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Peak Oil Demand: The Role of Fuel Efficiency and Alternative Fuels in a Global Oil Production Decline

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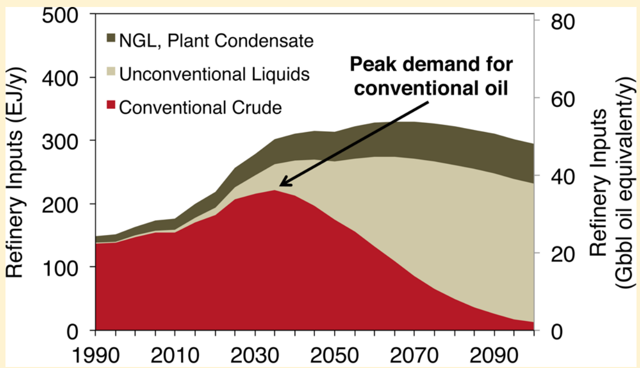
Supporting Information



ABSTRACT: Some argue that peak conventional oil production is imminent due to physical resource scarcity. We examine the alternative possibility of reduced oil use due to improved efficiency and oil substitution. Our model uses historical relationships to project future demand for (a) transport services, (b) all liquid fuels, and (c) substitution with alternative energy carriers, including electricity. Results show great increases in passenger and freight transport activity, but less reliance on oil. Demand for liquids inputs to refineries declines significantly after 2070. By 2100 transport energy demand rises >1000% in Asia, while flattening in North America (+23%) and Europe (−20%). Conventional oil demand declines after 2035, and cumulative oil production is 1900 Gbbl from 2010 to 2100 (close to the U.S. Geological Survey median estimate of remaining oil, which only includes projected discoveries through 2025). These results suggest that effort is better spent to determine and influence the trajectory of oil substitution and efficiency improvement rather than to focus on oil resource scarcity. The results also imply that policy makers should not rely on liquid fossil fuel scarcity to constrain damage from climate change. However, there is an unpredictable range of emissions impacts depending on which mix of substitutes for conventional oil gains dominance—oil sands, electricity, coal-to-liquids, or others.

1. INTRODUCTION

The depletion of nonrenewable resources has been a routine interest of scientists, environmentalists, and policy makers since the *Limits to Growth* controversy of the 1970s. While some recent work has assessed the prospects for key minerals—such as nickel, rare earth oxides, and phosphorus[1,2]—it is the potential scarcity of energy resources (particularly liquid hydrocarbons) that has attracted the most significant attention. Typically, concerns over liquid hydrocarbon depletion are voiced as questions about "peak oil". The most strident peak oil arguments suggest that a peak in conventional oil production is imminent or has already arrived,[3−5] and that liquid fuel scarcity will follow, inducing economic contraction or major disruptions to our way of life. In this paper, we critically examine this causal sequence. First, is it possible for a peak and decline in oil output to occur due to a peak and decline in oil demand? Second, if so, when might such a peak occur? Third, what are the greenhouse gas (GHG) implications of a decline in demand for conventional oil as a transportation fuel?

Many authors have forecasted consequences of peak oil. These forecasts include a benign transition to other sources of energy;[6] a global "land rush" as countries seek to secure supplies of renewable fuel;[7] stunted economic growth;[8] or even calamitous shortages of transportation fuels, panic, and social collapse.[9] While the predicted economic ramifications of peak oil are negative, many authors see an environmental upside in terms of climate change. One analysis suggests that peak oil, coupled with a phase-out of coal emissions, can avoid the worst risks of dangerous climate change by holding atmospheric CO_2 concentrations to 450 ppm by 2100.[10] The underlying assumption is that readily available reserves of conventional oil will be exploited regardless of demand, meaning that coal should be a key focus for climate policy.[11] Another analysis suggests that a transition to hydrogen- and natural-gas-fueled vehicles—and the associated climate benefits—will partly be driven by dwindling oil supplies.[12] Other researchers argue that emissions under most IPCC scenarios will be constrained by coal[13] or total fossil fuel production, and thus the rise in global business-as-usual emissions may not be as dramatic as projected.

Predictions of peak oil typically result from a supply side or availability model. That is, they fit historical data on conventional oil production to an assumed functional form such as a logistic or Hubbert curve, constrained by overall

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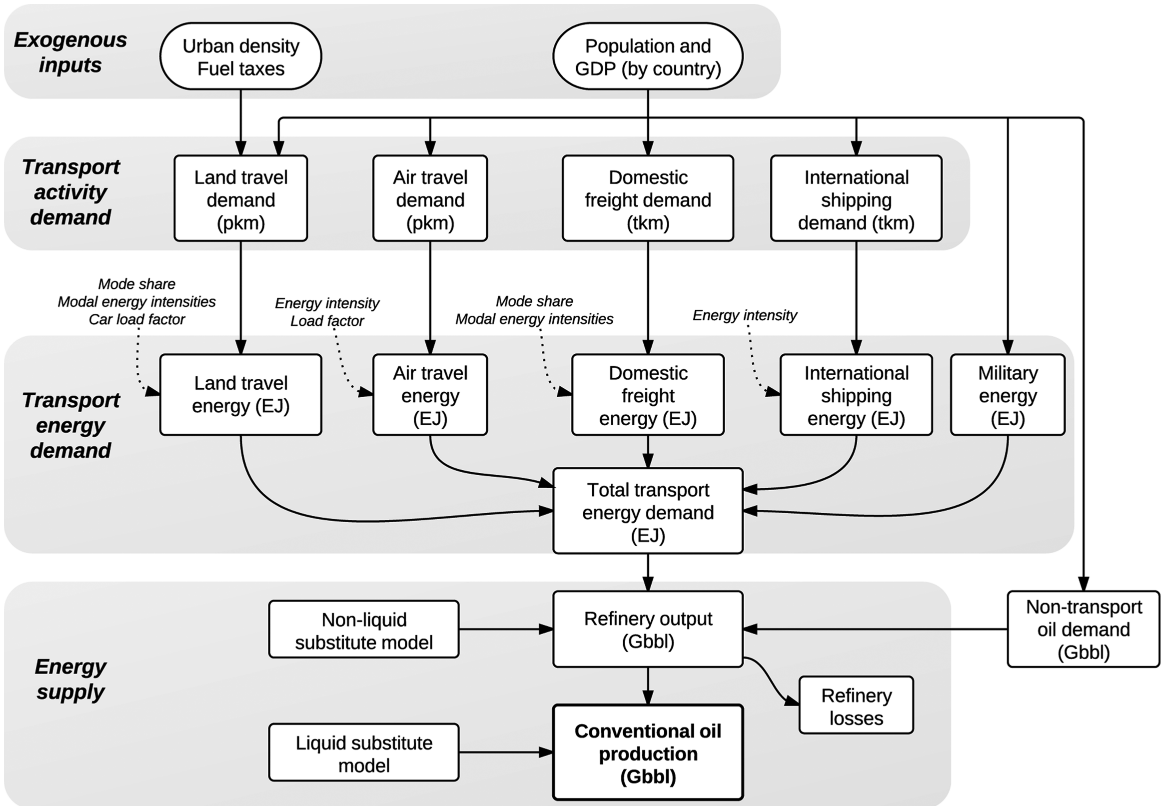

