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An activity-based assessment of the potential impacts of plug-in hybrid electric vehicles on energy and emissions using 1-day travel data

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ABSTRACT

This paper assesses the potential energy profile impacts of plug-in hybrid electric vehicles and estimates gasoline and electricity demand impacts for California of their adoption. The results are based on simulations replicating vehicle usage patterns reported in 1-day activity and travel diaries based on the 2000–2001 California Statewide Household Travel Survey. Four charging scenarios are examined. We find that circuit upgrades to 240 V not only bring faster charging times but also reduce charging time differences between PHEV20 and PHEV60; home charging can potentially service 40–50% of travel distances with electric power for PHEV20 and 70–80% for PHEV60; equipping public parking spaces with charging facilities, can potentially convert 60–70% of mileage from fuel to electricity for PHEV20, and 80–90% for PHEV60; and afternoons are found to be exposed to a higher level of emissions.

1. Introduction

Hybrid electric vehicles (HEVs) are a combination of a typical internal combustion engine (ICE) vehicle and a battery electric vehicle (BEV) with an electric motor capable of supplying auxiliary power to the drive train. Plug-in hybrid electric vehicles (PHEVs) take this concept one step further by adding additional batteries to the design, allowing the vehicle to be charged at night and be powered solely from stored electric energy during the day. The biggest barriers for PHEV market penetration have been limited driving range under electric power and cost. Under current market conditions, PHEVs cost about 10–20% more than a regular HEV, but technological advances and rising fuel prices portend that they will emerge as being economically competitive in the long term (Simpson, 2006). Although the pure electric driving range of PHEVs is quite limited, varying by type of vehicle and battery technology from between 10 and 60 miles, survey results indicate that about 47–55% of single vehicle usage within 1 day is less than 20 miles, with 82–88% of vehicles traveling less than 60 miles (Fig. 1); i.e., a figure that begins to make electric vehicle power viable.

With increased numbers of PHEVs in the fleet, major reductions in both fossil fuel energy consumption and emissions have been forecast (Sanna, 2005). In anticipation of the energy market's shift in demand to electricity, several studies have analyzed PHEV adoption (Electric Power Research Institute, 2007a,b). They have concluded that the growing PHEV market is expected to reduce gasoline consumption in the US, and further that today's US grid is able to satisfy the increased demand for charging. However, these assessments have been based on limited analysis are either based on macroscopic trend analysis or focus on modeling second-by-second mechanical operations of a single vehicle.

It is the usage pattern of the PHEVs that will determine the balance between their fossil-fuel and electric power consumption, and the dynamic, time-of-day, demand placed on the grid, as well as their emission profiles. Vehicle energy use and

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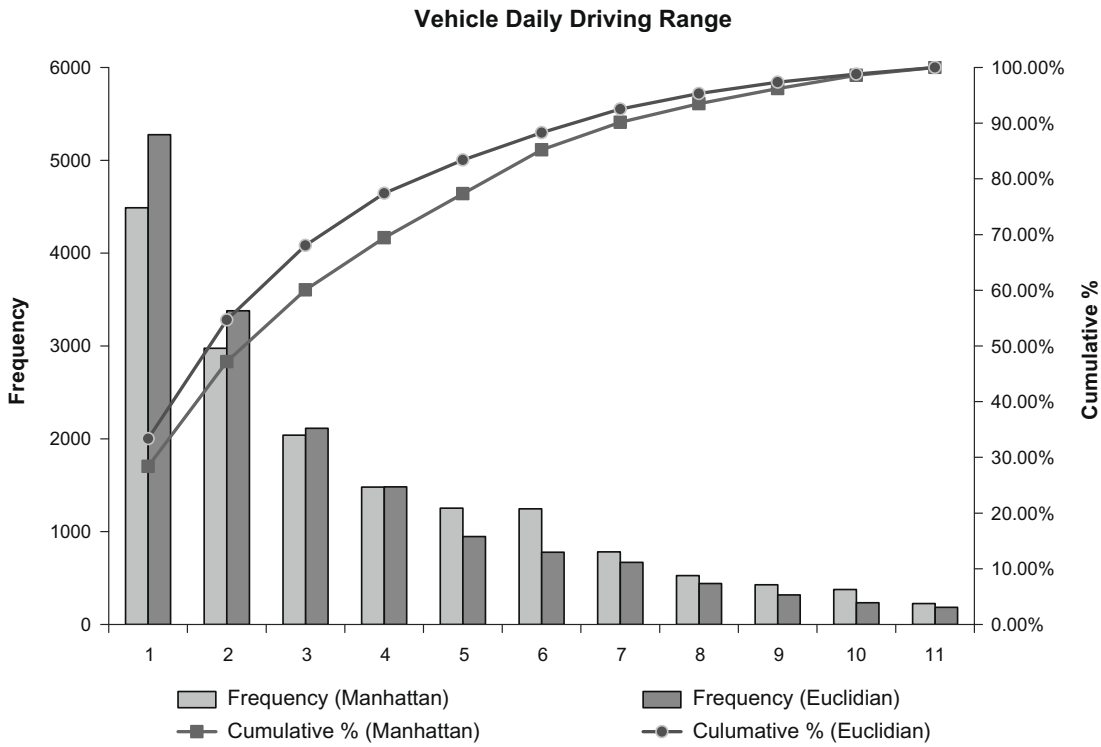

Fig. 1. 2001 California travel diary driving mileage and distribution under two network metric assumptions: Manhattan or Euclidean (N2).

emissions depend on the spatial–temporal linkages between the collection of activities that individuals and households perform as part of their daily schedules (Fig. 2). The nature of the interactions among households' vehicle usage lay at the heart of the limitations of conventional models and data to provide adequate measures of the potential impact of widespread PHEV adoption.

We introduce several aspects that distinguish it from previous studies of PHEV emissions and energy use. First, the assessment is applied to a large number of real vehicles and activities performed by households, with travel decisions made at the household level. Secondly, the reported vehicle travel of all members of the households is simulated, using a microscopic approach, both with their recorded vehicles as well as with PHEVs substituted for their current vehicles to assess potential savings in fuel consumption and reductions in emissions. Thirdly, we analyze the potential impacts of various electric supply/pricing strategies on vehicle usage and charging profiles.

Our methodological approach is quite simple. We pose the question: "Assuming travel/activity patterns among households do not appreciably change, what are the bounds of the potential impacts of widespread market penetration of PHEVs on: energy demands and shifts from mobile sources and power generation plants, demand on the grid, and energy profiles of the transportation sector?" For each scenario, we produce for each vehicle use pattern the associated temporal profiles of energy consumption and emissions generated (Fig. 3).

2. Activity-based approach, assumptions and data

We use activity-based modeling to assess the effects of PHEV effects on the environment, with individuals as trip decision makers who choose when and where trips occur, as well as how long the activities associated with the trips last. This allows us to incorporate the dynamics of travel demand, both in terms of providing emission profiles by time-of-day (TOD) as well as in estimating maximum loads on the grid.

Use is made of data derived from the Travel Diary, 2000–2001 California Statewide Household Travel Survey. The Travel Diary contains enumeration of daily travel activities and their purposes, together with their full location data, for 17,172 California household members' trips. Each trip has information on the vehicle used, departure and arrival times, trip/activity durations, and geo-coded information on longitude/latitude of the activity locations.

First, from the survey a subset of data having complete location information and PHEV substitutable vehicle types (i.e., excluding such vehicles as motorcycles or bicycles) is selected. Then, person-based trip/activity chains were constructed for those trips that were vehicle-based. (Vehicles not operated on the survey date are excluded.) This yields a data on 11,385 households with 15,823 vehicles in use during the survey day. There are 66,624 trips, with an average of 4.2 trips

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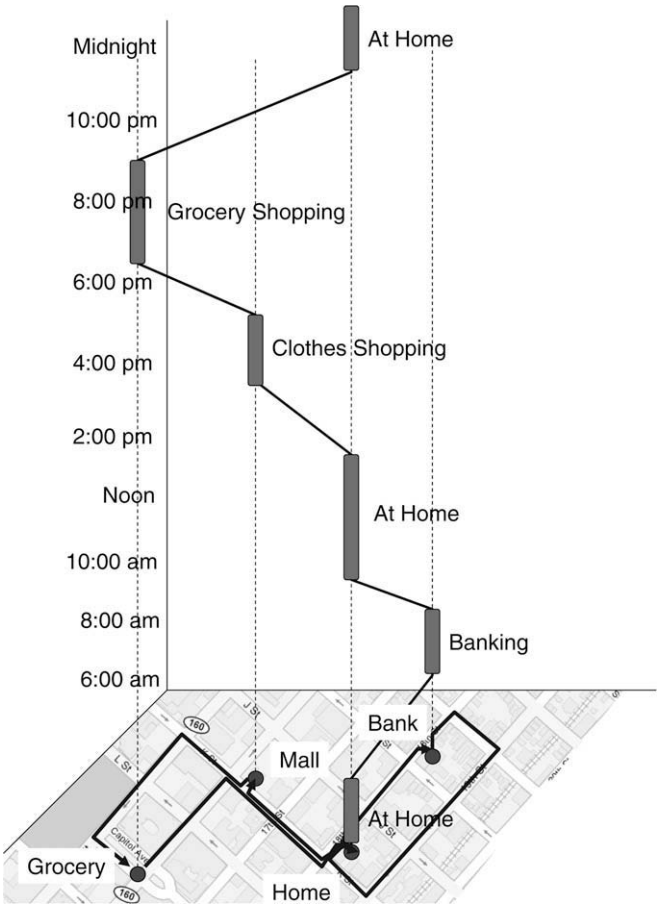

Fig. 2. Travel/activity pattern.

per vehicle per day, and 5.85 trips per household. Each trip has an average duration of 18.80 min, with a standard deviation of 25.09 min. The longest trip was 15 h and 14 min and the shortest was 1 min. The average "Euclidean-based" distance per trip is 9.06 miles; the corresponding average "Manhattan-based" distance is 7.16 miles, with standard deviations of 18.82 and 14.46 miles, respectively. This converts to a vehicle traveling 38.14 (Euclidean distance) or 30.14 (Manhattan distance) miles in 1 day, respectively, on average.

