, leaving more costly resources for later. The costs in any case are likely to remain far above the market price of oil under moderately aggressive global efforts to limit global warming.

5.2. Comparison of LDV assumptions with current and proposed standards

The efficiency measures assumed here for transportation and other oil uses are would appear to be not significantly more stringent than the most-efficient standards already planned in the near-future in some jurisdictions. The upper part of Table 6 gives currently enacted future fleet-average energy standards for LDVs in various countries, while the lower part gives fuel consumption by market segment and the weighted average as assumed here in NAM in 2014 and for 2050. The average LDV fuel consumption computed here for NAM is 10.4 l/100 km in 2014, which is close to the average on-road fuel consumption in the US in 2014 of 21.4 mpg (equivalent to 11.0 l/100 km) given in BTS (2015). The most stringent pending standard (in the EU, for 2021) is equivalent to 4.1 l/100 km, compared to a weighted average urban and highway standard here of 4.0 l/100 km in WEU by 2020 and 3.1 l/100 km by 2050.

However, there are three factors that weaken enacted standards compared to the future standards assumed here. First, fuel use under real-world driving conditions is often much higher than according to official testing procedures (on which standards are based). In the EU, this difference is estimated to have grown from only 5% in 2001 to 40% in 2015, so that real world CO_2 emissions (which is what the EU standard specifies) fell from 183 to 167 g/km rather than from 170 to 120 g/km, as prescribed by the standard (Tietge et al., 2016). Revised testing procedures, referred to as the World-Harmonized Light-Duty Vehicles Test Procedure (WLTP), will replace the current text procedure (the NEDC, or New European Driving Cycle). The 2021 EU standard will be increased to 109 g/km as measured by WLTP, which is equivalent to 95 g/km under the NEDC test (Mock, 2016). However, real-world emissions will still be higher than the standard, such that a 109 g/km test result is expected to correspond to be 134 g/km (23% higher) under real driving conditions. Mock (2016) suggests a standard of 90 g/km for 2025 and 69 g/km for 2030 (both on a WLTP basis). Neglecting loopholes and assuming the gap between test and real world emissions to remain at 23%, real-world emissions would be 110 g/km and 85 g/km in 2025 and 2030, which correspond to 4.8 l/100 km and 3.7 l/100 km, respectively. The latter is very close to the 2030 target assumed here under the Fast scenario.

Second, the future energy intensity standards assumed here apply to HEVs or to PHEVs when running on fuel, whereas national standards combine (in at least some cases) the fuel and electricity use into a single fuel-equivalent energy use (with different choices concerning how to convert electricity use into an equivalent fuel use) and also give disproportionate credit to electric vehicles in computing corporate average fuel economy, or (in the US) give credits for reducing refrigerant emissions from vehicle air conditioning systems, both of which increase the allowed fuel energy intensity. Under the US CAFE standards, the miles-per-gallon gasoline equivalent of electric vehicles is based on the actual electric energy required per mile driven (which already reflects the greater efficiency of electric compared to conventional drive trains), multiplied by the efficiency of producing and transmitting electricity compared to the efficiency of producing gasoline from crude oil (so that the comparison is in terms of relative primary energy requirements), but is then multiplied by a factor of 1/

Table 6
Recent past and currently-intended energy intensity standards for new LDVs in various countries, and those assumed to be achieved in the scenarios presented here. Average in-use values given in the lower part of the table are for NAM. The US LDV values assume that cars account for 66% of LDV distance travelled in 2015 and 67% in 2025. Source for national standards: ICCT (2016).