Figure 1. Simplified structure of the oil demand model. Historical data are used to select functional forms and parametrize each set of relationships between population and GDP and activity demand, between transport activity demand and energy demand, and for nonliquid and liquid substitution.

resource availability. This availability peak has been predicted to occur between 2005 and 2035, with the date shifting out over time.[6,14] More detailed models rely on field-level assessment of discovery and decline, but these face drawbacks due to the difficulty of modeling uncertain future discoveries.[15]

Most models used to predict peak oil do not address demand for oil, except to presume that demand will rise and fall as governed by an exogenously determined oil endowment. The underlying assumption is that the world will immediately use whatever oil can be pumped from the ground, and that supply is independent of demand — that is, oil exploration investments bear no relation to the current oil price or expectations of future demand.

Recent trends suggest that a demand-driven peak is increasingly plausible. First, demand for passenger travel may be saturating in industrialized countries.[16−18] Second, recent global efficiency standards for passenger vehicles,[19] international freight,[20] and domestic freight[21] present significant changes from decades of stagnation in efficiency. Third, price-competitive alternatives to conventional oil continue to expand. Between 2000 and 2010, biofuels production expanded from 0.3 to 1.8 Mbbl/d[22] and significant research efforts are underway in advanced cellulosic fuels. Announced and planned oil sands capacity exceeds 7.5 Mbbl/d.[23] Lastly, the number of alternative-fueled vehicles is expanding rapidly: natural gas vehicles fleets have increased 10-fold in the past decade to 12 M vehicles (∼1% of global vehicle fleet),[24] while sales of electric two-wheeled vehicles in China exceed 20 M per year.[25]

In this paper, we describe a transparent, user-operable, data-rich model to examine the possibility of whether "peak oil" may arise through falling demand for conventional oil. We consider three indicative scenarios that vary the rate of technological improvement and changes in fuel economy regulations. These three scenarios are not the only possibility: users can easily develop their own scenarios with different assumptions for economic and population growth; demand for passenger and freight travel; fuel economy; and the adoption rate of substitute liquid and nonliquid fuels.

2. A GLOBAL MODEL OF OIL DEMAND

Underlying our analysis is the Interactive petroleum Demand EStimation (IDES) model. The IDES model is an interactive spreadsheet tool that can be accessed as Supporting Information (SI).

2.1. IDES Modeling Approach. In building the IDES model, we follow the advice of Craig et al.:[26] simple, transparent models are often more useful than large and complex ones. Our modeling principles are as follows:

1. Data richness: Decades-long time-series data sets are used to generate sector-specific relationships among income, oil use, and oil substitute production.
2. Simplicity: simple models with a minimum number of parameters are fit to historical data for the purposes of extending trends into the future.
3. Transparency: we construct a user-operable model (see SI) such that any interested party can explore the sensitivity of the results to a range of parameter values supported by historical rates of change.

Our model focuses primarily on oil demand from transport, which is the dominant consumer of oil and the most constrained in terms of substitution possibilities. Demand for

Table 1. Major Data Inputs and Assumptions in Modeling

sector	primary data sources and historical coverage	key features and assumptions
GDP and population (affects all sectors)	• IPCC SRES	• uses standard projections for population and GDP
land travel	• data set in ref 16, eight countries, 1970–2009 • official national statistics on efficiency	• travel demand (passenger km) and mode choice (shares of private and public transport) are modeled as a Gompertz function of income, allowing saturation at high incomes • countries follow a weighted average of four pathways characterized by data from the U.S., Canada/Australia, Europe, and Japan. Travel demand and efficiency are pathway specific • load factors for private transport asymptotically decline with income to 1.6 persons per vehicle • efficiencies of private and public transport improve at an exogenous annual rate
air travel	• passenger km: data set in ref 49, regional groupings, 1980–2007 • load factors: data set in ref 50, 1950–2009 • efficiency: data set in ref 51, 1960–2009	• travel demand (passenger km) is modeled as a linear function of income, with separate trends for 11 OECD regions • efficiency improvements are modeled as an exponential function of time • load factors increase with global GDP • both efficiencies and load factors are constant across the world
domestic freight	• tonne km: OCED data from ref 52, 43 countries, 1970–2008 • energy intensity: data set in ref 53, 10 countries, 1990–2008	• freight demand (tonne km) and mode choice (shares of road and rail/water) are modeled as a piecewise linear function of income • countries follow one of two pathways, characterized by large, continental-scale countries (e.g., Canada, China) and all other countries; freight demand and efficiency are pathway specific • efficiencies of road and rail/water freight improve at an exogenous annual rate
international shipping	• tonne km: data set in ref 54, 1983–2008 • energy intensity: data set in ref 20, 1990–2007	• tonne km are modeled as a piecewise linear function of world GDP, with the rate of increase slowing at approximately twice 2010 world GDP • efficiency improves at an exogenous annual rate
military	• military expenditure: data set in ref 55 • military oil consumption: data set in ref 56 (1997–2009) and ref 57 (2007–09)	• constant fraction of GDP devoted to military spending for 15 largest countries • constant military energy demand per unit of military spending
nontransport	• International Energy Agency data from ref 58, 1971–2008	• nontransport oil demand is modeled as an exponential function of world GDP

