



Power System Level Impacts of Plug-In Hybrid Vehicles

Final Project Report

Power Systems Engineering Research Center

*Empowering Minds to Engineer
the Future Electric Energy System
Since 1996*



Power System Level Impacts of Plug-In Hybrid Vehicles

Final Project Report

Project Team

Sakis Meliopoulos, Project Leader

Jerome Meisel

George Cokkinides

Georgia Institute of Technology

Thomas Overbye

University of Illinois at Urbana-Champaign

PSERC Document 09-12

October 2009

Information about this project

For information about this project contact:

Sakis Meliopoulos
Georgia Power Distinguished Professor
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0250

Power Systems Engineering Research Center

The Power Systems Engineering Research Center (PSERC) is a multi-university Center conducting research on challenges facing the electric power industry and educating the next generation of power engineers. More information about PSERC can be found at the Center's website: <http://www.pserc.org>.

For additional information, contact:

Power Systems Engineering Research Center
Arizona State University
577 Engineering Research Center
Tempe, Arizona 85287-5706
Phone: 480-965-1643
Fax: 480-965-0745

Notice Concerning Copyright Material

PSERC members are given permission to copy without fee all or part of this publication for internal use if appropriate attribution is given to this document as the source material. This report is available for downloading from the PSERC website.

© 2009 Georgia Institute of Technology and University of Illinois at Urbana-Champaign. All rights reserved.

Acknowledgements

This is the final report for the Power Systems Engineering Research Center (PSERC) research project T-34 titled “Power System Level Impacts of Plug-In Hybrid Vehicles” We express our appreciation for the support provided by PSERC’s industrial members and by the National Science Foundation’s Industry / University Cooperative Research Center program under the grants NSF EEC-0080012 at Georgia Institute of Technology and NSF EEC-9615792 at University of Illinois, Urbana-Champaign.

The authors wish to recognize their postdoctoral researchers and graduate students that contributed to the research and creation of the reports:

Georgia Institute of Technology

- Curtis Roe, GRA

University of Illinois, Urbana-Champaign

- Renata Revelo Alonso, GRA
- Steven Judd, GRA

The authors thank all PSERC members for their technical advice on the project, especially (the companies shown were as of time of this project work):

- Navin Bhat – AEP
- Ali Chowdury – Mid-American
- Jim Crane – Exelon
- Bruce Fardanesh – NYPA
- Floyd Galvan – Entergy
- Jeff Gerken – AEP
- Sharma Kolluri – Entergy
- Mark Lauby – EPRI
- Mark McGranaghan – EPRI
- Mahendra Patel - PJM
- Darlene Radcliffe – Duke Energy
- John Richardson – TVA
- James Stoupis – ABB
- Raymond Vice - Southern Company

Executive Summary

Plug-in hybrid electric vehicles (PHEVs) offer an attractive solution to a growing dependence on imported foreign oil with potential benefits and issues to the electric power industry. The impact of PHEVs on the power grid is investigated. The methodology for this investigation is based on three procedures: (a) typical utilization of PHEVs that capture human habits and terrain on which cars are driven for the purpose of evaluating the energy consumption and split between electric and gas, (b) simulation of the electric infrastructure (distribution systems) and the loading patterns that results from PHEV deployment and the effects on the equipment and in particular the expected life of transformers, (c) impact of PHEV deployment on energy resource utilization in the power grid, and (d) impact of PHEV deployment on the operations and the security of the power grid. Proper models are utilized that capture all the interactions of the complex system that comprises the power grid, the distribution system and the PHEVs. The report consists of two volumes.

Volume I

First, four hybrid-electric vehicle (HEV) powertrain architectures are described. These architectures are commonly termed series, parallel, single-mode split-power, and dual-mode split-power. Conclusions suggest that either a parallel architecture or the GM 2-MT is the best choice.

Second, calculations of the electric energy consumed by PHEVs under typical scenarios are performed using both an analytic approach and computer simulation. The analytic approach utilizes estimates for the efficiency of PHEV components. Simulations are run using the *Powertrain System Analysis Toolkit (PSAT)* v.6.2 program developed by DOE's Argonne National Lab. A comparison of results from both methods is provided. Sample results show that if 10% of the entire US vehicle fleet is replaced by PHEVs, and vehicles travel an average of 12,000 miles per year the added electric load due to PHEVs would be 3.3% of the installed 950 GW generation capacity in the US; a small increase in the added electric demand.

Third, the vehicle emissions including nitrogen oxides (NO_x) and the greenhouse gas carbon dioxide (CO_2) are described. It is found that if a PHEV control algorithm can operate a vehicle such that, on average, 62% of the energy supplied to the powertrain comes from the battery, then, with a standard spark-ignited IC engine the regulated emissions meet the latest standard (Tier2-Bin5).

Fourth, two infrastructure implications are described (1) the impact of typical household infrastructure on PHEV recharging, and (2) the vehicle to grid interface. The household circuit capacity (120V / 20A) is capable of recharging the required battery capacity needed to drive 40 miles in charge sustaining mode (70% of the required energy per mile is derived from onboard electric energy over the entire 40 miles) in 6 hours; further, the size of this battery pack is feasible in terms of weight and volume using battery technology available today. Additionally, four levels of vehicle to grid interface are defined, increasing in functionality and complexity.

Fifth, the impact of PHEV charging on distribution transformers is described. This impact is quantified through a loss-of-life (LOL) calculation. The LOL calculation is based on distribution transformer hot-spot temperature. This temperature is estimated using an electro-thermal distribution transformer model and is a function of the transformer winding currents. These currents are computed using a center-tapped single phase transformer model. Results of this research show that a measurable LOL can occur due to PHEV charging. Areas of high ambient temperature show larger LOL over areas of low ambient temperature and highly loaded transformers show higher LOL over transformers with excess capacity. The LOL of transformers is very sensitive on whether the combined residential load and PHEV is near or exceeds the rating of the transformer.

Sixth, the impact of PHEV charging in terms of (a) primary fuel utilization shifts, (b) pollution shifts, and (c) total fuel cost for yearly vehicle operation is described. Vehicle and power system simulations are used. The vehicle fleet simulations compute: the amount of added electric load demand to charge the PHEV fleet, amount of gasoline used by both IC vehicles and PHEVs, and the amount of environmental air pollution (EAP) generated by both IC vehicles and PHEVs. The power system simulations simulate how much fuel usage and subsequent EAP are generated by a specific power system. Results from this research indicate that PHEVs offer cleaner transportation (depending on the generation mix used to charge the vehicles) with decreased gasoline utilization at a lower cost to consumers. Specifically, three different power system generating mixes are simulated with varying levels of PHEV penetration (defined as the percentage of the light duty vehicle fleet in the power system area replaced by PHEVs). Two of the three power system generating mixes simulated show a decrease in total system NO_x EAP and all three showed a decrease in CO₂ EAP.

Seventh, the benefit of using a heavy penetration of PHEVs to act as support to the grid during contingencies and also the costs incurred with security constrained control is described. PHEVs provide a completely new way to store massive amounts of energy from the power grid. It is found that (1) PHEVs have a great potential to save grid operating costs and reduce critical contingencies and (2) PHEVs have a significant effect on unenforceable security constrained optimal power flow (SCOPF) contingencies and maximum line overloads.

Eighth, a comparison of vehicles powered from hydrogen fuel to PHEVs is described. The significant hurdles involving production, storage, distribution, and use of hydrogen are outlined. Conclusions drawn are that hydrogen use with a fuel cell or even injected directly into an IC engine is not a near-term prospect for reducing the use of petroleum-based fuels.

Ninth, a comparison of battery-electric ZEVs to PHEVs is described. The advantages of ZEVs over PHEVs are: a simpler less expensive powertrain, less maintenance with only an electric drivetrain, zero tailpipe emissions, electric energy that could be produced by renewable sources. The disadvantages of ZEVs are large battery packs to get a reasonable range, and very long recharging times. The advantages of PHEVs over ZEVs are: that an appreciable amount of the driving energy comes from the electrical grid thus reducing the use of petroleum-based fuels and tailpipe emissions compared to conventional vehicles, range limitations are not limited as charge-sustaining operation is available, smaller battery packs can be used. The disadvantages of PHEVs are (a) more

complex and costly powertrain, and (b) use of a petroleum-based fuel with some tailpipe emissions when driven longer distances.

Volume II

Two studies are presented quantifying the impact of plug-in hybrid vehicles (PHEVs) on the power grid. The first study quantifies this impact in terms of (a) primary fuel utilization shifts, (b) pollution shifts, and (c) total cost for consumers. The second study quantifies this impact on distribution transformers.

In the first study vehicle fleet and power system simulations are used. The vehicle fleet simulations compute the amount of added electric load demand to charge the PHEV fleet, the amount of gasoline used by both internal combustion (IC) vehicles and PHEVs, and the amount of environmental air pollution (EAP) generated by both IC vehicles and PHEVs. The power system simulations simulate how much fuel usage and subsequent EAP are generated by a specific power system.

In the second study the impact on distribution transformers is quantified through a loss-of-life (LOL) calculation that is based on the transformers hot-spot temperature. This temperature is estimated using an electro-thermal transformer model and is a function of the transformer currents. These currents are computed using a center-tapped single phase transformer model.

The results from this research indicate that PHEVs offer cleaner transportation (depending on the generation mix used to charge the vehicles) with decreased gasoline utilization at a lower operating cost to consumers. The impact to the utility infrastructure is favorable from the security point of view and additional revenues to the utility and unfavorable to the expected life of distribution transformers. The last issue can be addressed in a variety of ways, including monitoring of distribution transformers and replacing them with larger units if the loading from PHEVs results in substantial loss of life.

In general the impact of PHEVs on the power grid is favorable. The unfavorable effect on the expected life of distribution transformers is not much different than the effect of increasing loads in a household or commercial building. Power companies deal with this problem routinely. It is suggested as a follow up to this research project to develop transformer life expectancy monitor. The technology exists today to develop a smart monitoring device that will track the loading and thermal history of distribution transformers and compute the loss of life in real time. This technology can provide alarms that quantify the impact of increased loading on the transformer life which can be used by utilities to prioritize the replacement of transformers. The increase of total load on the power grid, assuming expected gradual penetration of PHEVs in the market, is at a level comparable to what utilities have experience under normal economic conditions, i.e. few percentage points annually. Therefore gradual penetration of PHEVs can be easily handled by typical power system planning scenarios.

Power System Level Impacts of Plug-In Hybrid Vehicles

Volume I

Information about this volume

For information about this project contact:

Sakis Meliopoulos
Georgia Power Distinguished Professor
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0250

Power Systems Engineering Research Center

The Power Systems Engineering Research Center (PSERC) is a multi-university Center conducting research on challenges facing the electric power industry and educating the next generation of power engineers. More information about PSERC can be found at the Center's website: <http://www.pserc.org>.

For additional information, contact:

Power Systems Engineering Research Center
Arizona State University
577 Engineering Research Center
Tempe, Arizona 85287-5706
Phone: 480-965-1643
Fax: 480-965-0745

Notice Concerning Copyright Material

PSERC members are given permission to copy without fee all or part of this publication for internal use if appropriate attribution is given to this document as the source material. This report is available for downloading from the PSERC website.

© 2009 Georgia Institute of Technology and University of Illinois at Urbana-Champaign. All rights reserved.

Table of Contents

1. Project Description.....	1
2. Hybrid-Electric Vehicle Architectures	4
2.1 Introduction	4
2.2 Series Architecture	4
2.3 Parallel Architecture	5
2.4 Toyota Hybrid System-II (THS-II) Single-Mode Power-Split Architecture	7
2.5 GM Two-Mode Compound Split Architecture	8
2.6 Preferred PHEV Architecture	9
3. Grid-Supplied Energy Requirements for PHEVs	12
3.1 Introduction	12
3.2 Consideration of PHEV Control Algorithms	14
3.3 An Analytic Approach to Determine Daily Recharge Energy per Vehicle.....	15
3.4 PHEV Simulation Methodology.....	20
3.5 Engine-Only Fuel Efficiency Comparison	25
3.6 Grid Supplied Recharge Energy	26
3.7 Fuel Efficiency	29
4. Regulated Emissions and Greenhouse Gas Emissions for PHEVs.....	31
4.1 Introduction	31
4.2 Regulated Tailpipe Emissions	31
4.3 Comparison of NO _x Emissions Conventional Vehicles and PHEVs	32
4.4 PHEV NO _x Emissions from PSAT Simulations	34
4.5 Introduction to Greenhouse Gas Emissions	35
4.6 Comparison of CO ₂ Emissions from Conventional Vehicles and PHEVs.....	36
4.7 PHEV CO ₂ Emissions from PSAT Simulations.....	39
5. Household Supply Requirements and PHEV Vehicle / Grid Interface Design.....	41
5.1 Introduction	41
5.2 Feasibility of Battery Packs for PHEVs	42
5.3 Introduction to Vehicle / Grid Interface Design.....	43
5.4 On-Board Electronic Requirements	44
5.4.1 Level-0	44
5.4.2 Level-1	44
5.4.3 Level-2	45
5.4.4 Level-3	45
6. PHEV Infrastructure Impact	47
6.1 Distribution System Model.....	48
6.2 Transformer Electro-Thermal Model	49
6.3 Loss of Life Calculations.....	53
6.4 Results	54
6.5 Conclusion.....	57
7. PHEV Energy Utilization	59
7.1 Vehicle Simulations.....	59
7.2 PPC Simulation	64

