

# **IMPACT ASSESSMENT OF PLUG-IN HYBRID VEHICLES ON ELECTRIC UTILITIES AND REGIONAL U.S. POWER GRIDS PART 1: TECHNICAL ANALYSIS**

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## **ABSTRACT**

The U.S. electric power infrastructure is a strategic national asset that is underutilized most of the time. With the proper changes in the operational paradigm, it could generate and deliver the necessary energy to fuel the majority of the U.S. light-duty vehicle (LDV) fleet. This would reduce greenhouse gas emissions, improve the economics of the electricity industry, and reduce the U.S. dependency on foreign oil. This paper and a second companion paper investigate the technical potential and economic impacts of using the existing idle capacity of the electric infrastructure in conjunction with the emerging plug-in hybrid electric vehicle (PHEV) technology to meet the majority of the daily energy needs of the U.S. LDV fleet.

This initial paper estimates the regional percentages of the energy requirements for the U.S. LDV stock that could potentially be supported by the existing infrastructure, based on the 12 modified North American Electric Reliability Council regions as of 2002. For the United States as a whole, up to 84% of U.S. cars, pickup trucks, and sport utility vehicles (SUVs) could be supported by the existing infrastructure, although the local percentages vary by region. Using the LDV fleet classification, which includes cars, pickup trucks, SUVs, and vans, the technical potential is 73%, which has an estimated gasoline displacement potential of 6.5 million barrels of oil equivalent per day, or approximately 52% of the nation's oil imports. The paper also discusses the impact on overall emissions of criteria gases and greenhouse gases as a result of shifting emissions from millions of individual vehicles to a few hundred power plants. Overall, PHEVs could reduce greenhouse gas emissions, with regional variations dependent on the local generation mix. Total NO<sub>x</sub> emissions may or may not increase, dependent on the use of coal generation in the region. Any additional SO<sub>2</sub> emissions associated with the expected increase in generation from coal power plants would need to be cleaned up to meet the existing SO<sub>2</sub> emissions constraints. Particulate emissions would increase in 8 of the 12 regions. The emissions in urban areas found to improve across all pollutants and regions as the emission sources shift from millions of tailpipes to a smaller number of large power plants in less-populated areas. This paper concludes with a discussion about possible grid impacts as a result of the PHEV load as well as the likely impacts on the plant and technology mix of future generation-capacity expansions.

The second paper (Part II: Economic Assessment) discusses the economics of the new PHEV load from the perspective of a load-serving entity. It discusses the potential downward pressure on rates as revenues increase in the absence of new investments for generation, transmission, and distribution.

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## INTRODUCTION

The U.S. electric infrastructure is designed to meet the highest expected demand for power, which only occurs for a few hundred hours a year at most (about 5% of the time). For the remainder of the time, the power system is underutilized and could generate and deliver a substantial amount of energy needed to fuel the nation's light-duty vehicle (LDV) fleet: cars, pickup trucks, sport utility vehicles (SUVs), and vans. This paper estimates the percentage of the U.S. LDV fleet that could be supplied with energy from the existing U.S. power system without additional investments in generation, transmission, and distribution (T&D) capacities. This paper postulates an electric-vehicle scenario that is based on the concept of a plug-in hybrid electric vehicle (PHEV) with a battery size that would satisfy the daily average driving requirement of 33 miles per day solely on electricity. The battery is charged with electricity from the electric grid during off-peak hours, most of which occur during the night. Driving beyond the daily driving range (i.e., long distances) requires that the PHEV's gasoline engine be used. Because PHEVs are not commercially available, it is not clear if all PHEVs will feature an electric-only operating mode. Preliminary information about the Chevy Volt suggests that this option will be available.<sup>2</sup> However, other manufacturers may only provide a mixed electric-gasoline mode. For the purpose of this analysis, we assumed a vehicle with an electric range of 33 miles.

The analysis in this paper estimates the upper limit of the PHEV (or pure electric vehicles with similar electric performance) penetration without requiring new investment in generation and T&D capacity expansions. This paper should be viewed as a technical potential analysis that attempts to estimate a defensible limit of today's grid infrastructure to support a new transportation load, not as a forecast or prediction of what will happen in the future. We applied a methodology that froze our growing demands for transportation (in terms of vehicle miles traveled) and our steadily growing infrastructure in time and then estimated the percentage of the nation's LDV stock that could be "fueled" by today's grid. This approach deliberately disregards the fact that the penetration of PHEVs will occur gradually and that the electric infrastructure is constantly being upgraded to meet the native load growth of our established and existing end-uses in the residential, commercial, and industrial sectors. Furthermore, the future grid will become "smarter" and "greener," judging from the current investments in advanced metering infrastructure (AMI) and distribution automation, the existing renewable portfolio standards in 23 states and the District of Columbia, and the tightening of criteria emissions regulated by the U.S. Environmental Protection Agency's (EPA's) Clean Air Interstate Regulation (CAIR). In addition, vehicle technology will improve, resulting in cleaner and more efficient vehicles. Customer preferences may change, impacting the current vehicle class mix. Customers may like to replace an SUV with a car or lighter vehicle. Many complex energy policies and customer preference mechanisms need to be addressed in an analysis that looks into the future. By framing the PHEV impact discussion as a technical potential analysis of today's grid and vehicle class mix, we minimize the degree to which the outcome of this discussion is driven by the assumptions of the future power plant mix and vehicle fleet.

Even though we analyzed today's grid with today's LDV fleet and driving behavior, we applied several assumptions about the operating procedures of the entire electricity

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<sup>2</sup> Concept Chevy Volt information available at: <http://www.chevrolet.com/electriccar/>

infrastructure in which the grid has never been operated. We discuss the likely impacts of high utilization of the grid operating near capacity almost all the time.

This paper first describes the methodological approach for estimating the existing idle generation capacity to be used for PHEV charging and then comparing the resulting generation figure (in megawatt-hours, MWh) to the energy requirements of the U.S. LDV fleet for daily driving. The resulting percentage of the LDV fleet constitutes the upper limit of the electrification potential for the LDV fleet, displacing gasoline fuel with electricity. We presume that the transmission and distribution system would be capable of delivering the electricity to the new PHEV load and present a rationale for this assumption. Assuming that the upper limit of the technical fuel displacement potential would occur, we discuss the question of what are the net impacts to the overall emissions as the emission source shifts from millions of vehicle tailpipes to a smaller number of large power plants. There are favorable economic impacts associated with a high fuel displacement scenario. PHEVs provide power sales revenues without requiring additional new infrastructure. This translates into additional profits and, from a regulated electricity industry point of view, puts downward pressure on rates. The economics from both the electricity providers' and the customers' point-of-view are presented in the companion paper (Part II: Economic Assessment).

## **BACKGROUND**

In his 2006 State of the Union address,<sup>3</sup> President George W. Bush identified the U.S. dependency on foreign oil as a major national security issue. In the United States, transportation is the largest consumer of petroleum products of any economic sector. As a consequence, cars, vans, and light duty trucks are a logical target for alternative fuel supplies. High oil prices during 2005, exacerbated by the supply disruption in gasoline products in the aftermath of hurricanes Katrina and Rita, brought concerns about the supply of petroleum to the attention of the public.

These events have increased efforts to identify alternatives to petroleum, including biofuels and hydrogen. For the reasons noted by the President and national security experts, the faster the United States can reduce reliance on petroleum, the better. Rapid transition to new alternative fuels will require significant investment in new fuel production and distribution infrastructure. This is not the case for PHEVs, as the necessary charging infrastructure is already in place. As new alternative fuels enter the market, they can be used in PHEVs to further reduce the need for imported petroleum products.

## **METHODOLOGICAL APPROACH**

The study is divided into two analytical components. The first is an analysis of the upper limit of PHEV penetration using off-peak power for charging the battery. The second is an analysis that assesses the impact on the overall emissions as electricity displaces gasoline in the LDV fleet.

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<sup>3</sup> State of the Union Address available at <http://www.whitehouse.gov/>.

We used a conservative approach to identify the maximum use of PHEVs by restricting our analysis to the existing electric infrastructure that does *not* include expansion of generation and T&D capacity as PHEVs make inroads into the marketplace, increase the electric load, and alter the load shape. Because we do not know when and at what rate PHEVs may penetrate the market, nor do utility planners, constraining our analysis to the current power system infrastructure appears to be a defensible and plausible approach.

