Topic Paper #19

The Interaction Between Plug-in Electric Vehicles, Distributed Generation, and Renewable Power (Electric Vehicles for Distributed Storage)

On August 1, 2012, The National Petroleum Council (NPC) in approving its report, *Advancing Technology for America's Transportation Future*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Task Groups and/or Subgroups. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The Interaction Between Plug-in Electric Vehicles, Distributed Generation, and Renewable Power

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1 Introduction

For roughly 100 years, automobiles and electric power have evolved on parallel, but independent paths. Automobile reliance on petroleum has remained unchanged, and electricity generation has continued to rely on large, central facilities utilizing diverse energy sources ranging from water, to coal, to uranium. Automobile transportation and electric power generation are currently undergoing the most substantial changes in their histories. These changes will force society's two largest consumers of energy to collide. The interaction can either be very detrimental or extremely beneficial depending on the technologies and management strategies employed to best integrate electric and hydrogen powered vehicles with distributed generators and sustainable, but intermittent, renewable power sources.

Electric vehicles can act as energy storage devices, controllable loads, and potentially dispatchable generators. In these capacities, they can serve to compliment the intermittent operation of large-scale wind and solar power sources. Additionally, electric vehicles can aid the operation and economic justification of efficient distributed energy resources. At the local level, the plug loads associated with transportation may overwhelm existing distribution infrastructure, necessitating distributed generation.

2 Generation and Transmission Scale

2.1 Electric Grid

2.1.1 Integration of transportation and the electric grid

The integration of electric drive into passenger vehicles has been increasing dramatically. From standard hybrid vehicles having relatively small battery packs and motors that can mitigate the efficiency impacts of vehicle dynamics on combustion engines, to plug-in hybrid vehicles (PHEVs) enabling some portion of vehicle energy to be derived from the electric grid, to pure battery electric vehicles (BEVs) that rely entirely on grid electricity, and ultimately to fuel cell electric vehicles (FCEVs) capable of generating electricity cleanly onboard via a fuel cell, the advantageous transition to full electric drive appears inevitable. Electric drive offers substantial vehicle performance benefits including increased efficiency, improved torque and power characteristics, improved power density leading to advances in vehicle architecture for safety and comfort, reduced noise, and few moving parts for greater reliability.

As vehicles rely more heavily on electric drive, traditional electric generation energy sources and transportation energy sources will become much more intertwined. PHEVs and BEVs, collectively known as plug-in electric vehicles (PEVs), directly require grid electricity at increasing levels proportional to the number of electric miles travelled. Historically, coal, natural gas, nuclear, hydroelectric, and more recently, renewable wind and solar energy have been dedicated to the domain of electricity generation while petroleum has been predominately utilized for transportation. The advent of PEVs opens the door to allow transportation to utilize the wide array of energy sources previously available only to stationary power devices. Similarly, hydrogen powered FCEVs will require the same energy sources as electric generation. For example, hydrogen can be generated from reformation of natural gas, gasification of coal, or electrolysis of water using any electricity source. Resultantly, regardless of the eventual market proportioning of PEVs and FCEVs, transportation and stationary power will ultimately rely on the same sources of energy.

Resultantly, as society aims to reduce greenhouse gas emissions, improve urban air quality, and provide secure energy resources, it is imperative that future vehicle and electricity generation technologies be assessed as a parallel, integrated system.

2.1.2 New management strategies required to manage intermittent renewable power

The average electric generation mix in the United States currently consists of 68% combustion of coal and natural gas. Renewable wind, solar, biogas, and geothermal sources account for just 4.5%. Greenhouse gas reduction goals such as California's AB32, Renewable Portfolio Standards (RPS) mandated in 29 states to increase renewable energy sources, and increased siting, permitting, and operating costs for combustion technologies are driving a shift to greater portions of renewable power. Though environmentally preferable to traditional sources, wind and solar electricity sources are intermittent. The inability to accurately predict or control this power production will become increasingly troublesome as the portion of renewable power grows.

New energy management strategies are necessary to best utilize intermittent power which can lead to supply disruptions on a number of timescales.

