designed for fuel efficiency, regardless the “fuel” source. Finally, charging capability can be extended with the addition of 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 would significantly increase the fraction of PHEVs the WECC region could support.

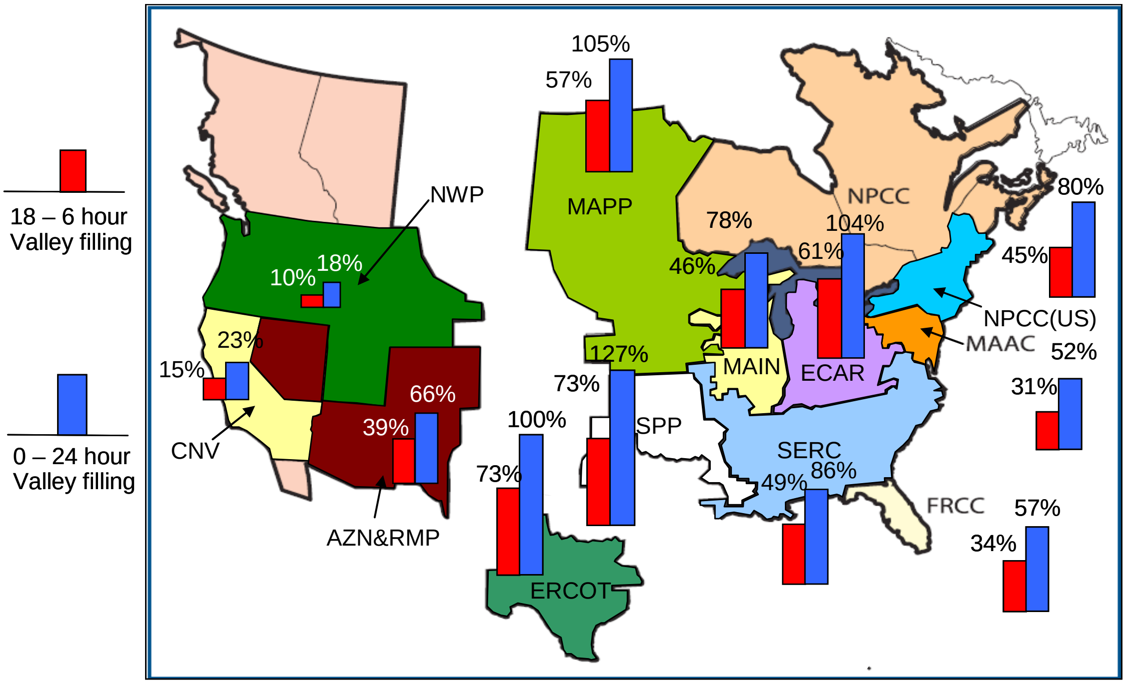

Figure 3: Technical Potential for Fueling the Regional Light Duty Vehicle Fleet with Available Electric Capacity

Table 2: Results of Technical Potential by Regions

		24-Hour Valley Filling	**6 pm–6 am Valley Filling**	**24-Hour Valley Filling**	**6 pm–6 am Valley Filling**
Region	**Total Number of Vehicles in Mill.**	**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
MACC	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
SERC	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
National Average *	**216.9**	**73**	**43**		

* 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 to 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 are expected to be reduced by 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 greenhouse gas emission improvements could be as large as 40%, as in ERCOT, which has a large penetration of natural-gas plants. Conversely, the improvement in greenhouse gas emission could be zero or slightly negative for the MAPP region with essentially all coal generation (see Table 3).

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 over-estimated 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_X) emissions are significantly reduced (31%), primarily because of the avoidance of the internal combustion process in the vehicle as well as eliminating the refining process to produce gasoline.

The total particulate emissions (PM10) are likely to increase nationally by 18%, caused primarily by increased dispatch of coal-fired plants. As can be seen in Table 3, however, in regions with a large contribution to the marginal generation from natural-gas fueled plants, the total particulate emission could improve. The total SO_X emissions are increased at the national level by about 125%, also caused by coal-fired power plants. However, while the particulate and SO_X emissions are expected to increase in total, they would be removed from the urban areas to the locations of the power plants, commonly at a considerable distance from the large urban population. All urban emissions are expected to significantly improve (see Table 3).