Estimating existing idle electric generation capacity in a region is based on a “valley-filling” methodology in which the margin between the installed system capacity and the system load is determined. The system load is based on the North American Electric Reliability Council (NERC) data for 2002. Because of the large regional differences in the load profiles and the generation mix, the analysis is performed for 9 eastern NERC regions as well as the 3 subregions of the Western Electricity Coordinating Council (WECC). The results from these 12 areas are aggregated to discuss the results from a national perspective. The Energy Policy Act of 2005 resulted in significant changes in the structure of the NERC regions. Because the data used for analysis predate the Energy Policy Act of 2005, this analysis is based on the regional structure as it existed in 2002.

Particular attention was given to the issue of power transfers that occur between regions. In some cases, a region’s native generation will be supplemented by interregional power transfers, while in others, the native generation will supply a load that exists outside the region. When determining the generation that is available to recharge PHEV batteries within a region, power transfers into and out of the region are taken into account.

The second component of the analysis assesses the impact on overall emissions as electricity displaces gasoline in the LDV fleet. We distinguish between total emissions and emissions released in urban areas with high human health implications. The emissions analysis employs a well-to-wheel analysis of the entire energy conversion path from extracting the primary energy out of the ground to delivering useful energy in the form of miles traveled. The Argonne National Laboratory’s Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model is used for this analysis (GREET, 2001). The emission analysis is performed for the 12 modified NERC regions to reflect the varying electric generation mix for charging the PHEV batteries. The analysis includes a discussion of the shift from mobile to stationary emission sources as well. Finally, this paper discusses the petroleum-displacement opportunity for the upper-limit PHEV penetration scenario.

### **Data Sources and Level of Aggregation**

Because of large variations with respect to the electric infrastructure, generation mix, and diversity in load profiles across the United States, this analysis has been performed on a regional basis, dividing the United States into 12 regions. The definition of a region is adopted from NERC and the Energy Information Administration (EIA) regionalization.

System load profile data were obtained from NERC. The most recent and complete data set available at the time of this analysis consists of hourly load data by NERC regions and subregions for the year 2002.<sup>4</sup> NERC compiles load data reported from load-serving

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<sup>4</sup> Data were obtained from NERCon February 24, 2006.

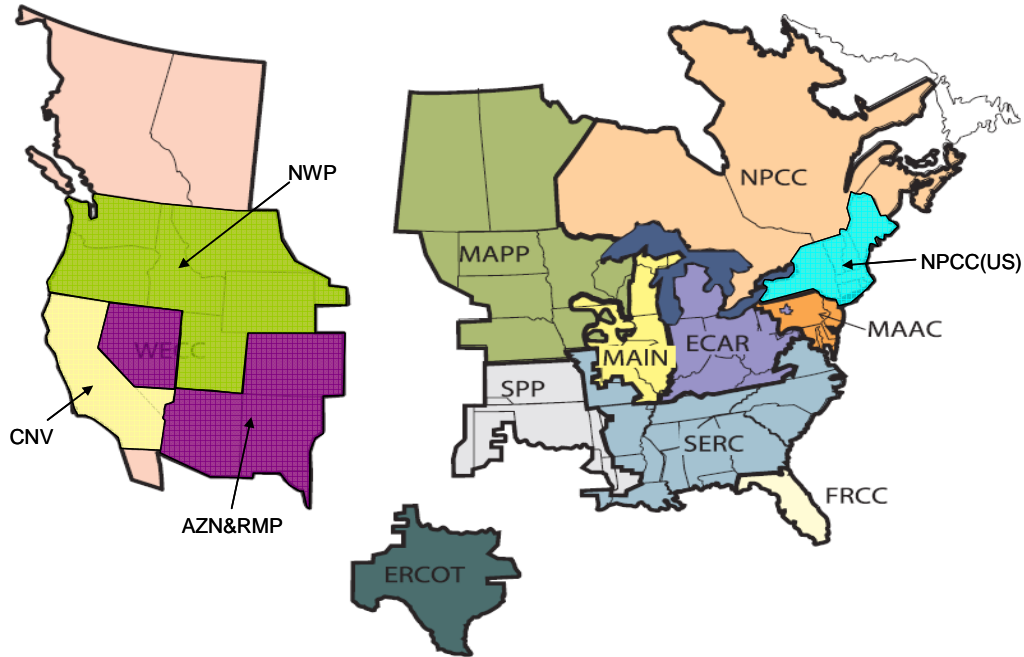
entities to perform system assessments and reliability analyses.<sup>5</sup> Of the 10 NERC regions, 9 are represented in their entirety in this study. WECC is disaggregated into three modified subregions according to EIA's definition for the Annual Energy Outlook (EIA, 2006a, 2006b). The analysis employed the following definition of regions:

1. ECAR (East Central Area Reliability Coordinating Agreement)
2. MAAC (Mid-Atlantic Area Council)
3. MAIN (Mid-America Interconnected Network)
4. MAPP (Mid-Continent Area Power Pool). Only the U.S. segment is used.
5. SPP (Southwest Power Pool)
6. ERCOT (Electric Reliability Council of Texas)
7. SERC (Southeastern Electric Reliability Council)
8. FRCC (Florida Reliability Coordinating Council)
9. NPCC (Northeast Power Coordination Council). Only the U.S. segment is used.
10. NWP (Northwest Power Pool Area), subregion of the WECC
11. AZN&RMP, combining two subcouncils: Arizona-New Mexico-Nevada Power Area and the Rocky Mountain Power Area within the WECC.
12. CNV (California and Southern Nevada), sub-region of the WECC.

Figure 1 shows the 12 modified NERC regions as used in the analysis. For the northern regions that include areas of Canada, NERC identified the U.S. segments so that only the U.S. load profile could be extracted. This applied to the regions of WECC, MAPP, and NPCC. The resulting 12 regional system load profiles for the year 2002 established the main data source for this analysis. Furthermore, EIA annual cumulative generation data are used as well as the installed capacity by major fuel and plant type for the year 2002. The EIA data are provided at the same regional disaggregation level as the NERC data set (EIA, 2006b).

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<sup>5</sup> NERC compiles system load data from different sources, including NERC's regional councils and Federal Energy Regulatory Commission (FERC) Form 714—Annual Electric Control and Planning Area Report.



**Figure 1. Definition of Regions Used in this Study—12 Modified NERC Subregions Based on the Pre-January 1, 2006 Regional Council Structure<sup>6</sup>**

### *Vehicle Stock and Vehicle Utilization Data*

The source for the U.S. vehicle stock is the 2001 motor vehicle registration, by states, as published by the U.S. Department of Transportation (DOT, 2002, Table 5-1). Registration figures were chosen for cars, light trucks, SUVs, and vans, generally referred to as LDVs. Motorcycles are not included. Approximately 217 million vehicles were registered in the LDV category in 2001. Registrations for cars, pickup trucks, and SUVs alone amounted to 198 million. Other heavier vehicles, such as busses and trucks, are not considered in this study, although there are no technical reasons that would prevent busses and trucks from adopting plug-in hybrid electric technology. This analysis strictly focuses on LDVs, excluding motorcycles.

The average daily driving per person is determined using detailed household travel survey data collected in 2001 (Davis and Diegel, 2006, pp 8–15). This survey estimated miles per year traveled in daily trips by personal vehicles to be approximately 12,000 miles per year per vehicle or about 33 miles per day per vehicle. Although this figure is valid strictly for personally owned vehicles, we assign it to all vehicles, including commercial vehicles. This simplification may underestimate the actual daily driving of the commercial vehicles in the LDV fleet. The 33 miles per day per vehicle is then used to determine the energy requirements to be provided by electricity. It would translate to a PHEV33, which notates the number of miles (33) that can be traveled in an electricity-only mode before recharging or the use of gasoline becomes necessary.

<sup>6</sup> After January 1, 2006, the Regional Reliability Councils—ECAR and MAAC—were aggregated into Reliability First Corporation. Sections of the MAIN merged into SERC and into the Midwest Reliability Organization (MRO). More information can be found at: <http://www.nerc.com/~org/entities/>.

Other researchers in the PHEV community often cite a 1990 survey performed by the U.S. Department of Transportation (Hu and Young, 1994) in which the cumulative percentage of personal automobiles is plotted over the average daily travel distance per vehicle. Using data of the 1990 survey, it is frequently emphasized that 50% of personal automobiles travel 20 miles or less daily, and 70% drive 33 miles or less (Graham, 2005; Taylor, 2003). The average daily miles traveled is about 28, slightly lower in 1990 than in the more recent survey (DOT, 2003, Table A-8). The cumulative percentage figures emphasize the distribution of personal driving patterns and point out that greater than 50% of personal travel will be less than 33 miles and that only a small percentage of the population drives significantly further than 33 miles per day, skewing the average upward. This means that the majority of the vehicles may not fully discharge their batteries with a 33-mile range. There will be a small population that would either drive on gasoline beyond the first 33 miles or recharge the battery sometime before they complete their daily trip, e.g., at work. Because this study assumes that *each* vehicle drives 33 miles per day, there is an implicit assumption that the electric energy not used to charge those that drive less is shifted to others that drive more than 33 miles per day.