Yearly: Peak loads are challenging for utility to meet (Figure 1)

Seasonally: Significant seasonal variation exists in wind and solar availability

Daily: Diurnal load variation requires most generation facilities to considerably turn down at night; this ability and operating profile increases costs, emissions, and fuel consumption (Figure 2)

Minutes: Intermittency of solar and wind resources will become an additional significant challenge as Renewable Portfolio Standards (RPS) push renewable penetrations to 20% or higher (Figure 2)

<Seconds: Power quality

Three solutions exist that can address the short term intermittency problems: (1) load shedding, (2) energy storage, or (3) dispatchable power generation. Careful integration of transportation and the grid can allow vehicles to serve as any, or all, of these 3 intermittency solutions. A vehicle charged by the grid represents a potential load that can be removed (1, load shedding), reducing the peak grid power demand and relieving the stress caused by temporary low renewable output. Additionally, the battery packs onboard vehicles can serve as energy storage (2, energy storage) if drivers can be coordinated to charge at times when excess renewable electricity is generated. Charging during times of excess will in turn reduce the need to charge during peak times. Future technology enabling vehicle energy to supply the electric grid, often referred to as vehicle-to-grid, or V2G, may enable vehicles to serve as dispatchable electricity sources (3, dispatchable power generation) that could be called upon as needed in times of low renewable output. However, the technology, economics, and overall attractiveness of V2G is still uncertain and likely decades from implementation, even in a best case scenario given the coordination necessary between consumers, automakers, and utilities.

PEVs can be used as load shedding devices based on existing mechanisms between utilities and customers. During peak load demand times (e.g. hot summer day with high air conditioner use), or during periods of low renewable power generation (e.g. when the wind is not blowing) the utility can either reduce the load, or supply more power. Current methods for reducing load include contractual agreements whereby consumers agree, for example, to turn off air conditioning or stop industrial operations when directed by the utility. In exchange, the customers receive monetary incentives. Homes and businesses are currently being retrofitted with "Smart Meters" in many markets throughout the U.S. which can access real-time rate information provided by the utility and communicate with appliances. Consumers will then have the opportunity to pre-program these appliances to run only when it is economical. By controlling rates, the utility ultimately controls load. A PEV could interface with the utility in the same way, allowing the utility to provide some control over when the vehicle is charged.

PEVs could be used as dispatchable power plants. The current method of supplying additional dynamic power is to call on "peaker plants" which can provide more power on short notice. Currently, natural gas fired turbines supply the bulk of peak power with a portion coming from hydro-electric facilities. In the future, V2G strategies may enable stored energy onboard vehicles to supply power to the grid if the vehicle is plugged-in, if the proper smart metering is established, and if the utility and EV owner agree on timing and pricing. The need to use PEVs to meet peak loads would be rare, likely on the order of only a few hours of each year, as shown in Figure 1.

