Impact of Plug-in Hybrid Electric Vehicles on Tehran's Electricity Distribution Grid

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Abstract: Hybrid electric vehicles (HEVs) are commercialized and plug-in hybrid electric vehicles (PHEVs) are becoming more popular. PHEVs are charged by plugging into electric outlets or on-board electricity generation. These vehicles can drive at full power in electric-only mode over a limited range. As such, PHEVs offer valuable fuel flexibility. The charging of PHEVs has an impact on the distribution grid because these vehicles consume a large amount of electrical energy and this demand of electrical power can lead to extra large and undesirable peaks in the electrical consumption. The improvements in power quality that are possible by using coordinated charging are emphasized in. It also indicates that not coordinating the charging of PHEVs decreases the efficiency of the distribution grid operation. Several automakers are preparing for the next generation of passenger transportation, Plug-in Hybrid Electric Vehicles (PHEVs). Using data from the Tehran Regional Electric Company (T.R.E.C), this study sought to understand how different charging scenarios for PHEVs could impact electricity demand in Tehran.

Keywords: *Plug-in hybrid electric vehicles; Charging scenario; Distribution grid*

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) are a new and upcoming technology in the transportation and power sector. As they are defined by the IEEE, these vehicles have a battery storage system of 4 kWh or more, a means of recharging the battery from an external source, and the ability to drive at least 10 miles in all electric mode [1]. These vehicles are able to run on fossil fuels, electricity, or a combination of both leading to a wide variety of advantages including reduced dependence on foreign oil, increased fuel economy, increased power efficiency, lowered greenhouse gas (GHG) emissions and vehicle-to-grid (V2G) technology [2–4]. These claims are backed by data suggesting that fueling a PHEV would cost the equivalent of 70 cents per gallon of gasoline when electricity costs 10 cents per kWh [4] and that an all electric driving range of 40 miles could lower oil consumption by two-thirds [4]. Currently, there is little storage available in the power grid so demand and generation must be perfectly matched and continuously managed to avoid frequency instabilities. PHEVs have an energy storage capacity which is rather small for each individual vehicle, but the number of vehicles will be large, yielding a significant energy storage capacity. At any given time, at least 90% of the vehicles are theoretically available for V2G [5,6]. These vehicles must be connected to the grid when idle. There must be enough vehicles plugged in during the day to provide grid services therefore it could be beneficial to give incentives to vehicle owners to stay plugged in. Most of the weekdays, vehicles follow a schedule which does not vary much from week to week [5]. The electrical storage of PHEVs could provide grid services via V2G concept and add a surplus value to the vehicle owner [7]. The reason for choosing Tehran for this study is the air pollution. Cut oil subsides in Iran is another reason for choosing Tehran for this study. At such low prices, domestic demand for energy in Iran has grown very rapidly. With the price reform, you will dampen domestic demand, which means more efficient energy use domestically, more energy available for profitable exports, and higher revenues for the country. From a domestic perspective, if prices are higher, the energy sector in Iran will become more profitable and hence be able to invest, extract, and produce more. Furthermore, if the Iranian people are able to restrain their consumption, this will have a positive side effect on the global oil market. This will also push the domestic automobile industry to modernize itself. The country produces about 1.5 million cars per year, targeting the domestic market of 74 million people. Since gasoline is almost free, carmakers have little incentive to make their product energy efficient. But when gasoline price rises to the international level, Iranian car manufacturers will have to change the way they operate and increase the energy efficiency of their vehicles. Once this happens, Iranian-made cars will be more competitive on the export market.

2. Transition from conventional vehicles to Plug-in Hybrid Electric Vehicles (PHEV)

For the first time it was German inventor, Nikolaus Otto, who made it possible to use combustions engines in cars for the first time by the invention of the first four-stroke internal combustion engine in 1862. These types of engines are continuously being used in so-called conventional vehicles. The low-efficiency of ICE (Internal Combustion Engines) and high emission production are the most negative points about these types of vehicles. In the figure 1, the recent development in car industry is been shown.