### ***Valley-Filling Approach for Estimating Available Electric Generation***

The valley-filling approach requires a dispatch of the electric generators to meet the regional load demand. Once the dispatch is complete, the total installed capacity less the dispatched units sets the upper limit on the generation available for charging PHEVs. A simplified approach is chosen that reduces the complexity of a production cost modeling that simulates and optimizes an 8,760-hour dispatch (1 year), to two 24-hour dispatches, a typical summer and winter day. The simplification applied a typical plant dispatch merit order to two limiting cases when the entire electric grid is likely to have the least reserve capacity and available generation resources for recharging the PHEV batteries. Spring and fall seasons commonly offer significantly more excess generation capacity because of reduced load demand. It is noted that reserve margins could be low during brief periods in the fall season when several power plant operators schedule planned outages for plant maintenance after high plant utilization during the summer. However, it is assumed that there is sufficient scheduling flexibility throughout the fall such that the available reserves remain always larger than during the peak summer season. This assumption will be the subject of future investigation.

The 24-hour generation dispatch is performed using a merit-order approach based on typical production costs, combined with the following rules, considering common plant operating practices. General plant-type categories as defined by EIA in the Annual Energy Outlook are used (EIA, 2006a, 2006b).

- Nuclear capacity. Nuclear power plants are operated as a base-load plant at maximum generation capacity. The common capacity factor is 0.90 (EIA, 2006b).
- Coal-fueled capacity. Coal plants are operated primarily to meet base load with capabilities to ramp up and down generation.
- Natural gas combined cycle and conventional steam plant. Plants can meet base load and intermittent load such as load following.

- Conventional hydro capacity. Hydro systems are used to meet base load, intermittent load, and peak load. The hydro systems in the west and the east have reached their annual generation capabilities already. Although there is significant hourly and daily generation flexibility in the installed hydro capacity, the total annual energy produced is constrained by the finite water resources and other operational requirements for wildlife preservation (Bonneville Power Administration [BPA], 2003)
- Renewable (nonconventional hydro) energy generation. This includes wind, solar, biomass, and geothermal capacities. Renewable-energy resources are used to the maximum generation capability to displace conventional fossil fuel generation.
- Peaking plants (combustion turbines). These plants are designed for a relatively short run-time. Typical capacity factors for combustion turbines are in the 0.15 to 0.20 range. Although the capacity factor could be increased to some degree, the significantly higher operating costs are unlikely to make combustion turbines a viable resource for PHEVs.

The dispatch is then performed for each modified NERC region for an average summer and winter day, defined as the average hourly system load over a 3-month period. The summer period started on June 1 and ended August 31. The winter period is defined as the period from December 1 through February 28. Each average summer and winter day generation dispatch is then projected for a 6-month period, and the combined annual generation figure is compared with annual generation data. The daily profiles are adjusted to meet EIA's annual generation data as reported for 2002 in the Annual Energy Outlook 2006 (AEO2006) (EIA, 2006b). The results of this step are two 24-hour generation dispatches representative of a typical summer and winter day.

To estimate the regional unused generation capability, we determined the difference between the total installed capacity (summer capacity de-rated by the availability factor) and the hourly generation that is already committed to meeting the current load demand. This level of potential generation is further curtailed by precluding the use of peaking plants for the charging of PHEV batteries. Peaking plants are designed for relatively short run-time operations and would be uneconomical for continuous operation over long periods of time. Figure 2 illustrates the valley-filling approach.

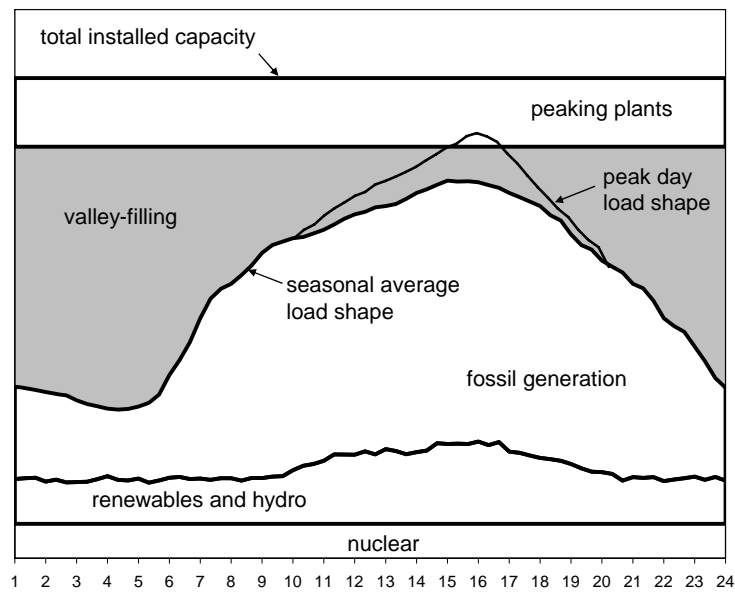
The remaining marginal generation capacity consists of coal-fired thermal plants, natural gas-fueled steam plants, and combined cycle plants. Not considered as marginal capacity for the valley-filling are nuclear, conventional hydro power, and renewable energy capacities because these are already fully utilized. Nuclear capacity is normally operated at its maximum capacity. Wind and solar generators are fully utilized whenever the resource is available. Conventional hydro generation is limited by finite water resources and seasonal water flows.

The installed coal and natural gas-fueled capacity is then de-rated by the availability factor to account for planned and forced outages. We chose the capacity factor as an approximation of the availability factor.<sup>7</sup> A capacity factor of 0.85 is used for both coal and natural gas plants (EIA, 2006c). This assumption implies that planned outages are scheduled uniformly throughout the year, which is a simplified approximation to the actual maintenance

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<sup>7</sup> Availability factor is the ratio of hours a plant is available to operate in one year divided by 8760 hours. EIA publishes only capacity factors, which are the ratio of total generation in (MWh) produced in one year over the total generation capability (rated capacity times 8760 hours).

schedule. Maintenance is typically scheduled during a low-load period (commonly in the fall and spring) to make the full generation capacity available for the peak seasons. Thus, the simplified approximation for outage scheduling represents a conservative estimation of the available capacity during the summer and winter months. Petroleum-fuel steam generators, with a small contribution to the total U.S. electric generation of 3%, are grouped together with the natural gas steam generators and are classified by EIA as “other” fossil steam generation (EIA, 2005b). Figures A.1 through A.6 in Appendix A show the winter and summer dispatch profiles for one winter-peaking region (NWP), and two summer-peak regions (ECAR and CNV). The figures show the generation for valley-filling generation denoted as “additional” generation resources.



**Figure 2. Stylized Load Shape for 1 Day During Peak Season, Generation Dispatch, and Installed Capacity**

The margin between the system load profile and the total installed capacity after all exclusions constitutes the power available for charging PHEV batteries, in megawatts (MW). When the MWs available for charging are determined for a 24-hour period, the total energy available for charging PHEV batteries in a single day can be estimated, in megawatt-hours (MWh). This is considered the technical potential for supporting the daily recharging of the PHEVs batteries. The size of this energy block is determined for both the typical summer and typical winter day. The lower value of the two is then used as the regional representative resource estimate in MWh for PHEV battery charging.

The simplified valley-filling approach warrants the following comments:

1. Simplifying the valley-filling approach to a daily problem with a 24-hour dispatch greatly reduced the computational complexity of the resource estimation. Of interest is the limiting case or cases that impose a lower bound on the resource assessment. This particular case occurs during peak conditions when most generators are being

used. Because the peak demand day may or may not be coincident with the day of the maximum dispatched generation, we represented the two load profiles, a summer and a winter day, to ascertain that the limited case is captured in the analysis.