7.3	Results	68
7.4	Conclusion.....	71
8.	An Evaluation of PHEV Contributions to Power System Disturbances and Economics.....	72
8.1	Literature Review	72
8.1.1	Justification for Integrating PHEVs to the Power Grid.....	72
8.1.2	Evaluation of Potential Grid Uses for PHEVs	72
8.1.3	Beginnings of Vehicle-to-Grid Connections.....	73
8.2	Case for Converting Vehicle Fleet to PHEVs	74
8.2.1	Personal Savings Over Current Vehicles	74
8.2.2	Greenhouse Gas Reduction	75
8.3	US Vehicle and Grid Connection Information.....	75
8.3.1	Estimation of PHEV Penetration.....	75
8.4	Test Cases.....	76
8.4.1	Solving an Optimal Power Flow for a Test Case	76
8.4.2	Solving a Security Constrained OPF for a Test Case.....	78
8.4.3	IEEE 24 Bus Test Case	78
8.4.4	IEEE 118 Bus Test Case	80
8.4.5	Utility 2,574 Bus Test Case.....	80
8.5	Test Scenarios Using PHEVs	80
8.5.1	Amount of PHEV Support for Simulations.....	80
8.6	Results	81
8.6.1	IEEE 24 Bus Test Case	81
8.6.2	IEEE 118 Bus Test Case	82
8.6.3	Utility 2,574 Bus Test Case.....	84
8.7	Conclusion.....	85
	References.....	87
	Project Publications	92
	Appendix A: Hydrogen Fuel as a Competing Technology to Charge-Depleting PHEVs	93
A.1	Introduction	93
A.2	Four Main Hurdles for Hydrogen as an Automotive Fuel	93
A.2.1	Production:	93
A.2.2	Storage:.....	94
A.2.3	Distribution:	95
A.2.4	Use:.....	95
A.3	Fuel-Cell Vehicle vs. PHEV Efficiency	96
A.3.1	Efficiency of process component in a Fuel-Cell Vehicle:.....	96
A.3.2	Efficiency of process component in a Plug-in Hybrid Electric Vehicle (PHEV):.....	97
	Appendix B: Battery-Electric Powertrains as an Alternative to PHEV Powertrains.....	98
B.1	Introduction	98
B.2	Specific Energy and Power Ratings for Batteries and Gasoline.	99
B.3	Energy Requirements of ZEVs and PHEVs.....	99
B.4	Estimate of ZEV and PHEV Driving Range	100
B.5	Recharging / Refueling Times.....	100

B.6	Summary.....	101
B.6.1	ZEV Advantages:	101
B.6.2	ZEV Disadvantages:.....	101
B.6.3	PHEV Advantages:	101
B.6.4	PHEV Disadvantages:	101
Appendix C: Power System Data Utilized in the Primary Energy Source Utilization		
	Experiments	105
C.1	RTS System Data	105
C.2	US System Data.....	108
C.3	Load Data	109

List of Figures

Figure 2.1: Series hybrid architecture wherein only the electric motor powers the driven wheels.	4
Figure 2.2: Post-transmission parallel architecture.....	6
Figure 2.3: The Toyota Hybrid System (THS-II) power split architecture.	7
Figure 2.4: The Toyota Hybrid System (THS-II) power split architecture.	8
Figure 2.5: The three Partnership for New Generation Vehicles (PNGV) with their key design accomplishments.	10
Figure 2.6: The GM Volt PHEV.....	10
Figure 3.1: Computation of grid-supplied recharge energy for PHEVs (kWh/mi) for four vehicle classes and $0 \leq k_{PHEV} \leq 1$. Also computed is the MWh/day and added gross income in \$/day.....	18
Figure 3.2: US06 driving schedule of 8 mi, over 600 sec with a peak speed of 80.29 mph, an average speed of 47.96 mph, and 5 stops totaling 45 sec duration.	21
Figure 3.3: UDDS driving schedule of 7.45 mi, over 1369 sec with a peak speed of 56.7 mph, an average speed of 19.58 mph, and 17 stops totaling 259 sec duration.	22
Figure 3.4: HWFET driving schedule of 10.26 mi, over 764 sec with a peak speed of 59.9 mph, an average speed of 48.27 mph, and 1 stop totaling 5 sec duration.....	22
Figure 3.5: Calculation of the grid-supplied energy per mile for the four vehicle classes.	27
Figure 3.6: Energy-per-mile that would be required from the grid by the four vehicle classes as a function of k_{PHEV} , the fraction of the total input energy from the battery.	28
Figure 3.7: Calculation of miles per gallon of gasoline for the four vehicle classes.....	29
Figure 3.8: Miles-per-gallon of gasoline as a function of the percentage of the total input energy from the battery.....	30
Figure 4.1: Regulated NO _x emissions for PHEVs.	33
Figure 4.2: NO _x emissions for Class 1 and 2 vehicles as a function of the percent of the total input energy from the battery.....	34
Figure 4.3: NO _x emissions for Class 3 and 4 vehicles as a function of the percent of the total input energy from the battery.....	35
Figure 4.4: PHEV emission of the greenhouse gas, CO ₂	39
Figure 4.5: CO ₂ emissions for Class 1 and 2 vehicles as a function of the percent of the total input energy from the battery.....	40
Figure 4.6: CO ₂ emissions for Class 3 and 4 vehicles as a function of the percent of the total input energy from the battery.....	40
Figure 6.1: Daily ambient temperature profiles used as limiting case scenarios [6.1].	48

Figure 6.2: Center-tapped single phase distribution transformer model [6.2].	48
Figure 6.3: Electro-thermal transformer model.	50
Figure 6.4: Increase in percent LOL for Tucson AZ and Fairbanks AK for a varying number of PHEVs included in the distribution system.	56
Figure 6.5: Increase in percent LOL for Tucson AZ and Fairbanks AK charging three PHEVs using different transformer sizes.	56
Figure 7.1: Probability density function of the available capacity of a generating unit. ..	64
Figure 7.2: Normalized inverted load duration curve	65
Figure 7.3: RTS generating capacity [7.5].	68
Figure 7.4: U.S. total generating capacity [7.6].	69
Figure 8.1: Internal combustion powertrain energy losses [8.16].	74
Figure 8.2: IEEE 24 bus test system.	79
Figure 8.3: Bus system cost vs. PHEV support normalized to OPF cost.	81
Figure 8.4: 24 Bus contingency violations vs. PHEV support.	82
Figure 8.5: 118 Bus system cost vs. PHEV support.	83
Figure 8.6: 118 Bus contingency violations vs. PHEV support.	83
Figure 8.7: 2,574 Bus System Cost vs. PHEV Support.	84
Figure 8.8: 2,574 Bus contingency violations vs. PHEV support.	85
Figure A.1: The Honda Clarity fuel cell vehicle.	94
Figure A.2: The fuel-cell cycle for using hydrogen as an automotive fuel.	95
Figure A.3: The PHEV stores the electric energy directly from the grid.	96
Figure B.1: Calculation of ZEV and PHEV driving range.	103
Figure B.2: Battery-Electric ZEV recharging times from a 240 V, 30 A receptacle.	104

List of Tables

Table 3.1: Definition of vehicle classes.....	12
Table 3.2: Average conventional vehicle parameter values for each vehicle class.....	13
Table 3.3: Required recharge energy for PHEVs in the four class sizes defined in Table 3.1 and Table 3.2 driven with 70% of the input energy from the battery ($k_{PHEV} = 0.7$)..	19
Table 3.4: Engine-only simulation results for the four vehicle classes.	23
Table 3.5: Hybrid powertrain simulation results for a compact Class-1, Ford Focus vehicle model, ICE = 40 kW, electric motor = 85 kW, mass = 1301 kg.....	23
Table 3.6: Hybrid powertrain simulation results for a full size Class-2, Ford Taurus vehicle model, ICE = 50 kW, electric motor = 125 kW, mass = 1638 kg.....	24
Table 3.7: Hybrid powertrain simulation results for an SUV Class-3, Ford Taurus vehicle model, ICE = 125 kW, electric motor = 150 kW, mass = 2159 kg.	24
Table 3.8: Hybrid powertrain simulation results for a Large Truck Class-4, GM Silverado vehicle model, ICE = 125 kW, electric motor = 225 kW, mass = 2497 kg.....	25
Table 3.9: Combined mpg for conventional vehicles (engine-only) from PSAT simulations and from the EPA average values for each vehicle class.	25
Table 4.1: Regulated exhaust emission standards in (grams per mile) [4.1].	32
Table 4.2: Minimum value of k_{PHEV} , the fraction of the total input energy that comes from the battery, required to meet the Tier2 Bin5 standard on each of the three driving schedules.	35
Table 5.1: Current rating in (A) for a 120 V circuit with a recharge time interval of 6 hours with $k_{PHEV} = 0.7$	41
Table 5.2: Battery pack rating for each vehicle class over the three driving distances (kWh / Ah).	42
Table 5.3: Data for available SAFT Li-Ion battery cells.	43
Table 6.1: Transformer dimension and oil volume data [6.5].	51
Table 6.2: Electro-thermal transformer capacitance results.	52
Table 6.3: Electro-thermal model circuit parameters.	53
Table 6.4: Normal insulation life times [6.7].....	54
Table 6.5: Aging rate constant [6.7].	54
Table 6.6: Base case and PHEV scenario percent LOL for Tucson AZ and Fairbanks AK varying the number of PHEVs charged using a 15kVA transformer.....	55
Table 6.7: Base case and PHEV scenario percent LOL for Tucson AZ and Fairbanks AK varying the size of the transformer used to charge three PHEVs.	55
Table 6.8: Increase in average electric load and resulting average transformer LOL.	57

Table 7.1: Change in primary energy source utilization.....	70
Table 7.2: Total system EAP.	71
Table 8.1: Fuel cost figures for generators.	78
Table 8.2: Cost curve values for generator types.....	79
Table 8.3: PHEV support in percent of peak load.	81
Table B.1: Specific energy and power for common battery chemistries and gasoline [B.1].	99
Table B.2: Recharging energy for ZEVs and PHEVs on the US06 driving schedule with the mpg for a conventional powertrain in each vehicle class.	99
Table B.3: Summary of battery sizes and range for ZEVs and PHEVs.	100
Table C.1: Fuel data [C.1].....	105
Table C.2: Generating unit reliability data [C.1].	106
Table C.3: Generating unit generation capacity data [C.1].	106
Table C.4: Generating unit heat rate coefficients [C.1].	107
Table C.5: TVA generator statistics [C.5].	107
Table C.6: Generating unit emission rate coefficients.....	108
Table C.7: Total U.S. generating capacity by energy source [C.2].	108
Table C.8: Net U.S. energy generating by source [C.3].	109
Table C.9: Estimated EAP by each fuel source in 2007 for the entire U.S. [C.4].	109
Table C.10: Weekly peak load in percent of annual peak [C.1].	110
Table C.11: Daily peak load in percent of weekly peak [C.1].	110
Table C.12: Hourly peak load in percent of daily peak [C.1].	111
Table C.13: Hydro energy per calendar quarter [C.1].	112

Nomenclature

2-MT	Two-mode transmission
$\delta_{Bat-RL}(t)$	Battery road-load coefficient
	$\delta(x_i) = \begin{cases} 1 & \text{if } x_i = 0 \\ 0 & \text{if } x_i \neq 0 \end{cases}$
$\Delta E_{Bat}(t)$	Battery output energy at time t over a time interval Δt (kWh)
ΔM_{PHEV}	Additional vehicle mass for conversion to a PHEV (kg)
ΔSOC	SOC range for charge-depleting operation
Δt_u	Transformer LOL time step (1 hr)
Δx_i	A small increment of power output used in the PPC algorithm, refer to this increment as the block (1-2 MW)
η_{Bat}	Battery turn-around efficiencies (%)
$\eta_{Charger}$	Efficiency of the power electronic battery charging-discharging circuits (%)
$\eta_{Control}$	Energy efficiency of the power electronic controller (%)
η_{Conv}	Fraction of the heat energy in a liquid fuel that an IC engine delivers to the driven wheels (%)
η_{Motor}	Energy efficiency of the electric drive motor (%)
$\eta_{Transmission}$	Efficiency of the vehicles transmission (%)
θ_u	Transformer aging acceleration factor
ρ	Density of air (1.202 kg/m ³)
ρ_f	Fuel price (\$/kg)
ρ_{Fuel}	Heat energy density of a given fuel (For gasoline 36.65 kWh/gal)
ρ_W	Electro-thermal model winding mass density (8.93 g/cm ³)
ϕ	Inverse tangent of the grade i.e.tan-1(Grade)
A	Vehicle frontal area (m ²)
AER	All electric range, or ZEV range (miles)
a_e	Constant emission rate coefficient (kg/h)
a_h	Constant heat rate coefficient (kcal/h)
AGC	Automatic generation control
A_i	A random variable representing the output of generating unit- i (MW)
A_j	The available capacity of generating unit- j , where $j = 1, 2 \dots n$ assuming there are n available generating units in the power system (MW)
$A_T^{(v,d)}$	A random value representing the arrival time of vehicle- v on day- d (hr)
B	Transformer aging rate constant
b_e	Linear emission rate coefficient (kg/MWh)
b_h	Linear heat rate coefficient (kcal/MWh)
$BC^{(c)}$	A random value representing the usable fraction of the PHEVs battery capacity for a PHEV in class- c (kWh)
BSFC	Brake Specific Fuel Consumption
$C(\Delta x_i)$	The expected heat consumed by block Δx_i (cal)
C	Electro-thermal transformer model thermal capacitance matrix (J/°C)