Figure1. Schematic on development in car industry

As it can be seen from the figure (1), the first important breakthrough in car industry after the implementation of ICE in vehicles is the transfer from conventional vehicles to hybrid electric vehicles. These types of vehicles are first commenced in 1997 in Japan by the introduction of Toyota Prius. The main specification of this type of vehicle is the operation of the ICE on its efficient interval by means of a regenerative braking system. The latest generation of the vehicle is introduced in the market recently. They are mostly called PHEVs (Plug-in Hybrid Electric Vehicles) with additional capability to be charged from the grid.

3. Plug-in Hybrid Electric Vehicles (PHEV)

A PHEV is basically has the same structure as a Hybrid Electric Vehicles (HEV) but the grid charging capability is additional feature which consequently result in the necessity of higher battery capacity.

Grid connection capability in PHEVs will make it possible to coordinate energy resources for domestic consumption and also will lead to lower emission production from private cars in the business and residential areas.

The large percentage of the total emissions production is from the low-duty cars which are private and company cars. Reducing emission production is a big challenge for both developed and developing countries. On the other hand, the other major challenge in today's world in the high consumption of fossil fuels with increasing price and diminishing number of resources. Low-duty cars are one of the major sources of fossil fuel consumption. Therefore, high fuel consumption and emission production are the major incentives to make changes in the low-duty car sector. Moreover, the new ways of electricity generation can be considered as an incentive for introduction of PHEVs.

Global green house gas emissions from the different sectors are show graphically in Figure 2. These gases are included Carbon Dioxide (72% in total), Methane (72% in total) and Nitrous oxide (26% in total) [8].

Table 1. Charging Times for Different PHEV-20s Vehicle Classes under Various Circuit Voltage and Amperage Levels

Vehicle Type	Pack Size (kWh)	Rated Pack Size (kWh)	Charging Circuit	Charging Size (kW)	Charger Rate (kWh/hr)	Time to Charge Empty Pack (hours)
Compact Car	5.1	4.1	120 V 15 Amp 120 V 20Amp 240 V 40 Amp	1.4 1.9 7.7	1 1.3 5.7	4 3 0.7
Mid-Sized Sedan	5.9	4.1	120 V 15 Amp 120 V 20Amp 240 V 40 Amp	1.4 1.9 7.7	1 1.3 5.7	4.7 3.5 0.9
Mid-Sized SUV	7.9	6.3	120 V 15 Amp 120 V 20Amp 240 V 40 Amp	1.4 1.9 7.7	1 1.3 5.7	6.3 4.7 1.1
Full-sized SUV	9.3	7.4	120 V 15 Amp 120 V 20Amp 240 V 40 Amp	1.4 1.9 7.7	1 1.3 5.7	7.4 5.6 1.3

As shown in the figure 2, 14 percent of the emissions are produced by transportation sector which is close to the industrial sector. This means that by removing the emissions from the transportation sector, the total emissions can be reduced approximately as much as industrial sector. The introduction of PHEVs can be even more interesting when the emissions from power station are low and the electricity is generated from clean resources.

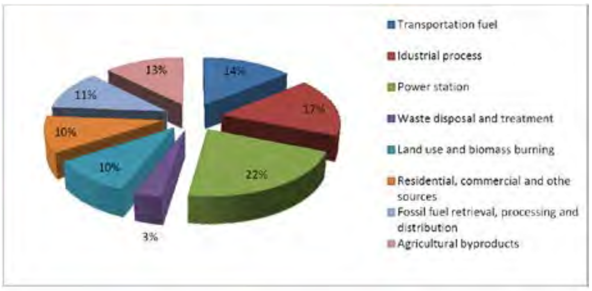

Figure2. Global Green house gasses emissions [8].

Conversion of the cars from the ones with fossil fuel consumption to the ones with electricity consumption is not just interesting from the car sector but also it is interesting from the grid point of view. The high intermittency of the electricity from renewable resources can be synchronized with the intermittency of consumption of electric cars. However, new generation is needed in order to charge the electric cars. The technical parameters of different plug-in vehicles are summarized in Table 1.