2. The choice of using a seasonal average load shape rather than the load shape of the peak generation day is motivated by the dual-fuel capability of the PHEV, recognizing that there may be a few days out of the year in which the PHEV battery may not be fully recharged to its maximum storage capacity. The lack of stored electric energy will then need to be compensated for using the internal combustion engine. Restricting recharging during these periods can be accomplished through price signals or other load-control methods.
3. The available capacity for valley-filling, using coal and natural gas plants, is de-rated by their capacity factors to represent an average availability and utilization of those plants. However, during peak seasons, most coal and natural gas plants are typically operated to their full name-plate capacity. The unavailability commonly occurs during fall and spring season when the load is generally reduced and less capacity is needed. By applying the 15% unavailability during the peak season, we underestimated the true capacity that is available.
4. By excluding peaking plants, in conjunction with de-rating the coal and natural gas capacity by 15%, the resulting maximum demand in MW for valley-filling never exceeds the maximum system peak demand. This implies that the valley-filling method of charging PHEV batteries will never require transfers of electric power through the T&D system (at least not through the transmission system) greater than those during system peak hours (see Figure 2).

The result of the estimated valley-filling resource estimate is a block of electric energy indicated in MWh. This energy resource then is converted into a percentage of the energy requirements for the daily driving of the regional LDV stock. The energy requirements per mile for selected LDV classes are adopted from Electric Power Research Institute's (EPRI's) Hybrid Electric Working Group [Duvall, 2002, 2003, and 2004] as listed in Table I.

**Table I. Specific Energy and Energy Storage Requirements by Vehicle Classes**

<b>Vehicle Class</b>	<b>Specific Energy Requirements [kWh/mile]</b>	<b>Size of Battery for PHEV33 [kWh]</b>
Compact sedan	0.26	8.6
Mid-size sedan	0.30	9.9
Mid-size SUV	0.38	12.5
Full-size SUV	0.46	15.2

The energy requirements of the vehicle classes above are used in the 2001 regional fleet proportions using the Department of Transportation (DOT) motor vehicle registration data set. Because the DOT data set did not further specify cars into compact and mid-size, we selected an arbitrary 50/50 split. Likewise, the same split is used for the full-size and mid-size SUVs. Pickup trucks are assigned the same energy requirements as SUVs. In addition,

an 8% loss in the transmission and distribution system is employed (Department of Energy [DOE], 2003). Efficiencies for the battery charger and the battery over a round-trip of full charge and discharge cycle are assumed to be 87% and 85%, respectively (Duvall, 2002).

### **Methodology for Emission Impact Analysis**

The emissions impacts as a result of the additional central plant generation for charging PHEV batteries are evaluated using the GREET model. The GREET model accounts for the entire energy flow from the well of the primary energy source to the final conversion in the vehicle, propelling it 1 mile. Many assumptions are made in GREET regarding the individual efficiencies and emissions along the entire well-to-wheel energy path. This analysis adopted all of the default assumptions of the Version 1.6 model (GREET, 2001). We used the electric-vehicle definition to represent a PHEV, recognizing that we modeled a PHEV when it is operating in an electric-only mode. We excluded any mixed electric/internal combustion engine driving modes.

Key input variables to the GREET model are the composition of the existing generation mix and the additional generation dispatched for PHEVs. The GREET model uses the existing generation (in GREET parlance “average generation mix”) for all conversion processes except for electric vehicles. The electricity used to fuel electric vehicles is called “marginal generation.” The GREET model uses market shares of the generation by five fuel types (residual oil, natural gas, coal, nuclear power, and others). The average generation mix for a given region is used from the Annual Energy Outlook (AEO) 2006 regional tables for the year 2002 (EIA, 2006b). The marginal generation is assigned using the result of the valley-filling approach, which is a combination of coal and natural gas resources. The GREET model simulates three vehicle types (passenger cars and light duty trucks, Class 1 and Class 2) for near-term and for longer-term. We use the near-term projections, which are based on car technologies and characteristics more amenable to today’s vehicles than the longer-term projection. The vehicle types, particularly the passenger car and the light duty truck, scale relatively well such that the results expressed as a ratio of PHEV to conventional vehicle varied negligibly across the vehicle types. All results are then expressed as emission ratios.

Although the GREET model accounts for all energy conversions and the release of emissions associated with the energy conversions from well to wheel, it is not designed to consider national emissions caps. For instance, Title IV of the Clean Air Act sets goals for reducing SO<sub>2</sub> emissions for U.S. power plants, and the more recent EPA CAIR sets even stricter rules for total SO<sub>2</sub>, NO<sub>x</sub>, and fine particulate emissions. EPA established a cap-and-trade system as a market-based mechanism to reduce emissions. These cap-and-trade mechanisms are complex and go beyond the scope of the GREET model. As a consequence, the GREET model results need to be screened for emission compliance within the larger national regulatory context.

## **DISCUSSION OF RESULTS**

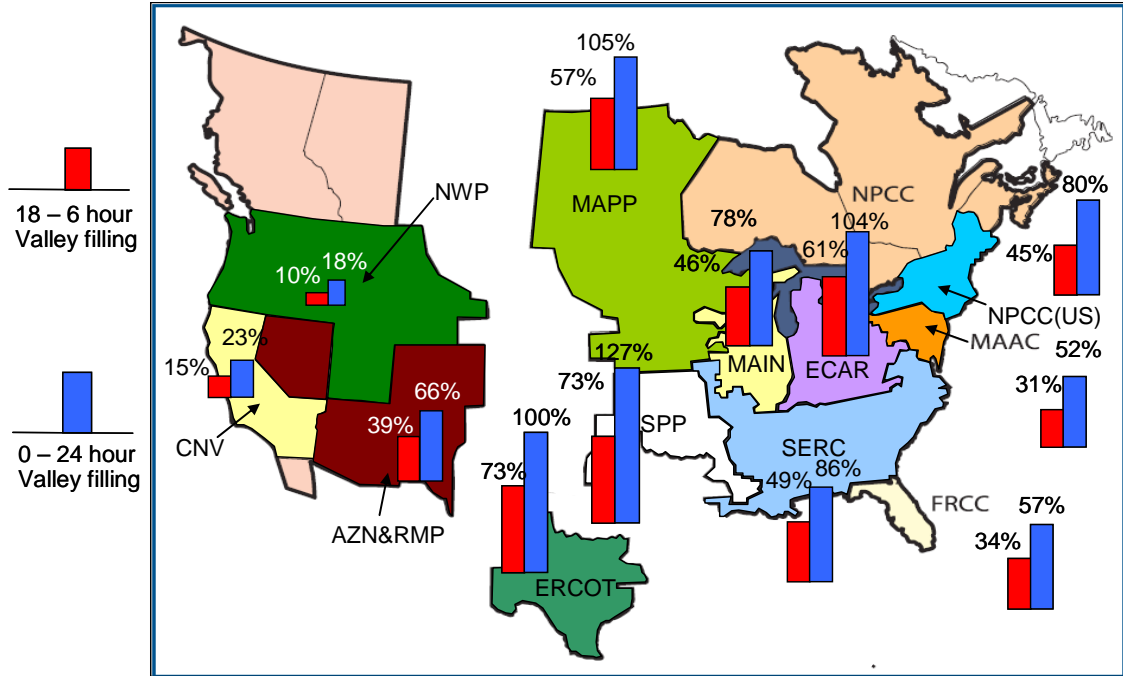
The results of the analysis indicate that significant portions of the U.S. gasoline-operated vehicle fleet could be fueled with the available electric capacity. For the nation as a whole, about 84% of the energy needed for operating cars, pickup trucks, and SUVs (or a maximum of 73% of the energy of the LDV fleet) could be supported using generating, transmission, and distribution capacity currently available. This would require power providers to use all of the available electric generation, base load and intermediate generation, at full capacity for most hours of the day. If charging periods are to be constrained to a 12-hour period starting at 6 p.m. and ending at 6 a.m., the technical potential would be reduced to 43% of the LDV fleet. From a regional perspective, there is some diversity in the technical potential.

The midwestern region of the United States with a significant level of coal generation could provide the necessary energy for the entire region's LDV fleet while still exporting excess power to neighboring regions, assuming no limiting interregional transfer constraints to the adjacent regions.<sup>8</sup> This would require the entire 24-hour time period for recharging the PHEV batteries. The technical potential for the western regions, while still significant, is only about one half of that of the eastern regions and about one quarter of that in the midwestern regions. A key contributing factor is the large share of hydroelectric generation, which is already at maximum sustainable generation levels. Results from ERCOT indicate it has one of the highest technical potentials because of its significant reserve capacity, some of which is taken out of service temporarily for economic reasons because of the existing excess capacity (Potomac Economics, 2006). With growing electricity demand, these generating units are expected to resume operation. Because ERCOT's link to the eastern interconnected system has only a small transfer capability, the export capability is assumed to be negligible, requiring all of the generation to be used for intraregional consumption. This lack of export capabilities reduces its technical potential of fueling 136% of ERCOT's LDV fleet to 100%.