Corresponding to each trip's geocoded origin and destination locations, we compute the travel distance between two locations as the sum of longitude and latitude differences (i.e., use a "city block" or "Manhattan" distance metric) that approximates to the longest distance that a vehicle can take (except when there is a detour) and thus provides an upper bound on the potential impacts.

PHEV20s and PHEV60s (having all-electric ranges of 20 miles and 60 miles, respectively) are considered as potential substitutes for vehicles being used by survey respondents. Fully-charged PHEV20s could handle the mileage of about 50% of vehicles without charging during the day (Fig. 1) while PHEV60s could cover 80% of vehicle operations.

Although there are two basic driving modes for PHEV vehicles—blended (with capability for contemporaneous ICE and battery drive) and binary (with capability only for either ICE or battery drive), we only look at the binary mode of operation. With this restriction, a fully-charged PHEV x can be run on the electric motor only for the first x miles; after which, the electric motor turns off and the internal combustion engine starts to operate. We further assume that the ICE, when being used to power the vehicle, has emission and energy usage similar to current ICV operation.

3. Charging scenarios and electricity demand increases

Charging time depends not only on battery size, but also on circuit voltages and amperage levels. Two cases are considered; charging complies with the existing charging infrastructure –120 V and 15 amps – with no extra upgrades, and an upgraded circuits case based on 240 V and 40 amps. Table 1 shows charging times, and associated estimated costs, for these circuit specifications for various vehicle types. These parameters are applied to assess charging profiles and peak loads for PHEVs under the assumption that people maintain the same activity/travel as with their ICVs.

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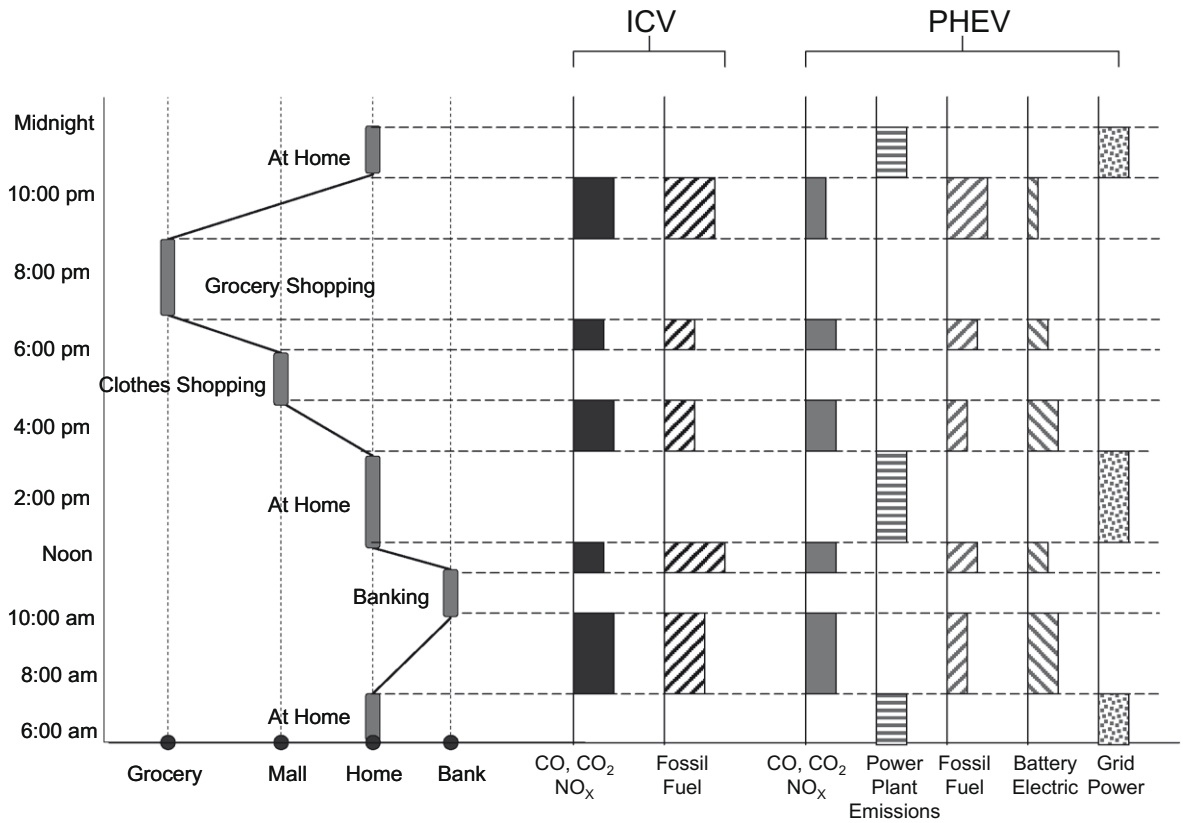

Fig. 3. Temporal linkages for environmental assessment of PHEVs.

Table 1
Charging times for various circuit voltage and amperage levels. Source: Electric Power Research Institute (2002).

Charging circuit	Charger size (kW h)	Charging rate[1] (kW h/hr)	Infrastructure costs ($)	Charging time (to charge empty pack[2])	
				PHEV20	PHEV60
Compact car					
Pack size				5.1 kW h	15.5 kW h
Rated pack size[3]				4.1 kW h	12.4 kW h
120 V 15 amp	1.4	1.0	0	4.0 h	12.3 h
120 V 20 amp	1.9	1.3	200	3.0 h	9.2 h
240 V 40 amp	7.7	5.7	1000	0.7 h	2.2 h
Mid-Size Suv					
Pack size				7.9 kW h	23.4 kW h
Rated pack size				6.3 kW h	18.7 kW h
120 V 15 amp	1.4	1.0	0	6.3 h	18.6 h
120 V 20 amp	1.9	1.3	200	4.7 h	14.0 h
240 V 40 amp	7.7	5.7	1000	1.1 h	3.3 h
Full-Size SUV					
Pack size				9.3 kW h	27.7 kW h
Rated pack size				7.4 kW h	22.1 kW h
120 V 15 amp	1.4	1.0	0	7.4 h	22.1 h
120 V 20 amp	1.9	1.3	200	5.6 h	16.5 h
240 V 40 amp	7.7	5.7	1000	1.3 h	3.9 h

[1] Charger efficiency assumed to be 82% for 120 V chargers and 87% for 240 V chargers.
[2] Battery efficiency assumed to be 85%.
[3] Rated pack size assumed to be 80% of nominal pack size.

Under the assumption that the vehicles in the survey are 'representative,' charging profiles can present useful guidelines to forecast future charging demand as well as providing projected maximum load increases on the current grid on an hourly basis. To approximate charging electricity per vehicle or per household to predict future demand, the results based on the survey data can be divided, respectively, by the number of vehicles or by the number of households. Based on some boundary

values inferred from the analysis, the results can then be used to provide guidance for adopting specific charging policies designed to meet goals of local agencies or for grid upgrades that may be required in the event that the current grids cannot meet the increased demand in the region.

Four charging behavior options are analyzed for each case.

3.1. Scenario 1: end-of-travel-day recharging

This assumes that drivers charge their vehicles following the last trip of the day; i.e., when they reach their final destination, which generally home. Charging times depend on the battery capacity (20/60 miles) and cumulative mileages throughout the day. Drivers are assumed to plug their vehicles into the grid as soon as they park their vehicles from their last trip of the day. Charging is assumed to start immediately and to stop when the batteries are fully charged to their equivalent 20 mile/60 mile capacity. Fig. 4 presents the results.

Charging is seen to increase rapidly starting late afternoon and has a peak at 7 to 8 pm for PHEV20 and 9 to 10 pm for PHEV60. It can be inferred from this that, although PHEV60s cover more trips and greater distances on electricity, their larger charging capacity results in base case (current circuit, no upgrades) charging hours of up to 22 h for large-sized PHEV60 SUVs, with some vehicles still being charged later than 9 am on the following day. This may hinder the completion of activities, or the vehicle may not operate with a fully-charged battery, on the following day.

As seen in Fig. 4, upgrading the charging infrastructure at individual homes reduces charging times significantly; with upgrades delivering faster charging, many fewer vehicles need to be charged through the next day. While the difference in charging time between PHEV20 and PHEV60s gets smaller with upgrades, the peak gets bigger, reaching over 20,000 kW h.

