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A Plug-in Hybrid Consumer Choice Model with Detailed Market Segmentation

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ABSTRACT

This paper describes a consumer choice model for projecting U.S. demand for plug-in hybrid electric vehicles (PHEV) in competition among 13 light-duty vehicle technologies over the period 2005-2050. New car buyers are disaggregated by region, residential area, attitude toward technology risk, vehicle usage intensity, home parking and work recharging. The nested multinomial logit (NMNL) model of vehicle choice incorporates daily vehicle usage distributions, refueling and recharging availability, technology learning by doing, and diversity of choice among makes and models.

Illustrative results are presented for a Base Case, calibrated to the Annual Energy Outlook (AEO) 2009 Reference Updated Case, and an optimistic technology scenario reflecting achievement of U.S. Department of Energy's (DOE's) FreedomCAR goals. PHEV market success is highly dependent on the degree of technological progress assumed. PHEV sales reach one million in 2037 in the Base Case but in 2020 in the FreedomCARGoals Case. In the FreedomCARGoals Case, PHEV cumulative sales reach 1.5 million by 2015. Together with efficiency improvements in other technologies, petroleum use in 2050 is reduced by about 45% from the 2005 level. After technological progress, PHEV's market success appears to be most sensitive to recharging availability, consumers' attitudes toward novel technologies, and vehicle usage intensity. Successful market penetration of PHEVs helps bring down battery costs for electric vehicles (EVs), resulting in a significant EV market share after 2040.

Introduction

Light-duty vehicles remain the largest oil consumers and the largest source of greenhouse gas (GHG) emissions in the transportation sector, accounting for 60% of transportation petroleum use and an equivalent share of transportation's 1.9 million metric tons of CO_2 emissions in 2008 (*1*). According to the U.S. DOE's most recent assessment, existing policies including higher fuel economy standards will only prevent an increase in petroleum use and greenhouse gas emissions by light duty vehicles through 2025 (*1*). For the United States to reduce oil dependence and reduce economy-wide greenhouse gas emissions by 50-80% by 2050, light duty vehicles will have to become much more energy efficient and transportation's energy sources will need to be substantially decarbonized (*2*). These growing concerns about energy security and global warming will require the development of new propulsion technologies for light duty vehicles. PHEVs integrate the energy efficiency of hybrid powertrains with the ability to partially substitute electricity for petroleum. On February 17, 2009, the American Recovery and Reinvestment Act of 2009 (ARRA) was signed into law, providing up to $7,500 of tax credit for each new PHEV purchase starting from 2010 (*3*).

How much reduction in petroleum use and greenhouse gas emissions can be expected from PHEVs depends on many factors and remains an open question (*4, 5, 6, 7, 8*). Market acceptance remains uncertain due to the current high cost of PHEV batteries and uncertainty about the gains achievable through technological change and learning-by-doing. There are also questions about how consumers will evaluate the opportunity to recharge vehicles at home, or react to other potential benefits such as the potential to use vehicles as a source of back-up power or the value of vehicle-to-grid (V2G) connections. Even the value consumers will place on increased fuel economy remains contentious (*2*). Market acceptance of PHEVs will also depend on the progress made by other, competing powertrain technologies. The fuel economy performance of PHEVs and the share of their energy use that will come from electricity can also depend strongly on how consumers use the vehicles. Their impact on the grid will depend on market success, recharging behavior and usage patterns. The greenhouse gas benefits of substituting electricity for petroleum will depend on the degree to which electricity generation becomes decarbonized over time.

To understand the likely impacts of PHEVs, it is necessary to simulate market demand for PHEVs and their use by representing the attributes and behaviors of consumers at a relatively detailed level. A consumer choice model relying on the preferences of a single, typical consumer would not be able to reflect key factors such as access to recharging, daily driving patterns and willingness to accept technological risk. Because PHEVs are a novel vehicle technology, much remains to be learned about how consumers will evaluate their attributes, as well as how they are likely to be operated. The approach taken in developing the (Oak Ridge National Laboratory (ORNL) PHEV model is to create a framework for integrating data and behavioral models at an appropriate level of detail, whether or not the data are fully available or the behaviors are fully understood at the present time. As more is learned about PHEVs and consumers' preferences towards them, the model will be continuously updated and improved.

This paper describes a model of consumer choice and use of 13 advanced vehicle technologies applied to two vehicles types: passenger cars and light-duty trucks. The household market is disaggregated into 1,458 segments by six dimensions: nine regions, three types of settlements, three attitudes towards technology risk, three categories of vehicle use intensity, three categories of parking and therefore access to home recharging, and two categories of access to recharging at work.

The next section of the paper describes the theory and structure of the ORNL PHEV model, focusing on features that are especially important to the market for PHEVs. Key issues in calibrating the model are highlighted. Next, a Base Case scenario, calibrated to the AEO 2009 Reference Case, is described. The Base Case is intended to characterize the future as one without explicit new policy intervention nor significant technological breakthroughs. The FreedomCARGoals Case is defined as an optimistic case to illustrate the behavior of the model.

THE ORNL PHEV MODEL: FRAMEWORK AND METHODOLOGY

Model Framework

The ORNL PHEV model is designed to predict vehicle choice probabilities (market shares) for advanced technologies dependent on consumer attributes, changes in the cost and performance of advanced technologies, energy prices, and policies. The core of the model is a nested NMNL module that estimates the probabilities that consumers in each of the 1,458 market segments will choose each of the 13 technologies. Each market segment represents a fraction of the potential buyers of new light-duty vehicles in the United States.

The model's predictions cover the period 2005 to 2050. Sales by market segments are aggregated to national sales by vehicle technology. A national vehicle stock turnover (scrappage) module estimates vehicle retirements by age and calculates the evolution of the vehicle stock by vehicle type and region (Figure 1). Vehicle use (annual miles of travel) and energy efficiency by vintage and technology type are used to compute energy use and CO_2 emissions.

Several recursive feedbacks loops are included. The previous year's sales volumes by technology affect the number of makes and models available for each technology, cumulative sales affect vehicle purchase prices via learning-by-doing, and the previous year's stock of alternative fuel vehicles affects the availability of alternative fuels.

The ORNL PHEV model draws information on households and their characteristics from census data and national travel surveys, obtains projections of vehicle sales, stocks, vehicle travel, energy efficiency and energy prices from the Energy Information Administration's AEO (*1*) and makes use of vehicle technology characterizations developed by vehicle simulation modelers at Argonne National Laboratory (*9*). However, in some cases the data needed do not exist or are highly uncertain or insufficiently detailed. In such cases we have made plausible assumptions with the intent of improving the assumptions as research on PHEVs and other advanced technologies progresses.