oil products in other sectors is included in simplified form. An overview of the model structure and logic is shown in Figure 1.

We project conventional oil demand in five-year timesteps until 2100 under a variety of scenarios of population and economic growth,[27] as well as varying rates of travel demand growth, efficiency improvement, and fuel substitution. Population and GDP projections are taken from IPCC SRES scenarios.[28,29] The model performs country-level calculations that are summed in some instances to larger regional aggregations (e.g., UN regions). Three indicative scenarios are considered in this paper: *Historical, Efficiency Policy* and *High Technology.* The *Historical* scenario uses relationships derived only from historical trends. The *Efficiency Policy* scenario takes account of recent adopted or proposed fuel economy goals. The *High Technology* scenario adds more rapid penetration of alternative liquid fuels, as well as continuing the trend of aggressive fuel economy improvements seen in recent years.

2.2. Economic Basis. Our model differs in two ways from traditional economic models of oil demand and integrated assessment models of energy use and emissions. First, we do not explicitly model energy prices. It is very difficult to predict future prices for liquid fuels with any certainty, as they follow a random walk.[30] In addition to long-run scarcity, oil price movements depend on cartel actions, speculation, and the short-term lag with which supply responds to increased demand; moreover, the relative determinants of prices have changed over time.[30] Adding prices to the model would introduce an additional layer of assumptions regarding the relationship of prices to short- and long-run scarcity; sector-level price elasticities of demand and how they change over time; and cartel behavior. Oil demand is also relatively inelastic,[30] and so price changes (while important) are likely to have less impact on demand than economic growth, efficiency improvements, and saturation of travel demand.

Instead of modeling prices explicitly, we make the assumption that long-run prices for liquid fuels will remain in the ranges observed in the period of our underlying data sets (1970–2010, 15 to over 140 \$/bbl in constant 2010 dollars). We then test whether this assumption is reasonable through (i) modeling the rate of increase in demand within the historical price range; (ii) comparing projected conventional oil demand to estimates of possible oil output; and (iii) assessing whether cumulative demand exceeds estimated oil endowment estimates. Support for our approach is provided by recent integrated supply demand modeling with a variety of oil substitutes. For example, in Brandt et al.,[31] the oil price rarely reached above 150 \$/bbl over the period modeled.

The major advantage of our approach is that projections of peak oil demand are inherently robust to a wide range of price scenarios. It is certainly possible that prices will rise beyond those driving our underlying data set. Under this condition, our model would underestimate electrification along with other shifts toward nonliquid fuels and the adoption of energy-saving technologies. Thus, demand would fall below our model's estimates. On the other hand, if prices fall, then this suggests that there is no imminent scarcity of liquid hydrocarbons relative to demand (e.g., as in an economic contraction where demand and price decline). Thus, in scenarios where availability of conventional hydrocarbon supply is a concern, our model is more likely to overestimate demand than to underestimate it.

The second major difference between our approach and traditional economic models is that we adopt a flexible specification for demand for different end-use sectors, fitted to long-run historical relationships. Thus, in contrast to many economic and integrated assessment models, we do not directly apply income elasticities through a constant elasticity[32,33] or generalized difference[34] formulation. Instead, we adopt different specifications for different end-use sectors, informed by both theory and historical data.

For example, in the case of passenger land travel, we allow for saturation effects in a similar way to Dargay and Gately[35] (who focus on vehicle ownership) and IEA[36] (who consider vehicle travel as well). Our estimated saturation levels are consistent with a growing literature suggesting that saturation has already occurred in industrialized countries, but are lower than IEA suggests (possibly because IEA assumes that the distance driven per vehicle will remain constant even as vehicle ownership saturates). In other sectors, such as freight and air travel, where neither historical data nor the theoretical literature provide extensive support for saturation, our functional forms assume continued growth in energy demand in line with increasing income.

2.3. Defining Oil. IDES defines "conventional oil" as hydrocarbons with density greater than 15° API and produced via primary and secondary recovery, and excluding natural gas liquids (NGLs). This is a common definition used by modelers and corresponds closely to what the public understands to be "oil." For example, those concerned with peak oil do not typically consider bitumen from oil sands as a part of conventional oil, but instead as a substitute for conventional oil.

Therefore, in IDES, substitutes for conventional oil include natural gas liquids; enhanced oil recovery (EOR); low-quality hydrocarbons such as bitumen[23] and extra-heavy oil;[31,37] coal derived fuels (CTL); natural gas-derived fuels (GTL, CNG, LNG); biofuels; and electricity.[38−40]

2.4. Sector-Specific Example. We use a dimensional identity framework to model future oil demand,[41] in a similar fashion to the well-known Kaya Identity.[42,43] For example, energy use E in a generic sector could be modeled most simply as

$$E = P \cdot g \cdot e.$$

In this framework, extensive variables are given capital letters, as in P = population. Intensive variables are given lower-case letters, such that g = GDP per capita and e = energy use per unit of GDP. Our model equations are generally more complex than this (e.g., each term can be a nonlinear function of income).