3.2. Scenario 2: uncontrolled home charging

Here, drivers are assumed to charge their vehicles each time the vehicle is parked at home; i.e., that drivers routinely connect the vehicle to the electricity outlet in their home garage. As seen in Fig. 5, this has the effect of dispersing the charging demand to earlier hours than in Scenario 1 and both PHEV20 and PHEV60 peaks decreased slightly. The number of vehicles being charged after 9 am the next day also decreases somewhat and charging demand is reallocated to some extent due to the shift to earlier home charging. But, overall, this behavioral change are not significantly different to those observed in Scenario 1.

Even with the faster charging times obtainable with circuit upgrades, this behavioral assumption does not lead to significant reallocation of charging demand. And again, upgraded grid capacity results in higher peaks than with the base circuits.

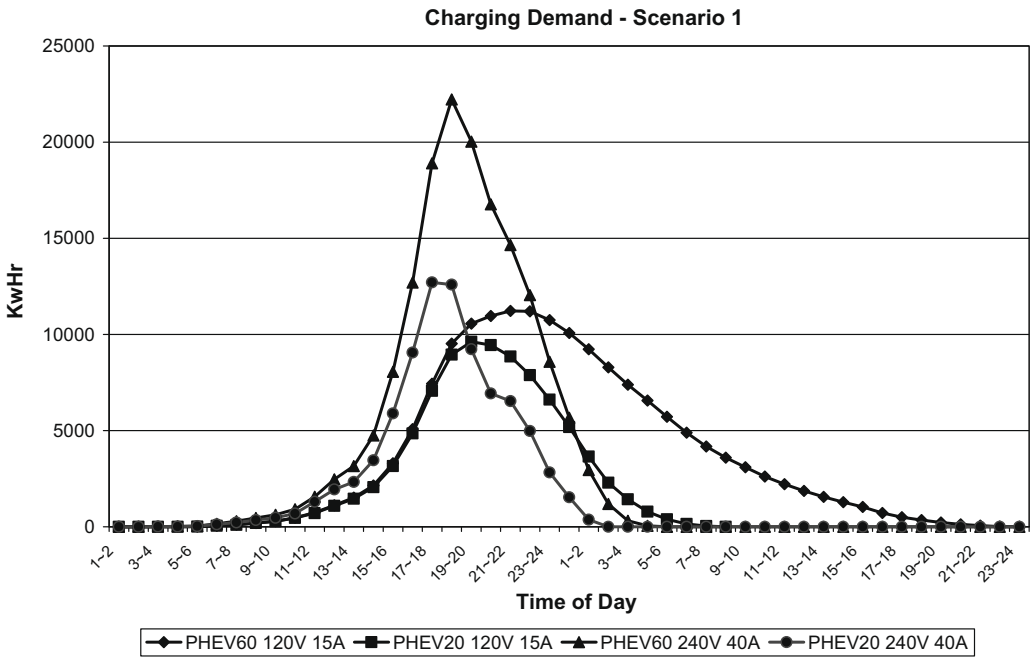

Fig. 4. Hourly PHEV charging demand: Scenario 1.

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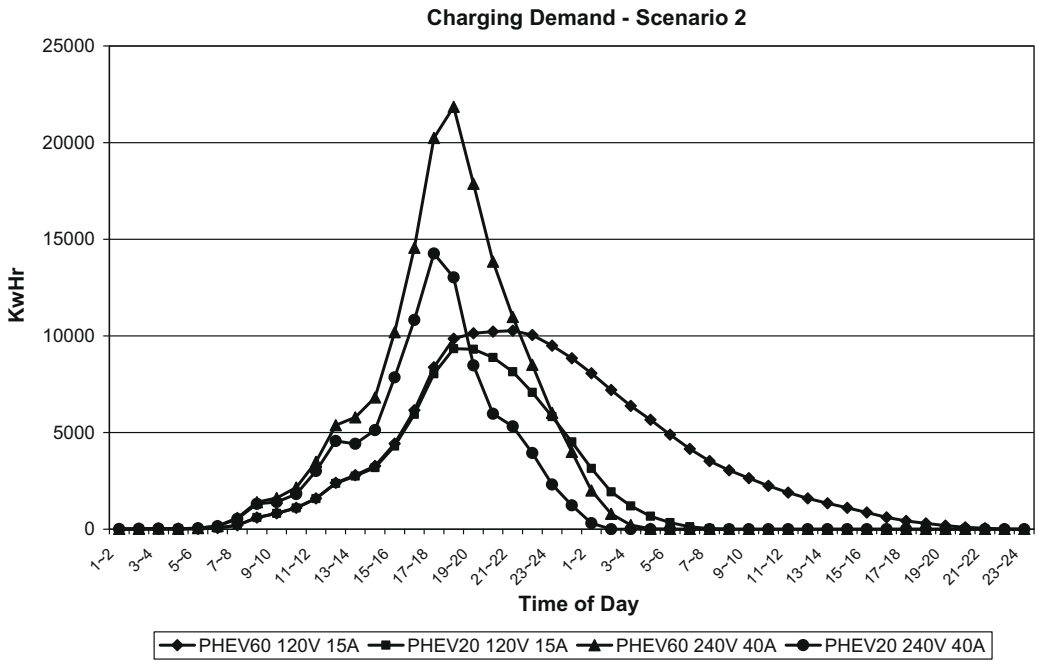

Fig. 5. Hourly PHEV charging demand: Scenario 2.

3.3. Scenario 3: controlled charging (restricted to 10pm or later)

To avoid additional increases in daytime high-demand hours of current electricity usage, it is assumed that charging is allowed only from 10 pm through the next morning. The intent is to evaluate whether or not charging can be accommodated using existing off-peak grid capacity with no extra infrastructure improvement.

Scenario 3's charging profiles are shown in Fig. 6. Although their is off-peak charging for most of the cases, the shifting of PHEV60 charging to later hours causes more vehicles to be charged throughout the next day. With upgraded circuits, peaks

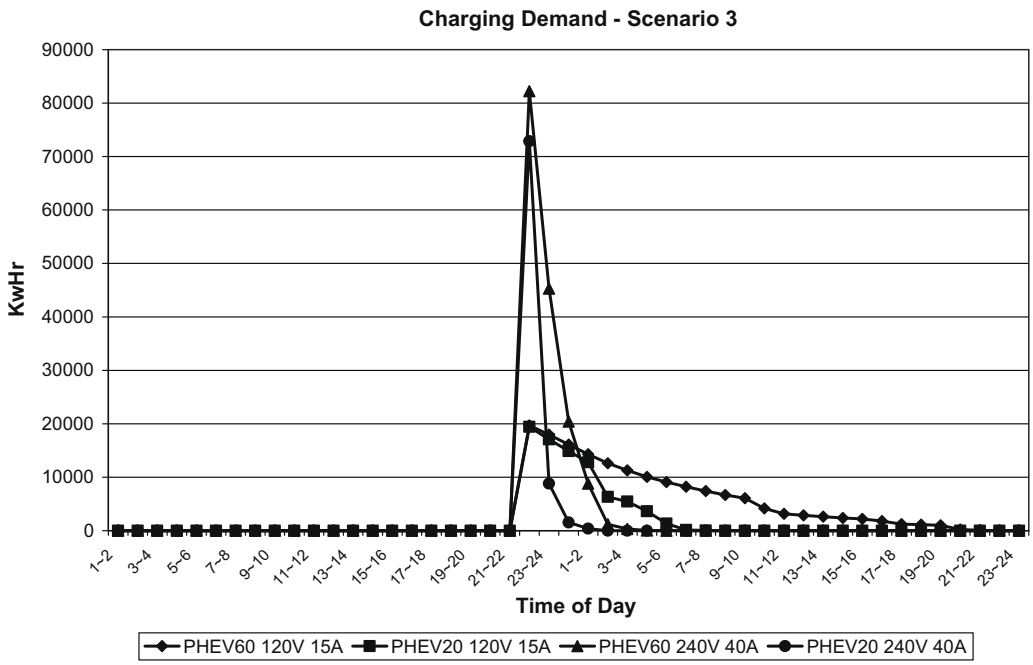

Fig. 6. Hourly PHEV charging demand: Scenario 3.

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become more pronounced, reaching over 80,000 kW h during the peak hour. An option, should the resulting peaks cause problems for electricity generation or grid capacity, would be differential charging time windows.

3.4. Scenario 4: Publicly-available electricity charging

Scenario 4 assumes that the basic infrastructure to support PHEV charging is installed in all public/private parking spaces and charging electricity from the grid can be bought at these locations. Although the costs of electricity may be changed to encourage drivers to charge their vehicles during off-peak periods, we assume that drivers charge their vehicles during any activity in which the vehicle is stationary and at a public location for more than an hour, regardless of cost. Charging ends either when the battery is fully charged or when the next trip starts.

Results for this scenario are presented in Fig. 7. The charging profile has two peaks, ostensibly following two traffic peaks—morning and evening work-related trips. As expected, these peaks are not as pronounced when compared to other scenarios, with the demand more temporally dispersed. However, in this scenario, the charging times are clustered around daytime hours when electricity demand is highest. In the PHEV60 case, a smaller number of vehicles require charging during the next morning due to the availability of earlier daytime charging.

With upgrades, the charging time difference between PHEV20 and PHEV60 decreases, while the peaks are higher than in the base case; similar to the other scenarios.