Figure 3 displays the results in graphical format, and Table II shows the results in tabular format. Results are shown for a 24-hour and a 12-hour night-charging period to illustrate the impacts of a constrained charging period to 12 hours (6 pm to 6 am). Even when constraining the battery charging to the night period, a significant fraction of the regional vehicle fleet could still be supported with the existing grid infrastructure. Furthermore, additional vehicles could be supported if one makes the reasonable assumption that PHEVs will not be electrified clones of existing vehicles, but optimally designed for fuel efficiency, regardless of the "fuel" source. Finally, the charging capability could be extended by adding generation from traditionally "intermittent" resources, such as wind turbines, because PHEVs provide a ready use for this power whenever it is available. The addition of new wind generation could increase the fraction of PHEVs the WECC region could support.

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<sup>8</sup> Based on the National Electric Transmission Congestion Study, the midwestern regions were not identified as critical congestion areas, nor as congestion areas of concern. Only when assuming high wind penetration in the midwestern regions may significant congestion occur (DOE, 2006).



**Figure 3. Technical Potential for Fueling the Regional LDV Fleet with Available Electric Capacity**

**Table II. Results of Technical Potential by Region**

Region	Total Number of Vehicles in Mill.	24-Hour Valley Filling	6 p.m.–6 a.m. Valley Filling	24-Hour Valley Filling	6 p.m.–6 a.m. Valley Filling
		Technical Potential in %		Technical Potential in Mill. Vehicles	
ECAR	27.7	104	61	28.6	16.8
ERCOT	15.5	100	73	15.5	11.3
MAAC	20.0	52	31	10.4	6.2
MAIN	16.7	78	46	13.1	7.7
MAPP	5.8	105	57	6.1	3.3
NPCC (U.S.)	19.6	80	45	15.6	8.9
FRCC	11.5	57	34	6.5	3.9
SERC27	37.8	86	49	32.5	18.4
SPP	11.9	127	73	15.1	8.7
NWP	15.7	18	10	2.8	1.6
AZN&RMP	8.8	66	39	5.8	3.4
CNV	25.8	23	15	6.0	3.9
<b>National Average*</b>	<b>216.9</b>	<b>73</b>	<b>43</b>		

\* Weighted average of all regions. Those regions with technical potential greater than 100% are assumed to export to regions with potential less than 100%. ERCOT's technical potential is truncated from 136% to 100% because of negligible transfer capability out of ERCOT.

## Results of Emissions Impacts

The conversion of LDVs to PHEVs has significant implications for overall emissions as electricity displaces gasoline. The net balance in the emissions of this fuel-displacement process along the entire fuel cycle from the extraction of the primary energy to the final conversion in the vehicle into useful energy is discussed below.

For the nation as a whole, the total greenhouse gases<sup>9</sup> are expected to be reduced by a maximum of 27% from the projected penetration of PHEVs. The key driver for this result is the overall improvement in efficiency along the electricity generation path compared to the entire conversion chain from crude oil to gasoline to the combustion process in the vehicle. Fundamental to this result is the assumption that a PHEV by itself would be more efficient than a conventional gasoline car because of the regenerative braking capability that stores the kinetic energy in the battery during deceleration and because the engine operates at near optimal conditions more of the time than in conventional vehicles. On a regional basis, the improvements in greenhouse gas emissions could be as large as 40%, as in ERCOT, which has a large penetration of natural gas power plants. Conversely, the improvement in greenhouse gas emissions could be zero or slightly negative for the MAPP region with essentially all coal generation (see

### Table III).

Total volatile organic compounds (VOCs) and carbon monoxide (CO) emissions would improve radically by 93% and 98%, respectively, as a result of eliminating the use of the internal combustion engine. The VOC emissions reduction may be significantly overestimated because PHEVs will still have gasoline in their tanks and vent to the atmosphere during refueling and to some extent while parked and during driving. The total nitrogen oxides (NO<sub>x</sub>) emissions are significantly reduced (31%), primarily because of the avoidance of the internal combustion process in the vehicle as well as reducing the volume of gasoline to be produced in refineries.

The total particulate emissions (PM<sub>10</sub>) are likely to increase nationally by 18%, caused primarily by the increased dispatch of coal-fired plants. As can be seen in

Table III, however, in regions with a large contribution to the marginal generation from natural gas- fueled plants, total particulate emissions could improve. The total SO<sub>x</sub> emissions require special interpretation. The GREET indicates an increase at the national level by about 125%, primarily caused by additional generation from coal-fired power plants. However, because of the current EPA emissions regulations (Clean Air Act and Clean Air Interstate Rule), the total emissions from U.S. power plants are capped. To meet these regulatory requirements while at the same time increasing the generation from existing coal-fired power plants requires additional technologies for reducing sulfur emissions. The capital requirements for the necessary emission reductions are difficult to estimate and require complex production cost and capacity expansion modeling tools.

It should be noted that with the emergence of PHEVs, the emission sources will shift from millions of individual vehicles to a few hundred central generation facilities. All urban emissions are expected to significantly improve (see

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<sup>9</sup> Greenhouse gases are defined as: carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) (Brinkman, Wang, Weber, Darlington, 2005, p. 13).

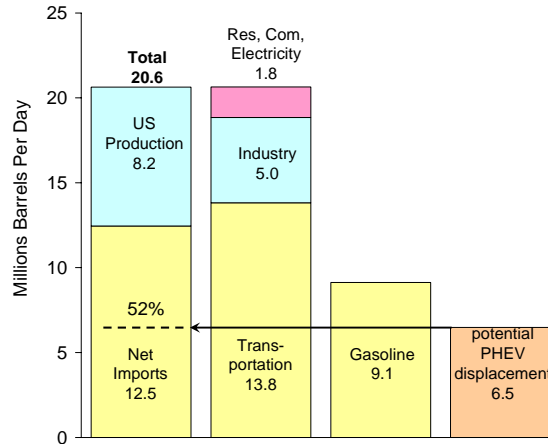
**Table III).** The economics for emission-reduction and carbon-sequestration technologies may look much more attractive when installed at central power plants rather than in motor vehicles, especially when the costs are spread over longer operating periods and billions of additional kilowatt hours.

**Table III. Emissions Results Using the GREET Model**

	ECAR	ERCOT	MACC	MAIN	MAPP	NPCC	FRCC	SERC	SPP	NWP	AZN& RMP	CNV	U.S. total
<b>Power Generation Composition</b>													
Natural Gas	32%	94%	74%	42%	1%	91%	69%	57%	78%	43%	63%	93%	
Coal	68%	6%	26%	58%	99%	9%	31%	43%	22%	57%	37%	7%	
<b>Emissions Ratio (Electric Vehicle/Gasoline Vehicle)</b>													
GHGs	0.87	0.60	0.69	0.83	1.01	0.61	0.71	0.76	0.66	0.84	0.73	0.61	0.73
VOC: Total	0.11	0.04	0.06	0.10	0.14	0.04	0.07	0.08	0.06	0.10	0.07	0.04	0.07
CO: Total	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
NOx: Total	1.02	0.38	0.59	0.93	1.35	0.41	0.64	0.76	0.54	0.93	0.71	0.39	0.69
PM10: Total	1.55	0.81	1.06	1.45	1.94	0.86	1.13	1.26	0.99	1.46	1.19	0.84	1.18
SOx: Total	3.94	0.42	1.68	3.59	5.96	0.64	2.05	2.67	1.34	3.77	2.35	0.53	2.25
VOC: Urban	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CO: Urban	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NOx: Urban	0.10	0.11	0.11	0.10	0.09	0.11	0.11	0.10	0.11	0.10	0.10	0.11	0.10
PM10: Urban	0.60	0.62	0.62	0.60	0.58	0.62	0.61	0.61	0.62	0.61	0.61	0.62	0.61
SOx: Urban	0.35	0.04	0.14	0.30	0.51	0.05	0.17	0.22	0.12	0.31	0.20	0.04	0.19

### Potential to Reduce Dependency on Foreign Crude Oil Imports

One of the key premises of the PHEV technology, from a policy perspective, is the potential to reduce U.S. dependency on imports of foreign crude oil. To illustrate the potential benefits of a conversion from a gasoline-driven LDV fleet to PHEVs, we estimated a displacement potential on the total national consumption of gasoline. This figure is an upper-bound estimate on the gasoline-displacement potential. The realizable potential will most likely be smaller to account for the long-distance driving above 33 miles per day and the few days during the year when PHEVs may not be fully charged because of maximum peak conditions on the grid. **Error! Reference source not found.**4 shows that in 2005, the United States consumed gasoline at a rate that required 9.1 million barrels of crude oil per day (EIA, 2005a). Considering that the LDV fleet consumes 97% of the entire gasoline supply, the conversion of 73% of the LDV fleet to PHEVs could reduce gasoline consumption by a crude oil equivalence of 6.5 million barrels per day (MMBpd). This reduction in the U.S. gasoline consumption is the equivalent of 52% of foreign petroleum imports.