Recent past and currently-intended future LDV energy intensity standards				
Jurisdiction	New-LDV fuel standard (litres/100 km) and applicable year			
	Recent		Future	
US				
Cars	6.5 (2015)		4.3 (2025)	
Light trucks	8.7 (2015)		6.0 (2025)	
LDV average	7.2 (2015)		4.8 (2025)	
EU	5.1 (2014)		4.1 (2021)	
Japan	5.0 (2013)		5.1 (2020)	
S Korea	6.0 (2015)		4.2 (2020)	
China	6.6 (2015)		4.9 (2020)	
India	5.6 (2012)		4.8 (2022)	
Brazil	6.4 (2012)		5.8 (2017)	
Mexico	7.4 (2013)		6.7 (2016)	
Assumed here				
Market segment	Average in-use today		HEV for new LDVs in 2050 for the Fast Scenario	
	Urban	Highway	Urban	Highway
Compact car	9.35	7.36	2.27	2.53
Mid-size car	10.13	7.82	2.35	2.59
Small SUV	11.43	9.31	2.76	3.16
Mid-size SUV	13.07	10.31	3.13	3.67
Light truck	15.72	12.75	3.62	4.29
Weighted average	11.24	8.92	2.40	2.67

0.15 (=6.67) so as to be similar to the way other alternatives to gasoline have been treated (see DOE (2000)). However, the denominator factor of 0.15 comes from the treatment of E85, a fuel consisting of 85% ethanol and 15% gasoline, so that the resulting mpg value for E85-fueled vehicles is miles per gallon of gasoline only. Under EPA rules initiated under the Obama administration, each PHEV and BEV is counted as more than one vehicle during the transition period 2017–2021 but not for the final 2025 standard (C2ES, 2016). In the EU, every car (including PHEVs and BEVs) with CO_2 emissions averaging less than 50 g/km will count as 2.0 vehicles in 2020, 1.67 vehicles in 2012, and as 1.33 vehicles in 2022 when determining corporate average sales-weighted CO_2 emissions (ICCT, 2014).[9] In China, under the Corporate Average Fuel Consumption (CAFC) system that was introduced in 2013, fully electric vehicles are assumed to have zero CO_2 emission and each one counts as 5 vehicles, while vehicles (such as PHEVs) with a fuel consumption less than 2.8 l/100 km count as 3 vehicles (Transport Policy, 2016a). Interestingly, Mock (2016) finds that a 70 g/km NEDC standard (80 g/km WLTP or 3.5 l/100 km) can be achieved with no electric share, thereby supporting the ANL study (Moawad et al., 2011) conclusions.

Third, existing standards tend to be tied to the size or mass of vehicle, with a weaker standard for larger or heavier vehicles. Thus, there are separate standards in the US and Canada for cars and light trucks (as shown in Table 6), and allowed CO_2 emissions increase with vehicle mass in the EU (Thiel et al., 2014), Japan (Transport Policy, 2016b) and Korea (Oh et al., 2016).[10] Thus, if consumer preferences shift toward larger and/or heavier LDVs (as tends to happen when fuel prices fall), energy use will increase.

Thus, it is important that anticipated near-future energy intensity standards be achieved in practice, are tightened by a further 15–60%, and are made to apply to vehicle fuel consumption without averaging in the 3 times more efficient electricity use in PHEVs or assigning credits for the sale of electric vehicles. Meeting tighter fuel economy standards through advanced conventional vehicles and HEVs is a less costly means of achieving early CO_2 emission reductions than promotion of PHEVs and BEVs according to Bishop et al. (2014). Sales of electric vehicles (PHEVs and BEVs) would then be encouraged by other means, such as through higher gasoline taxes, but without public subsidies. Fleet-wide standards need to be set that are independent of the average size or mass of vehicles sold by a given vehicle manufacturer, which in turn will give vehicle manufacturers an incentive to promote smaller and/or less massive vehicles.

5.3. Comparison of truck freight energy intensity assumptions with currently-mandated future standards

Only four jurisdictions in the world have regulations to require reductions in the energy intensity of commercial trucks: US, Canada, China and Japan. The required reductions are 11–14% over the period 2014–2015 or 2014–2018 (GFEI, 2016). The US is (or was) considering a Phase 2 regulation that would require a 20–45% reduction (depending on the type of truck) for new trucks relative to 2010 by 2027. By comparison, an average energy intensity reduction of 50% by 2035 or 2050 is assumed here. As trucks account for the single largest share (35%) of transportation energy use on a global basis (see Fig. 1b), it is particularly important that more attention be devoted to truck fuel economy.