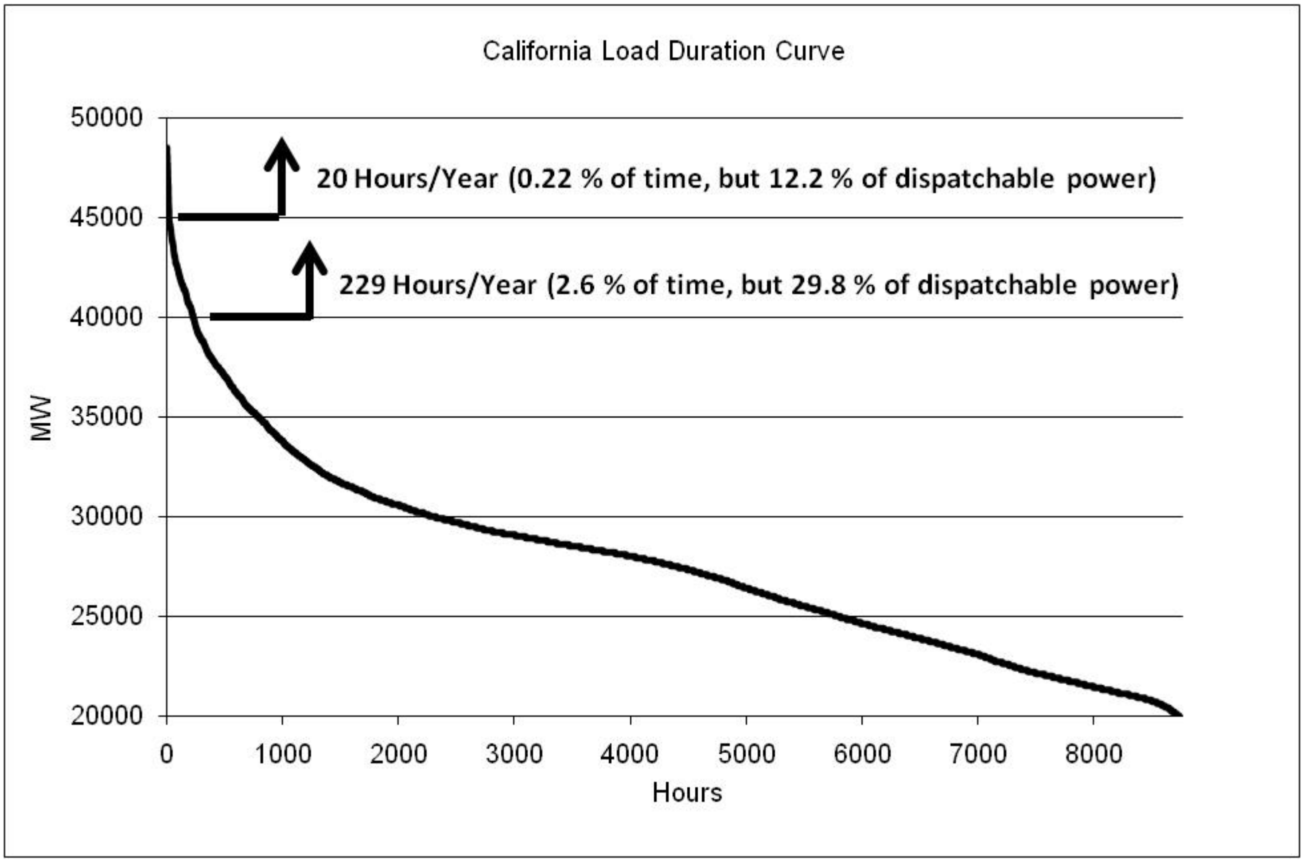

Figure 1. Hourly California system load ordered from highest to lowest.

Figure 1 shows California electric load in MW versus each hour of the year (8,760 hours). The hours are arranged in order of highest to lowest load. This clearly shows that the high peak power requirements only occur for a few hours each year. Nearly 1/3 of dispatchable generation capacity is required to meet the load demand for just 229 hours each year. 12% of the dispatchable generation is only used for 20 hours each year.

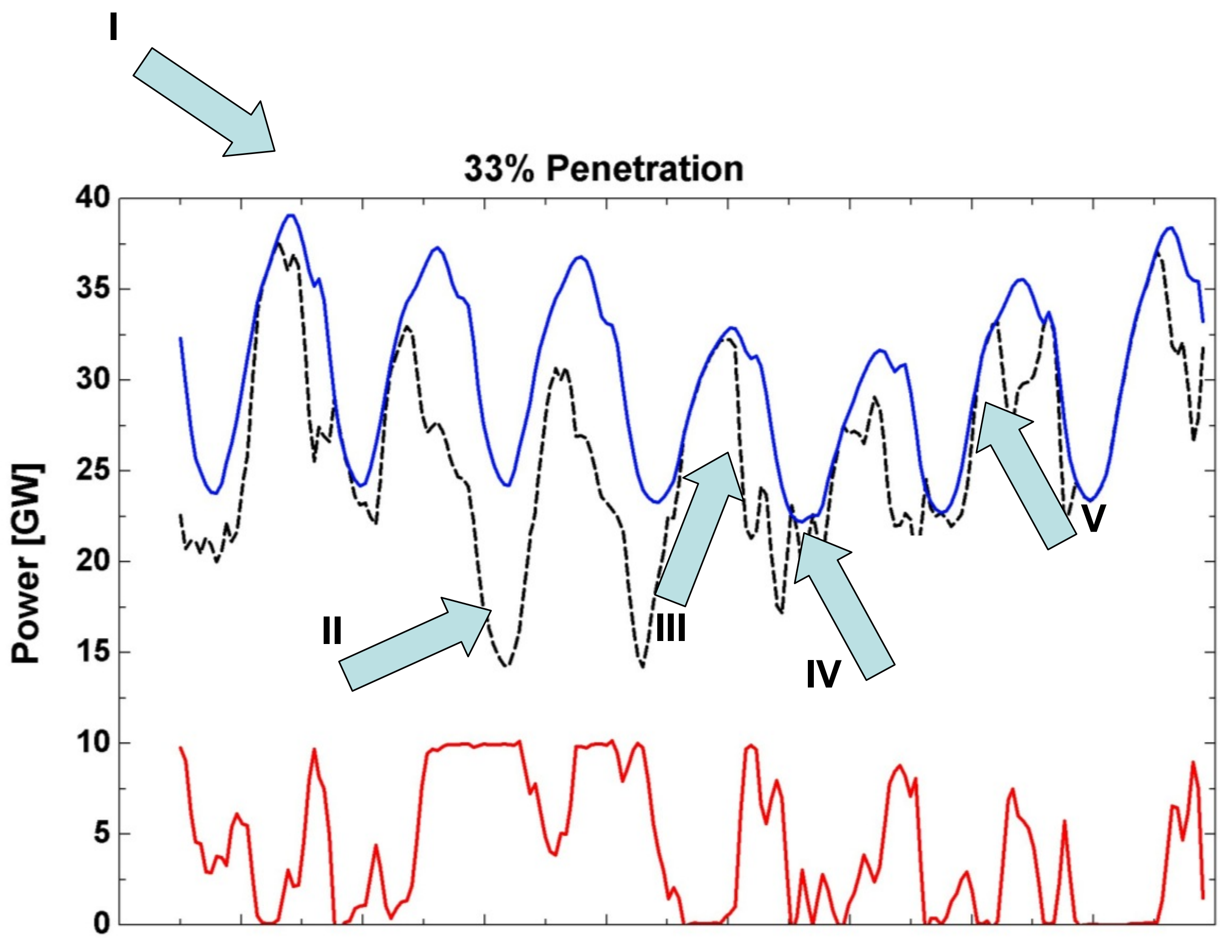

Figure 2. California system load for one week showing diurnal variation and impact of 33% wind power on other generation types.