**Figure 4. Petroleum Supply, Consumptions, and PHEV Displacement Potential**  
(Figure based on Energy Flow Diagram, p. 3, EIA, 2005a)

### Other Electric System Impacts

Providing 73% of the daily energy requirements of the U.S. LDV fleet with electricity would add approximately 910 billion kWh, an increase of about 24% of the total U.S. annual generation in 2002 (EIA, 2006b). Without further infrastructure investments, the current electric power system would be heavily loaded for most hours of all days. It is questionable whether today's electricity infrastructure and capacity mix will be able to support this level of loading on a sustained basis. Planned outages for plant maintenance would likely need to occur more frequently, making it more difficult to schedule maintenance. Furthermore, the overall system reliability could be reduced in this high-use scenario as less reserve capacity is available to the system operators for managing system emergencies. Grid operating procedures would need to be changed to shift some of the ancillary services to load resources to free up generation capacity for energy production. "Smart" PHEV charging systems that recognize grid emergencies could mitigate the extent and severity of these grid emergencies. Vehicle-to-grid (V2G) concepts (not examined in this study) could potentially provide additional reliability enhancements using the storage capacity of the PHEV by reversing the power flow from the battery to the grid (Kempton, 2005a and 2005b). Particularly with high system utilization, smart loads become an attractive reliability resource that could become more prevalent with current communications and automation investments.

The valley-filling methodology is predicated on the notion that the entire PHEV load is managed to fit perfectly into the valley without setting new peaks. One approach to realizing load management is via electricity pricing that discourages customers from charging the PHEVs during peak periods and encourages them to charge during off-peak periods. The PHEV charger would need to be a smart device equipped with communications or—in the most simple way—a timer to prevent charging during peak periods.

While we rationalized that PHEV charging could be done without setting new system peaks and causing new transmission congestions, it represents a significant shift from a power system with peaks and valleys to one that is constantly loaded. While the bulk power system is designed to operate reliably at these levels during peak periods, sustained operation

at these levels may reveal new constraints. For example, there may be intraregional transmission constraints that come into place when transmission lines are heavily loaded for extended periods. Specific and detailed regional studies would reveal these delivery constraints. Similarly, the distribution system may impose some additional constraints on the delivery limits to off-peak PHEV charging. System components such as transformers may not be designed to sustain a constant high loading without a period of lower load conditions during which the equipment can cool down. Preliminary analyses of residential distribution feeders load data suggest that the characteristics of the residential load shapes are similar in proportion to the peaks and valleys as observed at the regional system level.<sup>10</sup> This provides some evidence that the additional load could potentially be accommodated in the off-peak valley without setting a new peak during the former off-peak period. However, additional analyses of impacts on the distribution system with a different composition of industrial, commercial, and residential customers are warranted to investigate the assumptions made in this study.

The expected anti-cyclical load shape of the emerging new PHEV load will flatten the overall load duration characteristics, and, as a result, it is likely to change the mix of future power plant types and technologies with important implications to base-load coal and nuclear technologies. This is potentially beneficial for these power generation technologies, as they typically have the lowest power-production costs. Similarly, PHEVs provide a ready source of demand for power from intermittent renewable resources that may allow greater utilization of power from the wind and sun than otherwise. However, with an increasing share of intermittent resources to the total generation mix, the load-following and regulation services requirements increase to compensate for the growing intermittency and variability in the power supply. This reduces the availability of the capacity of some intermediate power plants to provide base-load energy. Instead, this capacity is required for meeting the increased load-following needs.

In the short run, the expected increased use scenario will affect wholesale electricity markets as supplies of generation resources remain tight over longer periods. One result could be an upward pressure on wholesale electricity prices, although the persistence of higher prices will induce investments in new generation and transmission capacity. In the long term, the supply will follow the load to meet the growing demand. The development of a new transportation load may facilitate the financing of low-cost base-load generation and renewables that is currently lacking in the marketplace. The potential for short-term price increases and longer-term price and rate decreases needs to be analyzed further and considered as part of the public policy debate. A fuller discussion of the economic assessment of PHEVs is in the companion paper (Part II: Economic Assessment), which examines impacts to the revenue requirements and the electric rates in a fully regulated utility environment.

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<sup>10</sup> Based on substation and feeder data from predominantly residential feeders in Southern California Edison's and Allegheny Power's service territory.

## SUMMARY

The results of the technical potential analysis are listed below:

- The existing electricity infrastructure as a national resource has sufficient available capacity to fuel up to 84% of the nation's cars, pickup trucks, and SUVs (198 million) or about 73% of the light duty fleet (about 217 million vehicles) for a daily drive of 33 miles on average.
- There are potentially significant emissions impacts if the gasoline-based LDV fleet were to transition to a PHEV technology. Greenhouse gases and some criteria emissions would be reduced based on total emission figures. Particulates emissions would increase as a result of increased dispatch of coal-fired power plants. Furthermore, the increased generation from coal power plants requires SO<sub>2</sub> emission-reduction technologies to meet EPA regulations. There are also regional differences that depend upon the mix of coal and natural gas-fired power plants. All emissions in urban areas are expected to improve because of the shifting of the emission sources from millions of individual vehicles in population centers to central generation plants that are traditionally located away from population centers.
- A shift from gasoline to PHEVs could reduce the gasoline consumption by up to 6.5 MMBpd, which is equivalent to 52% of the U.S. petroleum imports.
- Several other grid-related impacts are likely to emerge when adding a significant new load for charging PHEVs. Higher system loading could impact the overall system reliability when the entire infrastructure is used near its maximum capability for long periods. However, "smart" PHEV charging systems that recognize grid conditions could mitigate the extent and severity of grid emergencies. Near maximum utilization of the nation's power plants is also likely to impact wholesale electricity markets. The mix of future power plant types and technologies may change as a result of the flatter load-duration curve favoring more base-load power plants and intermittent renewable energy resources.