4. Plug-in Hybrid Vehicle Charging Scenarios

Electric Power Research Institute (EPRI) has performed studies regarding the energy requirements for potential PHEV vehicle designs. This information, which is summarized in Table 1, provided a basis for the charging scenarios. Figure 3 shows the power demanded for different PHEV-20 vehicle classes using a standard household electrical circuit of 120 volts and 15 amperes.

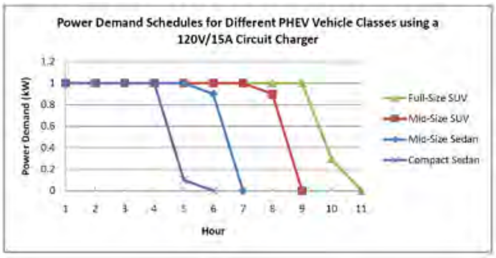

Figure 3. Power Demand Schedules for Different PHEV Vehicle Classes using a 120V/15A Circuit Charger.

The power demand schedules in Figure 3 show a consistent draw of power for the first few hours and then a partial power demand during the last hour of charging. For example, the Compact Sedan PHEV-20 requires 4.1 kWh of energy to fully recharge the battery from a 20% SOC. 1.0 kW of power is needed over the first 4 hours, and 0.1 kW during the 5th hour. This compact sedan therefore would require 4.1 hours to recharge at a rate of 1.0 kW per hour. Since most household outlets already contain 120 volt/15 amp outlets, it was assumed that most PHEVs that reach the market will charge through these circuits. Mid-sized sedan plug-in hybrids with all-electric ranges of 20 miles were used as the standard in the baseline scenarios. Variations to the electric range were used later in this paper. Using the information on charging rates and battery capacity, PHEV power demand curves were generated based around three types of charging scenarios.

The three scenarios representing how vehicle owners might charge their vehicles in the course of a day are summarized below:

Simultaneous Charging: All PHEV owners charge their vehicles at a specified time. This scenario is an adequate upper limit since recharging all the vehicles at one time maximizes the power demanded by plug-in hybrids

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Continuous Charging: A random percent of PHEVs are connected to the grid throughout the day, requiring a continuous demand of power. A random value between 1% and 50% were established for each hour, representing the percent of PHEVs that are connected to the grid.

Normal Distribution Charging: PHEV charging follows a normal distribution around a specific hour of the day (or mean hour). This represents a scenario between the two limits.

For the simultaneous and normal distribution charging scenarios, an evening charge time of 6 pm is used for the baseline. In the simultaneous charging scenario all PHEVs plug in at 6 pm. For the normal distribution recharge, most of the PHEVs begin charging between the hours of 4 pm and 8 pm (mean hour of 6 pm and standard deviation of 2 hours). Combining the charging scenarios above with the time of day charge and charging circuit size provided the baseline scenarios for this study. Each of these is scenarios are summarized in Table 2.

Table 2. Description of Baseline Scenarios

Scenario	
Scenario 1	All mid-sized sedan PHEV-20s begin charging at 6 pm using 120V/15A charging circuits.
Scenario 2	A random percent between 1% and 50% of mid-sized sedan PHEV-20s charge throughout the day, using 120V/15A charging circuits.
Scenario 3	Mid-sized sedan PHEV-20s charge as a normal distribution about mean hour 6 pm, with a standard deviation of 2 hours, using 120V/15A charging circuits.

Different penetrations of plug-in hybrids were used with each of the charge scenarios above. The PHEVs penetrations represented 5%, 10%, 15%, and 20% of the number of registered vehicles in Tehran.

5. Baseline Charging Scenarios

Using knowledge from previous EPRI studies on lithium-ion battery technology and power demand (table 1), baseline scenarios were created and applied to electricity load demand from the Tehran Regional Electric Company (T.R.E.C). The results from the different baseline scenarios are presented with peak load day. As a reference, the average load in August 2010 is also shown. Figure 4 provides a visual representation of how different penetrations of PHEV-20s recharging at typical household electrical outlets might affect electricity load in Tehran.