It should be noted that with the emergence of PHEV, the emission sources will shift from millions of individual vehicles to a few hundred central generation facilities. 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 3: Emissions Results Using the GREET Model

	ECAR	ERCOT	MACC	MAIN	MAPP	NPCC	FRCC	SERC	SPP	NWP	AZN& RMP	CNV	U.S. total
						Power Generation Composition							
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%	
Emissions						**Emissions Ratio (Electric Vehicle/Gasoline Vehicle)**							
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 the 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. Figure 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, 2005]. 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.

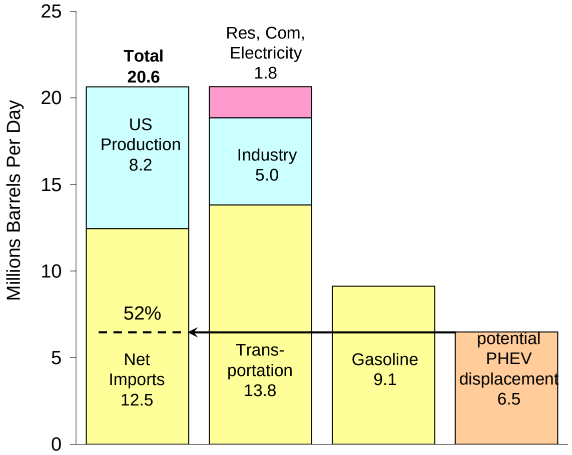

Figure 4: Petroleum Supply, Consumptions and PHEV Displacement Potential [EIA, 2005]

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. 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 utilization scenario as less reserve capacity is available to the system operators for managing system emergencies. "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 approximate a 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 reliability at these levels during peak periods, sustained operation at these levels may reveal new constraints. For example, there may be intra-regional 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 impose additional constraints on the delivery limit because they 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 peak and valley as observed at the regional system level.[5] 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

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[5] Based on substation and feeder data from predominantly residential feeders in Southern California Edison's and Allegheny Power's service territory.

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.

In the short run, the expected increased utilization 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 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.

SUMMARY

The results of the analysis are listed below:

- The existing electricity infrastructure as a national resource has sufficient available capacity to fuel 84% of the nation's cars, pickup trucks, and SUVs (198 million) or 73% of the light duty fleet (about 217 million vehicles) for a daily drive of 33 miles on average.
- There are significant emissions impacts resulting 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 and SO_X emissions would increase as a result of increased dispatch of coal-fired power plants. There are 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 source 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 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 significant new load for charging PHEVs. Higher system loading could impact the overall system reliability as the entire infrastructure is utilized near its maximum capability for long periods. "Smart" PHEV charging systems that recognize grid emergencies could mitigate the extent and severity of grid emergencies. Near maximum utilization of the nation's power plants is 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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APPENDIX A