Figure 2 shows California load dynamics over a 7 day period assuming a 33% penetration of wind power (33% renewable is mandated in California for the year 2020).

- Arrow I shows a situation where wind power is low and load is high; other generation is forced to meet the load requirements.
- Arrow II shows a situation with high wind power and low statewide load. The power output required by other generators at this point is less than half of what is required at Arrow I.
- Arrow III shows wind power output increasing very rapidly. In order to utilize this wind resource, the power output of other generators must drop very rapidly.
- Arrow IV shows a series of significant power level changes required in a short time period.
- Arrow V shows the steep power increase required of other generators when wind power is very low.

As utilities strive to meet RPS goals with non-dispatchable solar and wind resources, dispatchable power sources and controllable loads will become even more valuable.

2.1.3 PEVs can either mitigate or severely worsen the impact of intermittencies

PEVs have the opportunity to play a major role in the integration of renewable power sources into the existing grid mix. Figure 3 shows the Southern California Air Basin (SoCAB) electrical load profile for a peak summer day having a characteristic dip in the early morning hours corresponding to low activity and lower temperatures, and an early afternoon peak corresponding to high activity and air conditioner power consumption.

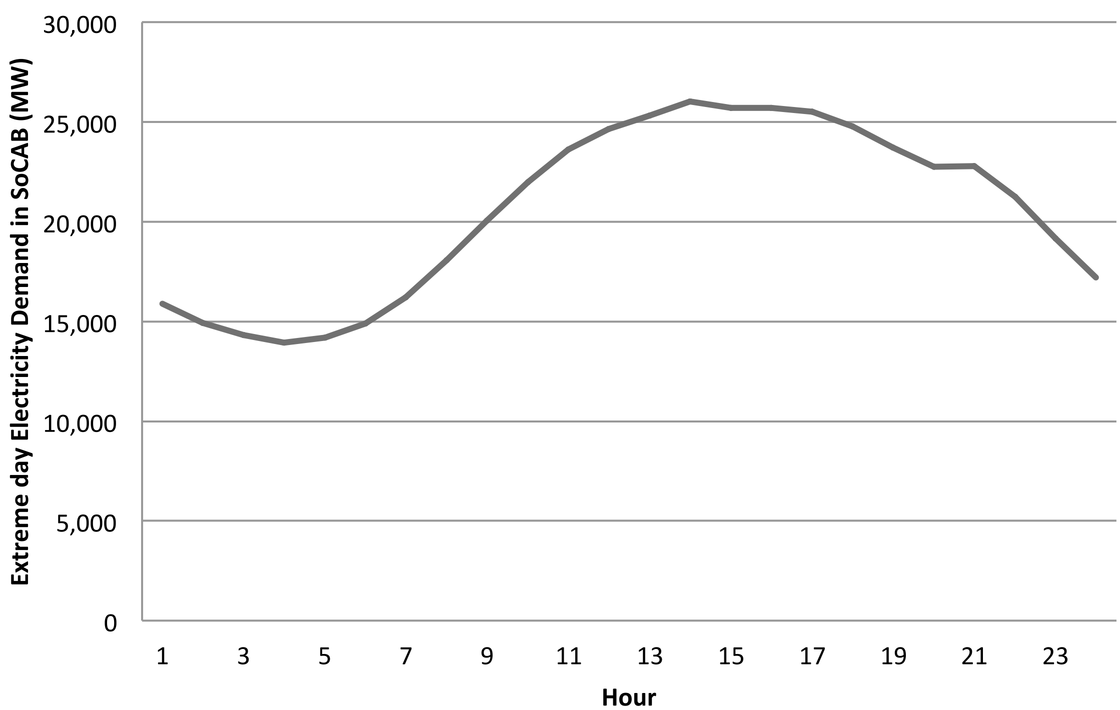

Figure 3. Temporal electricity power demand for extreme summer day in southern California.

In a longer term outlook, the intermittent peak-and-valley nature of wind and solar power will tend to shift the daily occurrence of the minimum and maximum effective load demand to unconventional times, affecting the compatibility of the electric grid system with technologies that have time-constrained dispatchable loads. As a result, the grid-preferred optimum charging times may change from what they are today, and may even change from day to day based on wind and solar irradiation occurrences.