In the following sections, key modules of the model are further described.

THE NMNL MODULE AND CHOICE SET

The consumer choice module is an NMNL model with fixed preferences for most vehicle attributes and random utility components varying across individuals and nests. In principle, each market segment could have different preferences for all attributes. However, there is insufficient information to specify preferences at such a level of detail. For example, in the current version of the model, the proportion of consumers in each technology risk category (early adopter, early majority, late majority) does not vary by region, residential area or any other category. Other attribute values, on the other hand, do vary across market segments. The value of fuel economy and range, for example, will vary with factors that affect vehicle travel, including region, residential area and daily driving distribution. At present, preferences for attributes do not vary over time, except as energy prices change.

At the top of the NMNL decision structure is the choice between a passenger car and a light-duty (LD) truck (Figure 2). Within each vehicle type consumers choose among thirteen advanced powertrain technologies, grouped into three classes: (1) conventional/HEV, (2) hydrogen, and (3) battery-electric vehicles. Within the conventional/HEV class, technologies are grouped into conventional internal combustion engines (Spark Ignition Conv and Compression Ignition Conv), hybrid electric vehicles (SI HEV and CI HEV), and SI PHEVs. SI PHEVs come in three types according to their on-board electricity storage capacity and electric motor power: (1) 10-mile all electric range (AER), (2) 20-mile AER, and (3) 40-mile AER. All the PHEV designs (SI PHEV10, SI PHEV20, and SI PHEV40) are blended hybrids with limited all-electric capabilities. It is relatively easy to change the model's nesting structure or to add or subtract technologies from the choice set.

The probability that a consumer will choose technology i, given a choice among the vehicles in nest jkl, is given by a NMNL function of the weighted attribute values of technology i.

$$p_{i|jkl} = \frac{e^{\beta_{jkl} \cdot c_{ijkl}}}{\sum_h e^{\beta_{jkl} \cdot c_{hjkl}}}$$
$$\sum_i p_{i|jkl} = 1 \qquad \textbf{(1)}$$

In equation 1, c_{ijkl} is the generalized cost, or utility value in present value dollars of technology i in nest jkl. The parameter β_{jkl} determines the sensitivity of technology choices in nest jkl to their generalized cost. Each technology's generalized cost is comprised of a weighted sum of functions of the values of its attributes. Let the z^{th} attribute's value be represented by x_{zijkl} , its function be $f_z(x_{zijkl})$, and its weight w_{zjkl} . The generalized cost for choice ijkl is given by equation 2. Note that generalized cost c_{ijkl} could vary across market segments.

$$c_{ijkl} = \sum_z w_{zjkl} f_z(x_{zijkl}) \qquad \textbf{(2)}$$

At present the following attributes are included in the generalized cost function.

- vehicle retail price
- fuel and electricity cost
- battery replacement cost
- acceleration
- cargo space
- towing
- range
- home backup power

- refueling and recharging accessibility cost
- model availability
- technology risk
- policies
- purchase subsidy, tax credit, HOV access, free parking, etc
- V2G costs and revenues
- implemented but not reflected in the current scenario runs
- greenness (placeholder)

Generalized costs of the choices within a lower nest are “averaged” and passed up to the next level.

$$c_{jkl} = \frac{1}{\beta_{jkl}} \cdot \ln(\sum_i e^{\beta_{jkl} \cdot c_{ijkl}}) \quad (3)$$

The choice among nests at the next level is a logit function of their generalized costs, c_{jkl} , and price sensitivity at the next level of the nest, represented by β_{kl}.

The unconditional choice probability for technology i in nest jkl, is the product of the conditional choice probabilities.

$$p_{ijkl} = p_{i|jkl}\, p_{j|kl}\, p_{k|l}\, p_l \quad (4)$$

At present the model does not include a “no buy” option, also referred to as an “outside good.” As a consequence, total light-duty vehicle sales are fixed at the levels of the AEO projection to which the model is calibrated. A “no-buy” option will be included in future versions of the choice model.

LDV Sales Market Segmentation

Through market segmentation, market barriers associated with consumer attributes can be exposed and equity implication of policies can be inferred. The model groups all U.S. new light-duty vehicles (LDV) consumers by six dimensions (region, area, attitude toward technology risk, vehicle usage intensity, home parking, and work recharging) into 1,458 segments.

The model is calibrated to AEO 2009 projections of LDV sales by each census division over the period 2005-2030, extended to 2050 by assuming growth continues at the average growth rate from 2015 to 2030. LDV sales within each census division are split into three residential areas, Urban, Suburban, and Rural, based on the census population data (*10*).

Within each area, sales are further subdivided by attitude toward technology risk into Early-Adopter (16%), Early-Majority (34%), and Late-Majority (50%), based on innovation diffusion theory (*11, 12*). An Early-Adopter perceives some benefit of owning a vehicle with a novel technology (novelty measured by the accumulated stock of the technology). Members of the Early-Majority perceive a cost and those in the Late-Majority perceive an even higher cost. Benefits or costs decay in a manner analogous to a learning-curve, approaching zero as the vehicle stock of that technology increases and the technology becomes less novel.

Within each attitude group, three levels of vehicle usage intensity are defined, Modest-Driver (driving 8,656 miles annually), Average-Driver (16,068 miles), Frequent-Driver (28,288 miles). The shares of these driver types by region and area are estimated from the National Household Travel Survey 2001 (*13*). Each driver type is also characterized by a daily vehicle usage distribution, explained later in this paper.

The LDV market is then further split by home parking amenities into Garage/Carport, Offstreet Parking, and Neither. Consumers in the Garage/Carport group can recharge their PHEV at home, while those in the other two groups cannot. The share estimates are based on the number of households by each parking type in each census division and each residential area, according to the 2005 American Housing Survey (*14*). Similarly, the market is also split by work recharging availability into With_Work_Recharge (20%) and Without (80%), according to an early survey (*5*).

LDV sales by each segment change over time but are exogenous. That is, no LDV demand competition between segments is considered in this paper. Within each segment, the LDV sales are endogenously split by the NMNL module into sales by vehicle technology type.

Vehicle Daily Usage Distribution

In practice, a PHEV with the battery fully charged will first run on blended charge-depleting (CD) mode then switch to charge-sustaining (CS) mode when the battery is depleted to a certain low level of state-of-charge (*4*). As a consequence, the driving distance between recharge intervals can strongly impact the share of electricity or fuel consumption, as also observed in survey research (*4*, *15*). To accurately estimate energy consumption and GHG impact, it is necessary to characterize both driving behavior and recharge behavior.