[9] The allowed credit cannot exceed 7.5g/km averaged over 2020–2022.

[10] This had also been the case in China, under the Phase 1 to Phase 3 standards of 2005–2012 (Transport Policy, 2016a). Under the CAFC system, a single fuel consumption target (6.9l/100km in 2015, 5.0l/100km in 2020) applies to all manufactures, irrespective of fleet average vehicle mass although, as noted above, PHEVs and BEVs are disproportionately weighted in computing averages.

5.4. Implications for efficiency cost-benefit analysis

The standard procedure in the analysis of the economic benefits (through reduced fuel consumption) of LDV and other transportation efficiency measures is to compute the present value of lifetime energy cost savings, assuming some variation of fuel costs over time that is not affected by the efficiency measures themselves. The analysis presented here shows that stringent fuel efficiency standards implemented in any one region, and especially if implemented globally, can have a material effect on energy prices. Thus, cost-benefit analysis of proposed more stringent standards should take into account the effect of reduced demand on energy prices. This would lead to a substantially larger estimate of the economic benefit, and so provide a stronger economic rationale (apart from reducing global warming damage and other benefits) for stringent fuel economy standards.

5.5. Required taxes

As fuel economy standards are less stringent for larger and/or heavier vehicles, and there is a tendency for consumer purchases to shift toward these more energy-intensive vehicles when fuel prices fall, some mechanism will be needed to at least maintain present-market shares of medium and small vehicles, not to mention increasing their shares in the Green scenarios. This could be done through vehicle sales taxes that increase with decreasing fuel economy, or through taxes on transportation fuels. Fuel taxes would in any case be needed to prevent the cost of driving a given distance from decreasing as fuel economy improves, which would otherwise lead to an increase in travel (the “rebound” effect) that would erode some of the energy savings that would otherwise occur and worsen congestion (Small and Van dender, 2007; Hymel et al., 2010; Steren et al., 2016; Moshiri and Aliyev, 2017). Increasing taxes can be made more palatable by communicating the fact that, in the absence of the reduction in oil demand induced by such taxes, the price of oil-based fuels will go up, with the extra revenue going to oil-producing countries instead of to the country levying the higher tax. A reduction in the price of oil of \$75/bbl (from, say, \$125/bbl to \$50/bbl) corresponds to a decrease in the cost of gasoline of \$0.51/l (given that 1 barrel = 159 l, and assuming 7% refining losses and direct pass-through of the cost savings). A cost reduction of \$75/bbl applied to present world oil consumption of about 90 Mbbl/day corresponds to a compensating tax revenue of \$2.5 trillion/yr (global GDP in 2015 was \$114 trillion).

6. Concluding comments

The analysis presented here identifies combinations of efficiency, behavioral, drive-train and fuel switching measures that, collectively, would achieve the global near-elimination of oil use by 2060 or 2100, the former being in line with the emission reductions needed to have a 60% chance of limiting global mean warming to no more than 2.0ºC above the pre-industrial mean. A key component in the oil phaseout scenarios presented here is a strong emphasis on improving passenger and freight energy efficiency, and in particular, closing loopholes in existing LDV fuel economy standards and greatly tightening these standards beyond 2020–2025. The analysis shows that, should the measures identified here be implemented globally, the remaining cumulative global oil consumption (up to the point where there is no further oil demand) could be entirely satisfied by oil with production costs of no greater than \$27–45/bbl. Thus, barring events that artificially limit the supply of low-cost oil, any oil that is more expensive than this to extract would entail a financial loss and so, on economic grounds, would remain in the ground. This includes the Canadian tar-sands oil, much of the shale oil, and deep-water and Arctic oil. At the same time, countries that are dependent on revenues from oil prices substantially above \$30–50/bbl should prepare as quickly as possible for the possibility of oil prices remaining indefinitely below their current budgetary requirements, some of which could be politically destabilized by prolonged low oil prices (Rowland and Mjelde, 2016).

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2017.05.045.

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