At present, the maximum load demand occurs typically during the daytime hours when commercial and industrial sectors become active, or during the early evening hours when residential loads peak as a result of people returning home from work and utilizing their in-home appliances. Rate structures for the price of electricity, forecasting of load demand and the scheduling dispatch of electric generators are highly dependent on knowledge of this pattern. As intermittent renewables are added in large amounts to the system, however, this pattern changes and at certain renewable penetration levels, the occurrence of the maximum load demand becomes unpredictable. Solar power will act to reduce the daytime peak, shifting the maximum to evening or morning hours. Wind power may or may not occur during the time of the new peak depending on region and strength of intermittency, and therefore the peak of the effective load demand that must be managed becomes difficult to predict.

This has implications for technologies which rely on being able to provide benefit by acting during certain time periods. For example, one assumption is that PEVs should charge during the nighttime hours when the effective load demand is at a minimum. With increased intermittent renewable penetration levels, however, the nighttime hours designated for charging may or may not necessarily be a time of minimum load, especially when other time-constrained dispatchable loads are considered.

Therefore, in order to address these challenges, the load-balancing infrastructure must be refined such that the utilization of installed generator resources remains high while maintaining system robustness, reliability, and higher renewable penetrations. Energy management strategies such as the implementation of energy storage at different scales, and implementing and increasing the flexibility of dispatchable loads such as PEV charging present a multi-faceted set of options for helping to mitigate these challenges when implemented synergistically.

2.2 Local DG and DER

2.2.1 Local DG and DER (Distributed Energy Resources) can offset large-scale remote renewable intermittencies

Electric generation has historically occurred at large, central facilities requiring transmission and distribution infrastructure to route power to consumers. There have generally been many advantages to central, remote location of large electric facilities such as improved efficiency of larger heat engines, pollutant emissions located away from population centers, easier distribution of fuel (e.g. coal delivered by rail), and ease of siting and permitting. However, with the advent of clean, quiet, and efficient small generators such as photovoltaic panels, micro gas turbines, or stationary fuel cells, many advantages of localized power production, or distributed generation (DG) can be realized.

Distribution of power generation enables the utilization of waste heat from combustion engines or fuel cells. The heat can be used for industrial processes, space, or water heating to offset other heat sources, generally the combustion of natural gas. In this configuration, DG installations can easily achieve 70-90% fuel-to-useful product efficiency. Additionally, DG eliminates transmission system losses, allows for local control, and increases power reliability when grid connected.

Stationary fuel cells and ultra-low emitting gas turbines provide generation options for urban areas where traditional large plants cannot meet governing regulations. This allows additional power to be generated to mitigate production sags that could occur as the result of high renewable penetrations. As the grid transitions to real-time pricing with smart meters and more dynamic generator operation due to renewable power, price fluctuations will increase and widen. Controllable DG sources will facilitate significant economic benefits.

2.2.2 DG Technologies

2.2.2.1 Fuel Cells

Fuel cells are devices that electrochemically combine fuel and oxidant to efficiently, and quietly, generate electricity while emitting virtually zero criteria pollutants. Fuel cells have been utilized on all manned space missions and have reached broader commercial success as stationary generators in the 21st century. Hydrogen powered fuel cells for transportation applications are nearing commercialization, likely in 2015 in select worldwide markets.

Unlike the random fuel and oxidant reactions of combustion processes, fuel cells control the flow of electrons to directly produce DC electricity, without the need for a rotating generator. Fuel cells have high electrical efficiencies (as high as 50%), produce near negligible amounts of pollutants, and emit less carbon dioxide than traditional combustion power sources. Unlike combustion engines, fuel cell efficiency is virtually independent of the size of the device. Consequently, a small, quiet fuel cell located in a residential neighborhood can be competitive on an efficiency basis with an enormous combustion power plant located many miles away. This attribute can allow fuel cell waste heat to be readily integrated into the built environment in a distributed generation network.

Several types of fuel cells have been commercialized for distributed applications, with differences characterized by materials, fuels, and temperatures. Proton Electrolyte Membrane (PEM) fuel cells generally operate below 100°C and require high purity hydrogen fuel. Phosphoric Acid Fuel Cells (PAFCs) operate around 200°C on slightly less pure hydrogen. Molten Carbonate Fuel Cells (MCFCs) operate near 650°C and Solid Oxide Fuel Cells (SOFCs) run at temperatures as high as 1000°C. Due to these high temperatures and the catalytically active anode chambers, both MCFCs and SOFCs can operate on a variety of hydrocarbon fuels, most commonly methane.

Low temperature PEM fuel cells designed for residential and light commercial distributed generation applications are commercially available from companies such as Plug Power and ClearEdge. Due to the requirement of this technology for pure hydrogen fuel, and the common supply of residential natural gas, each is fitted with a small reformer system that converts natural gas to hydrogen as needed. The technology has reached a maturity level sufficient to meet performance and durability requirements, but the cost and size must be reduced modestly before mass commercial adoption is likely.