Early research on PHEV users indicates that the overwhelming majority of drivers with home recharging will fully recharge their vehicles during the night (*15*). Then, the task can be simplified as estimating the distribution of daily vehicle usage. However, longitudinal travel data are not readily available, especially nationwide. As an alternative approach, Greene (*16*) assumes the gamma distribution for vehicle daily usage and then obtains maximum likelihood estimates of the parameters based on longitudinal refueling survey data of over 2000 vehicles.

The gamma distribution is suitable for representing household vehicle travel due to its non-negativity and skewness flexibility. Another desirable attribute of the gamma distribution, making it easy to estimate is that it contains only two parameters: shape and scale. The product of shape and scale equals the mean of the distribution, which can be treated as the average daily vehicle usage. The difference between mean and scale is the mode of the distribution, i.e. the most frequently occurring daily distance. It may be a reasonable approximation to assume that for full-time workers whose main commute mode is driving, the commuting round-trip distance is the mode of their daily vehicle usage distribution. Therefore, the distribution can be estimated by only knowing the average daily driving distance and the commuting distance.

A subset of the NHTS2001 data was selected, containing 3,755 new car owners that are full-time workers, who mainly drive to work and rarely work at home. A data set including their weight in the population, annual usage of the primary vehicle, commuting distances, and associated region and residential area are extracted. 3,755 gamma distributions of daily vehicle usage are then estimated by following the previously described relationship between the distribution parameters and the daily usage mean and mode.

For simplicity, these 3,755 distributions are clustered in three levels of vehicle usage intensity: Modest-Driver, Average-Driver, and Frequent-Driver. The average distribution of each intensity group is estimated for all drivers within the same intensity group, as shown in Figure 3. The shares of Modest-Driver, Average-Driver, and Frequent-Driver by region and area are also obtained.

Vehicle Characterization

The data characterizing vehicle technologies were provided by researchers at Argonne National Laboratory (*9*, *17*, *18*). The process of constructing the data is fully explained in their Multi-path draft report (*18*). This paper highlights several important issues and presents some key data.

An LDV is is assumed to consist of a powertrain and a glider. Within each of the car and light-duty truck types, 13 powertrain technologies share the identical glider. The same set of vehicle performance standards, e.g. 9 second for 0-60 mph and 65 mpg at 6% grade for 20 minutes, applies to all 26 car and truck technologies. The Powertrain System Analysis Toolkit (PSAT) from Argonne National Lab is then used to size the powertrain components in meeting these standards, and simulate the vehicle operation with the two EPA test cycles (*18*). Component costs are calculated based on component sizes.

One performance requirement that varies among technologies is range. All technologies with a gasoline or diesel tank are assumed to carry 60 kg of fuel onboard. Hydrogen related technologies are designed to have a range of 190 miles during the period 2005-2015 and 320 miles starting from 2030. The range target and efficiency determines hydrogen storage capacity. Values between 2015 and 2030 are based on linear interpolation. For PHEV, battery capacity is determined by the required AER range and adds to the total vehicle range. The range for EV is designed to be 150 miles for both vehicle types.

The vehicle retail price is the sum of glider and powertrain component costs multiplied by 1.5, as shown in Equation 5. The details of each component cost function $f_i(S_i)$ can be found in (*18*). Such a retail price varies over time, due to component cost reduction, and thus reflects technological progress due to R&D, but does not reflect lack of production experience or scale. That is, the price, called fully-learned price, is based on mass production and sufficient learning experience.

$$P_\infty = 1.5 \times (C_g + \sum_i f_i(S_i)) \tag{5}$$

One common approach to represent learning effects is the experience curve, in which the logarithm of new product prices has a linear relation to the logarithm of cumulative production (*19*). A problem with the experience curve is that price can approach zero when the cumulative production is sufficiently large. Alternatively, the price can be assumed to approach a horizontal asymptote (*20*). Price P_n is an exponential function of the cumulative production n, governed by the fully-learned price of the vehicle technology P_∞, the fully-learned price of the reference technology P_{ref}, and two parameters a and b (Equation 6). With the asymptotic learning-by-doing function, the retail price is formed by amplifying the fully-learned price difference between the vehicle technology of concern and the reference technology (gasoline conventional vehicle). The fully-learned prices are based on the data in Table 1. The parameters a and b are calibrated by ensuring the equivalent varying progress ratio falls close to the mean of the empirical range 0.7-0.9 (*19*).

$$P_n = (1 + ae^{bn})(P_\infty - P_{ref}) + P_{ref} \qquad b < 0 \tag{6}$$

Energy efficiency is the key factor determining energy costs. PSAT provides detailed energy efficiency characterizations, including 4 fuel efficiency estimates for PHEVs (CD and CS modes, UDDS and HWFET cycles) and 2 electricity efficiency estimates (CD only, 2 test cycles), wherever applicable.

The fully-learned prices and UDDS CS fuel efficiencies are presented in Table 2. The Base Case represents engineering potential according to the literature and expert estimates. In the FreedomCARGoals Case, for non-hydrogen related technologies, cost estimates are based on the assumption that the DOE FreedomCAR goals are met as scheduled (*21*). Energy efficiency estimates represent a postulated future market that attaches a very high priority to vehicle efficiency (*18*). For performance and prices of hydrogen-related technologies in FreedomCARGoals Case are based on engineering potential, except reflecting the DOE goals of battery technology for fuel cell PHEV. The price and efficiency estimates in the FreedomCARGoals Case are significantly more optimistic than the Base Case and generally more optimistic than other studies (*22*, *23*, *24*).

PHEV and EV batteries must endure deep discharge and frequent recharge, raising the concern on battery life and replacement cost (4, *18*). This paper assumes a 10-year or 100,000 mile life for PHEV and EV batteries, whichever comes first depending on vehicle usage intensity. Battery costs are multiplied by 1.5 to obtain retail price equivalents, and discounted to compute the present value of battery replacement. No learning by doing is considered for battery replacement cost. The need to consider a longer battery life is acknowledged as well as the possibility that if replacement is needed, the replacement battery will likely be a cheaper one, either used or produced for the aftermarket. Battery cost and capacity data are shown in Table 2.

Refueling and Recharging Availability

Lack of available public recharging is more likely to be a barrier for potential PHEV consumers without home or work recharging. For hydrogen related technologies, refueling availability in the early stage is a more obvious barrier for all potential consumers. A FC PHEV will face both availability issues.