C_*	General terms for the distribution transformer model individual winding thermal capacitive values (J/°C)
c_h	Quadratic heat rate coefficient (kcal/(MW ² ·h))
$C_{h,h}$	Electro-thermal transformer model high voltage winding thermal capacitance (J/°C)
$C_{1,1}$	Electro-thermal transformer model low voltage winding one thermal capacitance (J/°C)
$C_{2,2}$	Electro-thermal transformer model low voltage winding two thermal capacitance (J/°C)
$C_A^{(q)}$	The maximum hydro capacity available in calendar quarter- q (MW)
CARB	California Air Resources Board
CO	Carbon monoxide (ppm)
CO ₂	Carbon dioxide (ppm)
$CO_2^{(c)}(k_{PHEV})$	The CO ₂ EAP performance metric function for a PHEV in class- c with design variable k_{PHEV} (kg/mi)
$CO_{2,gas}$	Pounds of CO ₂ formed when burning one gallon of gasoline (lb/gal)
$cost(\Delta x_i)$	The cost of operation of block Δx_i (\$)
C_r	Wheel rolling coefficient
$C_T^{(v,d)}$	The daily recharge length of PHEV- v on day- d (hr)
CVT	Continuously variable transmission
c_W	Electro-thermal model winding specific heat capacity (0.385 J/(g·°C))
d	ZEV designated driving distance (miles) $d = 20$ for a PHEV-20, etc.
$\frac{df(z)}{dz}$	The incremental heat rate of generating unit- i
D	Drag coefficient
$D_E^{(v,d,c)}$	The daily required grid energy for PHEV- v on day- d in class- c (MWh)
$D_{EAP}^{(v,d,c)}$	The daily amount of EAP generated for PHEV- v on day- d in class- c (kg)
$D_T^{(v,d)}$	A random value representing the departure time of vehicle- v on day- d (hr)
$e(P)$	Generating unit emission rate function (kg/h)
$E(\Delta x_i)$	The expected energy to be produced from block Δx_i (MWh)
$E^{(c)}(k_{PHEV})$	A PHEV performance metric function representing the required grid electric energy rate for a PHEV in class- c with design variable k_{PHEV} (kWh/mi)
$E_A^{(q)}$	The hydro energy available in calendar quarter- q (MWh)
EAP	Environmental Air Pollution
EAP	The total EAP generated by a vehicle fleet with P_{PHEV} penetration of PHEVs (kg)
EAP_{IC}	The total EAP generated by the IC vehicle in the light duty vehicle fleet (kg)
$\overline{EAP_{IC}^{(c)}}$	The IC vehicle population average EAP produced (kg/vehicle)
EAP_{PHEV}	The total EAP generated by a fleet of PHEVs (kg)

E_{Bat}	The amount of energy delivered by the batteries to the electric drive per mile (kWh)
E_{Engine}	The amount of energy delivered by the engine to the electric drive per mile (kWh)
E_{Grid-i}	Required grid-supplied recharge energy per mile for each vehicle in class- i (kWh/mi)
$E_{Grid-Total}$	The total recharge energy required per day for the entire system area (MWh/day)
$E_{Input-i}$	The energy input per mile from the fuel tank for a vehicle in class- i (kWh/mi)
EPA	U.S. Environmental Protection Agency
E_L	Transformer equivalent life (hr)
E_{Total}	Total energy at the driven-wheels required to drive a defined driving schedule (kWh)
$f(z)$	The heat rate curve of generating unit- i
FHDS	Federal highway driving schedule
$F_L(l)$	Function describing the probability distribution function (or cumulative probability function) of the total load on the system
FOR	Forced outage rate
FUDS	Federal Urban Driving Schedule
$fuel(\Delta x_i)$	The fuel required for the operation of block Δx_i
g	Acceleration of gravity (9.807 m/sec ²)
$G(\Delta x_i)$	The expected amount of pollutants from block Δx_i .
G	Electro-thermal transformer model thermal conductance matrix (W/°C)
G	The total light duty vehicle fleet gasoline usage (gal)
$G_{h,h}$	Electro-thermal transformer model high voltage winding internal heat conductance (W/°C)
$G_{1,1}$	Electro-thermal transformer model low voltage winding one internal heat conductance (W/°C)
$G_{2,2}$	Electro-thermal transformer model low voltage winding two internal heat conductance (W/°C)
$G_{h,1}$	Electro-thermal transformer model high voltage winding to low voltage winding one internal heat conductance (W/°C)
$G_{h,2}$	Electro-thermal transformer model high voltage winding to low voltage winding two internal heat conductance (W/°C)
$G_{1,2}$	Electro-thermal transformer model between low voltage windings heat conductance (W/°C)
GHG	Greenhouse gases
G_{IC}	The amount of gasoline a fleet of N_T IC vehicles would consume (gal)
$G_{IC}^{(c)}$	The vehicle fleet population average gasoline usage (gal)
G_{PHEV}	The amount of gasoline a fleet of $N_T \cdot P_{PHEV}$ PHEVs would consume (gal)
$h(P)$	Generating unit heat rate function (kcal/h)
H_E	100% of the available hydro energy (200 GWh)
HEV	Hybrid electric vehicle

h_f	The heat content of fuel (cal/kg)
HFCs	Hydrofluorocarbons
$H_p^{(q)}$	Hydro power available in calendar quarter- q (MW)
HWFET	Highway Dynamometer Driving Schedule
I^*	The maximum current available from the PHEV charging circuit (15 A for a 120 V connection and 30 A from a 240 V connection)
I_0	Distribution transformer high voltage winding current (A)
I_1	Distribution transformer low voltage line one winding current (A)
I_2	Distribution transformer low voltage line two winding current (A)
$I^{(v,d,c)}$	The recharge current for vehicle- v on day- d in class- c (A)
$I_{Bat}(t)$	Battery terminal current (A)
I_h	Transformer electro-thermal model high voltage thermal winding current (W)
$I_{l,1}$	Transformer electro-thermal model low voltage thermal winding one current (W)
$I_{l,2}$	Transformer electro-thermal model low voltage thermal winding two current (W)
IC	Internal combustion vehicle
$IC_{CO2}^{(c)}$	The CO ₂ EAP rate for the IC vehicles in class- c (kg/mi)
ICE	Internal combustion engine
$IC_{EAP}^{(c)}$	A general term for either $IC_{NOx}^{(c)}$ or $IC_{CO2}^{(c)}$ (kg/mi)
$IC_{MPG}^{(c)}$	The fuel efficiency of the IC vehicles in class- c (mpg)
$IC_{NOx}^{(c)}$	The NO _x EAP rate for the IC vehicles in class- c (kg/mi)
$I_{Recharge-i}$	Recharge current for vehicle in class- i (A)
ISO	Independent system operator
k_{PHEV}	Fraction of the conventional fuel input energy per mile in provided by the electric drive (%)
l	General load on the system in the PPC simulation description (MWh)
$L(l)$	Functional representation of the normalized inverted load duration curve
l_a	The apparent system load (MWh)
L_a	Random value representing the apparent system load (MWh)
LDV	Light-duty vehicle
Li-Ion	Lithium-Ion
LMP	Locational Marginal Pricing
LOL	Loss-of-life
M	Vehicle mass (kg)
$M^{(v,d)}$	The daily driving distance for vehicle- v on day- d (mi)
M_{Conv}	Conventional vehicle mass (Curb weight + Total Cargo weight) (kg)
$M_E^{(c)}$	The distance a PHEV in class- c can drive in charge sustaining mode (mi)
MLE	Maximum Likelihood Estimator
mpg	Miles-per-gallon of liquid fuel

$MPG^{(c)}(0)$	The fuel efficiency of a PHEV in class- c in the charge sustaining mode (mpg)
$MPG^{(c)}(k_{PHEV})$	The performance metric function representing the fuel efficiency of PHEVs in class- c with vehicle design variable k_{PHEV} in the charge depleting mode (mpg)
MPSC	Michigan Public Service Commission
mpy	Average miles driven per year
MTTF	Mean time to failure (hr)
MTTR	Mean time to repair (hr)
N_L	Transformer normal insulation life (hr)
NLEV	National Low Emission Vehicle
N_{PHEVs}	The number of PHEVs in the light duty vehicle fleet
$N_{PHEV}^{(c)}$	The number of PHEVs in class- c
NO _x	Nitrogen-oxide (NO) and nitrogen dioxide (NO ₂) gases
$NO_x^{(c)}(k_{PHEV})$	The NO _x EAP performance metric function for a PHEV in class- c with design variable k_{PHEV} (kg/mi)
n_t	Distribution transformer turns ratio
N_T	Total number of vehicles in a defined system area excluding large trucks (18-wheelers, etc.) and busses
OPF	Optimal power flow
p	Probability a generating unit is available for production
P	In the heat rate and emission rate functions representing the generated power (MW)
$P^{(c)}(k_{PHEV})$	A general term for either $NO_x^{(c)}(k_{PHEV})$ or $CO_2^{(c)}(k_{PHEV})$ (kg/mi)
$p^{(h)}$	Random value representing the real power demand at a typical three house distribution circuit in hour- h (kW)
Pb-Acid	Lead-Acid
p_f	The price of fuel (\$/kg)
PFCs	Perfluorocarbons
PPC	Probabilistic Production Costing
P_{PHEV}	The percent penetration of PHEVs in the power system area light duty vehicle fleet
p_i	Percentage of vehicles in class- i in a defined area that are PHEVs
PHEV	Plug-in hybrid electric vehicle
P_L	Transformer percent LOL
PNGV	Partnership for a New Generation of Vehicles
P_{RL}	Total road-load power (W)
PSAT	Powertrain System Analysis Toolkit
p_v	The total recharge power per hour for all PHEVs (MW)
q	Probability a generating unit is it is unavailable ($q = 1 - p$)
q_h	Electro-thermal transformer model high voltage thermal winding current input (W)
q_1	Electro-thermal transformer model low voltage thermal winding one current input (W)

q_2	Electro-thermal transformer model low voltage thermal winding two current input (W)
$Q^{(h)}$	Random value representing the reactive power demand at a typical three house distribution circuit in hour- h (kVA)
$\vec{Q}$	Electro-thermal transformer model heat input vector (W)
R_A	Distribution transformer series resistance (p.u.)
RTS	Reliability Test System
SCOPF	Security constrained optimal power flow
S_{L1}	Distribution transformer 120 V complex load one (kVA)
S_{L2}	Distribution transformer 120 V complex load two (kVA)
S_{L3}	Distribution transformer 240 V complex load (kVA)
$S_{\text{transformer rated}}$	Distribution transformer rated power output (kVA)
SOC	Battery state of charge (SOC=100% when fully charged)
t	The duration of time the load is greater than or equal to l in the PPC simulation description
T	The duration of the time period considered in the PPC simulation
$T^{(v)}$	The total distance driven by vehicle- v in the simulation period (mi)
$\vec{T}$	Electro-thermal transformer model components temperature vector ($^{\circ}\text{C}$)
T_{Charge}	Time interval for recharging (hr)
$\tilde{T}_u$	Transformer hot-spot temperature at time- u ($^{\circ}\text{C}$)
THS-II	Toyota Hybrid System II
u	Hourly time index used in the electro-thermal model numerical integration (hr)
UDDS	Urban Dynamometer Driving Schedule
V_*	General term for a volume of the particular distribution transformer winding (in^3)
V_1	Distribution transformer 120 V load one terminal voltage (V)
V_2	Distribution transformer 120 V load two terminal voltage (V)
V2G	Vehicle-to-grid
$V^{(v,c)}$	The recharge voltage for vehicle- v in class- c (V)
$v(t)$	Vehicle velocity as a function of time (m/sec)
$V_{\text{Bat}}(t)$	Battery terminal voltage (V)
V_{Outlet}	Voltage rating of outlet used for recharging (V)
V_s	Distribution transformer model input terminal voltage (kV)
X_A	Distribution transformer series reactance (p.u.)
x_j	The output of generator unit- j , where $j = 1, 2 \dots n$ assuming there are n available generating units in the power system (MW)
$Y_{\text{EAP}}^{(v,c)}$	Yearly EAP generated for PHEV- v in class- c (kg)
$Y_{\text{EAP}}^{(c)}$	PHEV population average yearly EAP generated by PHEVs in class- c (kg/vehicle)
$Y_G^{(v,c)}$	Yearly gasoline usage for PHEV- v in class- c (kg)
$Y_G^{(c)}$	PHEV population average gasoline usage in class- c (kg/vehicle)
Z_0	Distribution transformer high voltage winding impedance (Ω)

Z_1	Distribution transformer low voltage winding one impedance (Ω)
Z_2	Distribution transformer low voltage winding two impedance (Ω)
$Z_{\text{base high voltage}}$	Distribution transformer high voltage base impedance (Ω)
$Z_{\text{base low voltage}}$	Distribution transformer low voltage base impedance (Ω)
$Z_{\text{p.u.0}}$	Distribution transformer high voltage per unit winding impedance (p.u.)
$Z_{\text{p.u.1}}$	Distribution transformer low voltage per unit winding one impedance (p.u.)
$Z_{\text{p.u.2}}$	Distribution transformer low voltage per unit winding two impedance (p.u.)
ZEV	Zero emission vehicle (i.e. a vehicle run solely on stored battery energy)

1. Project Description

At present, the U.S. is importing crude oil at the rate of 10.0 Mb/day [1.1]. In addition, approximately 5.1 Mb/day of crude oil are produced domestically [1.1]. Two-thirds (62.9%) of this oil is refined into gasoline and diesel fuel to power U.S. passenger vehicles and trucks [1.2]. The political and economic effect of this "addiction to oil", particularly imported oil, is well documented, and is recognized as a serious national problem. With a growing world-wide demand for crude oil, and the OPEC cartel controlling a large portion of its supply, there has been a significant rate-of-change in its market price now standing (June, 2009) at \$65.62 per barrel [1.3]. Also, the burning of petroleum fuel emits CO₂, the most serious greenhouse gas, into the atmosphere at levels now believed to be causing a global warming effect with very serious changes in global weather patterns. There is a real national need to reduce consumption of crude oil, particularly imported oil.