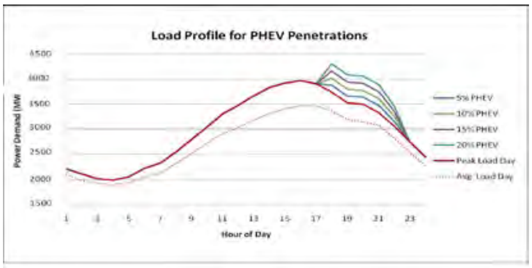

Figure 4. Load profile for PHEV-20 with varying penetrations charging under Scenario 1.

As shown by the peak load day and average August load curves, electricity load is the lowest (below 2500MW) between midnight and 8 am. Electricity generation begins to ramp up starting at 4 am up until 4 pm where it peaks. Electricity load decreases at a faster rate than its initial ramp-up and between the hours of 7 pm and 9 pm, load levels are sustained for a brief period. Peak hours roughly occur between 2 pm and 6 pm. The scenario above represents vehicle owners that all recharge at the same time in the evening (6pm) resulting in a sudden spike in demand.

Figure 5 represents a continuous charging scenario, where up to 50% of PHEV owners could begin to recharge their vehicles at any one particular time. While its probable that PHEV owners will follow a more structured recharge pattern, this scenario helps demonstrate how free access to recharging can spread the demand throughout the day, with slight fluctuations.

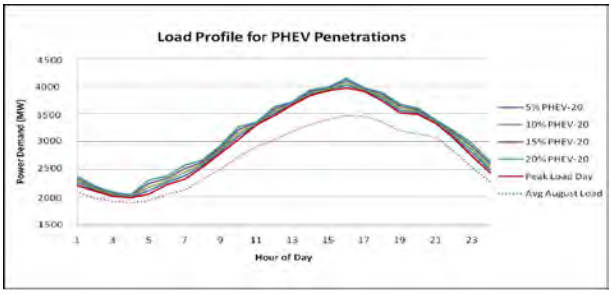

Figure 5. Load profile for PHEV-20 with varying penetrations charging under Scenario 2.

The amount of PHEV-20s that are allowed to charge at any given time is constrained to 50% in the above figure. Open access to the power grid for PHEV owners in this scenario distributes the additional power demand throughout the day, creating a completely new load profile curve.

A more realistic scenario is represented in Figure 6, where recharging occurs as a normal distribution around a specific time period. In this case, it is assumed that most PHEV-20 owners will begin recharging once home from work, around 6 pm.

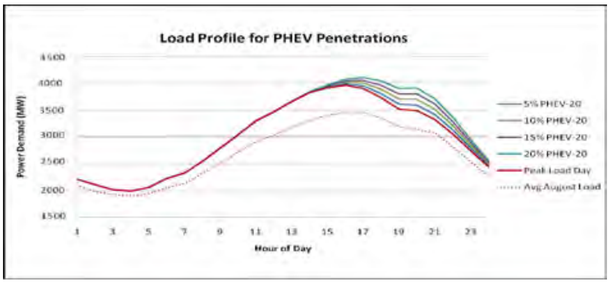

Figure 6. Load profile for PHEV-20 with varying penetrations charging under Scenario 3.

Under Scenario 3, the initial wave of PHEV owners begin charging at 3 pm, and at 6 pm, almost 20% of the owners begin charging. Since the PHEV-20s that connected to the grid between 3 and 5 pm still have not finished fully charging, this lengthens the amount of load necessary to meet demand. The maximum additional electricity demand in this scenario occurs around 8 pm and the last set of PHEV-owners charge at 10 pm, requiring additional power into the late nighttime hours.

The additional power demand at any given hour for the simultaneous scenario represents the load that is sustained for the duration of the charge, in this case, over four hours. Whereas the simultaneous demand occurs over a short period, the continuous charging maintains a consistent load on the grid throughout the day with much smaller power required. The range for the normal distribution scenarios display the lowest power demand when the fewest PHEV-20s are charging, and the largest demand which occurs at 8 pm, when most vehicles are connected to the grid.

6. Time of Day Charging Variations

The first variation from the baseline scenario is altering the time of day that charging of plug-in hybrid vehicles begin. Shifting the charging to the morning creates the potential for additional load during peak hours. Figure 7 below shows the load profile for the peak day, applying a morning (mean hour of 9 am) charge to the load curve.