It is difficult to quantify the value of public recharging to PHEV owners without home or work recharging, because recharging is not required to use the vehicle. The frequency of visiting a public recharging station, if available, depends on how much the owner wants the vehicle to be more like a true PHEV rather than a regular hybrid vehicle. An early survey found that PHEV owners are generally eager to plug in (*15*). Thus, for PHEV owners without home or work recharging, one recharge is assumed to be needed during those days with driving distance exceeding the CD range of PHEV. For the other days during the year, the probability of wanting a recharge is proportional to the ratio of daily distance to the CD range. For PHEV owners with home or work recharging, a full recharge per day is assumed.

To quantify the annual travel time related to refueling or recharging, the linkage between fuel availability and travel time of each refueling or recharging trip needs to be established. The refueling travel time is found to follow a power function of the number of stations, when the locations of stations are optimized to minimize refueling travel time (*25*, *26*, *27*). If the refueling or recharging availability is known (measured by the ratio of the number of alternative stations to the number of gasoline stations) then the annual refueling or recharging travel time can be determined.

The growth of fuel or recharge availability is assumed to be a logistic function of the ratio between the stock of the particular technology and today's SI Conv. stock. The functions for gasoline and diesel are calibrated to historical data including vehicle stock and the number of diesel and gasoline stations. The functions for hydrogen and electricity recharge are based on analogy to gasoline and diesel but reflect the relative cost of these stations.

Model Diversity

In both the NMNL model and in reality, greater diversity of choice among makes and models of vehicles leads to greater utility for consumers. This is because the value attached by the consumer to each model is uncertain and thus the wider the range of options the more likely a consumer is to find one that suits his preferences (*28*, *29*). New vehicle technologies are very likely to be offered with a limited number of models, putting them at disadvantage relative to established technologies.

According to the MNL theory, the value of model diversity V_d can be estimated as a function of the number of makes and models offered n_j, and the ratio of a parameter γ to the price slope μ, as in Equation 7. Assuming γ =2/3, the estimated cost of lack of diversity is in the range of \$3000-\$8000 if only one make and model is available and still as large as \$500-\$1000 even if 40% of all makes and models offer the particular technology, depending on relative price elasticity of the technology to its direct competitors (*28*).

$$V_d = \frac{\gamma}{\mu} \log_e \left(\frac{n_j}{N} \right) \tag{7}$$

It is difficult to predict model diversity as this involves uncertain marketing strategies. However, it is reasonable to assume that the number of available models increases with sales of the same technology. This paper assumes the maximum model number N is 80 for each technology in the choice set and calibrates an asymptotic exponential relationship (Equation 8) between model number and sales to the historical sales and model numbers of hybrid vehicles.

$$n_j = 80 + a \times e^{b \times \text{Sales}} \qquad a, b < 0 \tag{8}$$

Other Model Assumptions

The home backup power market is growing, and if a PHEV can be plugged in at home, it can also be used as home backup power, thereby providing additional value to consumers who need home backup power. Early surveys (*30*) asked consumers their willingness-to-pay for PHEV as a home backup power. The median value by region is used in this paper.

V2G revenue could be a significant value of owning a PHEV or EV. The model has structurally implemented this component in the NMNL utility function. However, due to limited knowledge in projecting demand for peak power and reserved capacity by region, the potential value is not reflected in this paper.

Scenario Definition

Two scenarios are used to illustrate the behavior of the model, Base Case and FreedomCARGoals Case, with the two sets of vehicle characterization data previously presented. The same energy prices are used in the two cases. The 2005-2030 prices of gasoline, diesel, and electricity by census division come from AEO 2009 Updated Reference and extrapolated for 2031-2050 at a constant annual rate of change equal to that from 2015 to 2030. The average (unweighted across census divisions) gasoline retail price grows from $2.77/gallon to $4.38/gallon in 2050. Hydrogen price comes from the HyTrans model (*31*, *32*), decreasing from $3.5/gge in 2005 to $2.8/gge in 2050.

The American Recovery and Reinvestment Act of 2009 (ARRA) has been signed into law and therefore its PHEV subsidy policy is reflected in both the Base and FreedomCARGoals cases. If the PHEV has a gross vehicle weight rating less than 14,000 pounds, has a battery capacity no less than 4 kWh, and is purchased before the manufacture's PHEV cumulative sales reaches 200,000 units, the buyer earns the tax credit starting at $2,500 plus additional $417 for each kWh above 5kWh. The total amount is capped at $7,500.

The Base Case maintains the current policy environment and is calibrated to the 2009 AEO Updated Reference Case (*1*) regarding on-road LDV VMT and stock and sales shares of cars and light-duty trucks. On-road LDV travel begins at 2,634 billion VMT in 2005, increasing by 37% by 2030. The LDV stock grows from 222 million in 2005 to 294 million by 2030, a 32% increase. The sales share of light-duty trucks decreases from half of LDV sales in 2005 to 36% by 2030.

RESULTS

In the Base Case, conventional gasoline vehicles initially dominate the market with small shares for hybrid (HEV) and diesel vehicles. Even in 2050, conventional internal combustion engine (ICE) vehicles account for more than half of the light-duty vehicle market (Figure 4). Over time, as technology costs fall and performance improves, first HEVs and later PHEVs gain increasing shares of the market. HEV and PHEV are more successful in the passenger car segment, while diesel engines do better in the light-duty truck market. Sales of hybrid cars and light-duty trucks reach 2 million per year by 2022 and climb to 5.8 million by 2050. PHEV sales grow to one million per year in 2037 and eventually reach 3 million by 2050.

Fuel demand does not increase in the Base Case due to the improvements in fuel economy across all technologies. In 2050, light-duty vehicles are consuming just over 8 million barrels per day of petroleum, nearly all of which is gasoline (Figure 4). Advanced spark-ignition internal combustion engine vehicles account for most of the petroleum use, 5.3 million barrels per day, due to their lower fuel economy.

The performance improvements but more importantly the cost reductions of the FreedomCARGoals Case have a major impact on the success of both hybrids and PHEVs. By 2050 advanced ICE vehicles account for only 20% of the new vehicle market (Figure 5). Sales of hybrid vehicles reach 7.5 million units by 2020 and remain nearly constant thereafter. PHEV sales take off after 2020, increasing from just over 1 million units in that year to 7 million units by 2035. Cumulative sales of PHEVs reach 1.5 million by 2015, exceeding the goal of 1 million PHEVs on the road by that year. After 2030, sales of battery electric vehicles become significant, rising to over 2 million units by 2050.