A number of solutions have been proposed for this problem, including finding more oil, increasing fuel economy, the use of ethanol, and the use of conventional hybrid electric vehicles (HEVs). While all of these solutions have merit, we believe another solution exists that could be extremely attractive to the electric utility industry – the Plug-In HEV (PHEV). The needed modifications to a conventional HEV powertrain to make a PHEV are simply to increase the energy capacity of the battery pack, and to modify the control strategy. The basic idea is to use a charge-depleting control strategy wherein battery stored electric energy, mainly provided from the electric-power grid, is substituted for gasoline energy. USA driving pattern studies have shown that on average half the vehicles drive 25 miles or less each day, and 78% drive 45 miles or less each day [1.4]. This means that with relatively modest increases in battery energy capacity, an appreciable fraction of these miles could be driven with minimal use of the gasoline engine. Unlike a pure battery electric vehicle, only the gasoline remaining in its tank limits the range of the PHEV. If the stored battery energy should reach some set lower limit, either due to not recharging the previous evening or that the vehicle is being driven on a long trip, then the powertrain control strategy would revert from a charge-depleting mode to a charge-sustaining mode, and the vehicle would operate in the same way as conventional HEVs now on the market.

The PHEV is an evolutionary change from the current HEVs now commercially available. By increasing the battery capacity, the PHEV becomes a dual-fuel vehicle in which electric utility supplied, primarily off-peak energy, could be used to replace much of the gasoline energy now used in conventional vehicles. From a consumer point of view the incremental cost of driving a PHEV using electric utility energy can be surprisingly attractive. For example, gasoline has an energy content of 0.125 MBtu/gallon, or 36.5 kWh/gallon. Assuming a \$3/gallon price, the cost of this energy is about 8.22 cents/kWh. While this appears to be on par with average residential energy prices, one needs to consider energy conversion efficiencies. Moving energy from the wall socket through a battery pack and electric motor, and then into the wheels has an average efficiency of perhaps 70%. In contrast, the overall efficiency of taking gasoline

energy, through an internal combustion engine might have an average of 12.5% efficiency [1.5]. Hence the incremental operating cost of the PHEV would be about 1/5 that of a traditional gasoline engine. Furthermore, since the PHEV batteries could be charged at night (off-peak), substantially lower-priced electric energy could be used.

From an electric utility point of view the use of PHEVs could also be quite attractive. At a minimum they represent new, primarily off-peak users of (in aggregate) substantial amounts of electric energy. To gauge the potential market, consider that in the U.S. we currently use about 400 million gallons of gasoline a day [1.6]. To meet this energy requirement completely with electric energy (again assuming the above 70% to 12.5% efficiency ratio) would require an additional 2.62 million MWh per day, a value on par with our current daily electric usage of 18.24 million MWh [1.7]. While certainly no one would expect 100% of the vehicles to be PHEVs, even a small percentage represents a major new electric load. But in addition to just being energy users, in aggregate PHEVs could also provide large amounts of potentially controllable stored energy. For example, if a single PHEV has an energy storage capacity of 15 kWh, one million such vehicles in a large metro area could provide 15,000 MWh of energy storage capability. And, since many of these vehicles will be driven into the downtown areas during the day, they could represent potential emergency energy reserves, often in the locations on the grid where they are needed most. Of course, in order to obtain these system-level benefits the PHEVs need to be treated as an integral part of the grid. At a minimum this requires that when parked they be plugged in (at least much of the time). But just as importantly, they also need to have networked communication capabilities with the ability to know the consumer's desires about how the utility could utilize their PHEV. While setting up such an ad-hoc parking lot network would have been nearly impossible several years ago, with the advent of ubiquitous wireless communication it is certainly technically feasible. For example, at home the consumer might just desire that the PHEV be fully charged by 7 am, while at work they might request it be fully charged by 5 pm as long as the price is sufficiently low, and that the energy in the PHEV would be available to the utility at a specified price. Given that the efficiencies in moving energy from the wall socket to a battery can exceed 90%, energy could be placed in the PHEV during off-peak hours, i.e. midnight to 6 am, when the price is low, only to be retrieved by the utility later in the afternoon.

With such a network the stored energy in the PHEVs and their energy storage capacity could become a highly controllable, system-level resource. Potential applications include the ability to greatly reduce spinning generation reserves, the ability to increase transmission system capacity by providing a responsive post-contingent control, and the ability to mitigate Locational Marginal Pricing (LMP) market volatility. For example, the energy in the PHEVs in the above example could be quickly made available to temporarily replace the energy lost during the unexpected outage of a large generator.

The key items contained in this report are discussions of:

- Existing HEV architectures.
- Grid-supplied energy requirements of PHEVs.

- Household supply requirements and PHEV vehicle to grid interface design issues.
- Probabilistic PHEV infrastructure impact analysis.
- Probabilistic production simulation that incorporates plug-in hybrid vehicles.

Included in the appendices are:

- Nomenclature used in the report.
- A discussion of hydrogen fuel as a competing technology to charge-depleting PHEVs.
- A comparison of battery-electric powertrains as an alternative to PHEV powertrains.
- A detailed list of the power system data used in the primary energy source utilization experiments.
- Curtis Roe's Georgia Institute of Technology MSEE Thesis documenting the infrastructure impact and production simulation methodologies.

2. Hybrid-Electric Vehicle Architectures

2.1 Introduction

At present, there are no Plug-in Hybrid-Electric Vehicles (PHEVs) available from any of the auto manufacturers. All of the hybrid vehicles commercially available are designed to be charge sustaining. Thus, the storage batteries in the powertrains of these vehicles are sized only to provide accelerating power for the electric drive to work synergistically with the IC engine in providing propelling torque. These battery packs are therefore small in energy storage capacity, and their state-of-charge (SOC) is maintained nearly constant about a relatively high level by the onboard internal combustion (IC) engine. A typical value for SOC is around 80% in order to allow for maximum use of regenerative braking recapturing some portion of the vehicles kinetic energy. A higher SOC could cause the batteries to overheat on regeneration not storing energy as desired. Generally during driving periods that involve constant speed cruising and regenerative braking, battery energy used for acceleration is replaced. In effect, these charge-sustaining hybrid powertrains use only a single liquid fuel; usually petroleum based, and are not designed to have their batteries recharged from the electric power grid. PHEVs are a modified design with larger capacity battery packs and a revised control algorithm such that operation is intended to be charge depleting, thus substituting stored electric energy in the battery for petroleum-based fuel.

2.2 Series Architecture

In a series architecture an internal combustion (IC) engine drives an electric generator whose electrical output is connected to an electric bus connected to the battery pack and the electric motor controller. This configuration is shown in Figure 2.1.

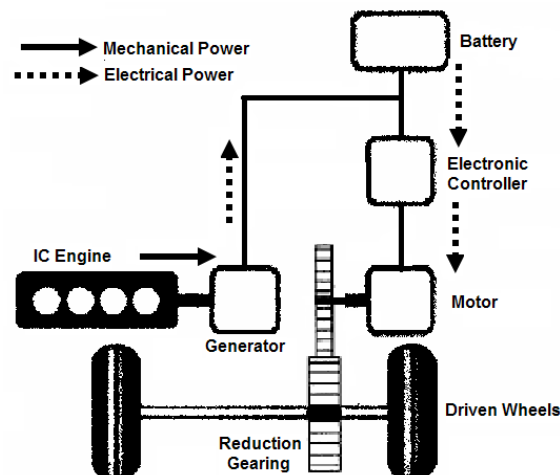


Figure 2.1: Series hybrid architecture wherein only the electric motor powers the driven wheels.

The mechanical output of the motor is geared to the driven wheels, and only the electric motor provides driving torque in this configuration. The mechanical power out of the IC engine is converted from mechanical to electrical power by the generator and then back to mechanical power by the motor. The disadvantages of this series architecture include the fact that this double energy conversion reduces fuel efficiency. Also two electrical machines are required with the IC engine and generator sized to meet the largest sustained road-load for the vehicle. The electric motor must be sized to meet this sustained load plus have an additional capacity to meet some vehicle acceleration specification. This maximum sustained load could be approximately 80 mph up a 6% grade with the vehicle at its maximum allowable weight with passengers and cargo. The advantages of a series architecture are simplicity in the operational control algorithm, and the fact that the IC engine speed is completely decoupled from the vehicle speed. The control algorithm being proposed by GM does not start the IC engine driving its generator as long as the battery SOC level is above its desired low set point. For example, with this scheme, if the set point at a minimum SOC $\approx 20\%$, and the battery SOC = 100%, the powertrain would run as a pure electric vehicle (ZEV Zero Emission Vehicle), depleting the battery until the SOC $\approx 20\%$ level was reached. The IC engine would then go on and off, with some defined hysteresis characteristic maintaining a range of SOC values about the SOC $\approx 20\%$ level. Regenerative braking can use the motor as a generator thus converting some of the vehicles kinetic energy into electric energy that is stored in the batteries. The normal friction brakes that waste this kinetic energy in the form of friction produced heat are still needed to completely stop the vehicle as regenerative braking diminishes as the vehicle speed goes to a zero value.

Mechanically decoupling the IC engine from the vehicle speed allows the IC engine to be operated at an optimal speed, minimum fuel state point for some desired output power level. An IC engine has a power-speed operating state giving a minimum Brake Specific Fuel Consumption (BSFC) in terms of grams of fuel consumed per kWh of output energy, sometimes known as the “sweet spot”. Operating the IC engine at this state is generally not optimal as the excess electrical energy by the driven generator (i.e. the energy not taken by the motor) must be stored in the battery with a subsequent penalty imposed by the turn-around losses when this stored energy is later extracted. Less fuel may be consumed by operating the IC engine at a power level that more closely matches the power into the drive motor, thus keeping the SOC at its lower limit avoiding the energy turn-around inefficiency of the battery. No charge-sustaining HEVs on the market use a series architecture. However, GM has announced that its first PHEV scheduled for 2010, named the “Volt”, will have this series configuration. The Volt is advertised to have a 40 mile all electric range (AER) before the IC engine needs to be started. Thus during this all electric operation the engine and generator are just non functioning “dead weight”. Also the performance of the Volt is limited to the driving power that can be provided by the motor alone.

2.3 Parallel Architecture

In a parallel architecture the IC engine is mechanically geared to the driven wheels. Thus, all the mechanical output of the IC engine can provide direct torque to power the

vehicle, as there is no energy conversion of the engine's output power. This architecture also includes a single electric machine whose mechanical shaft is also geared to the driven wheels. The general form of the parallel architecture is shown in Figure 2.2. The shaft of this electric machine can be mechanically coupled to the engine output shaft before the multi fixed-gear-ratio transmission or to the output shaft of this transmission, as is shown in Figure 2.2. These two parallel configurations are known pre-transmission and post-transmission parallel hybrid powertrains, respectively.

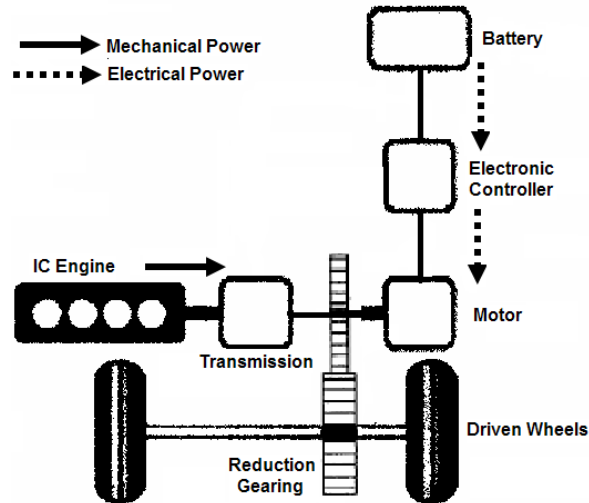


Figure 2.2: Post-transmission parallel architecture.

Another interesting configuration for a parallel hybrid electric powertrain is known as a “through the road architecture” where the IC engine powers one pair of wheels and the electric motor powers the other pair of wheels. The torques of the two drives are added together through the road. The electric machine, when operated as a motor, has its electrical terminals powered by the battery pack. In a charge-sustaining HEV, the electric machine provides the bulk of the torque required for acceleration with the IC engine providing steady-state constant speed cruising torque. When cruising, the electric machine can be controlled to switch from motoring operation to generator operation thus recharging the battery pack with the energy previously drawn for acceleration.

The control algorithm is much more complicated than in a series configuration as the torques from these two drives need to be blended to optimize some objective function. With a charge-sustaining HEV, the control should minimize fuel consumption while maintaining the battery SOC in the neighborhood of some relatively high value. For a PHEV, the battery SOC would be allowed to fall to a much lower value as the control algorithm depletes the battery in trading stored electric energy for gasoline. When this much lower SOC value is reached, the control would then operate as a charge-sustaining algorithm maintaining this lower SOC level by operating the motor as a generator during periods of constant speed operation. As in the series architecture, regenerative braking is always used to reduce the waste of stored kinetic energy as heat in the mechanical friction brake pads. The advantages of the parallel architecture mainly are due to the fact

that with two sources powering the vehicle both the IC engine and single electric machine can be smaller than in a series configuration. In addition, there is a synergistic effect whereby the electric motor provides torque for acceleration and the IC engine provides cruising torque. In a PHEV, the operation should still maintain this synergism of the two torque sources. Thus generally, the powertrain should not be operated with the electric motor alone until the battery is at its lower SOC limit, and then turn on the IC engine alone for continued operation. If operated consecutively instead of together, thus losing synergism, each drive will have to be much larger than when operated together. This synergism is lost in the GM Volt series hybrid architecture.

2.4 Toyota Hybrid System-II (THS-II) Single-Mode Power-Split Architecture

Toyota has developed their THS-II power split architecture that they are using in the Prius and other current Toyota HEVs. The THS-II architecture is shown in Figure 2.3.