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

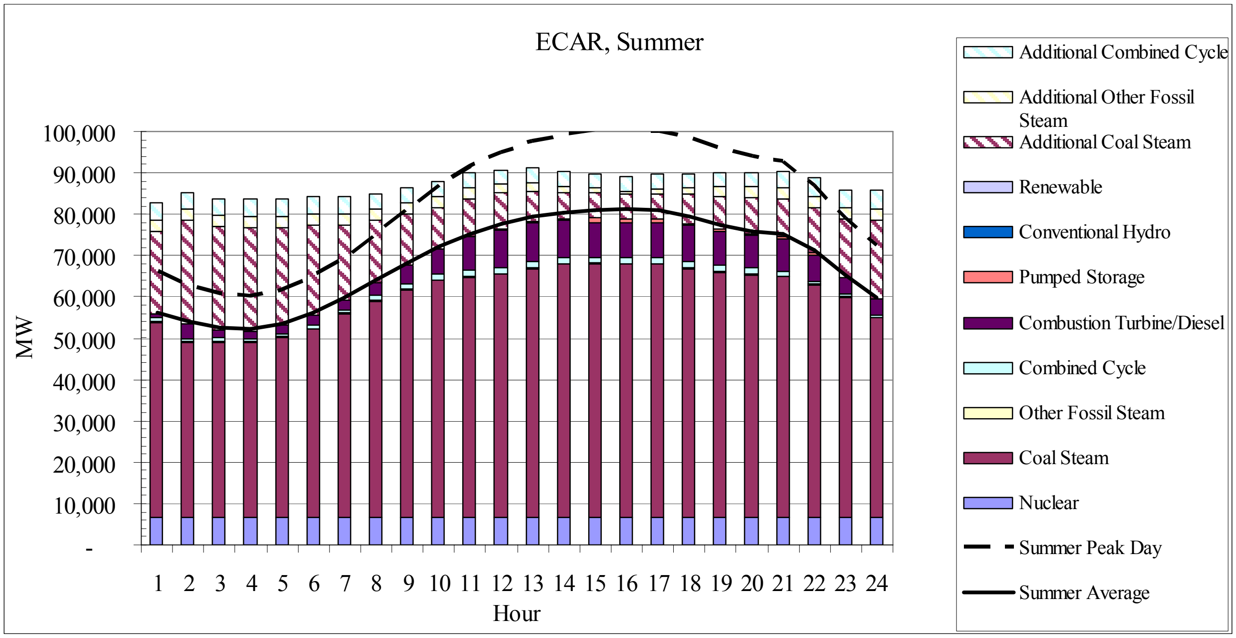

Figure A.1: ECAR Dispatch for Summer Average Load Profile, Valley-Filling Potential, and Peak Day

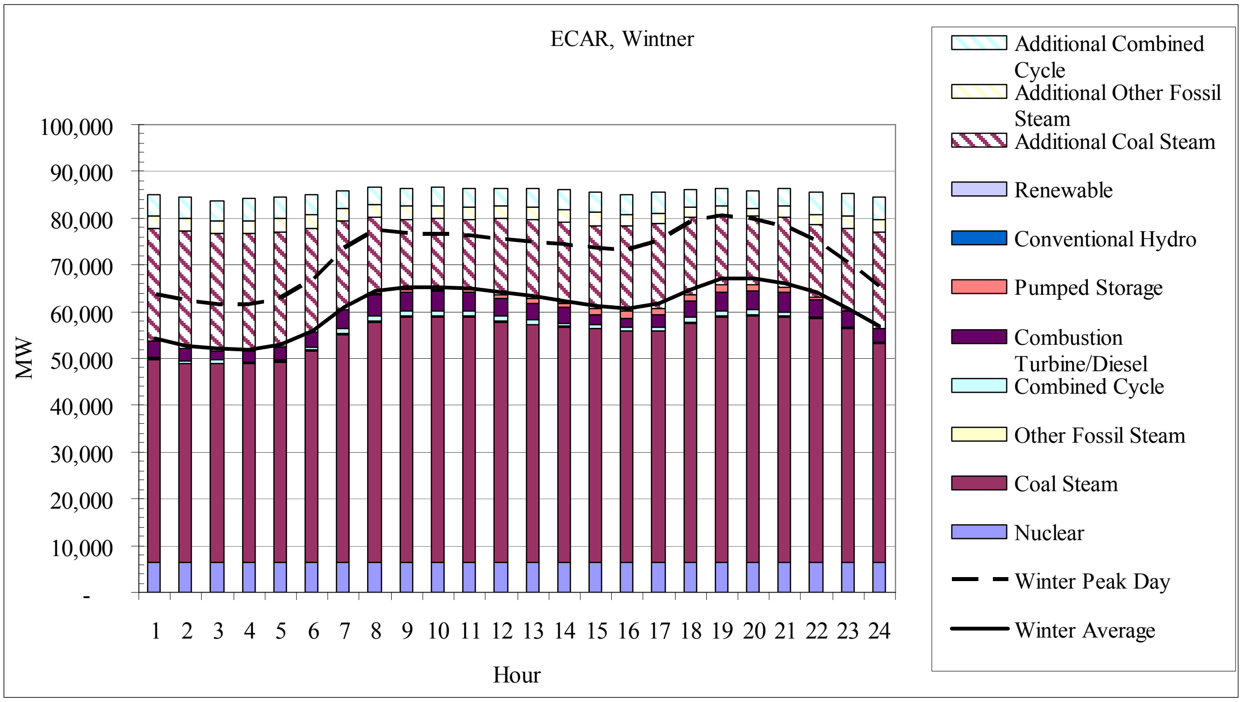

Figure A.2: ECAR Dispatch for Winter Average Load Profile, Valley-Filling Potential, and Peak Day