In both the Base and FreedomCARGoals cases, PHEV-10 vehicles dominate the PHEV market. In the PHEV consumer choice module, PHEV-10s, PHEV-20s, and PHEV-40s occupy the same nest as close substitutes. Because PHEV-10s achieve most of the fuel economy benefits of the longer AER PHEVs at a lower cost, they dominate the PHEV market. While PHEV-10 sales reach 7.5 million in 2050, combined sales of PHEV-20s and PHEV-40s amount to less than 100,000 units. At present, little is known about the value consumers might attach to all electric range or the potential for greater on-board electricity storage to create opportunities for adding value to a vehicle. As a result, this study may be undervaluing AER and related opportunities, such as V2G connection.

PHEV market shares within each segment vary greatly as a result of market disaggregation. In Figure 6, the gray shaded area represents the envelope of market shares for all 1,458 segments. The no-marker black line shows the PHEV10 market share within the reference segment (SouthAtlantic, Suburban, EarlyAdopter, FrequentDriver, Garage, and NoWorkRecharge) during the period 2010-2025. By changing one segment dimension at a time, another five segment curve representing their PHEV10 market shares are also shown to illustrate the variation of segment choice behavior. Early-adopter, frequent drivers, with garage parking in urban areas of the South Atlantic region are close to the maximum market penetration. The same consumer who has neither a garage/carport nor off-street parking nor the opportunity to recharge at work (and thus effectively nowhere to plug in his vehicle) is essentially uninterested in a PHEV. A similar consumer having a garage but a low tolerance for technology risk (late majority) is initially uninterested but gains interest as PHEVs penetrate the market and by 2023 is in essentially the same place as his early-adopter counterpart. Those traveling fewer miles each day value the PHEV’s fuel economy less and are about half as likely to choose a PHEV. The sudden dip in market shares after 2016 is due to the expiration of government incentives for PHEVs. Generally, those segments that are more interested in PHEVs are more sensitive to the tax credit incentive. Clearly the detailed segmentation of the market matters and may be crucial to accurately modeling the earliest phases of market evolution.

Light-duty vehicle fuel use in the FreedomCARGoals Case falls from about 8.5 mmbd in 2009 to less than 5 mmbd in 2050 (Figure 5). Yet even with HEVs, PHEVs, and EVs making up 80% of vehicles on the road in 2050, the reduction in petroleum use by light-duty vehicles is only about 40% versus the Base Case. However, the Base Case includes very optimistic assumptions about technological advances in energy efficiency, and represents significant reductions in petroleum consumption over the original 2009 AEO Reference Case. In the AEO2009 Reference Case, light-duty petroleum use reaches 9.3 mmbd in 2030, the final year of the projection. Still, this is not enough to achieve the up to 80% reductions in greenhouse gas emissions that are likely to be necessary across the economy to protect against dangerous climate changes (*33*, *34*).

Even in the FreedomCARGoals Case, the quantity of electricity required for light-duty vehicles is modest relative to total U.S. electricity supply. In 2050, PHEVs and EVs use 120 billion kWh of electricity (Figure 7). This amounts to only 3% of the total electricity generated in 2008 and 2.5% of the projected generation supplied to the grid in 2030. If most light-duty vehicle electricity demand could be directed to off-peak hours it would require little or no additional capacity and improve the overall efficiency of electricity generation in the United States.

SUMMARY AND NEXT STEPS

A model that projects market shares of PHEVs and other advanced vehicle technologies for a highly disaggregated U.S. market has been developed and tested. Market success is seen to differ significantly across the market segments, indicating that the segmentation is important to adequately representing the evolution of markets for advanced powertrain technologies. The model's predictions are highly dependent on the degree of technological progress assumed. In addition, much remains to be learned about the 1,458 market segments represented in the model, as well as how consumers are likely to value the novel attributes of advanced technologies. As research on in these areas continues to progress, the PHEV model can be updated and enhanced.

Future research and development will focus on improving the model in several key areas:

- elaboration of the model's structure to include a no-buy option,
- expansion of the technology list to include, e.g., flex-fuel vehicles,
- enhancement of the disaggregated market data, e.g., with a more precise estimation of the distribution of the population by preference for technology risk and daily driving distributions,
- addition of lifecycle greenhouse gas emissions estimates and the sensitivity of emissions from electricity generation to GHG mitigation policies,
- automation of the calibration of the model to new AEO projections and,
- development of a convenient user interface.

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TABLE 1 Vehicle Retail Price and Fuel Economy (2005 USD / MPGGE)

	Base			FreedomCAR Goals		
Technology	**2010**	**2015**	**2045**	**2010**	**2015**	**2045**
SI_Conv_Car	21541 / 32.3	21583 / 34.4	23186 / 43.5	22485 / 41	22946 / 42.7	23823 / 49
CI_Conv_Car	24637 / 37	24408 / 38.4	25450 / 45	25055 / 42.6	25118 / 46.1	25420 / 53.5
SI_HEV_Car	27759 / 50.1	26305 / 52.4	26242 / 61.5	26109 / 60.7	24451 / 69.6	24046 / 86.9
CI_HEV_Car	31045 / 54.9	29203 / 56.6	28632 / 67.7	28826 / 66.4	26714 / 75.8	25742 / 93.9
SI_PHEV10_Car	31416 / 53.3	28351 / 56	26951 / 63.8	27421 / 63.1	24856 / 72	23912 / 88.4
SI_PHEV20_Car	36814 / 53.1	32396 / 55.4	29248 / 63.7	29917 / 62.8	26070 / 71.9	24389 / 88.6
SI_PHEV40_Car	46576 / 51.8	40100 / 54.2	33733 / 62.3	34376 / 61.6	28347 / 70.8	25297 / 88.6
H2_Conv_Car	29680 / 26.5	27892 / 31.3	28243 / 35.9	29680 / 26.5	27892 / 31.3	28243 / 35.9
FC_HEV_Car	39032 / 67.9	34235 / 76.6	30640 / 86.2	38155 / 67.9	33076 / 76.6	29334 / 86.2
FC_PHEV10_Car	40890 / 69.2	34885 / 78.1	30773 / 85.4	36882 / 69.2	31320 / 78.1	28438 / 85.4
FC_PHEV20_Car	47154 / 68.3	39427 / 77.1	33491 / 84.5	39805 / 68.3	32709 / 77.1	29119 / 84.5
FC_PHEV40_Car	58244 / 66.4	48245 / 75	38558 / 82.6	45010 / 66.4	35376 / 75	30173 / 82.6
EV_Car	95266 / 268.3	67792 / 253	51835 / 229.2	54870 / 229.5	35152 / 197.7	26427 / 161.3
SI_Conv_Trk	24364 / 24.1	24338 / 26.1	26282 / 30.2	24305 / 31.5	24792 / 32.4	25559 / 37.5
CI_Conv_Trk	26619 / 29.1	26197 / 30.4	27321 / 33.1	26933 / 33.3	26844 / 35.9	27079 / 41.1
SI_HEV_Trk	32362 / 35	30267 / 37	29417 / 41.7	29601 / 41.8	27056 / 47.9	26115 / 56.9
CI_HEV_Trk	34895 / 39.5	32527 / 41.3	31238 / 47.3	31773 / 47	28967 / 53.2	27624 / 62.4
SI_PHEV10_Trk	37837 / 37.2	33394 / 39.5	30787 / 43.7	31698 / 43.6	27923 / 49.2	26112 / 57.8
SI_PHEV20_Trk	45649 / 36.9	38939 / 39.2	34032 / 43.3	35204 / 43.3	29616 / 49	26842 / 57.6
SI_PHEV40_Trk	59100 / 36.3	49711 / 38.3	40539 / 42.5	41665 / 42.4	32781 / 48.2	28196 / 57.2
H2_Conv_Trk	33024 / 20.9	32010 / 24.4	32104 / 27.8	33024 / 20.9	32010 / 24.4	32104 / 27.8
FC_HEV_Trk	47656 / 47.2	40225 / 54.7	36057 / 58.1	46655 / 47.2	38859 / 54.7	34505 / 58.1
FC_PHEV10_Trk	50350 / 47.9	41736 / 55.1	36438 / 57.6	44877 / 47.9	37091 / 55.1	33207 / 57.6
FC_PHEV20_Trk	59082 / 47.3	48120 / 54.4	40335 / 56.9	49031 / 47.3	39259 / 54.4	34183 / 56.9
FC_PHEV40_Trk	74907 / 45.9	60010 / 53	47846 / 55.5	56528 / 45.9	42924 / 53	35921 / 55.5
EV_Trk	127311 / 391.7	86852 / 364.1	67202 / 345.6	70829 / 340.2	43305 / 295.5	31080 / 255.4