4. California electricity supply with PHEV charging demand increases

The sample profile results are used to forecast electricity demand with increased PHEV charging. For example, assuming that the PHEV20 penetration rate is 50%, this means that half of households in California, some 11,502,870 homes, consume extra electricity for charging their PHEVs. Using hourly electricity generation data provided by the California ISO (2008), CAISO (http://www.caiso.com), which supplies about 75% of electricity in the state and assuming these rates hold for charging demand we can forecast the future electricity load on an hourly basis. In Figs. 8 and 9, hourly demand is based on a 5 weekday's average.

At a 50% penetration rate for PHEV20, none of the 120 V 15A case scenarios' estimates require any systemic changes to the grid. Electricity demand stays within the available resources forecast that CAISO has set for current usage (Fig. 8). However, the maximum demand increase is produced by the upgrade (240 V, 40 amp) case, which consumes over five times more electricity per unit time than the base case. When circuit upgrades are in place, all scenarios approach the available resources forecast limits (Fig. 9) under the 50% penetration scenario. In particular, for Scenario 3, the peak is extremely high and far exceeds grid capacity. The implication drawn from this sort of forecast is that having Scenario 3 and circuit upgrade to 240 V and 40 amp at the same time is not very practical.

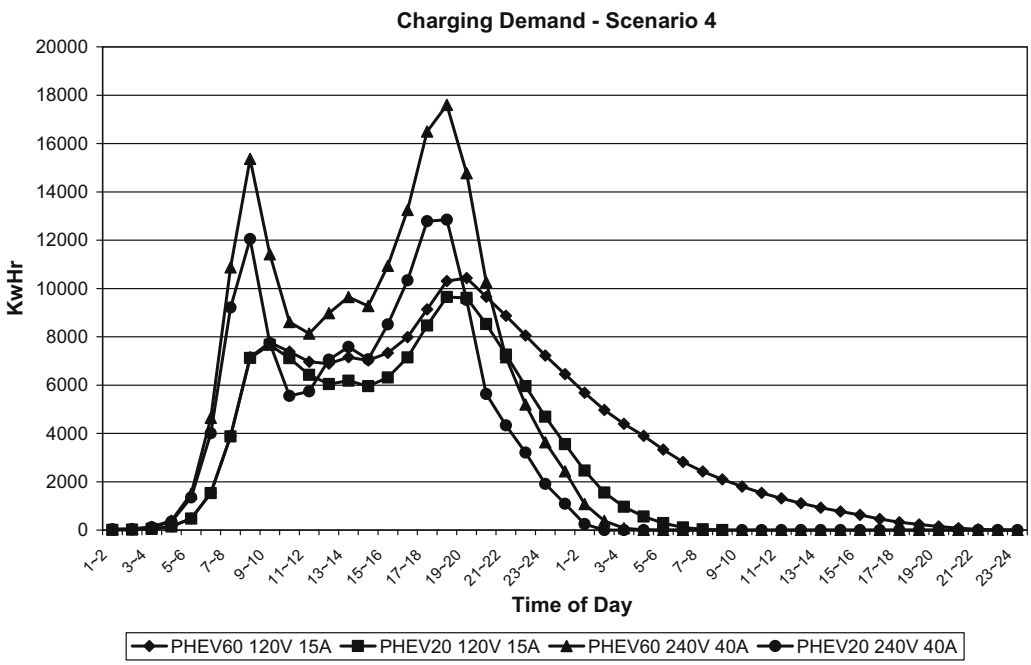

Fig. 7. Hourly PHEV charging demand: Scenario 4.

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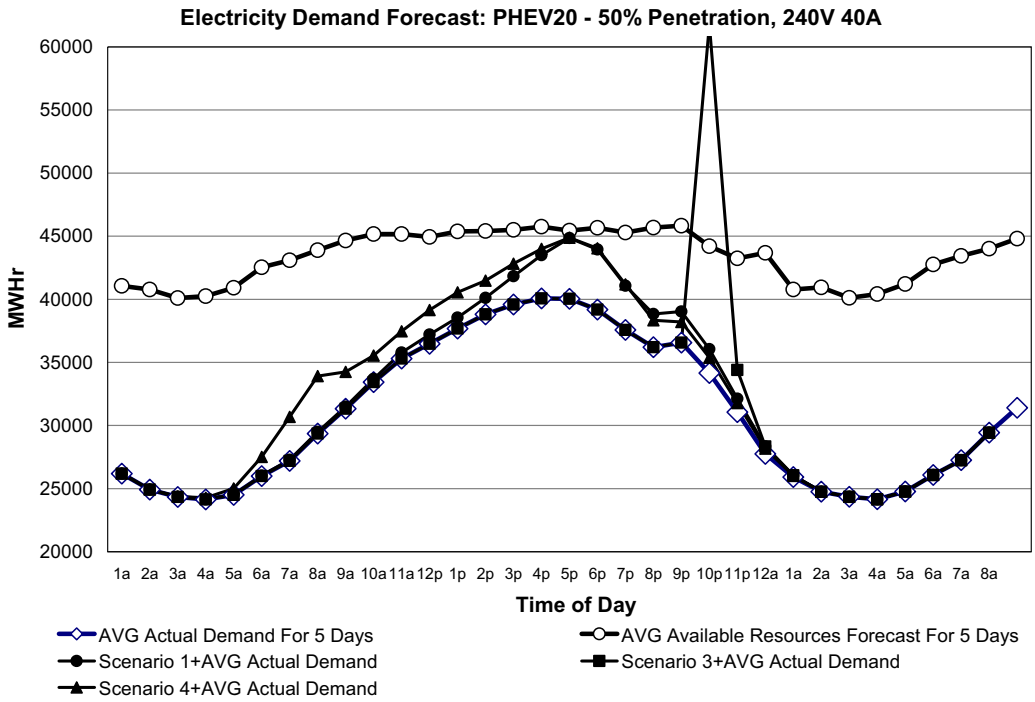

Fig. 8. Electricity demand forecast (MWh) for PHEV20, 50% penetration (120 V, 15 amp).

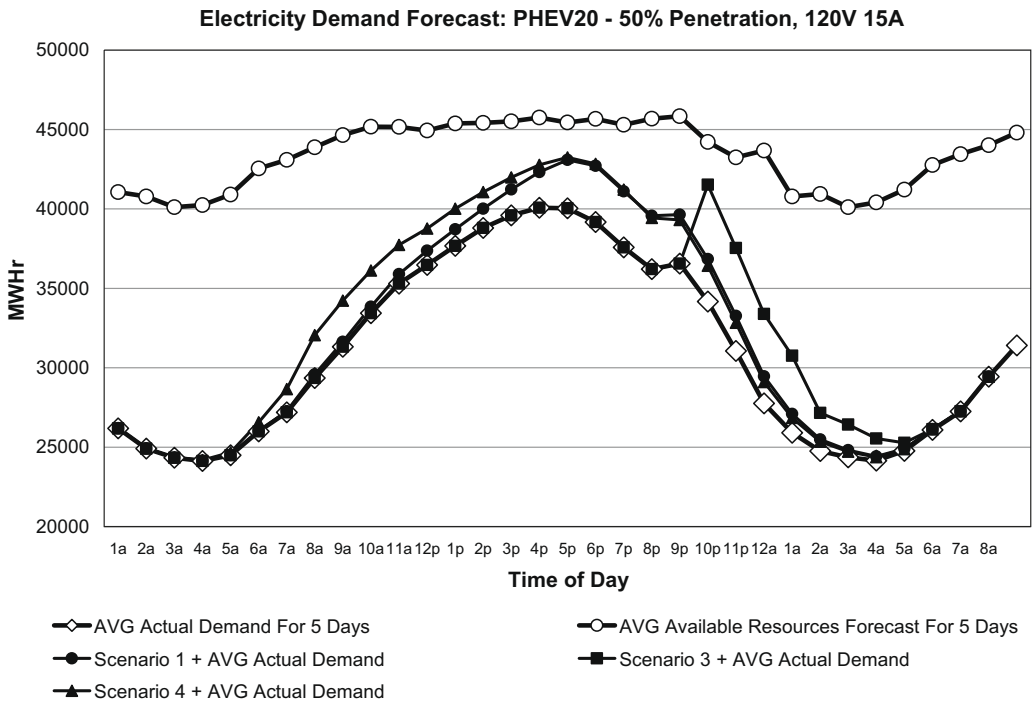

Fig. 9. Electricity demand forecast (MWh) for PHEV20, 50% penetration with Circuit Upgrade (240 V, 40 amp).