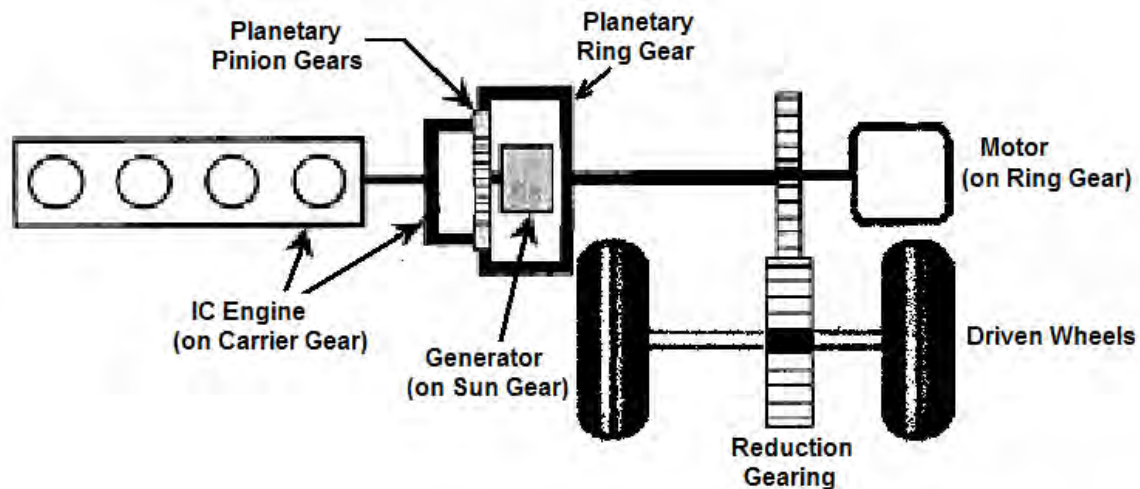


Figure 2.3: The Toyota Hybrid System (THS-II) power split architecture.

A complete explanation of this power-split architecture can be found in [2.1]. In brief, the power-split architecture, as implemented by Toyota, has an IC engine mechanically connected to the carrier gear of a planetary. An electric machine (called the generator) is connected to the sun gear of the same planetary. Finally, the ring gear is connected to the shaft of a second electrical machine (called the motor) with this same shaft mechanically coupled through fixed gearing to the driven wheels. The name power-split comes from the fact that the IC engine power is split between a mechanical path to the driven wheels and an electrical path through the generator and its controller to a bus connected to the motor controller and the battery pack. An advantage of this architecture involves the fact that the IC engine speed is decoupled from the vehicle speed as in the series architecture. However, the price paid for this decoupling involves the fact that some of the IC engine output power goes through an electrical path that involves two energy conversions also as in a series architecture. With some of the engine power going directly to the driven wheels this power-split architecture partially includes the synergism of a parallel architecture, whereby the engine torque and motor torque can be blended to power the

vehicle. The control of the two electrical machines for minimum fuel operation is complicated with Toyota not publishing details of the control algorithm being used. The use of the THS-II in a PHEV would require a higher capacity battery pack and a modified control algorithm that would allow for depletion of the battery stored energy to some set lower limit with charge sustaining operation continuing beyond this range.

2.5 GM Two-Mode Compound Split Architecture

The General Motors Two-Mode Transmission (2-MT) represents an extension of the Toyota THS-II, and is presently being used in rear-wheel drive, three planetary, hybrid versions of the Tahoe and Yukon SUVs. In addition a front-wheel drive version of the 2-MT is scheduled for use in the Saturn Vue due out in 2009. A functional view of the front-wheel drive 2-MT is shown in Figure 2.4.

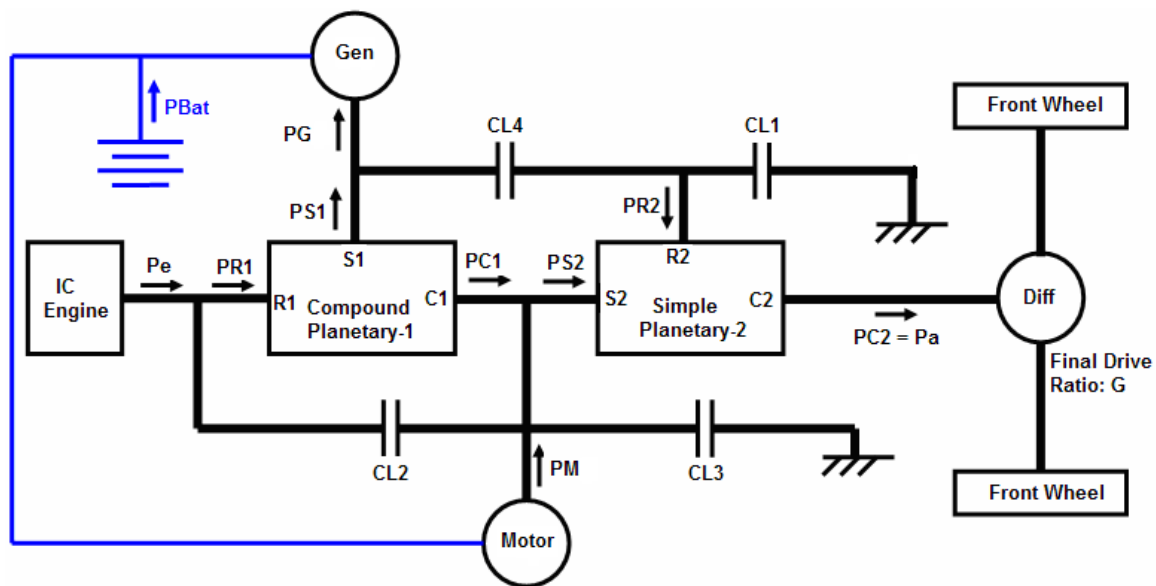


Figure 2.4: The Toyota Hybrid System (THS-II) power split architecture.

This version of the 2-MT contains two electric machines, one operating as a motor and the other as a generator, two planetary gear units, two electrically controlled torque transmission clutches CL2 and CL4, and two electrically controlled braking clutches CL1 and CL3. A complete explanation of the operation of this 2-MT can be found in [2.2]. By operating specific pairs of two clutches at a time, the 2-MT allows for four fixed gear ratios from its input to output shafts, thus constraining the engine speed to one of four values for a given vehicle speed. In its fixed-gear ratio operation, the engine output power is mechanically transmitted to the driven wheels as in a conventional non-hybrid vehicle with a four-speed automatic transmission. In each of these four fixed-gear ratios, the electric machines can provide additional propelling torque, identical to a parallel architecture. In addition, and of great importance, is that the 2-MT also has two additional operating modes, designated as Modes-1 and -2, where the speed of the engine is decoupled from the speed of the vehicle, thus in effect giving CVT (continuously

variable transmission) operation. Mode-1 requires the closure of only CL1, with Mode-2 obtained by the closure of only CL4. Operation in Mode-1 is essentially identical to the operation of the Toyota THS-II powertrain. At higher vehicle speeds, with fuel efficient lower engine speeds, the operation of the THS-II has a reverse energy flow in its electrical loop, whereby in Figure 2.3, the motor operates as a generator and the generator operates as a motor. This reverse energy flow causes greatly increased electric machine losses that can only be alleviated by increasing the engine speed to a less efficient operating state. The 2-MT avoids reverse energy flow in the electrical loop by switching from Mode-1 to Mode-2. The use of the 2-MT thus incorporates the main advantage of the series architecture with the decoupling of the engine speed from the vehicle speed and the main advantage of the parallel architecture with the synergistic summing of the engine and motor torques. The major advantages over series, parallel, and even the THS-II architectures obtained in using the 2-MT are summarized as follows [2.3]:

- Smaller electric machines and a smaller battery pack than the THS-II can be used.
- Higher efficiencies (i.e. lower fuel consumption) over a wide range of driving schedules can be achieved.

These are significant advantages over the other three architectures. The GM Two-Mode Split-Power Architecture is the most advanced hybrid-electric powertrain on the market. What is most interesting is that the GM Volt PHEV is using a series architecture. GM's own U.S. Patent 6,953,409, Column 1, Lines 42 – 54 gives a clear concise argument against using series architectures in a vehicle hybrid-electric powertrain.

2.6 Preferred PHEV Architecture

Starting in 1993 the U.S. Department of Energy under the Clinton administration provided substantial funding (\$1.5 billion) to the big-three auto manufacturers, GM, Ford, and Chrysler, to develop hybrid-electric vehicles under the Partnership for a New Generation of Vehicles (PNGV) program. The main objective of PNGV was to develop a mid-sized vehicle with fuel efficiency not less than 80 mpg. All three companies produced prototype vehicles using diesel engines producing driving torque in parallel with an electric drive that essentially met this three-time increase in fuel efficiency. GM produced a vehicle known as the Precept. Ford's vehicle was the Prodigy, and Chrysler produced the ESX3 based on their Intrepid. Particularly GM's Precept was a very promising prototype with an extremely low reported drag coefficient $C_d = 0.16$, and a fuel efficiency of 80 mpg. This C_d value is extremely low, on the order of half the value of current sedans. In fact, this value is even lower than GM's now abandoned very aerodynamic battery-electric EV-1 that had a $C_d = 0.19$. The last report of an independent review committee in 2001 recommended continuation of the program [2.4]. Figure 2.5 shows these three vehicles. All three of these vehicles represented substantial progress towards charge-sustaining HEVs and subsequent development of charge-depleting PHEVs. With the change to the Bush administration following the year 2000 election, the PNGV program was abandoned with no further government support, and even more surprising, by no further work by the three U.S. auto companies.

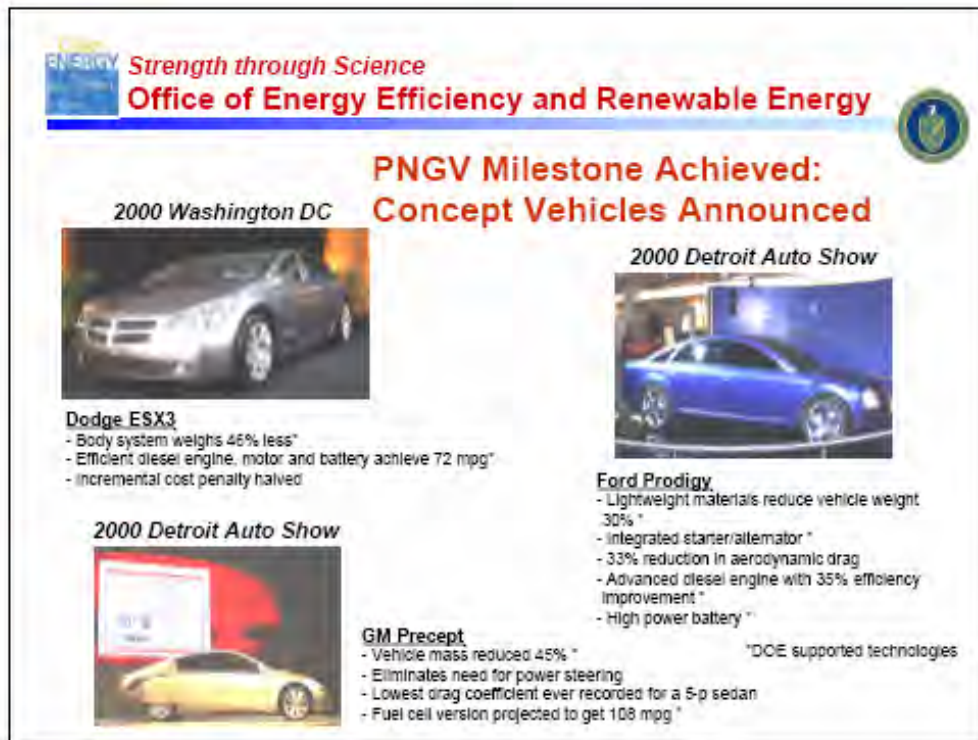


Figure 2.5: The three Partnership for New Generation Vehicles (PNGV) with their key design accomplishments.

The point here is that the preferred architecture for the PNGV program was parallel. In fact, all non-plug-in charge-sustaining HEVs currently on the market use either parallel architectures or the THS-II for Toyota and Lexus vehicles. Now GM has recently announced that they will have a PHEV on the market in late 2010 known as the Volt, shown in Figure 2.6.



Figure 2.6: The GM Volt PHEV.

The architecture chosen for the Volt has been announced to be a series architecture. The operating strategy is to drive up to 40 miles under battery supplied power, and then to start the IC engine for extended range driving. The battery energy used would then be mainly replaced by a plug-in grid connection.

The main argument favoring the series architecture for a PHEV seems to be that more electric energy can be substituted for petroleum energy by an all electric drive that would cover most of the driving done each day. However, the performance in terms of acceleration for the series design is limited by what torque the drive motor can provide. With the parallel design or either of the two split-power designs, the performance is governed by what torque the motor (or motors) working synergistically with the engine could provide. These architectures have a rated drive power greater than the series architecture by an amount equal to the rating of the engine. The parallel architecture provides the opportunity to blend the torques of the engine and the drive motor, thus giving greatly improved performance. Also with a charge-depleting control strategy, the parallel and split-power architectures can operate with electric energy substituted for petroleum energy

3. Grid-Supplied Energy Requirements for PHEVs

3.1 Introduction

In order to determine the effect that Plug-In Hybrid Electric Vehicles (PHEVs) would have on the electric power grid, an analysis of the energy requirements for these vehicles needs to be formulated. At present, there are no PHEVs available from any of the auto manufacturers. All of the hybrid vehicles commercially available are designed to be charge sustaining, and all have various forms of parallel architectures, the Toyota Hybrid System II (THS-II) architecture, or the GM Two-Mode transmission (2-MT) architecture. No commercially available hybrid-electric powertrains on the market use a series architecture. Thus, the storage batteries in the powertrains of these vehicles are sized only to provide accelerating power for the electric drive to work synergistically with the internal combustion (IC) engine in providing propelling torque. These battery packs are therefore small in energy storage capacity, and their state-of-charge (SOC) is maintained nearly constant about a relatively high level by the onboard IC engine. Generally during driving periods that involve constant speed cruising and regenerative braking, battery energy used for acceleration is replaced. In effect, these charge-sustaining hybrid powertrains use only a single liquid fuel; usually petroleum based, and are not designed to have their batteries recharged from the electric power grid. PHEVs are a modified design with larger capacity battery packs and a revised control algorithm such that operation is intended to be charge depleting, thus substituting stored electric energy in the battery for petroleum-based fuel. With no PHEVs on the market, the analysis presented here spans over a number of parameters in order to include a wide degree of penetration of vehicles that operate on two fuels; one liquid and the other grid-supplied electricity.