Note: energy efficiency represented by electricity consumption in Wh/mi for EV and combined unadjusted fuel economy in MPGGE for all others; for PHEV, the value is for charge-sustaining mode

TABLE 2 Battery Cost and Capacity for PHEV and EV (2005 USD / kWh)

	Base			FreedomCARGoals		
Technology	2010	2015	2045	2010	2015	2045
SI_PHEV10_Car	4466 / 4.1	3156 / 3.9	1754 / 3.5	2089 / 3.6	997 / 2.7	369 / 2
SI_PHEV20_Car	8010 / 7.8	5768 / 7.5	3274 / 6.8	3720 / 6.8	1789 / 5.2	683 / 3.9
SI_PHEV40_Car	14375 / 16	10811 / 15.4	6170 / 13.7	6617 / 13.8	3248 / 10.8	1292 / 8.1
FC_PHEV10_Car	4858 / 4.4	3402 / 4.3	1938 / 3.9	2186 / 3.7	1026 / 2.8	382 / 2.1
FC_PHEV20_Car	8897 / 8.6	6389 / 8.3	3648 / 7.6	3997 / 7.3	1911 / 5.6	733 / 4.2
FC_PHEV40_Car	15981 / 17.8	11981 / 17.1	6970 / 15.5	7158 / 14.9	3402 / 11.3	1380 / 8.6
EV_Car	48950 / 65.3	31548 / 52.6	20771 / 55.4	22400 / 56	10060 / 40.2	4410 / 29.4
SI_PHEV10_Trk	6256 / 5.7	4359 / 5.4	2530 / 5.1	2950 / 5	1429 / 3.9	534 / 3
SI_PHEV20_Trk	11385 / 11	7989 / 10.4	4625 / 9.6	5230 / 9.5	2529 / 7.3	1004 / 5.8
SI_PHEV40_Trk	20200 / 22.4	15014 / 21.4	8877 / 19.7	9387 / 19.6	4575 / 15.2	1884 / 11.8
FC_PHEV10_Trk	6665 / 6.1	4551 / 5.7	2712 / 5.4	3016 / 5.1	1454 / 4	558 / 3.1
FC_PHEV20_Trk	12278 / 11.9	8608 / 11.2	5168 / 10.7	5577 / 10.1	2701 / 7.8	1067 / 6.2
FC_PHEV40_Trk	22293 / 24.8	16223 / 23.2	9925 / 22.1	10041 / 20.9	4833 / 16.1	1976 / 12.3
EV_Trk	68389 / 91.2	42660 / 71.1	29638 / 79	31504 / 78.8	14269 / 57.1	6499 / 43.3

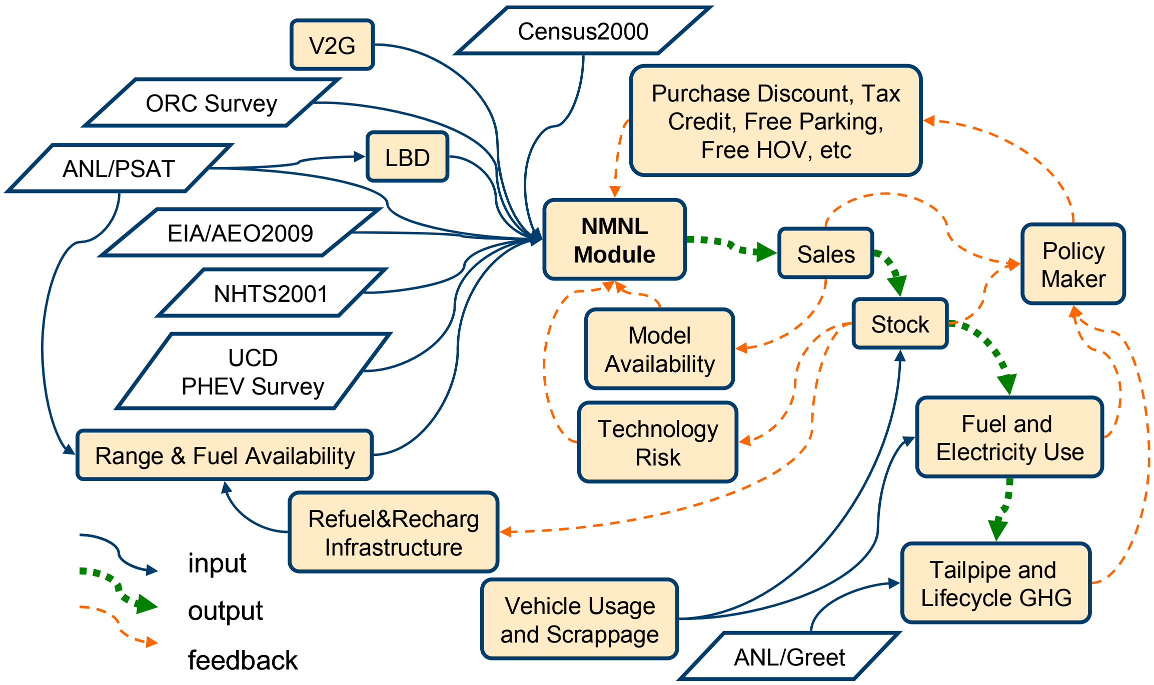

FIGURE 1 Illustrative diagram for the model.