Table 1 summarizes the data sources and assumptions for each sector in the model. The structure of IDES is best illustrated through a more detailed example of one key sector, land transport, which is further divided into public and private land transport. The following equation gives energy demand E from private land transport:

$$E = P \cdot t \cdot m \cdot f \cdot \eta$$

Here, the land travel demand t is a function of per-capita GDP g. The modal split m is the fraction of travel provided by private transport as a function of per-capita GDP. The vehicle load factor f, and vehicle efficiency η together determine the energy use per passenger kilometer.

Land travel demand t is modeled probabilistically using four idealized pathways p, which are based on historical relationships between income and travel demand in the U.S., Australia/Canada, Europe, and Japan. Assignment of countries to pathways is performed via a discrete choice model using urban population density and gasoline taxation level (see SI for details). Each pathway is modeled with a modified Gompertz function that captures the observed leveling out of per-capita travel at higher income levels, in line with previous studies of vehicle ownership:[35,44]

$$t = \sum_{p=1}^{4} [[a_p \exp[b_p \exp(c_p g)] + d_p] \Pr[p_c = p]]$$

where a_p, b_p, c_p, and d_p are parameters for countries in Pathway p that, respectively, control the saturation level; time shift (income levels at which growth in travel begins and saturates); growth rate (how fast travel grows to the saturation level) and floor (minimum level of travel). $\Pr[p_c = p]$ is the probability that country c will follow pathway p, and so an individual country follows a weighted average of the U.S., Australia/Canada, Europe, and Japan pathways based on the estimated probabilities.

The mode share split m is modeled using a similar functional form to represent shifts toward preferences for private travel as wealth increases. Vehicle occupancy factor f is modeled as a declining function of income, and asymptotically approaches 1.6 persons/vehicle (see SI). Lastly, vehicle efficiency η improves using historical ranges of yearly fuel economy improvement rate (0.6% per year in *Historical* scenario) and proposed fuel economy goals (1.5−2.4% in other scenarios). Note that even the most aggressive rate of improvement that we consider is below the potential through 2030 or 2035 as estimated from engineering studies.[45−47] In the second half of the century, further improvements are possible due to electrification, light-weighting, autonomous vehicles, and other energy-saving technologies.

2.5. Substitutes for Conventional Oil. A similar approach is adopted to model energy demand E for other sectors and subsectors: land (public transport), freight, international shipping, air and military transport. Most of these sectors are treated as linear or piecewise-linear functions of GDP (see SI). Total energy demand is the sum of demand from each sector.

Only a portion of this demand, however, will be met by conventional oil. The model allows for two classes of substitutes that can also provide for transport energy demand: nonliquid substitutes, such as natural gas, hydrogen or electricity; and liquid substitutes, such as oil sands, synthetic fuels from natural gas and coal (GTL and CTL), oil shale, and biofuels. Within each class, we do not attempt to predict the exact substitute that will dominate (for example, whether electricity, hydrogen fuel cells, or natural gas will prevail in the passenger car market), but rather model the aggregate contribution of alternatives to conventional oil.

Because of the significant uncertainty involved in market shifts to alternative fuels, historical data for a variety of historical transitions in both primary fuels and vehicle technology were used to generate a range of possible market substitution scenarios. These data are modeled with logistic market penetration functions,[48] as shown for historical cases in Figure 2a. From these historical ranges, indicative model rates and ranges are chosen for each substitution type (e.g., bounds and cases for *Historical*, *Efficiency Policy*, and *High Technology* scenarios). For example, the fraction of fuel supplied by liquid fuels is given by

$$l(y) = 1 - f_{\max}^{\mathrm{nl}}\left(\frac{\exp(ay + b)}{1 + \exp(ay + b)}\right).$$

Here the exponential term for market penetration of nonliquid fuels increases from 0 to 1 as year y increases. Parameters a and b are fitting terms for the rate and delay in market penetration, respectively, which vary by sector (e.g., longer delay and slower transition for the air sector than the land travel sector) and model setting (see Figure 2b and c). Because not all transport needs are likely to be met by nonliquid fuels in the time frame of the study, the parameter $f_{\max}^{\mathrm{nl}}$ represents the maximum fraction that can be met with nonliquid fuels, which varies by sector (see SI for details). Note that the transition rates chosen (especially for three indicative scenarios) are well within the range of historically observed transitions.

3. RESULTS

3.1. Global Results. The results for the *Historical* scenario are shown in Figure 3. Panel A shows demand for transport energy, and the proportions of energy demand that are satisfied by liquid and nonliquid fuels. Several features, which are also evident in the *Efficiency Policy* and *High Technology* scenarios, are of particular note. First, total transport energy demand increases approximately linearly through ∼2060, but the growth slows toward the end of the century. Second, nonliquid fuels make significant inroads after ∼2030 in private passenger land transport, but are of little importance in other sectors until the end of the century. This is due to the assumption that penetration will be slower for road freight, air, and water transport because of the presently low energy densities of nonliquid substitutes such as electricity. Third, the rates of growth and decline in demand for transportation energy, liquid fuels, and conventional oil are much less rapid than those in most peak oil models, where a logistic functional form is assumed.

Lastly, land passenger transport becomes less important, due to saturation in wealthy countries[16−18,33] and projected efficiency improvements. In contrast, air travel and freight become more significant. Decades of observed data[49,50] and theory [59] of air travel demand show no near-term saturation, so air travel continues to grow with wealth. Similar relationships hold for freight, with decoupling occurring only at high levels of economic output.[60] Nontransport uses of oil continue their decades-long decline in relative importance.