We begin by defining four classes of passenger vehicles in Table 3.1, and the percentage that are PHEVs by the vector $\vec{p}$ as follows:

Table 3.1: Definition of vehicle classes.

Vehicle Class	Description	% of PHEVs
1	Compact passenger cars	p_1
2	Full size passenger cars	p_2
3	Medium size SUVs and pick-up trucks	p_3
4	Large size SUVs and pick-up trucks	p_4

Thus, if a defined system area has N_T total passenger vehicles, then $(p_i \cdot N_T)$ are the number of these that are PHEVs in Class- i . The analysis here is based on a single defined system area, and excludes busses and large trucks such as 18-wheelers. This system area could be a single utility service area, a FERC region, or even the entire U.S.

For each vehicle class, Table 3.2 defines the basic parameters for an average conventional vehicle in terms of its mass, drag coefficient, frontal area, wheel-tire rolling coefficient, wheel rolling radius, and EPA combined mpg with 55% on the urban driving

schedule and 45% on the highway schedule. We assume that all these parameters stay constant for PHEVs.

Table 3.2: Average conventional vehicle parameter values for each vehicle class.

Vehicle Class	1 Compact	2 Full Size	3 Medium SUV & Pickup Truck	4 Large SUV & Pickup Truck
Curb Mass (kg)	1301	1638	2159	2497
D (Drag Coeff.)	0.335	0.320	0.425	0.463
A (Frontal Area (m ²))	2.037	2.200	2.560	3.169
Cr Rolling Coefficient	0.0070	0.008	0.0090	0.0100
Wheel Rolling Radius (m)	0.3057	0.3075	0.3775	0.3870
EPA mpg (miles/U.S. Gal)	29.72	24.84	17.11	16.70

The data in Table 3.2 are average values for the following vehicles in each class:

- Class 1: Honda Civic and Ford Focus
- Class 2: Honda Accord and Ford Taurus
- Class 3: Ford Explorer and Ford F-150
- Class 4: Chevrolet Suburban and Chevrolet Silverado

The Environmental Protection Agency (EPA) has used specific urban and highway driving schedules with the vehicles operating on chassis dynamometers that simulate the road load to determine miles-per-gallon (mpg) fuel efficiency and regulated tailpipe emissions. These profiles are known as the Urban Dynamometer Driving Schedule (formerly Federal Urban Driving Schedule (FUDS)) (UDDS), and the Highway Fuel Economy Test (formerly the Federal Highway Driving Schedule (FHDS)) (HWFET) driving schedule. In recent years drivers have found that in actual driving, these EPA mpg figures were not actually realized, and the EPA is issuing revised driving schedules to reflect better actual vehicle use. The EPA mpg value in Table 3.2 is the average for the two vehicles in each class using the standard EPA estimate that 55% of the miles are on the UDDS urban schedule and 45% of the miles are on the HWFET highway schedule. This report also uses a newer more aggressive driving schedule, known as the US06 schedule [3.1].

Even though there are currently no production PHEVs, a categorization commonly in use is denoted by the suffix -XX, where -XX represents the all electric range (AER) for the vehicle. Thus, for example, a PHEV-40 would have a battery capacity to propel the vehicle 40 miles as a pure battery-electric vehicle commonly known as a zero emission vehicle (ZEV). This AER concept comes from the idea that a PHEV would operate in a ZEV mode until the battery was depleted to some lower limit on the SOC, and then operate on the engine alone. Generally, this is not an optimal strategy, as is discussed in

Section 3 and below in the Section 3.2 on control algorithms. A better categorization would designate the range over which the PHEV is operating under a charge-depleting algorithm with a given value of the parameter k_{PHEV} , defined in Equation 3.1, as the average fraction of the total input energy that is supplied from the battery. Thus a PHEV-40 would have a battery capacity such that the vehicle would operate for 40 miles charge-depleting, with a specified k_{PHEV} , and then would operate charge-sustaining for continued driving over a specified driving schedule.

3.2 Consideration of PHEV Control Algorithms

A key aspect of vehicle operation is the control algorithm used for the PHEV powertrain. A simplifying concept for the control of a charge-depleting PHEV is that this algorithm can be considered similar to a charge-sustaining hybrid-electric vehicle (HEV) algorithm in the following way. The control algorithm for a charge-sustaining HEV (the type now on the market) maintains the battery SOC at a relatively high level, generally around an SOC $\approx 80\%$. This control in a parallel or power-split architecture, either the THS-II of the 2-MT, generally uses the electric drive to overcome vehicle inertial forces, i.e. for acceleration. Then the IC engine is used primarily to provide sustaining torque to maintain essentially constant speed operation. Thus, if the battery started out at an SOC = 100% the algorithm would provide driving torque in such a fashion as to deplete the battery charge until the desired SOC $\approx 80\%$ level is reached, and then run charge sustaining about this level. We can consider a similar control algorithm for a PHEV except that a much lower SOC, perhaps an SOC $\approx 25\%$, is used before charge-sustaining control is implemented. The control being described (by GM) for their Volt in a series architecture has the battery energy alone powering the drive motor until this lower SOC level is reached. The IC engine coupled to its generator would then turn on and off, with some defined hysteresis range, to maintain this lower SOC level. Therefore, with parallel or split-power architectures the control is much more complicated as the IC engine with the drive motor must be controlled synergistically to minimize fuel consumption, while at the same time allowing for depletion of the battery energy down to its lower limit. In summary, all HEVs, including PHEVs, can be considered to be charge sustaining. The difference lies in the SOC level at which charge sustaining operation occurs. Thus, in all architectures a PHEV powertrain runs under a charge-depleting control algorithm until the defined lower limit on the SOC is reached, and then runs under a charge-sustaining algorithm. To date there is no such synergistic control algorithm in the open technical literature for accomplishing this control (to this author's knowledge). This is an open problem on the same level of importance to continued development of components such as battery chemistries, power electronic controllers, and electric machines.

In order to displace an appreciable quantity of petroleum-based fuels with grid-supplied electric energy, the battery energy storage capacity for a PHEV must be substantially increased over conventional HEVs now on the market. As discussed above, the present methodology for denoting this capacity is to designate the PHEV with a suffix indicating its pure electric range. For example, a PHEV-40 would have a battery capable of supplying enough electric energy to drive the vehicle 40 miles as a pure battery electric vehicle. The only problem with this designation is that the driving schedule for this 40-

mile electric-only operation is not usually specified. Driving 40 miles on a level grade at a constant speed of 35 mph takes much less energy than driving this same distance at 65 mph, particularly at some positive grade. In addition, repeated rapid accelerations consume much more energy than more gradual accelerations.

3.3 An Analytic Approach to Determine Daily Recharge Energy per Vehicle

This section presents an approach that gives an estimate of the liquid fuel and electric energy usage based on the EPA published mpg (miles-per-gallon) values. This methodology is based on using the average mpg values for each vehicle class to determine the energy input for the vehicle required for actual driving. The EPA publishes the overall vehicle mpg values assuming 55% usage on the UDDS- and 45% on the HWFET-schedule (i.e. 55% urban, 45% highway). Drivers generally observe their actual mpg to be only approximately 80% of this EPA value mainly because in actual driving higher vehicle speeds and other factors occur [3.1]. For example, the HWFET has a maximum cruising speed of only 55 mph. Actual highway driving is generally at speeds in the range of 65 – 75 mph, thus increasing the aerodynamic drag power that varies as the cube of the vehicle velocity. The calculation of the required recharging electric energy from the grid per day for each vehicle in class- i is computed as follows.

A key parameter in the operation of a PHEV, denoted as k_{PHEV} , gives the fraction of the total energy input (to the engine and to the electric drive controller) that is taken by the electric drive controller over a specified driving schedule. Thus, we have

$$k_{PHEV} = \frac{E_{Bat}}{E_{Engine} + E_{Bat}} \quad (3.1)$$

where $E_{Engine} + E_{Bat}$ is the total energy input to the engine and electric drive controller and E_{Bat} is the energy delivered by the batteries to the electric drive controller.

A value of $k_{PHEV} = 0$ represents a charge-sustaining HEV, since no net energy is drawn from the battery. Conversely, if the control algorithm would not start the engine at all, then $k_{PHEV} = 1.0$, and all of the driving energy comes from the battery supplying the electric drive controller. This is a ZEV pure battery-electric vehicle. For a PHEV the actual value of k_{PHEV} is somewhere between these two limiting values. We can reasonably assume that k_{PHEV} is independent of vehicle class- i under the concept that all control algorithms would be designed in a similar fashion to transfer the same fraction of the required energy per mile to the driven wheels. In other words, the battery energy is always to be blended with the energy from the IC engine to maintain performance criteria and minimize liquid fuel consumption, and this optimal blending is independent of vehicle class and even system architecture.

The primary dependence of k_{PHEV} is on the daily miles driven. For example, if the daily miles are within the ZEV range, and the control algorithm knew this fact apriori (i.e. before actually doing this daily drive), then a faster depletion of battery energy could be implemented and k_{PHEV} would have a larger value. Conversely, if the planned drive greatly exceeded the ZEV range, then a smaller fraction of the input energy would come

from the battery, and k_{PHEV} would have a smaller value. We use a range of values for $k_{PHEV} \in \{0, 1\}$.

For a conventional vehicle, the energy (kWh) input per mile from the fuel tank for a vehicle in class- i ($E_{Input-i}$) is given by

$$E_{Input-i} = \frac{\rho_{Fuel}}{mpg_i}$$

where ρ_{Fuel} is the energy density of the liquid fuel in kWh per gallon. It is well documented that on average a conventional powertrain transfers only a small portion of this fuel energy to the driven wheels. This fraction is denoted as η_{Conv} . A much larger portion of the battery output energy in a PHEV is delivered to the driven wheels due to the higher efficiency of the power electronic controller $\eta_{Control}$, and the higher efficiency of the drive motor η_{Motor} when compared to an IC engine. Thus, if the PHEV is driven only on the electric drive, termed ZEV operation, from stored battery energy, the required energy out of the battery would be

$$E_{Bat-i} = \frac{\eta_{Conv}}{\eta_{Control} \cdot \eta_{Motor}} \cdot E_{Input-i} = \frac{\eta_{Conv}}{\eta_{Control} \cdot \eta_{Motor}} \cdot \frac{\rho_{Fuel}}{mpg_i}$$

A second key parameter is the turn-around efficiency of the battery defined as η_{Bat} . This efficiency defines the average energy that can be withdrawn from the battery for a given amount of charging energy into the battery. Again we use some constant average value neglecting the fact that the energy that can be withdrawn from a charged battery is a function of the rate at which this energy is withdrawn (i.e. the instantaneous power out of the battery). The efficiency of the charger $\eta_{Charger}$ also needs to be included. Thus, finally we have the following expression for the recharging energy (kWh) per mile that would be required from the grid (E_{Grid-i}), as a function of k_{PHEV} , for each vehicle in the defined system area

$$E_{Grid-i}(k_{PHEV}) = k_{PHEV} \cdot \frac{\eta_{Conv}}{\eta_{Charger} \cdot \eta_{Bat} \cdot \eta_{Control} \cdot \eta_{Motor}} \cdot \frac{\rho_{Fuel}}{mpg_i} \quad (3.2)$$

The total number of vehicles in a defined system area, excluding large trucks and busses, is denoted as N_T . Table 3.1 defines the notation to compute the number of these vehicles that are PHEVs in each defined vehicle class. Now we need to estimate how many miles each vehicle is driven each day. A simple approach for this estimate is to assume an average total number of miles a vehicle is driven per year and then simply divide by the number of days in a year. Thus if we assume that on average a vehicle is driven $mpy = 12,000$ miles/year, this gives an average daily mileage of $(12,000/365) = 33$ miles/day. A more interesting approach would be to start with the probability function expressing the probability that a specified number of miles are driven each day. Then the resulting required recharge energy, per vehicle, per day would also be worked out in terms of a probability function. In other words, the load that a fleet of PHEVs would put on the grid would be expressed as a probabilistic function. Here initially we use the average calculation above.