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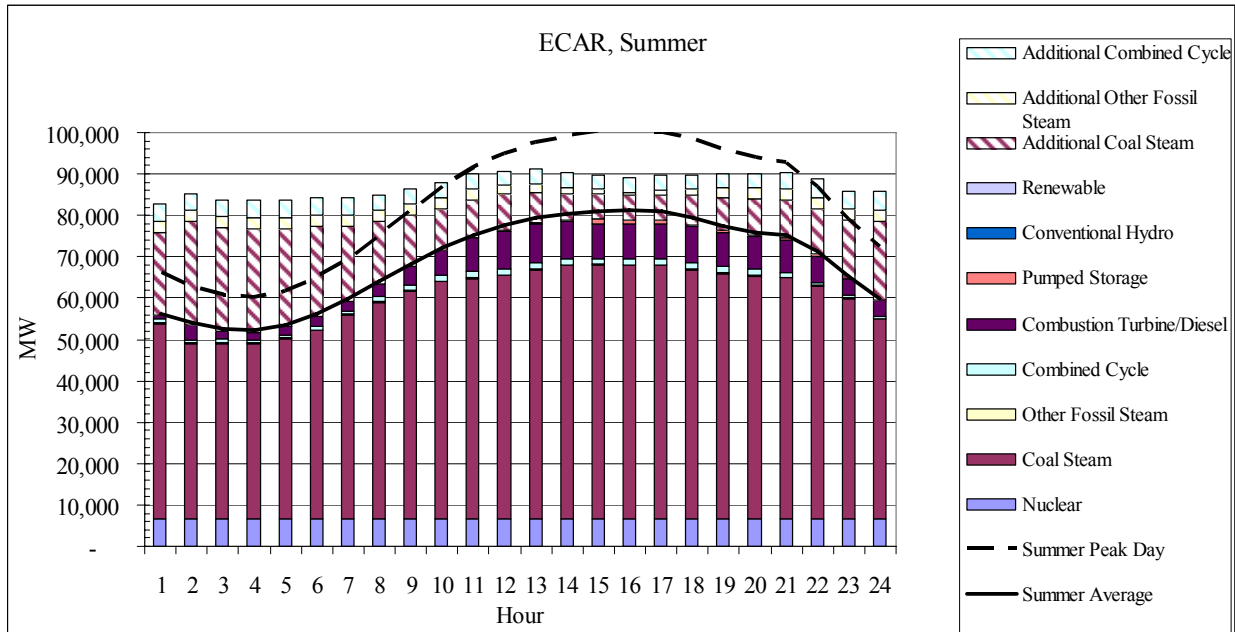
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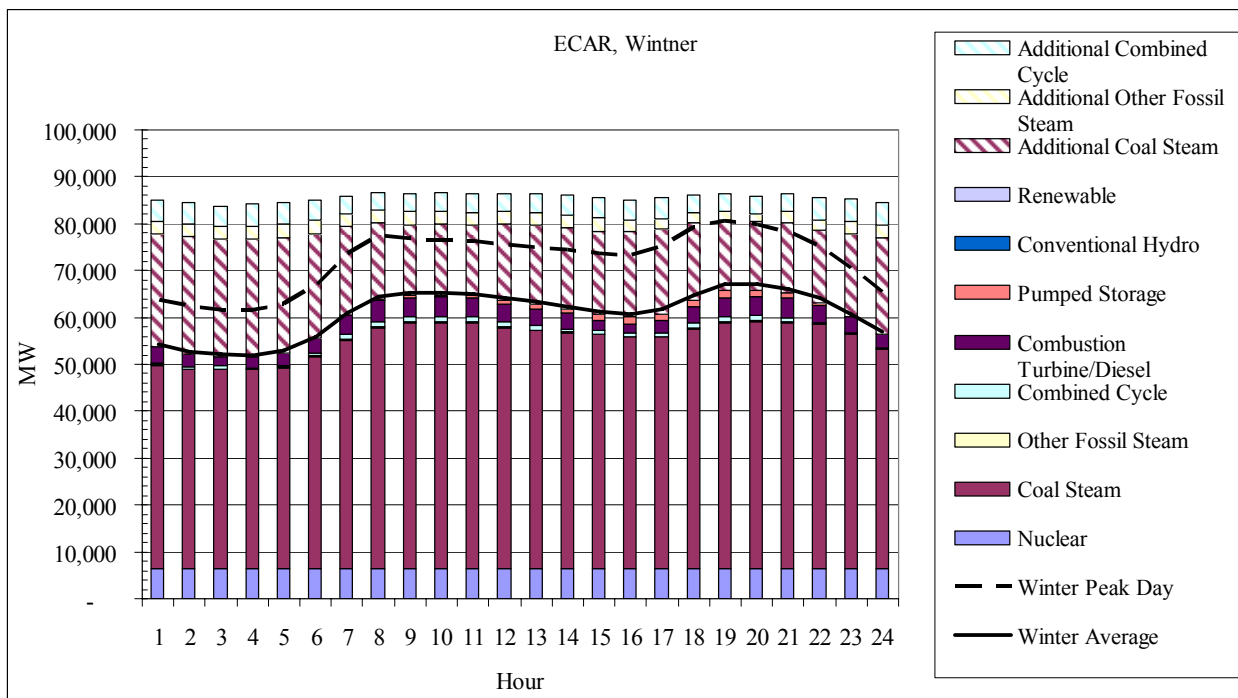
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## APPENDIX A

The figures below show for selected regions a daily load profile for the summer and winter seasons. Each figure shows 1) average seasonal load profile, 2) generation dispatch to meet average seasonal load profile, 3) valley-filling generation potential shown as hatched bars and denoted in the legend as “additional” plant type, and 4) seasonal peak load day.



**Figure A.1.** ECAR Dispatch for Summer Average Load Profile, Valley-Filling Potential, and Peak Day



**Figure A.2.** ECAR Dispatch for Winter Average Load Profile, Valley-Filling Potential, and Peak Day

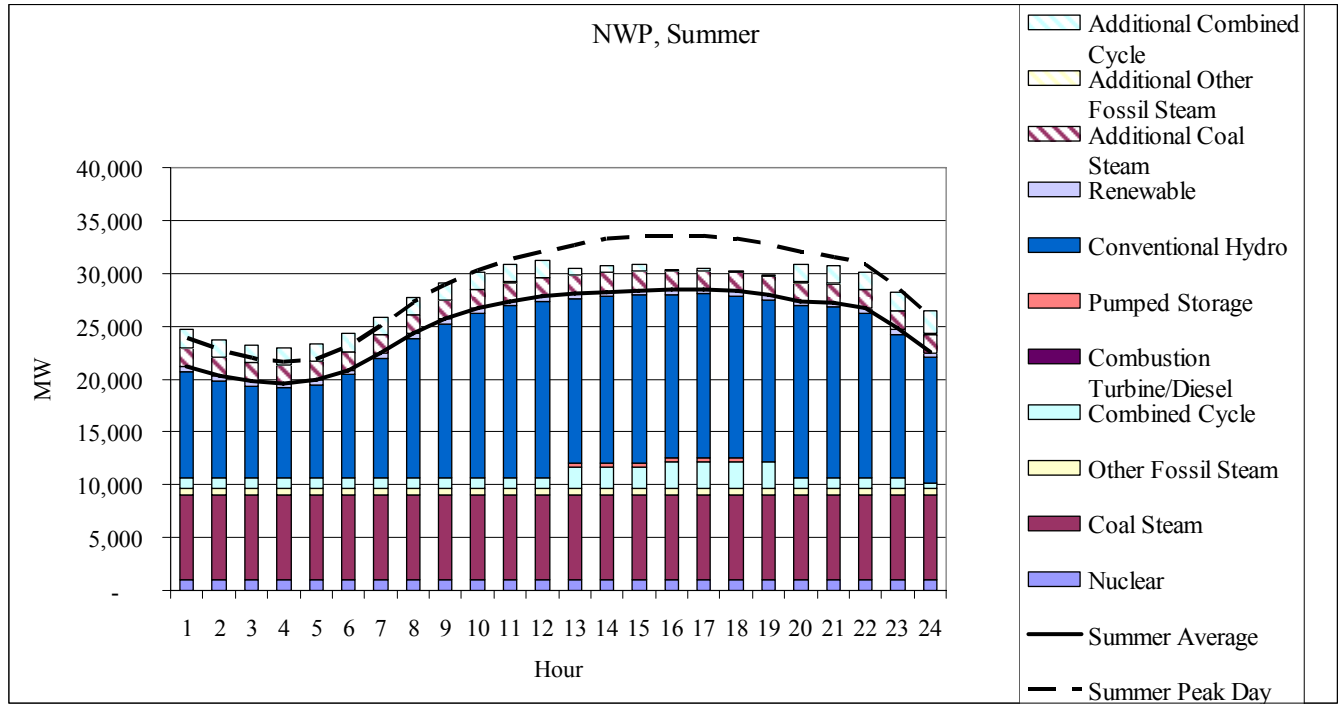


Figure A.3. NWP Dispatch for Summer Average Load Profile, Valley-Filling Potential, and Peak Day