The second panel, Figure 3b, shows the refinery inputs required to meet transport and nontransport liquid fuel demand. Peak demand for conventional oil occurs within 25

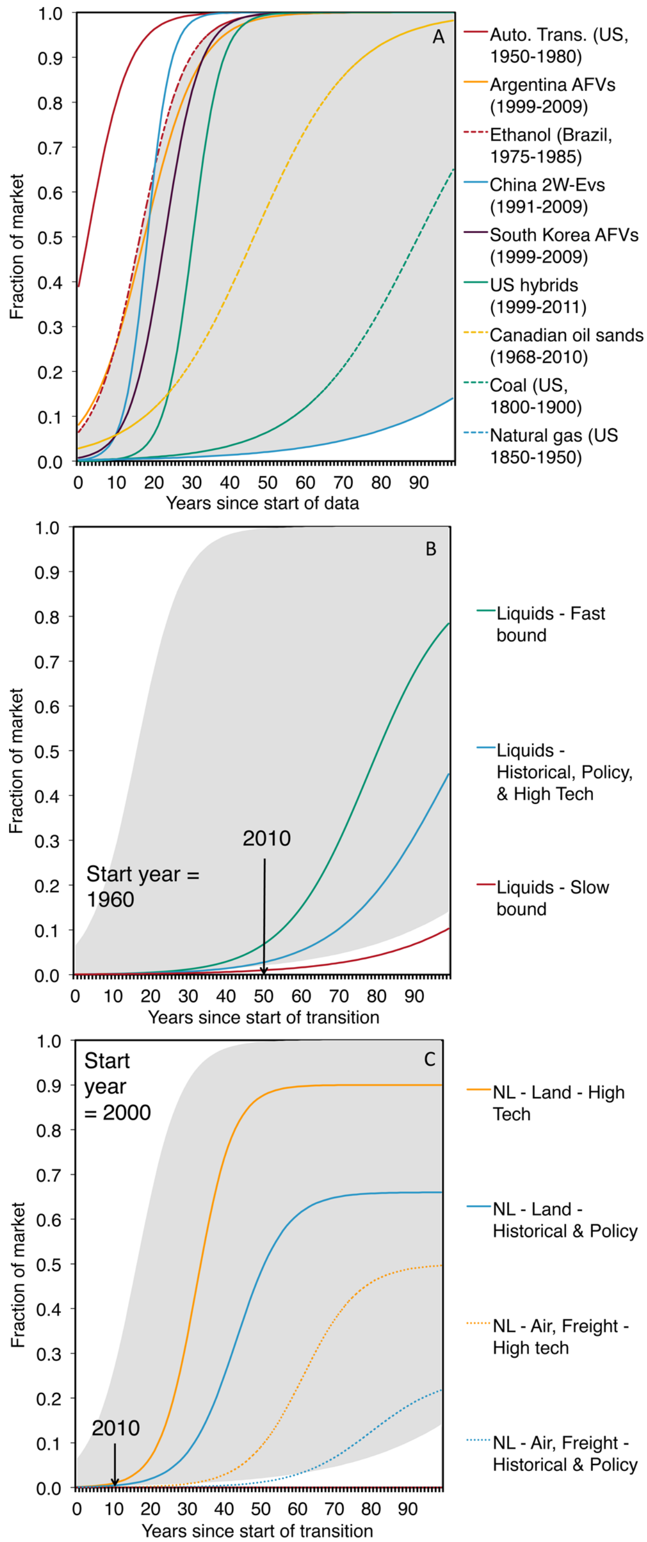

Figure 2. (A) Historical data for select fuel and vehicle transitions: Brazilian sugar cane ethanol substituting for gasoline (1970−1985); coal displacing wood in U.S. primary fuel share (1800−1900); Canadian oil sands output as function of total Canadian oil production (1968−2010); South Korean and Argentinian alternative fuel vehicle fleet shares (1999−2010); U.S. hybrid electric vehicles as fraction of total passenger vehicle fleet 1999−2011; Chinese electric two-wheeled vehicles as fraction of total two-wheeled vehicle fleet (1991−2009); U.S. automatic transmission sales fraction. (B) Bounds and indicative scenarios for liquids transitions compared to historical ranges of transitions outlined in gray (high = Brazilian ETOH from above, low

Figure 2. continued

from U.S. natural gas displacing coal and oil). Note that starting projection year in the model is y = 50 for the liquids transition, because historical data go back to 1960. (C) Nonliquids substitution in land (solid) and in air and freight applications (dashed). Policy cases are congruent with historical cases. Note that the starting projection year in the model is y = 10 for the nonliquids transition, as most data for alternative vehicles start in the late 1990s, so modeling is performed from 2000.

years. Total demand for liquid fuels continues to increase, albeit much more slowly, until ~2070. But after ~2020, this demand is increasingly satisfied by alternative liquid fuels.

Figure 3c shows the central projection of resulting oil demand (dark black line) compared to historically observed data. General agreement is observed between historical data and model predictions of those years. Figure 3c also shows the sensitivity of the resulting conventional oil projection to changes in the assumed rates of adoption of unconventional liquids and nonliquid technologies. Wide ranges are seen in the possible outcomes.

Figure 3d shows the resulting GHG impacts of this transition away from conventional oil. The central estimate from Figure 3c is used in all projections (i.e., this panel represents uncertainty due to carbon intensity of oil substitutes, not other model uncertainties). The central estimate represents 50% high-carbon liquids (oil shale) and 50% low-carbon liquids (cellulosic ethanol).[61,62] Similarly, the nonliquid fuels are represented by equal shares of low-carbon (offshore wind in EVs) and high-carbon (CNG) energy sources. Bounding cases are 75%/25% splits between low- and high-carbon substitutes.

Table 2 summarizes the model results in terms of peak demand. In all three scenarios, the peak occurs by 2035, and cumulative demand remains below the U.S. Geological Survey estimates of remaining conventional oil. Table 2 also highlights the effect of widespread adoption of fuel-saving policies and technologies under the *Efficiency Policy* and *High Technology* scenarios (Table 1). Under these scenarios, peak demand is reduced by 6−23%, and cumulative demand is reduced by 7−32%. The peak demand year for the *Efficiency Policy* scenario remains at 2035, whereas the *High Technology* scenario moves the demand peak earlier by a decade.