High temperature fuel cells such as Fuel Cell Energy's DFC 300 molten carbonate fuel cell operating at roughly 650°C and UTC Power's lower temperature PureCell 400 phosphoric acid fuel cell operating at roughly 200°C produce electricity at nearly 50% efficiency while providing high quality heat with virtually zero pollutant or noise emissions. These devices serve as ideal distributed generators if they can operate in a constant, baseloaded fashion. Neither technology currently offers dynamic load ramping capability, due in part, to their need to maintain high operating temperatures and avoid slow heating and cooling cycles. As a result, direct PEV charging, preferably through direct current, would provide an excellent means to utilize excess power during periods of low power demand and allow the fuel cells to operate at constant power.

Another fuel cell technology, currently undergoing final testing before an August 2011 deployment in Fountain Valley, California, is the use of a high temperature fuel cell to cogenerate electricity, heat, and hydrogen. This recently developed and very promising strategy for generating hydrogen from methane tri-generates electricity, thermal energy, and hydrogen for vehicle refueling on a distributed scale. It is also referred to as an energy station. The station can utilize either a molten carbonate or solid oxide fuel cell system operating on a hydrocarbon fuel to produce all three products. Theoretical efficiencies for these systems can range from 59 – 85%, depending on the system operating parameters, fuel utilization, and internal or external reforming systems (Margalef, et al., 2011), making them more efficient than small-scale methane reformers and competitive with large-scale reformation plants for the generation of hydrogen, while correspondingly generating electricity at nearly 50% efficiency.

A HTFC energy station can also be operated on biogas. In this case, the products will be renewable, including the hydrogen fuel. This is an exciting strategy for hydrogen production because of the vast amount of potential for biogas in the United States. Landfills, green waste facilities, and wastewater treatment facilities are all potential sources for biogas that could power a HTFC energy station, or a standard stationary fuel cell.

2.2.2.2 Combustion distributed generation technologies

DG combustion technologies such as micro gas turbines (MTGs) or reciprocating engines provide better load following capability than commercially available fuel cell products. These devices have short start-up times on the order of seconds to minutes, and can often reduce power output by at least 50% if required. However, they do produce greater pollutant emissions and provide lower efficiency than fuel cells, especially at part load conditions. The dynamic capability and fast start-up of combustion DG technology can be used to offset power intermittencies created by renewable power sources and load fluctuations caused by PEV charging.

2.2.2.3 Intermittent distributed generation

Deployment of intermittent DG technologies such as rooftop mounted photovoltaic (PV) systems has grown substantially throughout the United States due to increased product offerings coupled with national and local incentives. PV power sources can provide fairly predictable average daytime power which varies seasonally based on the position of the sun. This output can match particularly well with typical summertime peak loads caused by air conditioner use during the hottest parts of the day. PV could be coupled to a battery storage device in order to recharge PEVs at nighttime (e.g. for home based systems) or utilized in real time to charge PEVs during the day (e.g. workplace based systems), assuming typical driving patterns whereby vehicles are parked at a residence in the night and at a workplace in the day.

2.2.3 Possible uses of DG technologies

2.2.3.1 Distributed generation can be used to directly charge PEVs

In addition to aiding the integration of intermittent renewable power sources into the existing grid network, DG sources can be used to directly charge PEVs. This avoids transmission and distribution losses, and has the potential for even greater efficiency improvements if direct current power is used. Stationary fuel cells, microturbines, and solar photovoltaic sources all produce DC electricity. Generally, this must be inverted, at a loss in efficiency, through power electronics to the commonly used form of AC. However, since batteries require DC electric input, potential exists to bypass the conversion process and charge vehicles directly, resulting in roundtrip efficiency improvements on the order of 10 percent.

2.2.3.2 PEV charging as a dispatchable load

DG becomes most economically viable when the operator can run the device at maximum rated output as often as possible. This enables the generation of the most power in a given period of time, thereby reducing the financial payback period. However, commercial, industrial, or household loads served by DG sources are rarely constant throughout a 24 hour period. Therefore, the DG system must either have the ability to operate dynamically to match the load, often at a loss of efficiency, equipment lifetime, and financial return, or have the ability to export power back to the electric grid. Grid connection rules vary from state-to-state based on generator type size.

One promising alternative may be to use excess DG generated power to recharge PEVs. This power would be low cost and beneficial to both the DG operator and the vehicle owner. As the normal DG load increased, vehicle charging could taper off; when normal DG loads reach a lull, PEV charging could be encouraged. The more constant utilization of DG would also enable more continuous heat production, often a limiting factor in DG applicability.