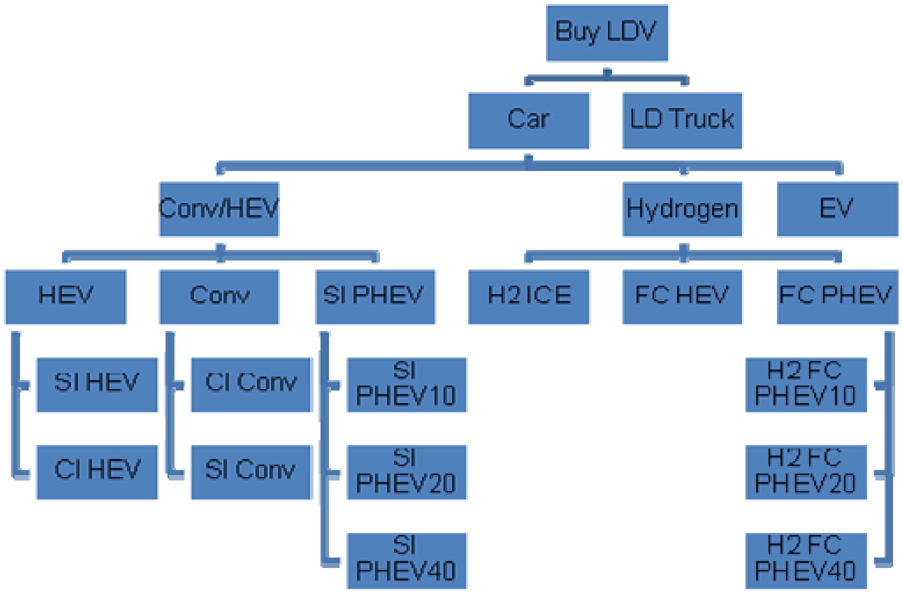

FIGURE 2 Nest structure.

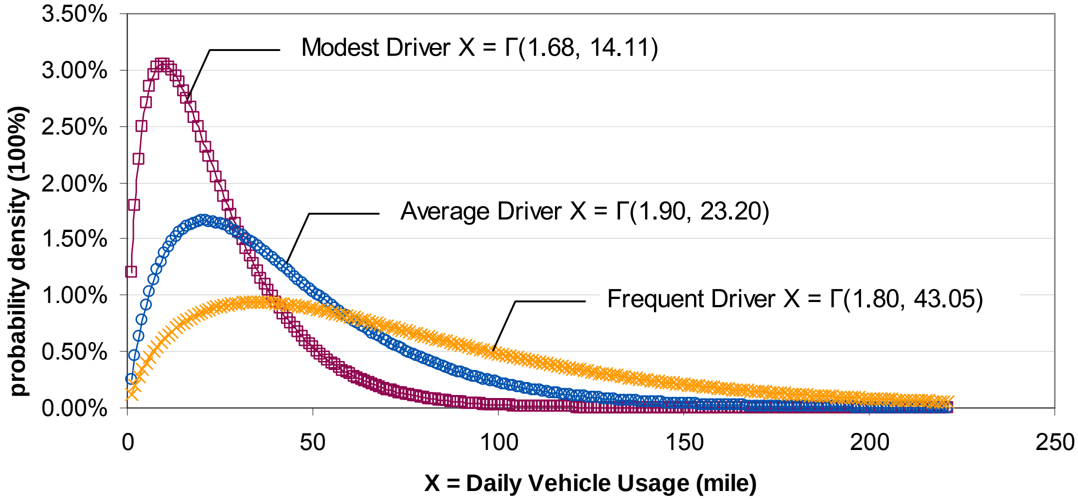

FIGURE 3 Daily vehicle usage by vehicle usage intensity.

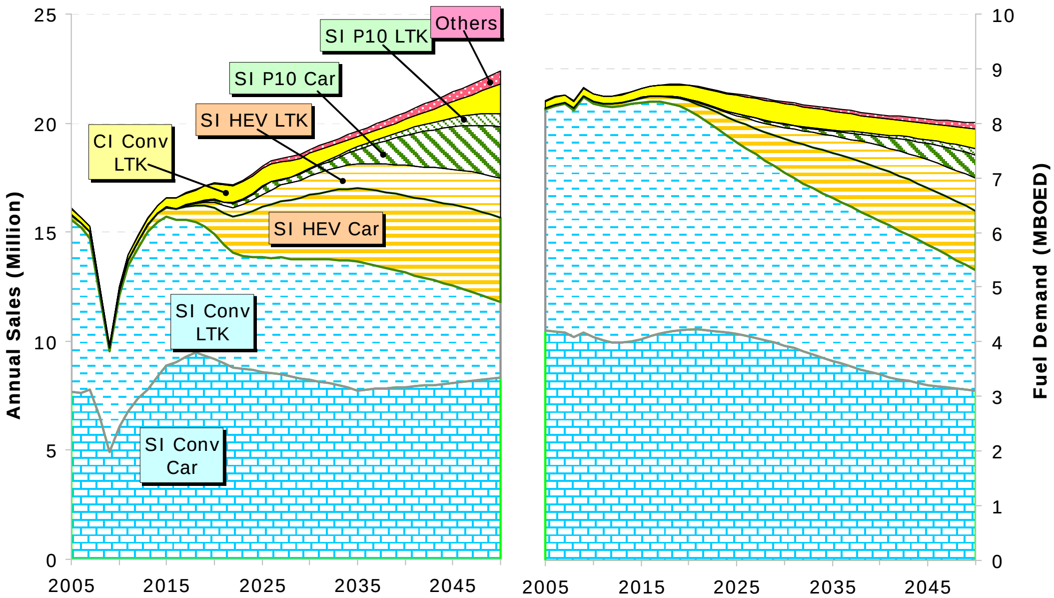

FIGURE 4 LDV sales and fuel use by powertrain technology: base case.