A simple test of the model's performance is to back-cast historical conventional oil demand. Using only historical drivers of GDP and population, the *Historical* scenario settings replicate observed global conventional oil demand to within ±5% for the modeled years 1990−2010. For UN world regions, deviation of approximately ±20% is found from IEA modeled regional consumption.[63] Although accuracy is less at the regional level (as expected given that our model does not include regionally specific parameters), under- and over-prediction are consistent across assessed years.

3.2. Regional Disaggregation. Results for 11 UN regions are shown in Figure 4 for per-capita travel demand (Panel a)

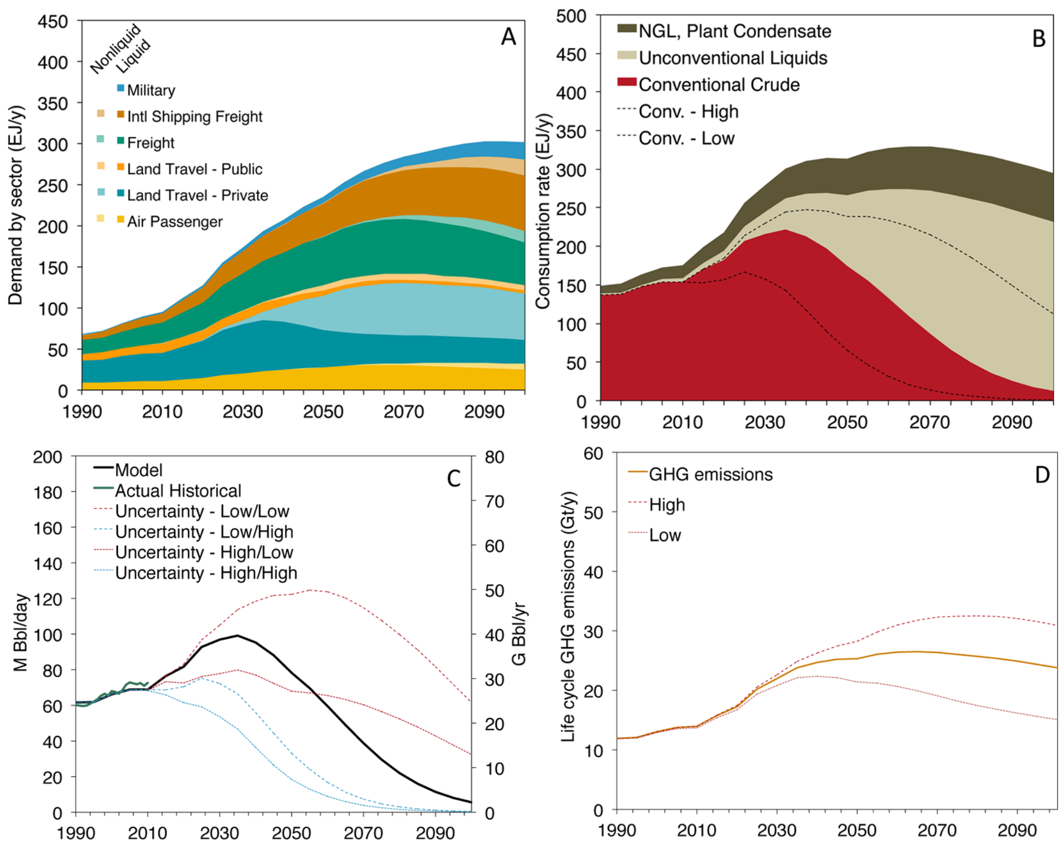

Figure 3. (A) Demand for transport energy, *Historical* scenario, including liquid fuels (dark tone) and nonliquid fuels (light tone). (B) Demand for refinery inputs, *Historical* scenario. (C) Range in uncertainties surrounding the conventional oil path given uncertainties in transition speed to nonliquids (slow in wide dash, fast in short dash) and transitions to alternative liquids (fast in blue, slow in red); (D) GHG emissions from oil and oil substitutes in transport for central path, assuming medium (50% low carbon, 50% high carbon substitutes) and low (75%/25%) and high (25%/75%), respectively.

Table 2. Results from Three Defined Scenarios[a]

	peak conv. oil demand (Mbbl/d)	year of peak demand	cumulative demand (2010–2100, Gbbl)
historical	99 (69–125)	2035 (2005–2055)	1915 (802–3353)
efficiency policy	93 (69–110)	2035 (2005–2045)	1778 (779–2964)
high technology	76 (68–87)	2025 (2005–2035)	1314 (682–2232)

[a]Conventional oil demand in this model includes liquid hydrocarbons produced using primary, secondary and tertiary technologies. It does not include other sources of liquids such as natural gas liquids, oil sands, synthetic fuels, biofuels, or oil shale. Parentheses indicate uncertainty range generated by using high and low bounds for fuel substitution in each case (e.g., low/low, high/high).