5. Projected activity-based energy and emissions profiles

The trip/activity chains of each vehicle in the sample are replicated, and results on energy and emission profiles based on different charging scenarios are examined. Fig. 10 presents an example of such a replication for an actual vehicle from California Travel Survey. This particular vehicle had 6 trips for 37 miles (Manhattan distance) of travel on this particular day. Based on

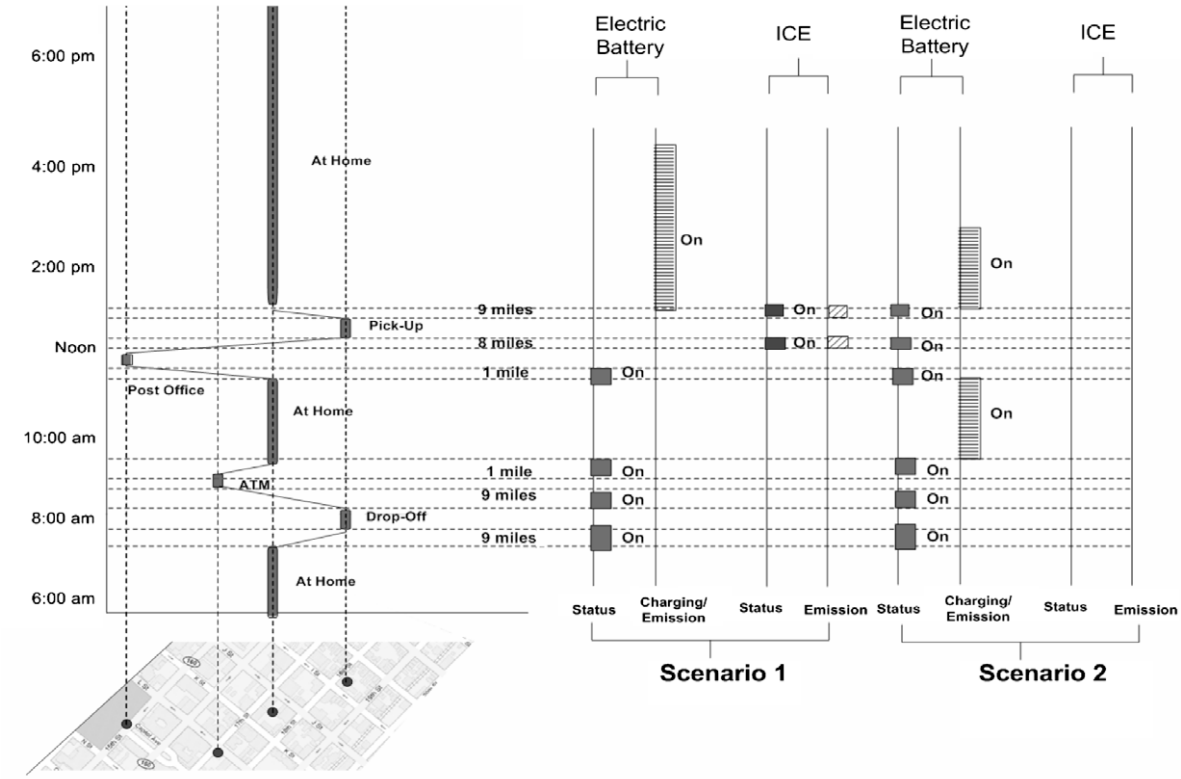

Fig. 10. Replication of a single vehicle.

charging Scenario 1 (or Scenario 3) behavioral assumption, this vehicle is run on 20 miles by electricity—with the remaining 17 miles by ICE—but, with home-charging (Scenario 2) between the trips, it can run purely on electricity. Associated emissions can be also derived, as shown in the figure. The statistics in this section are aggregated from this process for all 15,823 vehicles in the survey.

5.1. Electricity demand increase

Fig. 11 summarizes the electricity charging demand increase by households, for both PHEV20 and PHEV60, that would be required to maintain current activities and trips using PHEVs. The minimum and maximum bounds shown in the figure correspond to results when assuming distances between activity locations are determined by two different network assumptions (Euclidean vs. Manhattan distances); actual values are expected to be between these boundary values. PHEV20 cases have a peak demand of 100,000 kW h for private (in home) charging only, and 150,000 kW h for circumstances allowing public parking charging, i.e., Scenario 4. PHEV60 penetration results in around 200,000 kW h electricity sector demand increase daily.

Public parking charging (Scenario 4) enables daytime charging and therefore increased electricity for the PHEV20 case which will lead to less oil consumption for vehicle operations. However, for the PHEV60 case, provision of public charging stations (Scenario 4) yields only minor improvements over the three scenarios that involve private charging only. This can be explained by the fact that an energy equivalent of 60-miles stored in the battery (which typically can be achieved with overnight charging) covers most of the observed trip chains for 1-day activities. Although the circuit upgrade delivers shorter charging times, it does not considerably increase the amount of electricity substitute for ICE fuel (Fig. 12).

In general, higher charging demand indicates that a larger fraction of mileage is run by electricity with less gasoline consumed. However, depending on local fuel sources for electricity generation, this does not guarantee an improvement for emissions; to make claims regarding efficiency of energy usage or reduction in emissions, these results need to be further tested and analyzed. However, in terms of gasoline-dependency, converting fuel to electricity will undoubtedly lower the need for petroleum imports since electricity generation depends on a variety of energy sources.

5.2. Mileage substitution by electricity

Vehicle-based activity chains are analyzed with the first 20/60 miles run on the electric motor (assuming binary operation for PHEVs), and the remaining miles (if any) on ICEs. Alternate network assumptions (i.e., Manhattan vs. Euclidean distance metrics) provide maximum and minimum values, and represent ranges for estimated values of future energy usage.

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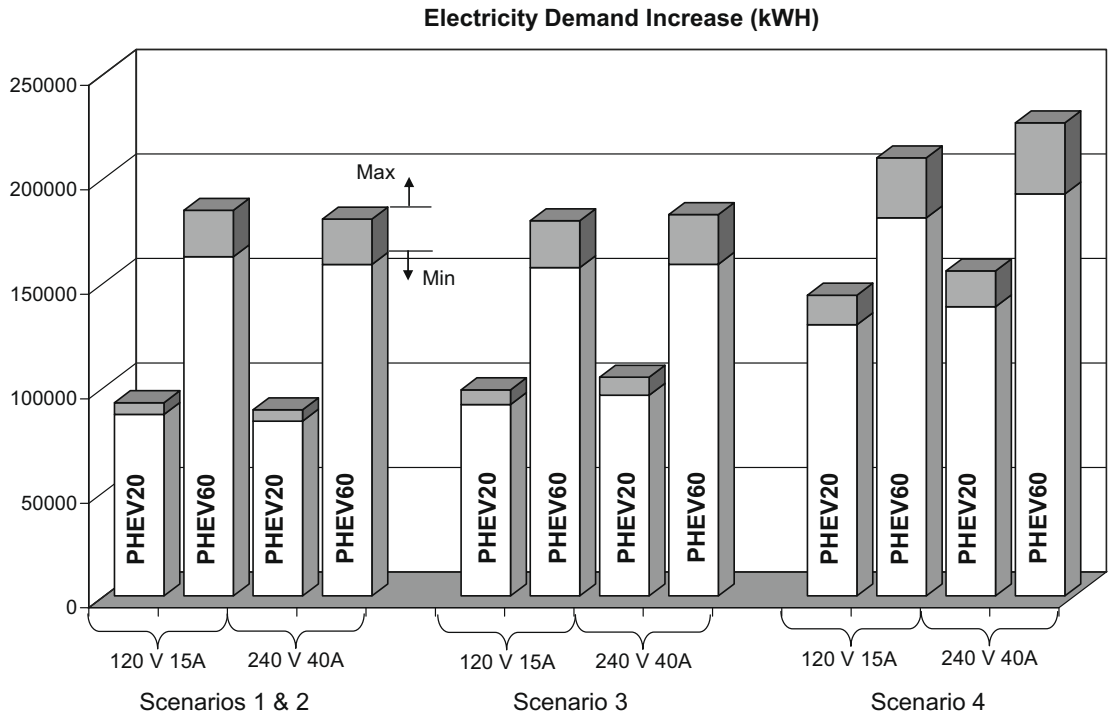

Fig. 11. Total PHEV charging demand (kW h).

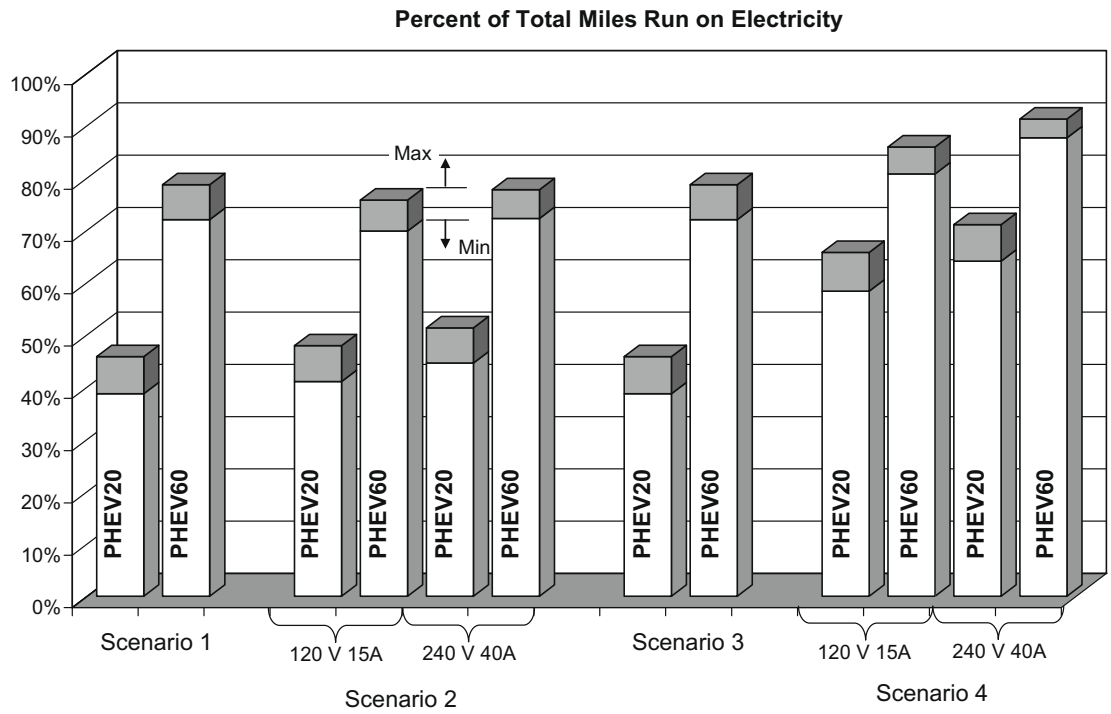

Fig. 12. Total mileage run on electricity.