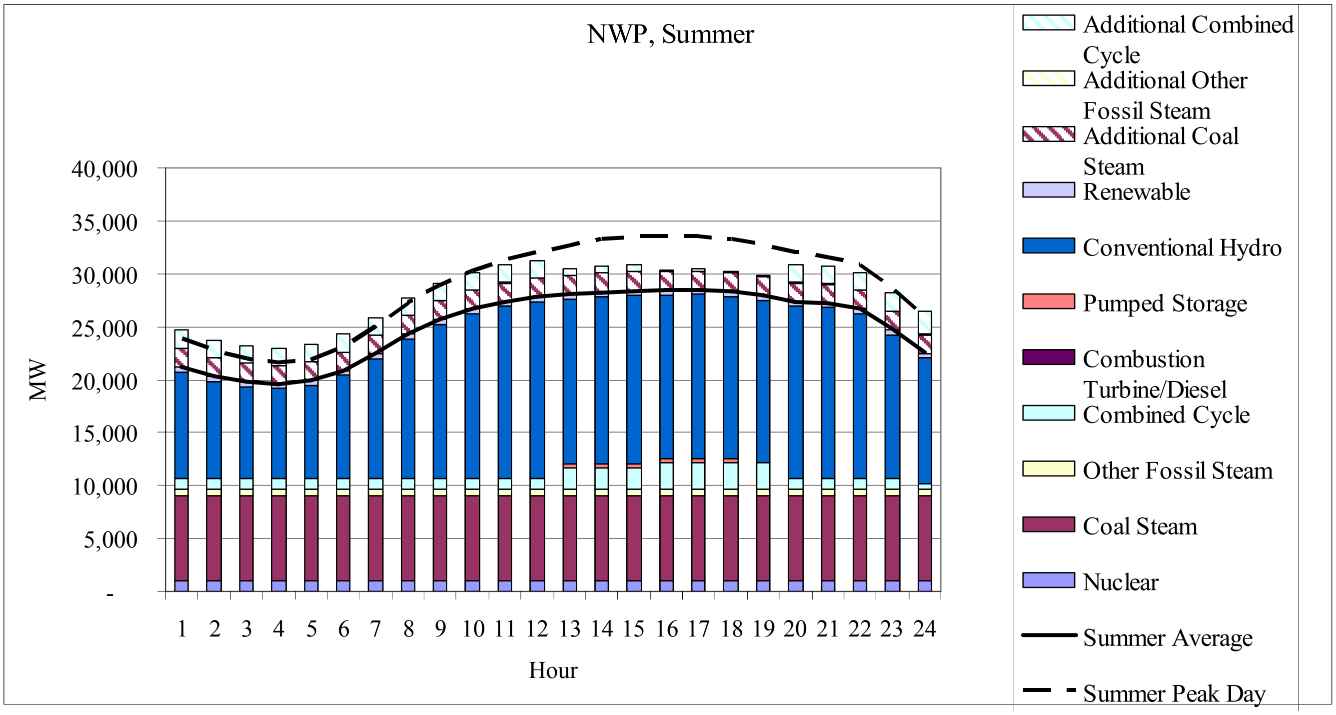

Figure A.3: NWP Dispatch for Summer Average Load Profile, Valley-Filling Potential, and Peak Day