2.3 Energy Storage

The implementation of energy storage is one strategy which allows electric grid operators to shape the effective load demand in a manner suited for the load-balancing infrastructure (electric generators, transmission infrastructure).

Energy storage can be used to mitigate intermittencies in renewable resource power output by decoupling fluctuations in wind or solar power generation from the electric grid and essentially rendering large scale renewable resource installations as partially-dispatchable generators, provided that the storage system is of sufficient scale. Additionally, energy storage can respond to variations in the effective load demand to maintain parameters relevant to the load-balancing infrastructure within acceptable ranges (capacity factor, peak capacity) and to a limited extent, selectively placing effective load demand peaks and valleys according to predictable, planned patterns in time. Depending on ramp-rate and power output, energy storage devices can provide contingency power, taking this burden off of conventional generators.

2.3.1 Electric Batteries

Electric batteries are electrochemical devices which allow the storage of electrical energy as chemical potential within an electrolyte material via the use of oxidation-reduction reactions which promotes the flow of ions when electrodes are connected to a load source to produce an electric current. For use as an energy storage medium, rechargeable batteries with reversible reactions must be used.

Electric batteries vary greatly in terms of the amount of energy that can be stored, maximum number of charge and discharge cycles, and response time, due to significant variation in the specific chemistry of battery types. A few example types are Lithium-Ion (Li-ion), Nickel-Cadmium (NiCd) and Vanadium redox batteries (flow batteries). In general, however, electric batteries tend to exhibit the following properties:

2.3.1.1 Relatively low energy capacity

The amount of energy that can be stored per unit mass of electrolyte is fairly low when compared to the scale of other energy storage systems and the scale of electricity used on the grid, on the order of 0.14 MJ/kg to 0.46 MJ/kg. This is due to the fact that chemical electrolytes are limited by the amount of charge that can be stored before reaching saturation. Therefore, fairly large masses of electrolyte are required to store a significant amount of energy.

2.3.1.2 Relatively high power capacity

Electric batteries are able to provide large amounts of power since the timescale of the redox chemical reactions is very short (from a load balancing perspective) and discharge power is limited primarily by practical limitations such as heat generation and damage to the structure of the battery.

2.3.1.3 Fast response time

Electric batteries respond very quickly to changes in power demand or charge, since the timescale of the redox chemical reactions is very short (from a load balancing perspective) and the system does not contain any physical inertia which must be overcome to charge/discharge the system. Electric batteries can respond as quickly as the millisecond timescale.

2.3.1.4 High round-trip efficiency

Electric batteries exhibit charge/discharge cycle efficiencies on the order of ~90% depending on battery chemistry and set up, as the redox reactions exhibit minimal losses.

2.3.1.5 High cost

Electric batteries tend to use fairly exotic materials and require involved manufacturing processes. Combined with a low energy density, these systems tend to be expensive when used in large amounts compared to other energy storage systems.

Based on these properties, electric batteries are likely suited to provide mitigation of fast timescale, large fluctuations in either load demand or renewable power output which do not exhibit long duration (energy) periods. Examples include quick increases or decreases in wind power due to gusts, or fast timescale variability associated with cloud passes over solar power installations. Outside of the load-balancing application, the very fast response time of batteries make such units suited for mitigating unwanted fluctuations on the transmission and distribution grid for managing power flow.

2.3.2 Pumped Hydropower Storage

Pumped hydropower storage involves the operation of conventional hydropower plants in a reverse operating mode. Conventional hydropower plants store potential energy from height differences in water levels, producing power by releasing water across the height difference and capturing gravitational potential energy by placing a turbine at the bottom of the height difference. This can be thought of as the discharge process. The mechanical work done on the turbine is then converted to electricity. In a pumped hydropower storage plant, the additional capability for using water pumps to pump water flow back up the height difference is installed, effectively charging the storage system. With this capability, the power plant gains significant flexibility in regulating its power output or power draw in response to renewable intermittency events or fluctuations in the load demand. Pumped hydropower plants tend to exhibit the following properties.

2.3.2.1 High power capacity

The power capacity of pumped hydropower plants are limited primarily by the maximum volume flow of the river and the amount of turbines placed in the plant. The former is very high and the latter is completely customizable.

2.3.2.2 *High energy capacity*
The creation of very large reservoirs within existing geographic features allows for the storage of a very large amount of water, and therefore a very large amount of energy.

2.3.2.3 *Moderate response time*
The timescale of response for pumped hydropower plants is limited by the modulation of water flow and the inertia of the turbines, which while small, is still significant and limits response to the multi-minute timescale.

2.3.2.4 *High round-trip efficiency*
The primary parasitic loss in pumped hydropower plants is the use of the pump, which has a very high isentropic efficiency since the liquid is incompressible. Round-trip efficiencies are on the order of 80-85%.