There are several remarks associated with electricity coverage on mileage that are evident from the results presented in Fig. 12. First, the circuit upgrade does not generally make a big difference in mileage substitution (by electricity). Scenario 4

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has the largest increase in mileage substitution with the circuit upgrade; when charging is available at public parking facilities, it is estimated to result in as much as a 5% point increase. The public parking case can lead to 70% coverage; however, PHEV20 adoption covers a maximum of 50% of current driving distances just with daytime charging at home and circuit upgrade.

For PHEV60, the base case with night home charging can cover a minimum of 70% of trip distances to being electric-powered. Daytime public parking charging with an upgraded circuit can deliver up to 90% of mileage; however Scenario 4 adds more demand during high-peak hours—this may become another problem for the grid and power generation. With the circuit upgrade, PHEV60 delivers a much larger shift from fuel to electricity in terms of mileage than does PHEV20. In addition, both Scenarios 1 and 3 (that assume end-of-travel charging behavior) of PHEV20 and PHEV60 cases, deliver mileage substitution slightly less than vehicle daily driving range distribution for the PHEV20 case (47–55%), and 82–88% for the PHEV60 case.

5.3. Trips by energy types

Because ICVs' emissions depend not only on mileage but also on the condition of the engine upon starting, the ranges of mileage coverage that PHEV adoption might achieve are not sufficient to derive emission reduction effects. For ICVs, engine starts determine a significant portion of emissions produced by trips. Here, the number of trips by energy source is analyzed to derive ranges for emission reduction effects more precisely vis-à-vis mileage coverage. In the following figures, the numbers of trips, which are equivalent to the numbers of engine starts, are presented for each PHEV type for several of the base case (no circuit upgrades) charging scenarios.

Fig. 13 presents breakdowns by projected type of power used for the number of trips (66, 624) observed in the sample relative the current (fuel only) case for some representative cases. In the figures, the 'electricity only' portion represents trips run purely on electricity; a similar notation is used for the fuel portion. The category 'Electricity + Fuel' represents trips started with power provided by the electric motor, and then at some point in the trip the battery was discharged completely and the ICE turned on. Although the figures do not specifically identify what portions of mileage were run on certain types of energy, they nonetheless provide an idea of the number of (or percentage of) trips in which the electric battery was depleted.

Compared to the statistics based on mileage coverage ranges, the same scenarios generally produce about 20% point more in terms of the number of trips by electricity only. For example, the 120 V 15A home charging Scenario 1 for PHEV20 has mileage coverage range of 38–46% but has almost 60–70% in terms of the number of trips on electricity only; the range is even larger with 'Electricity + Fuel' trips included. For the PHEV60 case with same scenario, more than 90% of trips are covered while a maximum of 78% of mileage is covered from the grid. This difference can be explained by the presence of long-distance trips. Since the maximum distance a PHEV covers is only 20/60 miles, long-distance trips might be categorized into a single 'Fuel' trip or 'Electricity + Fuel' trip, while the mileage on gasoline could be a much larger percentage of miles traveled. However, in terms of reducing ICE starts, these results are expected to contribute more emission reduction than those based on mileage results alone.

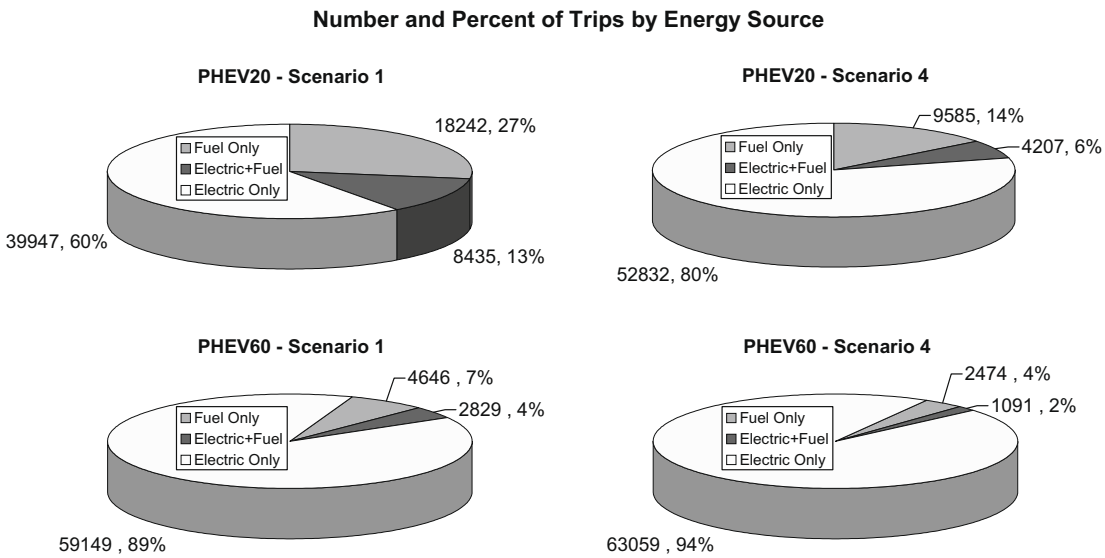

Fig. 13. Distribution of trips by energy source.

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5.4. Trips by initial engine status

Emission levels produced by cold starts and hot starts are known to be significantly different; cold starts produce significantly more emissions. Analyzing activity chains enables estimation of the starting status of a trip—a factor that cannot be captured in emission studies using conventional methods.

Here we present results on the potential impact of PHEVs on the number of cold vs. hot starts. Electric-only trips are not counted since they do not produce emissions. EPA has estimated 1 h of idle time for a heated ICE to cool down for vehicles with a catalytic converter. That is, if a trip (by a conventional engine) is followed by a trip (by conventional engine) within 60 min, the second trip is considered a hot start, and otherwise a cold start. However, whether or not the preceding trip was long enough to result in the engine being completely hot is not considered here. A trip started on battery power that exceeds the range of the current charge and requires switching to the ICE is considered a cold start.

The results are presented in Fig. 14 for Scenario 1. All of the trips in the sample are ICVs and comprise 68% cold start of starts. Fully-charged PHEV20s will reduce the number to 23–29% without daytime charging; fully charged PHEV60s will reduce this further to 5–9% of cold starts. The temporal distribution of start types gives a periodic trend of emissions regarding engine starts (Fig. 15a and b).

5.5. Temporal trip distribution by energy types

The activity-based approach employed herein specifically incorporates the temporal linkages between travel and activities and therefore enables the creation of hourly energy profiles of vehicle usage. Examples of aggregated energy profiles for the 15,823 vehicles in the sample are shown in Fig. 16a, b and c. These results can provide measurements for emission studies incorporating time-of-day adjustments relative to time-sensitive characteristics of air quality. Also, based on air circulation patterns, dynamic emission and energy profiles (within a time frame) may be used to estimate how long pollutants stay, how they travel and what impacts they would cause.

As expected, under the binary mode assumption that vehicles will drive with electric motors first with the ICE turning on only when batteries are depleted, more vehicles run on fuel in the afternoon (after 20/60 miles) trip chains. For the PHEV20 base case charging Scenario 1, roughly more than 50% of trips after 2 pm in the afternoon are run either on fuel or on a combination of fuel and electricity. Consequently, afternoons are subject to greater exposure to emissions from the transportation sector than are mornings, ostensibly concentrated more in such locations as major corridor and arterial roads in urban areas. As seen in Fig. 16b, with public parking charging plus daytime charging (Scenario 4), fuel usage drops dramatically. Under the assumption that all of the current vehicles are substituted with PHEVs with battery size PHEV60, the reduction in afternoon emissions is much greater (Fig. 16c).