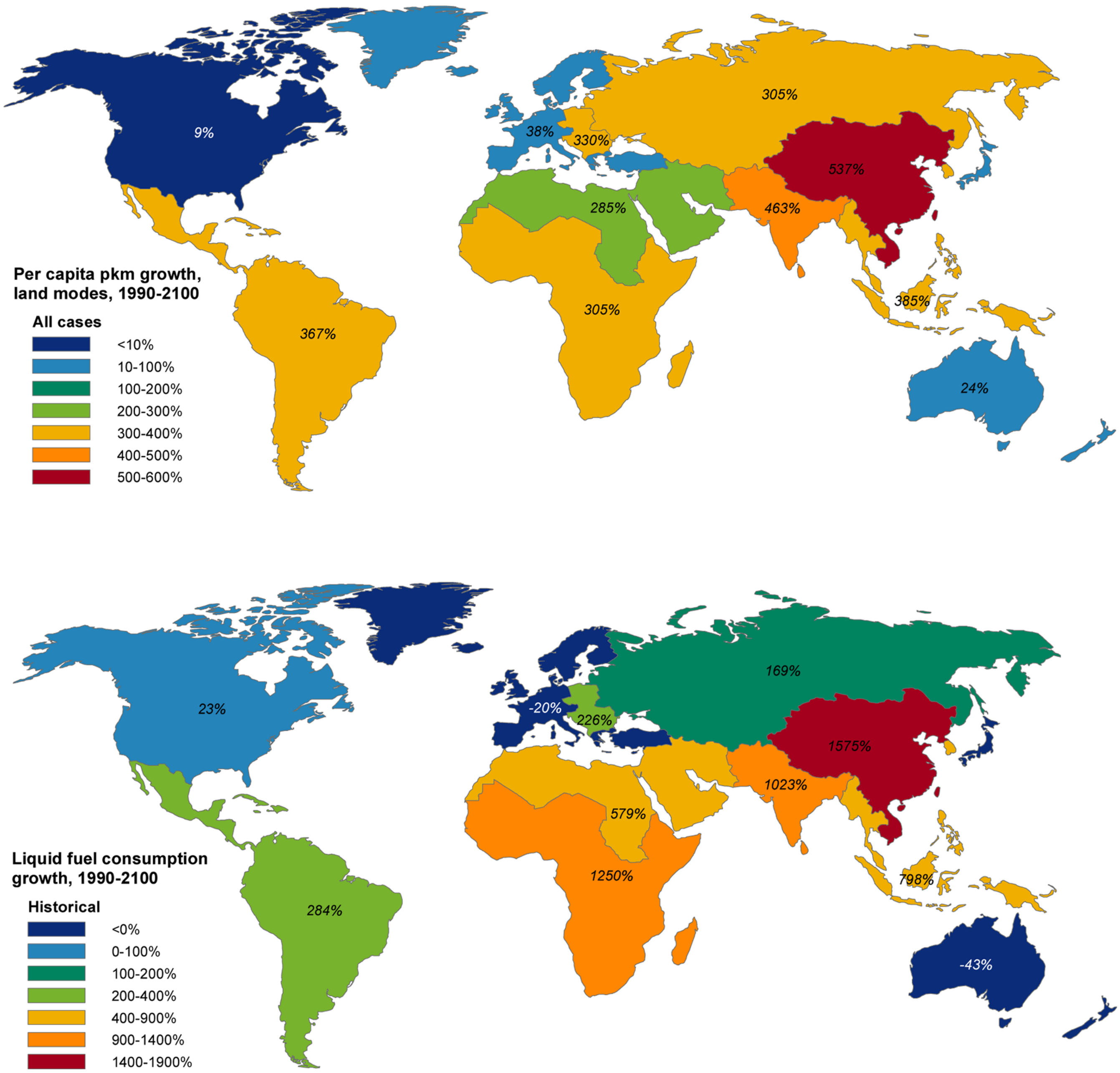

Figure 4. (A) Regional demand growth in per capita land passenger km (pkm) traveled (all scenarios). (B) Regional demand growth for all liquid fuels, including conventional oil and alternative liquid fuels (*Historical* scenario).

and total liquid fuel demand (Panel b). Although our model shows relatively moderate global demand growth for conventional oil, it predicts significant growth in demand for energy services: transport activity rises 300–530% and liquid fuel use rises >1000% in Asia and other growing regions. North American fuel use increases by ~23% while it declines by ~20% in Western Europe. Population growth over the 1990–2100 period is expected to be much greater in North America (44%) than in Western Europe (4%), which explains much of the difference between these regions. On a per capita basis, fuel use declines in both regions.

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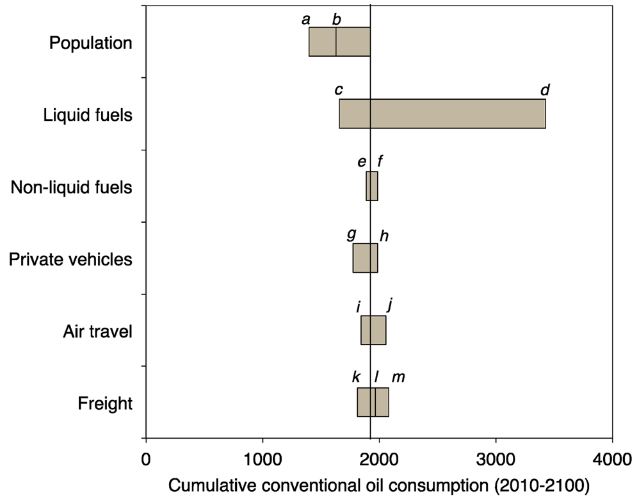

a Population/GDP given by A2 scenario
b Population/GDP given by B1 scenario
c Unconventional liquids given by transition to ethanol in US (1980-2010)
d Unconventional liquids given by transition to oil from coal and wood in US (1850-1950)
e Private land vehicles non-liquid technologies transition as in China transition to two-wheeled EVs (1991-2009)
f Private land vehicles non-liquid technologies transition as in transition from sailing ships to steam ships (1830-1930)
g Private vehicles efficiencies improve at 3% per year
h Private vehicle efficiency stops improving
i Air travel efficiency improves at double historic rate
j Air travel demand as function of GDP growth is double historical rate
k Trucking and international freight efficiency improvement rate doubles
l International freight demand increases linearly with GDP (no saturation)
m No further efficiency improvements in freight

Figure 5. Sensitivity of model results to input assumptions by sector and fuel transition. Plot shows cumulative conventional oil demand from 2010 to 2100, with *Historical* scenario shown as baseline.