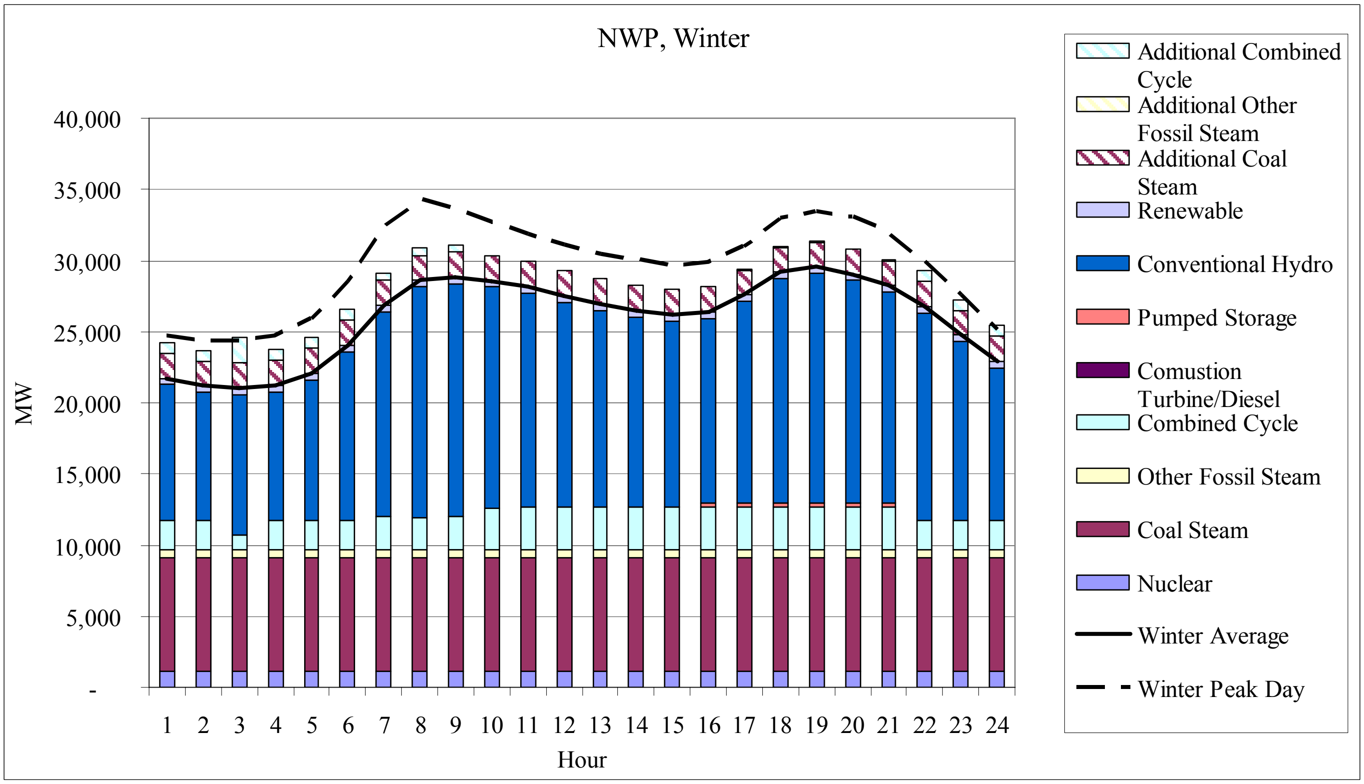

Figure A.4: NWP Dispatch for Winter Average Load Profile, Valley-Filling Potential, and Peak Day