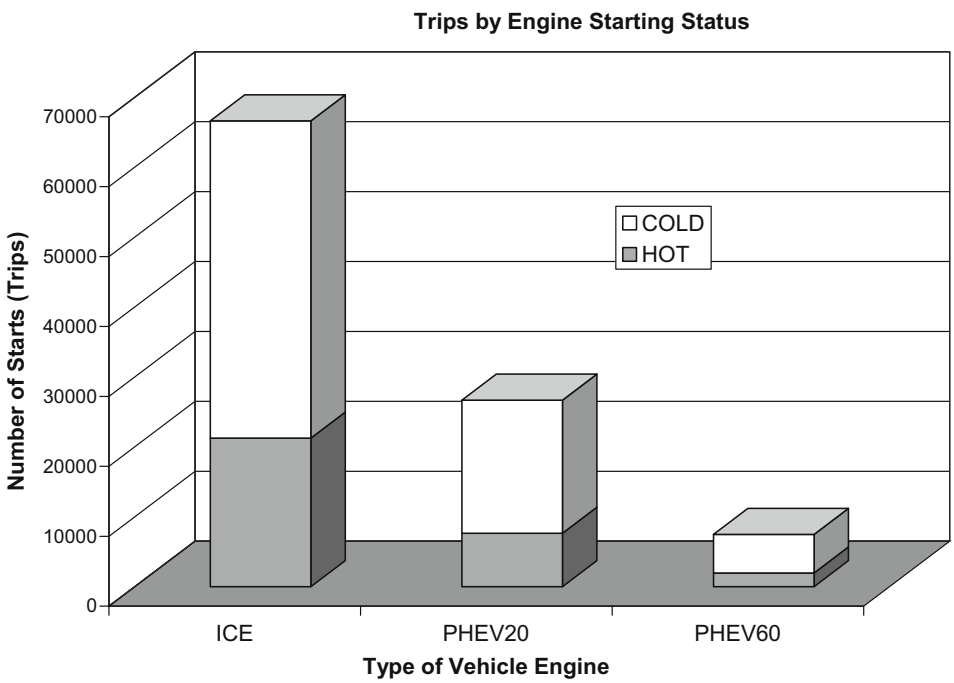

Fig. 14. Comparative number of trips by initial engine status (Scenario 1).

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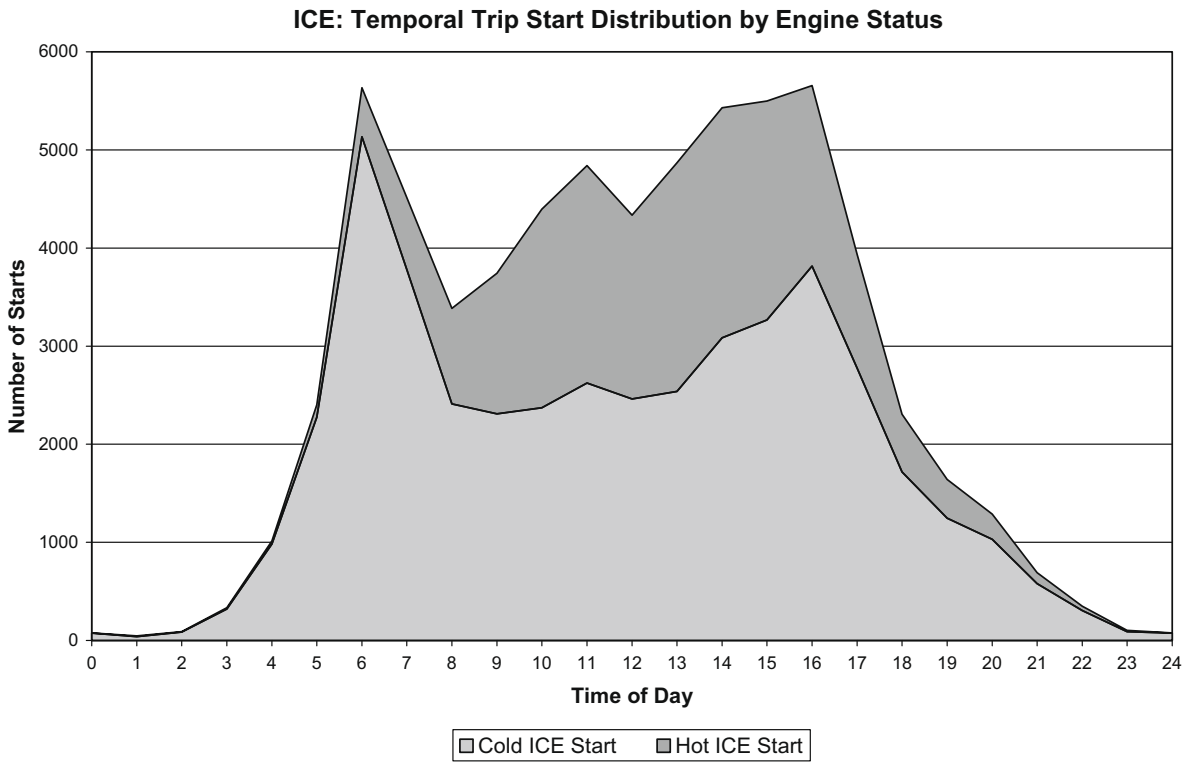

Fig. 15a. Temporal trip distribution by initial engine status (Current ICE).

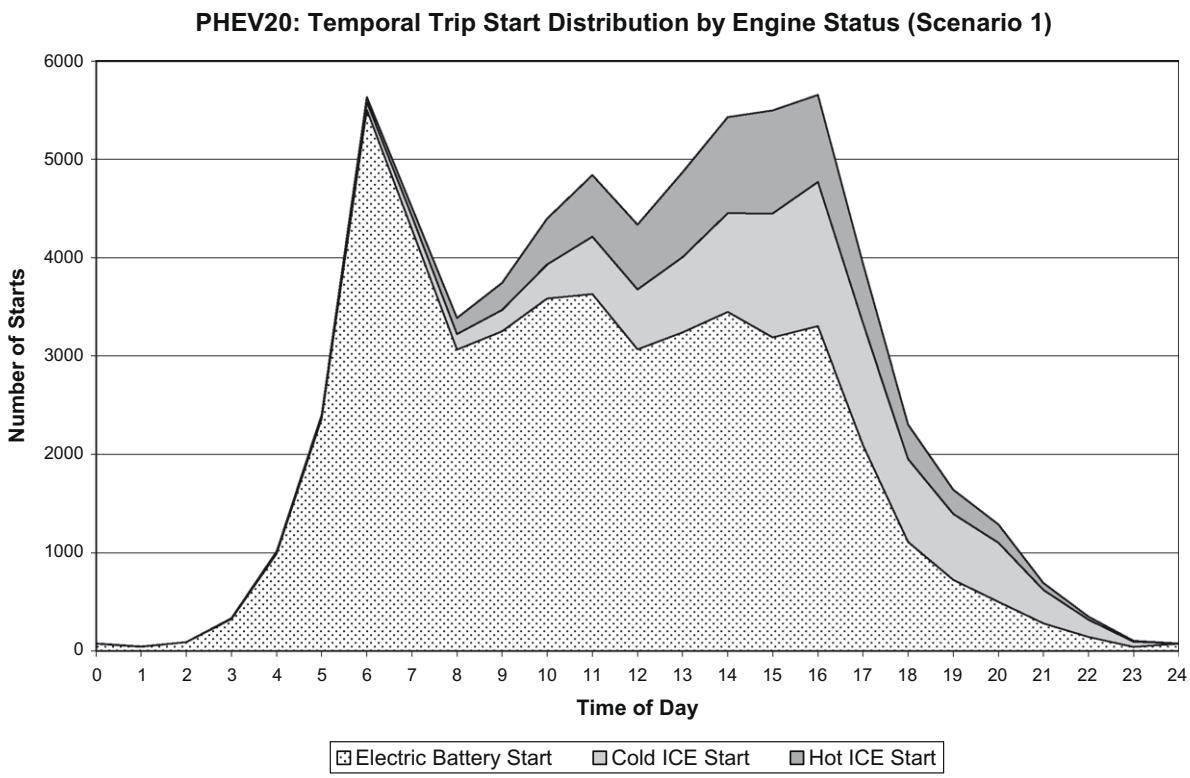

Fig. 15b. Temporal trip distribution by initial engine status (Projected PHEV20).

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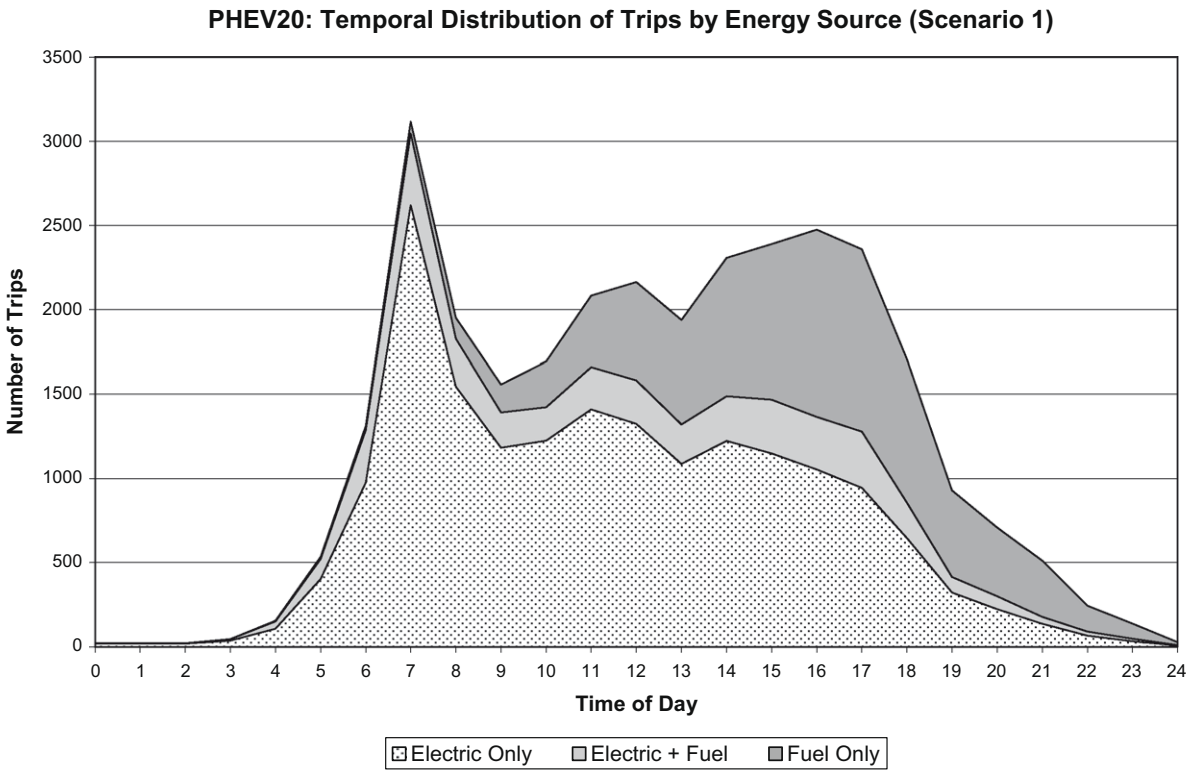