2.3.2.5 *Relatively low cost*
Since pumped hydropower plants would be created from retrofits of existing conventional hydropower plants and the components required are standardized and abundant, using and implementing these systems are relatively cheap.

2.3.2.6 *Geographically Limited*
Pumped hydropower plants can only be sited where conventional hydropower plants are sited: on large rivers which have maximum capacity constraints. Additionally, the use and proliferation of such systems is limited by water use and flood control constraints.

2.3.2.7 *Scale Limited*
Pumped hydropower plants tend to be very large installations since they are based at dams, therefore these installations are not suited for small scale applications.

Based on these properties, pumped hydropower storage tends to be best suited for bulk, centralized energy management on the electric grid. These properties render these systems suitable for load-balancing regulation in a wide range of applications such as renewable intermittency mitigation, load fluctuation management, and providing contingency power as long as it is tied directly to the grid and the application is large scale.

2.3.3 Large Scale Hydrogen Storage
Large scale hydrogen storage technology for use as electricity storage medium is less mature than electrochemical batteries or pumped water storage. The concept involves the use of electric power to produce hydrogen through electrolysis during times of excess renewable power, which is then stored in compressed cylinders or underground geological formations. The stored hydrogen can then be used to fuel a hydrogen fuel cell or combustion engine to produce electric power for load management, or used as a transportation fuel for hydrogen vehicles. The roundtrip efficiency of hydrogen production via electrolysis and subsequent conversion back to electricity in a fuel cell is poor compared to other storage methods. However, the potential quantity of energy stored is very large, and the ability to decouple energy storage from power capacity is attractive.

A promising scenario would be to utilize excess renewable power to generate hydrogen through electrolysis, and then use the hydrogen as a vehicle fuel. This route may provide good economic benefit to renewable power providers if a strong vehicle fuel demand develops for hydrogen. Additionally, this path avoids the inefficiencies and equipment costs of converting the hydrogen back to electricity, and overcomes the challenges of siting electrical transmission infrastructure required to direct remote renewable power to urban areas. Hydrogen pipelines could likely be more easily sited due to limited visual impact, an oft cited complaint from residents near transmission line corridors.

3 Distribution scale

3.1 Impact on distribution circuits

Many studies have been conducted on the impact of PEVs on the current grid and show that even at high penetrations, the vehicles' electricity demand is not comparable to the magnitude of the base case demand and the grid capacity would be enough to support this new load. However, the impact of PEVs on the distribution grid has not been as rigorously studied. The addition of a PEV to a household can result in doubling the household electricity demand peak, and having a cluster of these vehicles on a distribution transformer can result in an increase in the transformer temperature, harmonics, and consequently significant loss of the transformer life. These effects depend on charging profile, vehicle penetration, driving pattern, and time of charging of vehicles. Perhaps the most significant factor is the charging profile: these issues increase linearly as the penetration of PEVs increase. One study including 5 homes with 2 PHEVs showed that no scenario results in a transformer overload except all charging at a peak time with quick charging (Level 2), and concluded that the new load should be manageable in all cases with advanced and smart metering. Other studies have been conducted using various methods with different time resolutions for different regions, all concluding that in order to operate a more reliable and economic grid and to prevent transformer loss of life and outages, smart communication between the vehicle and the grid would be necessary. Due to these conflicting studies, the potential magnitude of the PEV impact on distribution grids requires further research to be fully understood.

3.2 PEVs present a new load on transformers

Given the relatively high cost of PEVs in the near-term, early consumers will likely have economic freedom and make purchases based on other factors such as environmental awareness. Consequently, wealthy communities may experience relatively high early adoption rates of PEVs, even if average nationwide sales are quite low. As a result, secondary distribution service transformers serving 8-12 homes may experience dramatic power increases if several of those homes implement EV charging. This seems particularly likely given the push towards home installation of Level 2 charging with 30-40 amp current draws, combined with lack of residential time-of-use electricity rates. Without economic incentives to shift power consumption, many consumers will simply begin charging when they arrive at their homes, often simultaneously around 5:00-6:00 pm after a normal workday.

Time-of-use pricing structures, or even real-time price signals, will off utilities a method to control PEV charging times. With adequate control, utilities may be able to use the potential load of PEVs to not only avoid transformer problems, but to improve hardware utilization throughout the day and levelize power demand.

4 Summary

In the early years of PEV commercialization, it is likely that wealthy, environmentally conscious consumers will purchase PEVs and install residential photovoltaic generation systems. This combination of energy sources and sinks at the end of the utility distribution system will present interesting and challenging hardware, management, and socio-economic challenges. The large battery packs onboard vehicles can mitigate the uncertainty associated with intermittent renewable power and provide dispatchable loads to help better utilize distributed energy resources. Concurrently, the addition of clean, environmentally preferred distributed power generation can provide a more sustainable fuel for transportation.