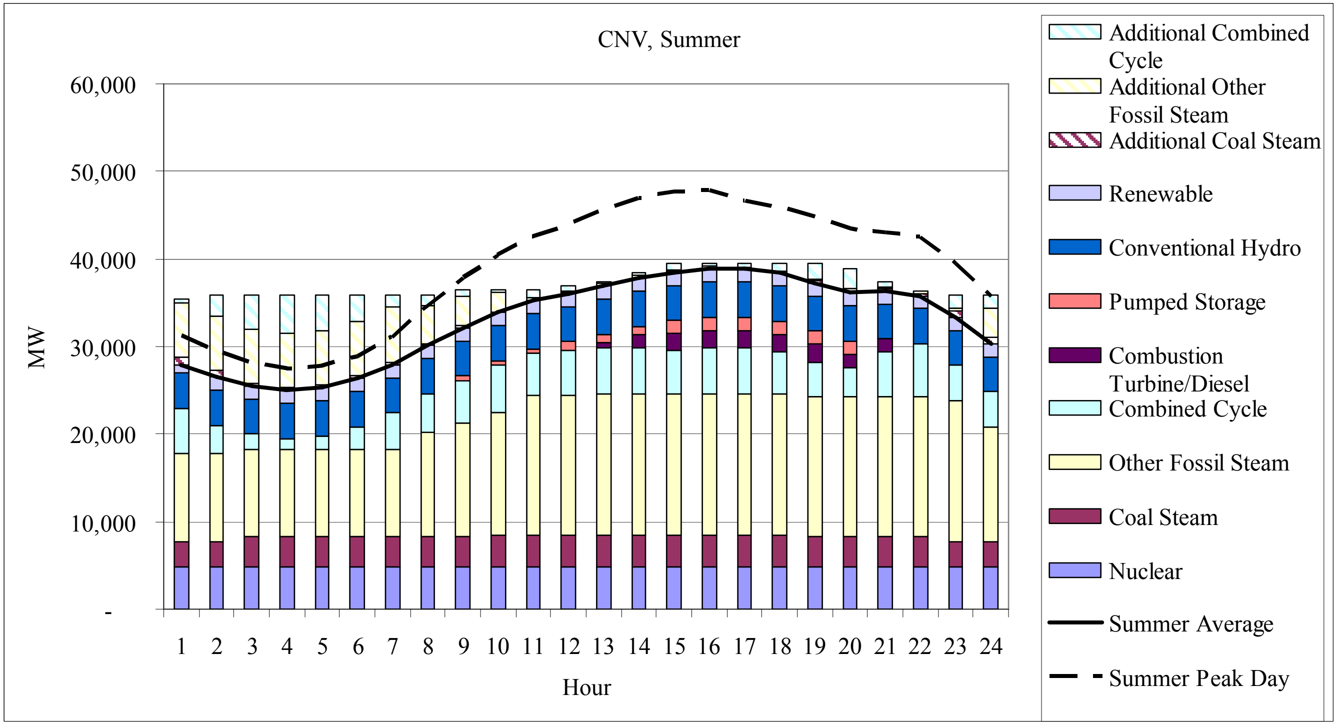

Figure A.5: CNV Dispatch for Summer Average Load Profile, Valley-Filling Potential, and Peak Day

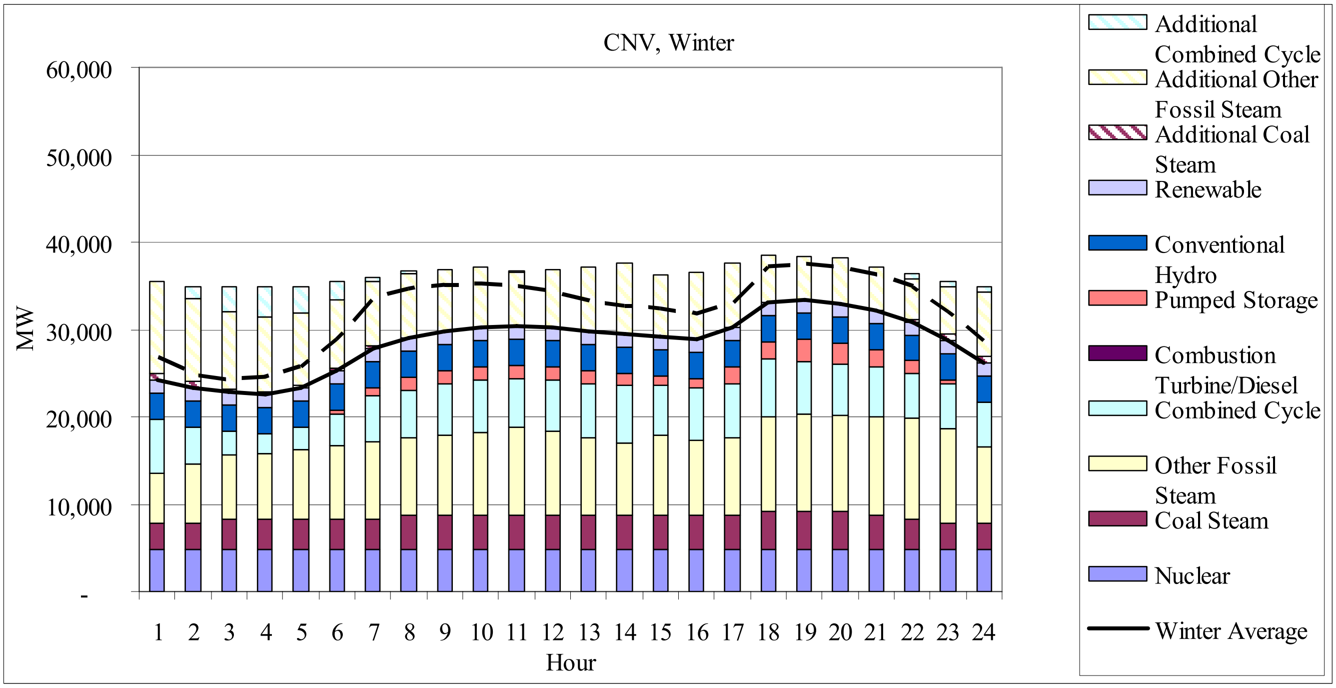

Figure A.6: CNV Dispatch for Winter Average Load Profile, Valley-Filling Potential, and Peak Day