Fig. 16a. Temporal trip distribution by energy source (PHEV20-Scenario 1).

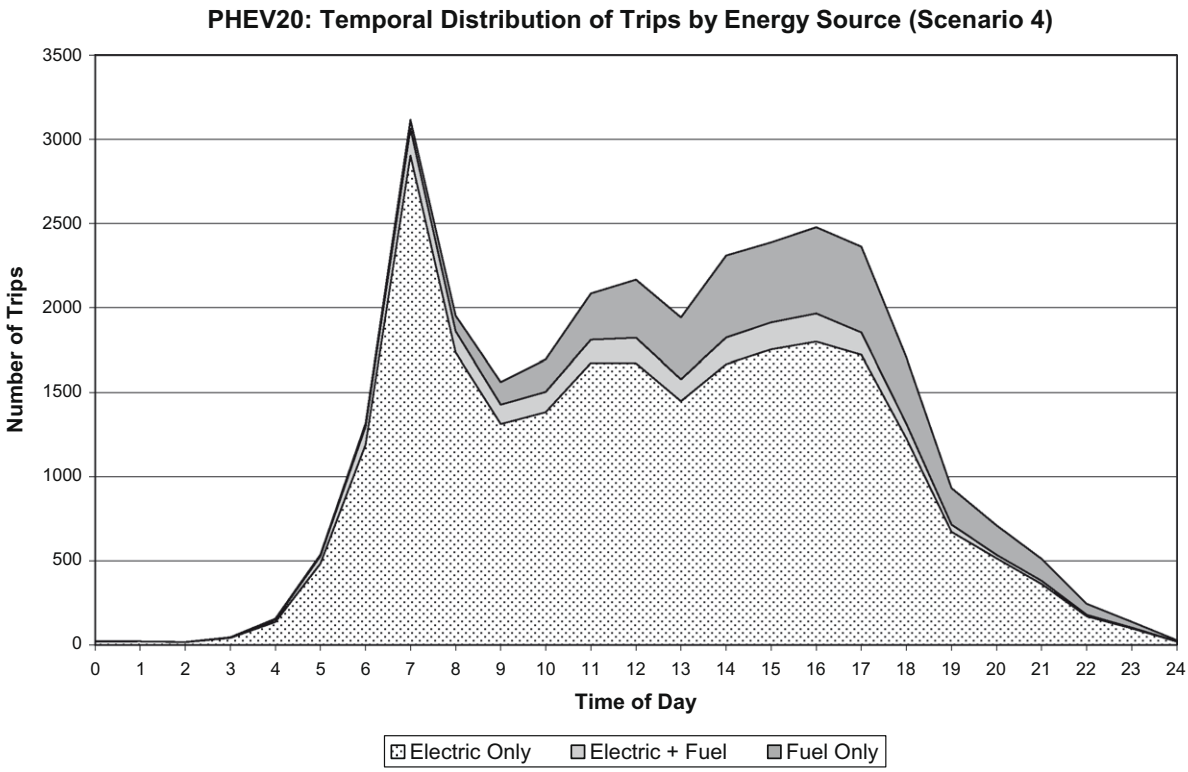

Fig. 16b. Temporal trip distribution by energy source (PHEV20-Scenario 4).

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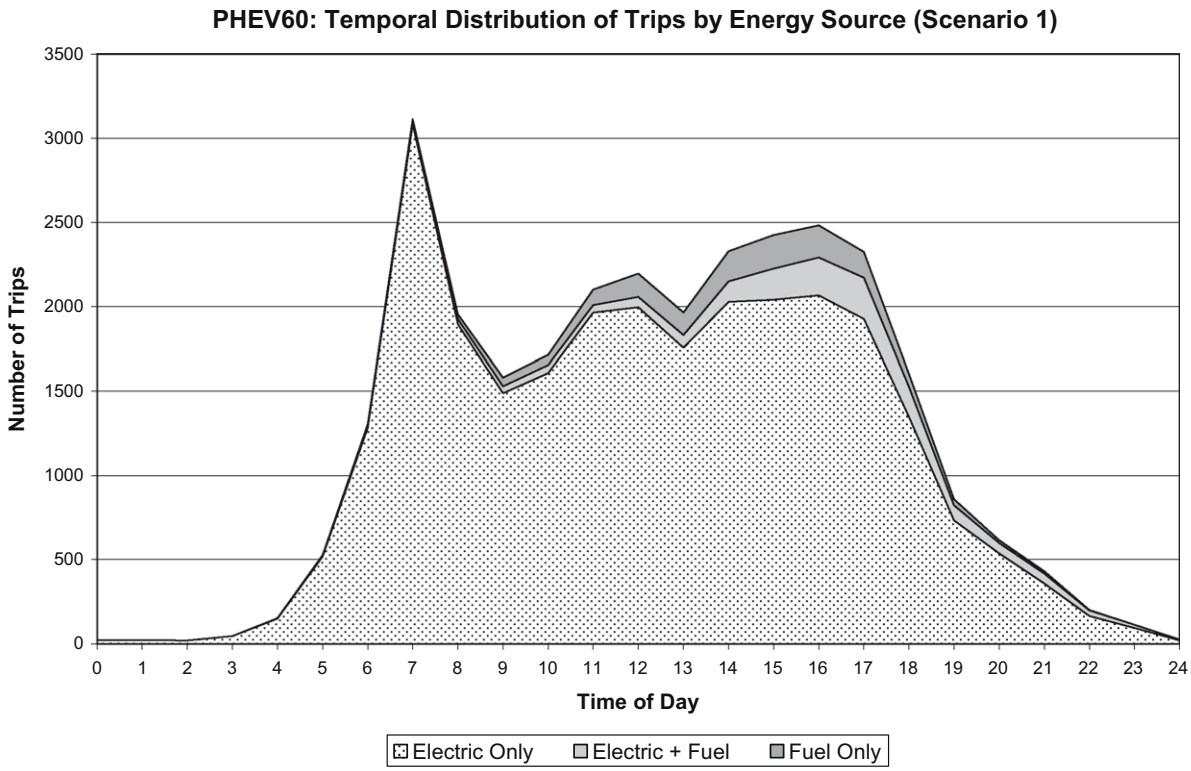

Fig. 16c. Temporal trip distribution by energy source (PHEV60-Scenario 1).

6. Conclusions

Commercial PHEV penetration in the automobile market in the near future will certainly bring positive impacts on pollutants, and foreign oil dependency. Additionally, with rising fuel costs, PHEVs can be expected to deliver a certain level of financial benefit to consumers. This paper presents estimates of potential PHEVs impacts and provides inputs for policy makers to assess the current states of electricity generation and infrastructure as they pertain to increased adoption of PHEVs.

Charging demand shifts on an hourly basis are presented for four different scenarios based on different electric circuit characteristics. Circuit upgrades bring faster charging times, and reduce charging time differences between PHEV20 and PHEV60. Home charging will replace 40–50% of distances currently travel using ICEs with electric power for PHEV20 and 70–80% for PHEV60. If charging facilities are available in public parking facilities, which will lead to more daytime charging, PHEV20 can convert 60–70% of mileage from fuel to electricity, and 80–90% for PHEV60. Emission reductions will be higher than those percentages since PHEVs will cover a greater fraction when measured by the number of trips, which emphasizes the equivalent number of ICE starts.

It is not certain that diverting charging demands to off-peak periods will maximize energy efficiency. As we document, daytime charging will allow more trips by electricity, but will result correspondingly in higher peaks for high-demand-periods.

There are limitations to the assessments provided by this research. The paper does not fully account for environmental impacts from PHEV penetration. Specifically, increased emissions and other types of energy usage regarding extra grid electricity demand are not assessed. Chemicals associated with electric batteries are not taken account. Life cycle analysis on environmental impacts regarding different mechanical parts of CVs and PHEVs are not analyzed. In further studies, more far-reaching environmental assessments are needed.

Acknowledgement

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