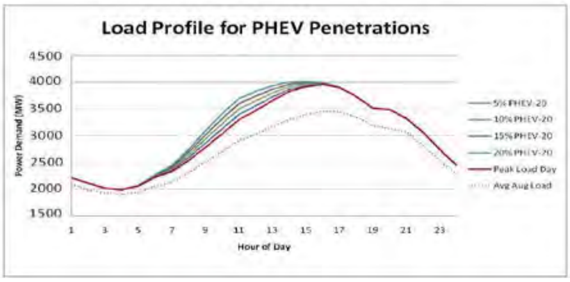

Figure 7. Load profile for PHEV-20 with aarying penetrations charging under a morning (9 am) normal distribution scenario.

As the morning charging scenario demonstrates additional that could occur when PHEV owners plug-in their vehicles after the morning commute leg, the following scenario shows how a nighttime charging scenario might impact Tehran's grid, as shown in Figure 8.

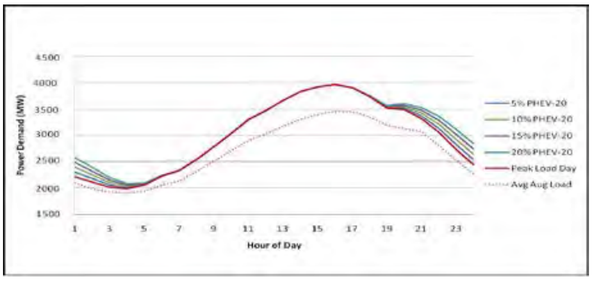

Figure 8. Load Profile for PHEV-20 with Varying Market Penetrations Charging under a Nighttime (10 pm) Normal Distribution Scenario.

Charging the PHEV-20s around a mean hour of 10 pm creates additional demand during the hours when load is diminishing, and reaches into hours when load is the lowest (3 and 4 am). Although the additional demand by PHEVs will ultimately require more electricity generation, charging during the nighttime hours, as shown above, helps to flatten the load curve. Utilizing electricity generation resources into hours when load is low and some electricity is unused, improves efficiency. Although more electricity supply is necessary to meet the demand from PHEVs in all cases, charging at night reduces the need for generating resources to be turned off and back on again.

7. Discussion

Under the simultaneous charging sharp increases can incur and although this is unlikely, it is important to understand this as a potential worst case scenario. The second recharge scenario, where less than 50% of PHEV owners are actively charging their vehicles, the overall load profile experiences a shift to meet the elevated demand. Although vehicle owners may have the capability to recharge their vehicles multiple times per day, due to the smaller battery power capacity of PHEV-20, vehicle owners may not frequently recharge. For longer electric range PHEVs, such as a PHEV-60, or larger vehicle designs, such as Sport Utility Vehicles (SUVs) which require more energy, the battery may require multiple recharges throughout the day, if the goal is to fully utilize electric drive capability. The final recharge scenario, where recharging follows a normal distribution around 6pm, demonstrates a more realistic behavior pattern. While no sharp increases in demand are expected, it is anticipated that a gradual ramp up in load demand occur during the late afternoon hours and that these resources would be utilized into the evening hours.

8. Conclusion

The results of the study have provided insight into the how Tehran's electricity grid may be impacted from the introduction of plug-in hybrid vehicles. Hours of the day when recharging is expected to occur in large numbers, such as when commuters arrive home from work, can have significant impacts on demand. In the absence of dramatic infrastructure changes with respect to charging stations for PHEVs, most owners will recharge using standard 120V/15A electrical outlets. The charging of PHEV-20 under a 120V/15A circuit would not inconvenience most vehicle owners. The time of day for recharging plug-in hybrid vehicles is an important factor to be considered when planning for this new technology. Late evening hour recharges create additional demand when electricity generation begins to ramp down, only requiring existing generating units to be utilized for a longer duration. If the addition of recharge stations in parking lots where incorporated into the scenario, it would be possible for a portion of vehicle owners to recharge when generation is beginning to ramp up, as shown in the morning charging scenarios.

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