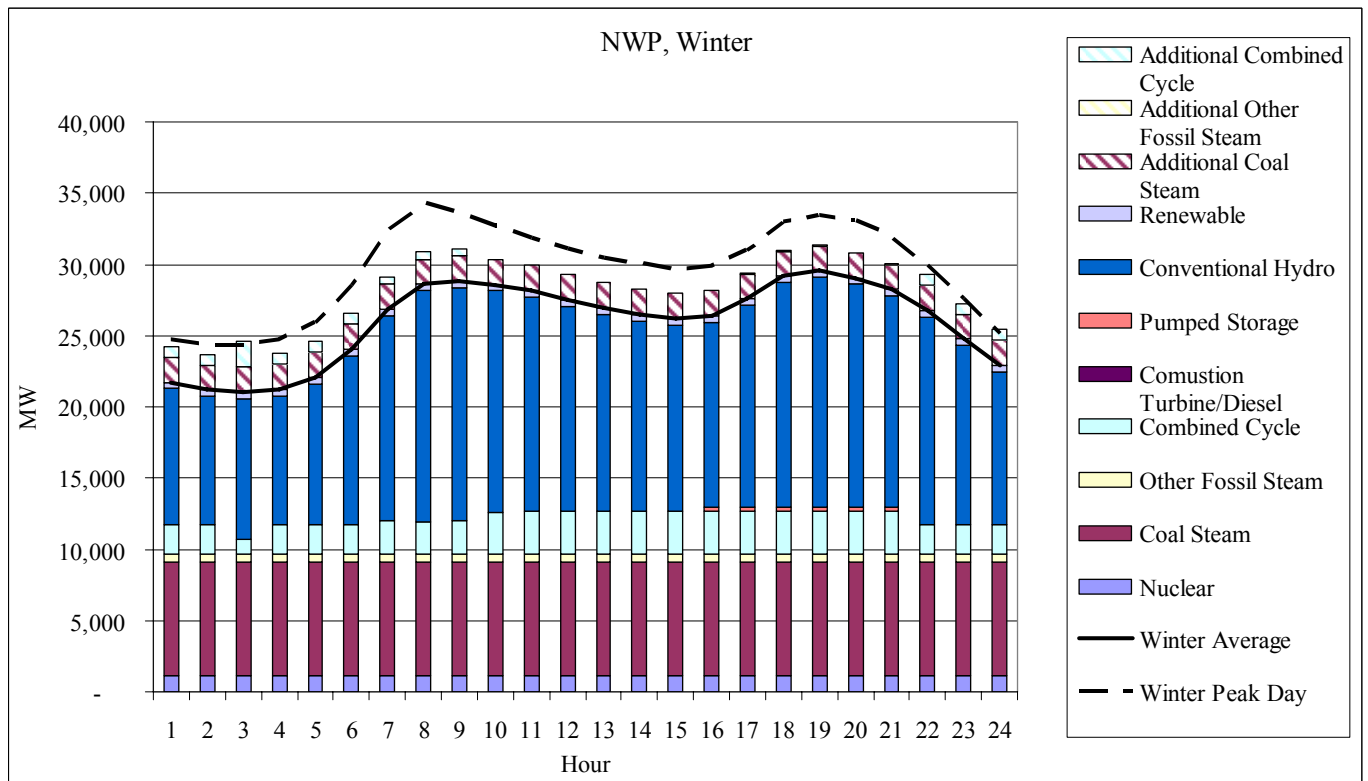
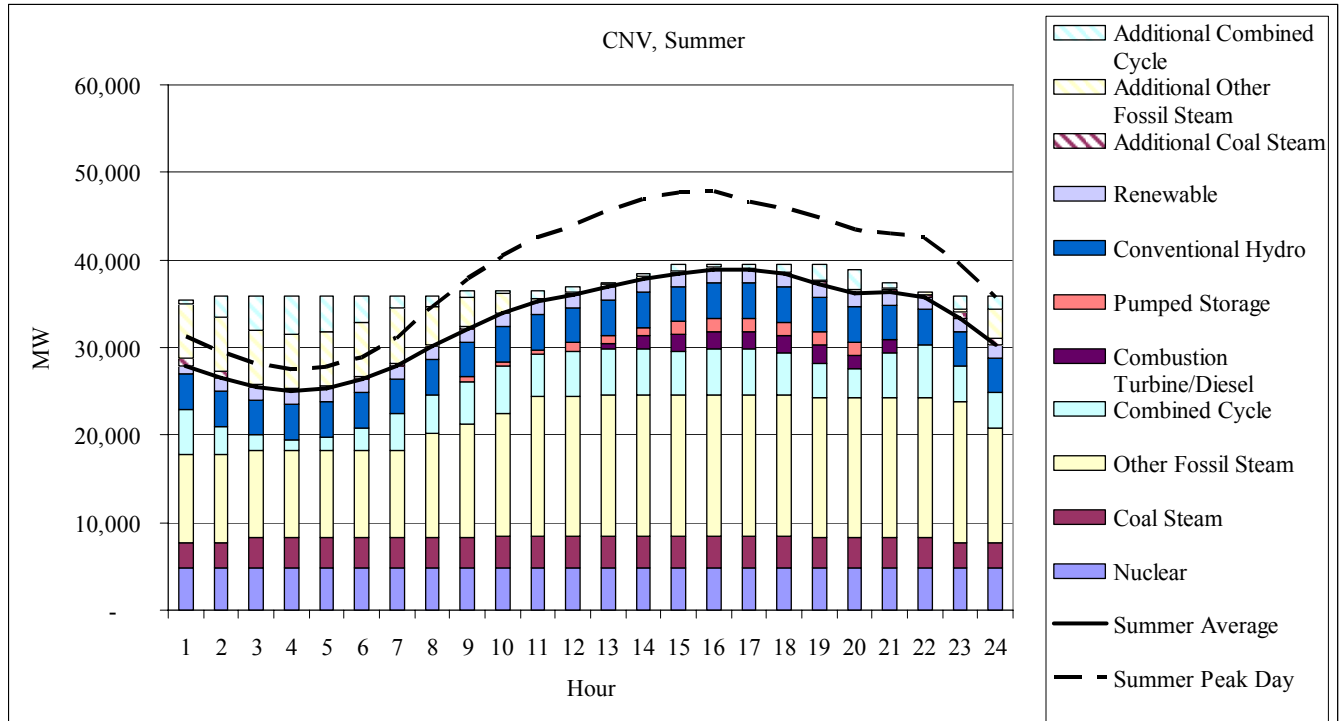
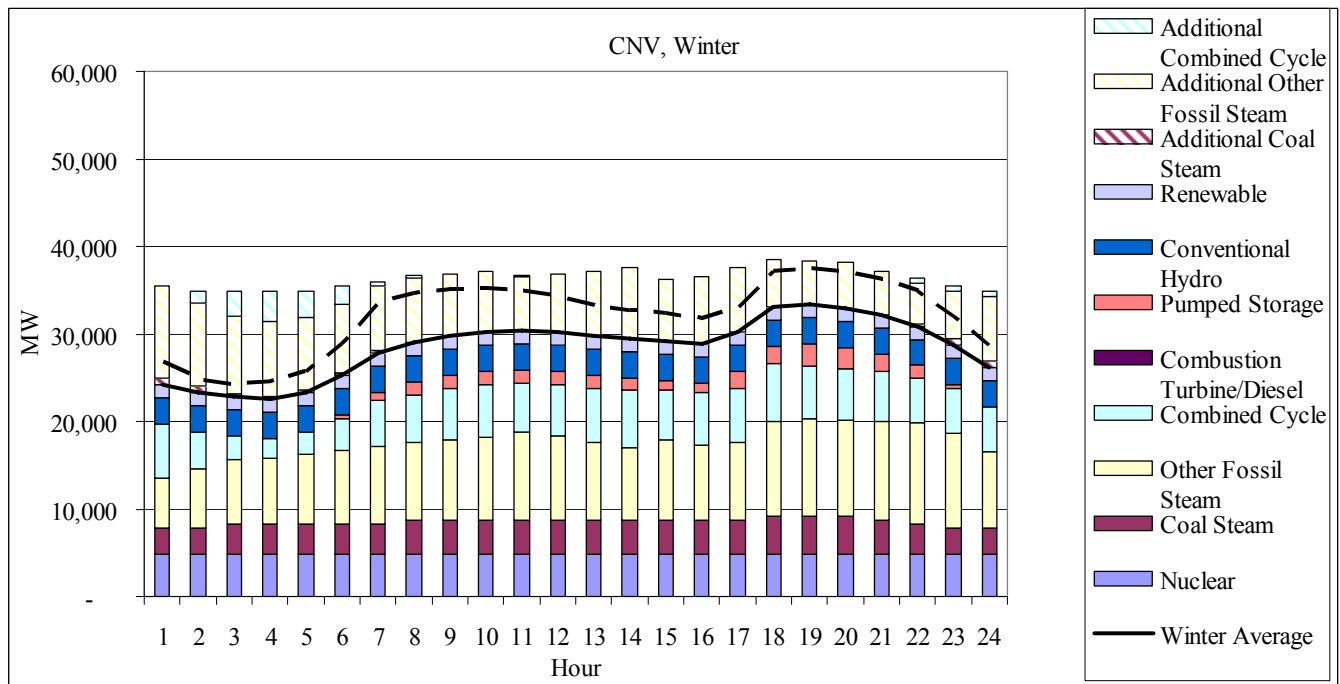


Figure A.4. NWP Dispatch for Winter Average Load Profile, Valley-Filling Potential, and Peak Day



**Figure A.5.** CNV Dispatch for Summer Average Load Profile, Valley-Filling Potential, and Peak Day



**Figure A.6.** CNV Dispatch for Winter Average Load Profile, Valley-Filling Potential, and Peak Day