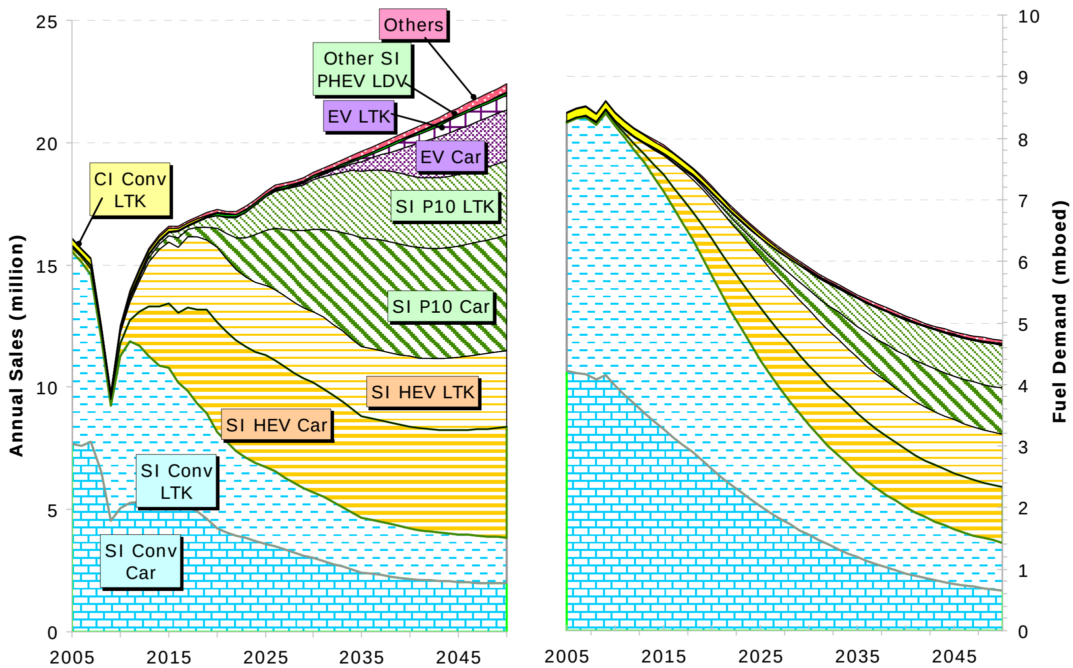

FIGURE 5 LDV sales and fuel use by powertrain technology: FreedomCARGoals.

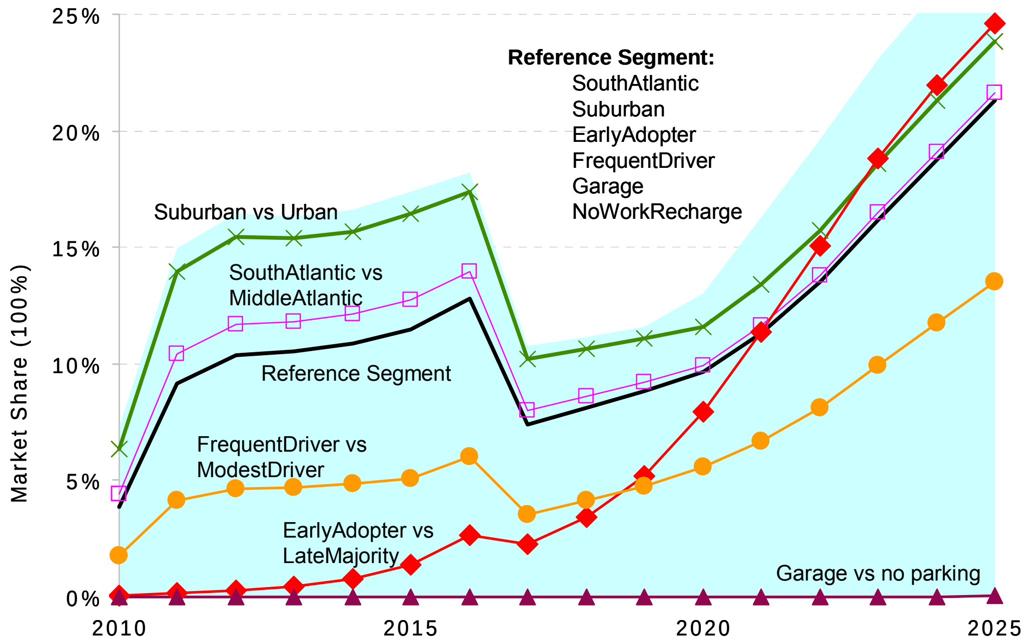

FIGURE 6 PHEV market shares for selected market segments: FreedomCARGoals.

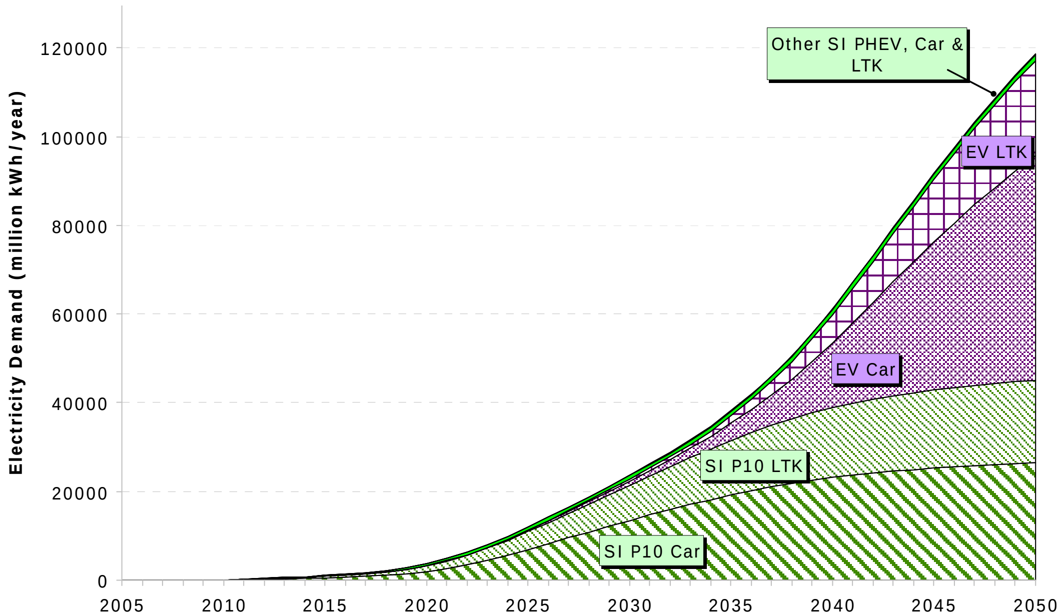

FIGURE 7 Light-duty vehicle electricity use: FreedomCARGoals.