Again, this pattern is driven by rapid economic growth in developing countries such as China, and the nonlinear relationship between income and demand for energy services. The fastest growth in demand for land passenger travel occurs in the GDP range of ~\$10,000−\$20,000 USD per capita, but incomes in Western Europe, North America, and Pacific OECD countries already exceed this range.

3.3. Sensitivity Analysis. Because of the enormous uncertainty involved at these time scales, sensitivity analysis was conducted. Figure 5 shows cumulative oil demand from 2010 to 2100 resulting from changes relative to the *Historical* scenario.

Sector-specific changes result in modest changes to oil demand. This is because most sector-level demands are small relative to total demands, and because of physical and technical limits. For example, the passenger load factor in airplanes cannot exceed 100%, and airplane efficiencies are expected to improve less in the coming 50 years than in previous decades. Even increasing the rate of private vehicle fuel efficiency improvement from 0.6% to 3% per year (Figure 5, pt. *g*) leads to cumulative reductions in demand of <250 Gbbl.

The rate of substitution of alternative liquid fuel substitutes has the largest impacts on future demand for conventional oil. These transitions are modeled using logistic market penetration functions.[48] The *Historical* case is parametrized with 50 years of historical production data for alternative liquid fuels.[64,65] Alternative liquid fuels increased from ~0% of total liquid fuel supply in 1960 to ~5% of liquid fuel supply in 2010.

Substitution with alternative liquid fuels is significant because alternative liquids can be used across all sectors. Bounding cases from history provide little guidance in narrowing the range of effects of liquids substitution. The post-oil-crisis Brazilian ethanol program of the 1970s resulted in 25% market penetration over 10 years. If replicated globally (an extremely unlikely occurrence) cumulative oil consumption would drop significantly. In contrast, if the transition to alternative liquid fuels follows the very slow century-scale US primary energy shift from coal to petroleum (1800−1950), which is also unlikely, cumulative oil consumption increases by ~1500 Gbbl (pt. *d*, same transition rate as green dashed curve in Figure 2a).

Nonliquid fuels such as natural gas and electricity have less impact than might be expected because they are limited to land transport with poor prospects for use in air and freight. For example, applying the recent rapid growth rate of Chinese electric vehicles would have a relatively minor effect if applied to private road vehicles (pt. *e*).

4. DISCUSSION

Although demand for transport services is likely to increase greatly over the coming decades, *Historical* trends show a growing divergence between transport activity and oil use. A simple continuation of the relationships between income and transport activity and the rates of efficiency improvement observed over the past 40 years would be sufficient to cause the transition away from conventional oil. The transition rates noted here are within historical envelopes of observed behavior. Concerted effort to reduce demand or introduce alternatives would only strengthen this conclusion. The important question surrounding peak oil therefore lies not with physical resource limitations, but with avoiding challenges that would impede a demand shift trajectory similar to historical rates of change.

The divergence between income growth, transport activity, and conventional oil demand is partly driven by moderated demand for passenger and freight transport, partly by improving energy efficiency, and partly by penetration by nonliquid and liquid substitutes for conventional oil. In particular, the speed of transition to alternative liquids is of key importance (see Figure 5). The substitution effect, dependent on policy and the prices at which alternative fuels and vehicles become competitive, is perhaps the most uncertain, but excessive pessimism is unwarranted. Recent examples such as wind power installation growth (rapidly declining cost leading to a decade of growth rates of 50% per year) or shifts in natural gas production and consumption in North America show the possibilities for rapid shifts in purchases and investment. Indeed, market changes can be rapid and profound once shifts in relative cost and convenience occur. For example, improvements in battery technology, coupled with increasing divergence between oil and electricity prices, could lead to a situation where small electric "city" vehicles become more convenient, cheaper, quieter, and generally more desirable for significant portions of the world's rapidly urbanizing population. At this point, oil substitution becomes the logical choice for an increasing number of consumers, and market changes could be rapid.

A variety of examples show that technology or resource-based determinism is not sufficient to explain trends in oil use and oil substitution. For example, Argentine natural gas vehicle fleets, which currently represent 15% of the Argentine vehicle population, are promoted by policies meant to favor the domestic natural gas industry. Also, as mentioned above, China has supported electric two-wheeled vehicles as a means to improve air-quality, and the resulting industry now ships more units per year than the entire passenger vehicle industry in the United States.

Our model is agnostic about which combination of alternative fuels will triumph. From the perspective of oil scarcity, the eventual winner is immaterial. For climate change, however, the nature of the substitutes will have a major impact (see Figure 3d). If the transition shifts from conventional oil to coal-to-liquids, oil sands, and palm oil (with associated emissions from land-use change in the latter case), peak output of conventional oil will be a significant net negative for greenhouse gas emissions.[66] If the transition is to natural gas and electricity generated from renewable sources, emissions from transport may well fall toward the middle of the century. This highlights the need for policies to direct the transition toward lower-emission substitutes for conventional oil,[67] as is already happening in countries such as Argentina. Either way, policy makers should not rely on peak oil to constrain emissions,[10] to constrain future emissions growth,[68] or to stimulate policy actions for energy conservation.[8]

Rather than the current focus on scarcity of conventional oil resources, we believe that more attention should be focused on understanding and anticipating the economic, environmental, and social consequences of adopting the various alternatives to conventional oil. For example, unconventional fossil resources could provide >10 Tbbl of alternative liquid fuels from oil sands, natural gas, coal, and oil shale,[66] although climate impacts could be profound. Potential biofuels production is also large, but the ecological and social costs of large scale biofuels production—such as effects on ecosystems and staple crop prices—could be much higher than societies are willing to tolerate. These challenges—not petroleum scarcity—should be our key concerns surrounding the inevitable transition away from conventional oil.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information provides full details of the model. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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