Starting from Equation 3.2 that is used to compute the daily recharge energy per vehicle in class- i , per mile driven we have the following expression for the total recharge energy (WMh) required per day for the entire system area

$$E_{Grid-Total} = N_T \cdot \frac{mpy}{365} \cdot \sum_{i=1}^4 p_i \cdot E_{Grid-i} \quad (3.3)$$

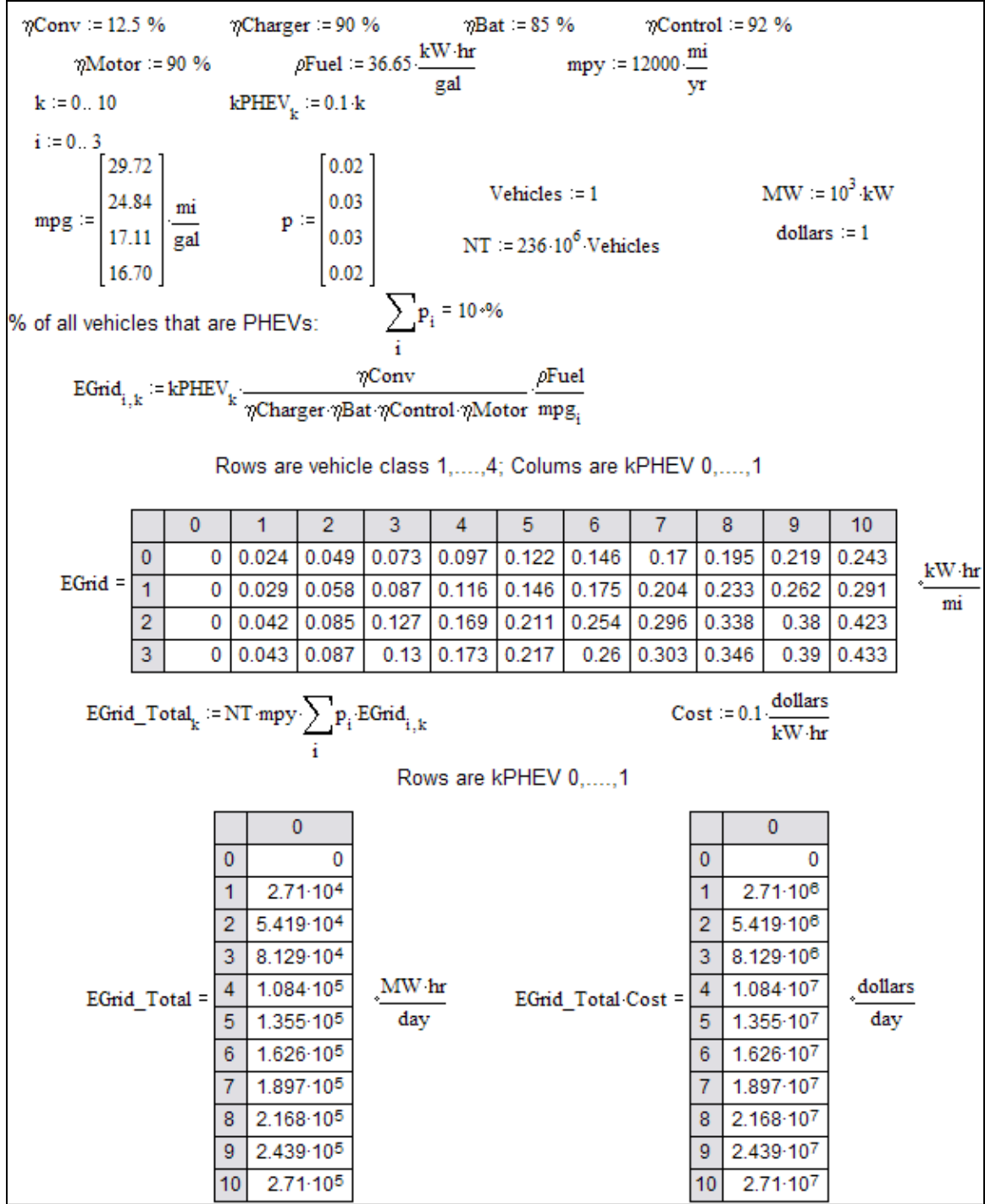


Figure 3.1: Computation of grid-supplied recharge energy for PHEVs (kWh/mi) for four vehicle classes and $0 \leq k_{\text{PHEV}} \leq 1$. Also computed is the MWh/day and added gross income in \$/day.

Note that Figure 3.1 uses MathCad software that has the ability to automatically change units. For example, if we define the variable $\text{mpy} = 12,000 \text{ mi/yr}$, then if we want the value of mpy in terms of mi/day, we simply need to specify the desired units as mi/day,

and MathCad automatically divides by 365 days/yr. Thus the factor 1/365 in Equation 3.3 does not explicitly appear in the evaluation of EGrid_Total in Figure 3.1 above.

Some details of the values used in the above Figure 3.1 are summarized as follows:

- The total number of light duty vehicles in the entire U.S. fleet is taken to be $N_T = 236 \cdot 10^6$ vehicles. The total number of these that are PHEVs is assumed to be $\sum_{i=1}^4 p_i = 10\%$ with the distribution by class as defined by the vector $\vec{p}$.
- The miles-per-gallon for each vehicle class are the values in Table 3.2.
- The total miles driven for each vehicle is assumed to average 12,000 miles/year.
- The retail charge for electric energy is assumed to be \$0.10 / kWh .
- All other parameters needed in Equations 3.2 and 3.3 are defined in Figure 3.1: Computation of grid-supplied recharge energy for PHEVs (kWh/mi) for four vehicle classes and $0 \leq k_{PHEV} \leq 1$. Also computed is the MWh/day and added gross income in \$/day.
- above.

With these parameter values and assumptions, we have the following key results: Table 3.3 summarizes the grid supplied recharge energy the four classes of PHEVs would require per mile driven with $k_{PHEV} = 0.7$ using the combined EPA mpg fuel efficiency to drive the Federal Test Procedure (FTP).

Table 3.3: Required recharge energy for PHEVs in the four class sizes defined in Table 3.1 and Table 3.2 driven with 70% of the input energy from the battery ($k_{PHEV} = 0.7$).

Vehicle Class	Grid Supplied Recharge Energy kWh/mile Driven
1	0.170
2	0.204
3	0.296
4	0.303

With ($k_{PHEV} = 0.7$):

- The recharge energy all these PHEVs (10% of all light-duty vehicles) would require computes to a value of 187.9 GWh/day.
- The added gross income at \$0.10 / kWh to the electric utilities supplying this electric energy computes to be \$18.97 million/day.
- If this recharging were all done in an off-peak 6-hour window each day, then the average total added generation over this period would be $189.7 \cdot 10^9 / 6 = 31.62$ GW.

With the total generating capacity in the U.S. at about 950 GW, this added off-peak generation is only 3.3% of this installed capacity. Without considering power generating availability in specific areas, the electric power system has plenty of capacity to meet the recharging needs of a fleet of PHEVs that are 10% of all light-duty vehicles. An

extensive analysis of the capacity of the existing U.S. electric power system to recharge the light-duty vehicle (LDV) fleet (i.e. cars, pickup trucks, and SUVs) concludes that 73% of all these vehicles could be supported using generating, transmission, and distribution capacity presently installed [3.2]. If the charging period were constrained to 6 pm to 6 am then this percentage is reduced to 43%. Clearly the present electric power system has the capacity to supply an appreciable fraction of our countries required transportation energy in terms of PHEVs.

3.4 PHEV Simulation Methodology

In this present section, results obtained for a set of model vehicles using the software vehicle simulation package Powertrain System Analysis Toolkit (PSAT) v.6.2 developed by DOE's Argonne National Labs are presented [3.3]. These results from simulation are compared to those obtained by the analytic calculation methodology in the previous Section 4.3. PSAT includes a multitude of Matlab/Simulink/State Flow models of the components in conventional and hybrid powertrains of various architectures. These individual component models can be assembled to represent a particular overall vehicle model that also includes models for the driver and a vehicle powertrain control strategy. This control strategy includes transmission shift maps for manual and automatic transmissions as well as torque-blending strategies for parallel and split-power hybrid powertrains. The engine models selected include emission maps for the three regulated emissions HC, CO, and NOx, and the greenhouse gas CO2. Once the complete vehicle model has been selected, PSAT allows for the simulated operation of this vehicle over a wide available selection of driving schedules

PSAT uses a fundamental simulation approach involving a determination of the road-load power each vehicle class requires over a specified velocity vs. time profile or driving schedule. Here we have selected to use three schedules, namely UDDS, HWFET, and US06. The approach used by PSAT requires values for the parameters of the vehicle including its mass, drag coefficient, frontal area, and rolling coefficient, as given above in Table 3.2 for our four vehicle classes. In addition, the road-load power is highly dependent on both the driving schedule and the road grade. The conventional equation to determine a vehicles road-load power is given by

$$P_{RL}(t) = \left[(M \cdot g(C_r \cos\phi + \sin\phi) + 0.5 \cdot \rho \cdot D \cdot A \cdot v(t)^2 + M \frac{dv(t)}{dt}) \right] v(t) \quad (3.4)$$

The symbols in this equation are defined in the Nomenclature section. Further, this equation describes the road load power required for vehicles in each class-*i*. This subscript has been removed for convenience. Please note that this convenience is also taken in the following equations in this section.

The terms in the square bracket represent the following four forces influencing the motion of the vehicle: rolling resistance, road grade, aerodynamic drag, and inertial effects, respectively. Multiplying these forces by the vehicle velocity $v(t)$ gives the total power required at the driven wheels to meet a specified velocity profile. Note that the road-load power can be negative due to a negative grade and/or deceleration with

$dv(t)/dt < 0$. PSAT computes this time dependent road-load power over the selected driving schedule. Then by using a model for the vehicle driver, more or less input power from the liquid fuel and the battery is commanded such that the vehicles simulated speed matches the driving schedule speed. When the driver model sees a speed error, more or less power is commanded similar to a real driver moving the accelerator pedal to achieve a desired speed.

The PSAT output summary for each simulation provides the values of the total energy provided by the liquid fuel (gasoline) fed into the engine, E_{Engine} , and the total energy supplied by the battery, E_{Bat} , over the specific driving schedule. By adjusting parameters in the control algorithm and the energy capacity of the battery, the relative values of E_{Engine} and E_{Bat} can be adjusted. Then the value of k_{PHEV} is determined from Equation 3.1.

Finally, the required grid supplied electric energy to replace the electric energy used over this driving schedule can be computed from

$$E_{Grid} = \frac{1}{\eta_{Charger} \cdot \eta_{Bat}} \cdot E_{Bat} \quad (3.5)$$

where $\eta_{Charger}$ and η_{Bat} are the efficiency of the power electronic charging circuit, and the turn-around efficiency of the battery, respectively. The vehicle emissions over a specified driving schedule are also computed by the PSAT simulations. PSAT provides data on the three regulated emissions of HC, CO, and NO_x, as well as the green-house gas CO₂.

Before presenting the simulation results, the three driving schedules used are shown in Figure 3.2, Figure 3.3, and Figure 3.4.

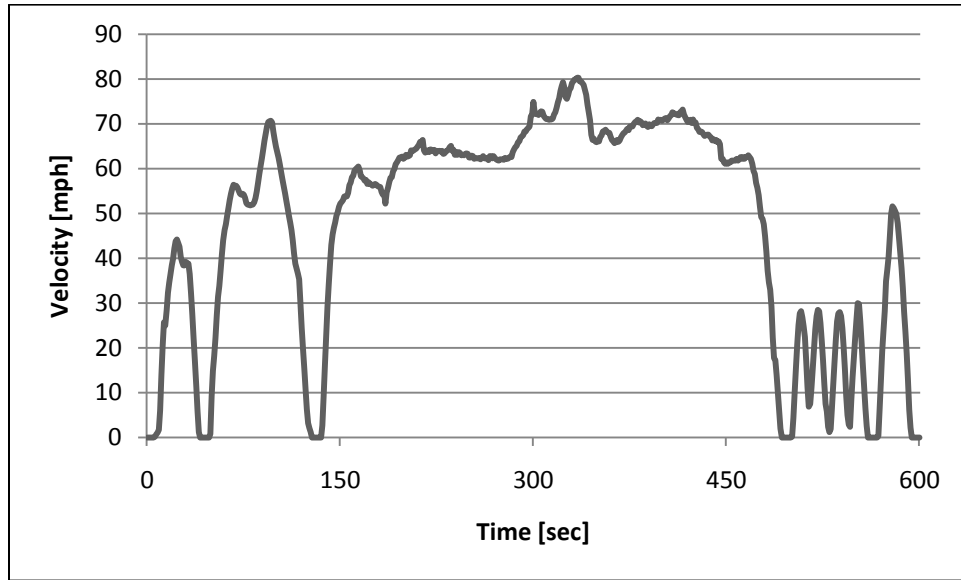


Figure 3.2: US06 driving schedule of 8 mi, over 600 sec with a peak speed of 80.29 mph, an average speed of 47.96 mph, and 5 stops totaling 45 sec duration.

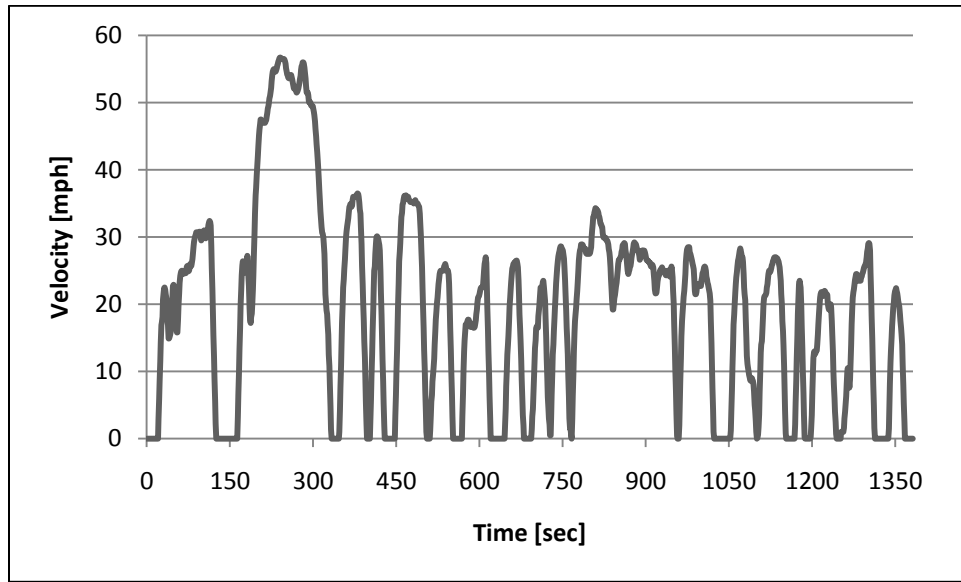


Figure 3.3: UDDS driving schedule of 7.45 mi, over 1369 sec with a peak speed of 56.7 mph, an average speed of 19.58 mph, and 17 stops totaling 259 sec duration.

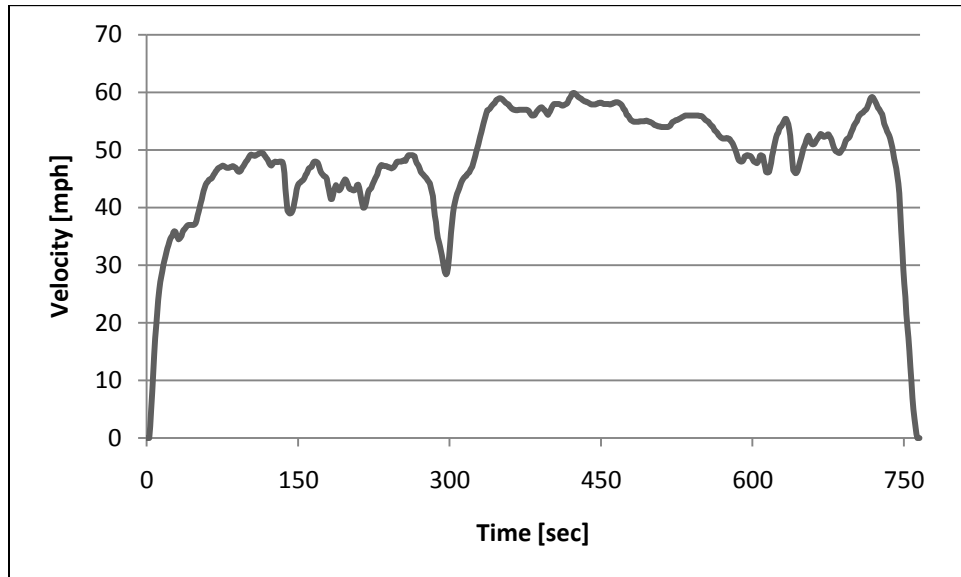


Figure 3.4: HWFET driving schedule of 10.26 mi, over 764 sec with a peak speed of 59.9 mph, an average speed of 48.27 mph, and 1 stop totaling 5 sec duration.

For the PHEV simulations, a pre-transmission parallel architecture was selected with a spark-ignited internal combustion engine and a single permanent magnet electric motor. Pre-transmission, as explained in Section 2.3, means that the torque of the engine and the electric motor are mechanically combined ahead of the gear-changing transmission. Thus both the torque outputs of the engine and motor are multiplied by the transmission gear ratio before being applied to the final drive and then to the driven wheels. Simulations in each vehicle class were also run for a conventional IC engine only architecture. Tables

3.4 –3.8 give the numerical results for the simulations of the engine-only powertrain followed by the four classes of hybrid powertrains, respectively. The table captions give details of the PSAT vehicle model, IC engine size, electric motor size, and vehicle mass.

Table 3.4: Engine-only simulation results for the four vehicle classes.

Class	Drive Schedule	MPG [mi/gal]	NO _x Per Mile[kg/mi]	CO ₂ Per Mile [kg/mi]
1	HWFET	33.21	9.190E-05	0.2715
	UDDS	26.17	1.508E-04	0.3446
	US06	25.82	2.042E-04	0.3483
2	HWFET	18.54	1.593E-04	0.4866
	UDDS	14.17	2.530E-04	0.6366
	US06	14.21	3.448E-04	0.6341
3	HWFET	19.31	1.453E-04	0.4674
	UDDS	12.17	2.651E-04	0.7411
	US06	14.20	3.090E-04	0.6351
4	HWFET	14.07	1.946E-04	0.6411
	UDDS	11.42	2.904E-04	0.7902
	US06	11.16	4.032E-04	0.8081

Table 3.5: Hybrid powertrain simulation results for a compact Class-1, Ford Focus vehicle model, ICE = 40 kW, electric motor = 85 kW, mass = 1301 kg.

Driving Schedule	k _{PHEV}	Electric Energy Per Mile [kWh/mi]	GPM [gal/mi]	NO _x Per Mile [kg/mi]	CO ₂ Per Mile [kg/mi]
HWFET	0.1156	0.0807	0.0146	7.720E-05	0.1316
	0.2183	0.1471	0.0125	5.100E-05	0.1123
	0.7196	0.2508	0.0023	6.700E-06	0.0208
	1.0000	0.2626	0.0001	0.00	0.00
UDDS	0.1461	0.1167	0.0162	7.080E-05	0.1457
	0.2757	0.1973	0.0123	4.790E-05	0.1109
	0.5193	0.2666	0.0059	2.040E-05	0.0528
	1.0000	0.2235	0.0001	0.00	0.00
US06	0.1141	0.1281	0.0235	1.273E-04	0.2115
	0.1803	0.1820	0.0196	1.016E-04	0.1760
	0.4114	0.3162	0.0107	4.920E-05	0.0963
	0.9463	0.4341	0.0006	2.300E-06	0.0052

Table 3.6: Hybrid powertrain simulation results for a full size Class-2, Ford Taurus vehicle model, ICE = 50 kW, electric motor = 125 kW, mass = 1638 kg.

Driving Schedule	k _{PHEV}	Electric Energy Per Mile [kWh/mi]	GPM [gal/mi]	NO _x Per Mile [kg/mi]	CO ₂ Per Mile [kg/mi]
HWFET	0.1131	0.0987	0.0183	1.025E-04	0.1651
	0.1210	0.1070	0.0184	1.022E-04	0.1659
	0.1340	0.1117	0.0171	9.500E-05	0.1538
	0.4617	0.2698	0.0074	3.250E-05	0.0671
	0.6035	0.2808	0.0044	2.230E-05	0.0393
	0.7829	0.2952	0.0022	9.300E-06	0.0197
UDDS	0.1898	0.1818	0.0186	8.860E-05	0.1680
	0.4534	0.3168	0.0091	3.100E-05	0.0820
	0.7613	0.3016	0.0023	7.800E-06	0.0203
	0.9664	0.2950	0.0002	1.000E-06	0.0022
	1.0000	0.2866	0.0001	0.00	0.00
US06	0.0992	0.1374	0.0300	1.370E-04	0.2692
	0.1215	0.1609	0.0278	1.367E-04	0.2492
	0.3608	0.3539	0.0149	6.960E-05	0.1336
	0.5108	0.4232	0.0097	3.990E-05	0.0864
	0.9199	0.4672	0.0010	3.600E-06	0.0087

Table 3.7: Hybrid powertrain simulation results for an SUV Class-3, Ford Taurus vehicle model, ICE = 125 kW, electric motor = 150 kW, mass = 2159 kg.

Driving Schedule	k _{PHEV}	Electric Energy Per Mile [kWh/mi]	GPM [gal/mi]	NO _x Per Mile [kg/mi]	CO ₂ Per Mile [kg/mi]
HWFET	0.0482	0.0780	0.0364	1.307E-04	0.3287
	0.2976	0.2950	0.0165	5.250E-05	0.1484
	0.4217	0.3790	0.0123	3.800E-05	0.1108
	0.7746	0.4143	0.0029	9.400E-06	0.0257
	1.0000	0.4247	0.0001	0.00	0.00
UDDS	0.0596	0.1145	0.0427	1.612E-04	0.3850
	0.3006	0.3927	0.0216	7.370E-05	0.1949
	0.6990	0.3889	0.0039	1.240E-05	0.0357
	1.0000	0.3872	0.0001	0.00	0.00
US06	0.0530	0.1165	0.0492	2.436E-04	0.4436
	0.1872	0.3362	0.0344	1.549E-04	0.3108
	0.3516	0.5259	0.0228	8.750E-05	0.2064
	0.4718	0.6694	0.0176	6.400E-05	0.1595
	0.7168	0.7204	0.0066	2.260E-05	0.0605

Table 3.8: Hybrid powertrain simulation results for a Large Truck Class-4, GM Silverado vehicle model, ICE = 125 kW, electric motor = 225 kW, mass = 2497 kg.

Driving Schedule	k _{PHEV}	Electric Energy Per Mile [kWh/mi]	GPM [gal/mi]	NO _x Per Mile [kg/mi]	CO ₂ Per Mile [kg/mi]
HWFET	0.0630	0.1024	0.0361	1.746E-04	0.3254
	0.2503	0.2985	0.0212	9.000E-05	0.1909
	0.5925	0.4820	0.0078	3.240E-05	0.0706
	0.9096	0.5155	0.0012	4.600E-06	0.0109
UDDS	0.0719	0.1494	0.0461	1.892E-04	0.4158
	0.3406	0.4816	0.0221	7.720E-05	0.1987
	0.7526	0.4819	0.0037	1.320E-05	0.0338
	1.0000	0.5189	0.0001	0.00	0.00
US06	0.0577	0.1360	0.0532	2.642E-04	0.4770
	0.3484	0.5736	0.0253	1.342E-04	0.2280
	0.4982	0.6986	0.0165	8.500E-05	0.1497
	0.6900	0.7606	0.0080	3.860E-05	0.0726
	0.8776	0.8530	0.0028	1.270E-05	0.0253

3.5 Engine-Only Fuel Efficiency Comparison

Table 3.4 shows the simulated results for a conventional IC engine-only vehicle over the three driving schedules for the defined four vehicle classes. The Federal Test Procedure (FTP) computes a combined mpg by assuming that 55% of the miles driven are on the urban UDDS schedule and 45% of the miles are on the highway HWFET schedule. The calculation of combined mpg uses the formulation given by

$$mpg_{combined} = \frac{1}{\frac{0.55}{mpg_{UDDS}} + \frac{0.45}{mpg_{HWFET}}}$$

Now using the mpg for these two driving schedules from Table 3.4 for each vehicles class, we obtain the combined mpg as given in . The EPA values from Table 3.9 are included for comparison purposes.

Table 3.9: Combined mpg for conventional vehicles (engine-only) from PSAT simulations and from the EPA average values for each vehicle class.

Vehicle Class	Simulated Values	EPA Average Values
Class-1 Compact	28.93	29.72
Class-2 Full Size Sedan	25.48	24.84
Class-3 Medium SUV	15.85	17.11
Class-4 Large Pickup Truck	12.48	16.70

The values in Table 3.9 compare fairly well except for the Class-4 Large Pickup Truck case. The Chevrolet Silverado is a vehicle in this Class-4. The standard engine for this

truck is 6.0 L, 360 hp (269 kW). The EPA value of 16.7 mpg would indicate that the actual Silverado has a more fuel efficient engine than the scaled-up engine model used in the simulation.

From the data in Tables 3.5 – 3.9, Figures 3.6 and 3.8 are plotted showing the energy required from the grid to recharge PHEVs and the miles-per-gallon of gasoline consumed, respectively, over the three driving schedules. In addition, these figures also contain computed results for these same operational variables using the analytic methodology presented above. The details of these computed plots are in Figures 3.5 and 3.7, respectively. The results are all plotted vs. the percentage of the total input energy that is supplied by the battery denoted as k_{PHEV} . This design parameter, in the range $[0, 1]$, is a key parameter in the control algorithm for a PHEV. The aim of this algorithm should be to maximize k_{PHEV} , for any given driving schedule, as this will minimize petroleum consumption and vehicle emissions. Note that, a k_{PHEV} value equal to 0 represents a charge-sustaining vehicle, and a k_{PHEV} value of 1 represents a pure battery electric vehicle.

3.6 Grid Supplied Recharge Energy

The computed plots in Figure 3.6 are determined by the calculations in Figure 3.7. For all vehicle classes these computed plots most nearly match the UDDS and HWFET schedules, as these two schedules are the basis for the EPA combined mpg values used in the calculations in Figure 3.5. Figure 3.6 is a plot of the recharging energy from the grid per mile that each PHEV class vehicle would require if driven over each of the three driving schedules. Figure 3.6 has been drawn assuming that the electric energy out of the battery per mile on each of the three cycles must be replaced by recharging energy drawn from the grid. Turn-around efficiency for the battery $\eta_{Bat} = 85\%$ has been assumed. Also, charger efficiency is set at $\eta_{charger} = 90\%$. Thus, $85\% \cdot 90\% = 76.5\%$ of the electric energy drawn from the grid actually comes out of the battery while driving. Note that, the most aggressive US06 driving schedule requires the most recharging energy, as would be expected.

Computing Grid Energy/mile as kPHEV is varied:

Calculation using Equation 4.2 to determine grid-supplied recharging energy per mile for the four vehicle classes:

Efficiencies of: Conventional powertrain, Battery turn-around, Battery charger, Motor controller, Motor.

$$\eta_{\text{Conv}} := 12.5 \% \quad \eta_{\text{Bat}} := 85 \% \quad \eta_{\text{Charger}} := 90 \% \quad \eta_{\text{Controller}} := 92 \% \quad \eta_{\text{Motor}} := 90 \%$$

$$\text{Energy density of gasoline:} \quad \rho_{\text{Fuel}} := 36.65 \frac{\text{kW} \cdot \text{hr}}{\text{gal}}$$

$$i := 0..3 \quad k := 0..10 \quad \text{kPHEV}_k := 0.1 k$$

Simulated combined conventional vehicle miles-per-gallon based on 55% UDDS and 45% HWFET for each vehicle class from Table 4.9.

$$\text{mpg} := \begin{bmatrix} 28.93 \\ 25.48 \\ 15.85 \\ 12.48 \end{bmatrix} \frac{\text{mi}}{\text{gal}}$$

$$\text{EGrid}_{i,k} := \text{kPHEV}_k \cdot \frac{\eta_{\text{Conv}}}{\eta_{\text{Charger}} \cdot \eta_{\text{Bat}} \cdot \eta_{\text{Controller}} \cdot \eta_{\text{Motor}}} \cdot \frac{\rho_{\text{Fuel}}}{\text{mpg}_i}$$

Note: Rows are vehicle classes 1-4, and columns are kPHEV [0, 1].

	0	1	2	3	4	5	6	7	8	9	10	
0	0	0.025	0.05	0.075	0.1	0.125	0.15	0.175	0.2	0.225	0.25	$\frac{\text{kW} \cdot \text{hr}}{\text{mi}}$
1	0	0.028	0.057	0.085	0.114	0.142	0.17	0.199	0.227	0.255	0.284	
2	0	0.046	0.091	0.137	0.183	0.228	0.274	0.319	0.365	0.411	0.456	
3	0	0.058	0.116	0.174	0.232	0.29	0.348	0.406	0.464	0.522	0.58	

Figure 3.5: Calculation of the grid-supplied energy per mile for the four vehicle classes.

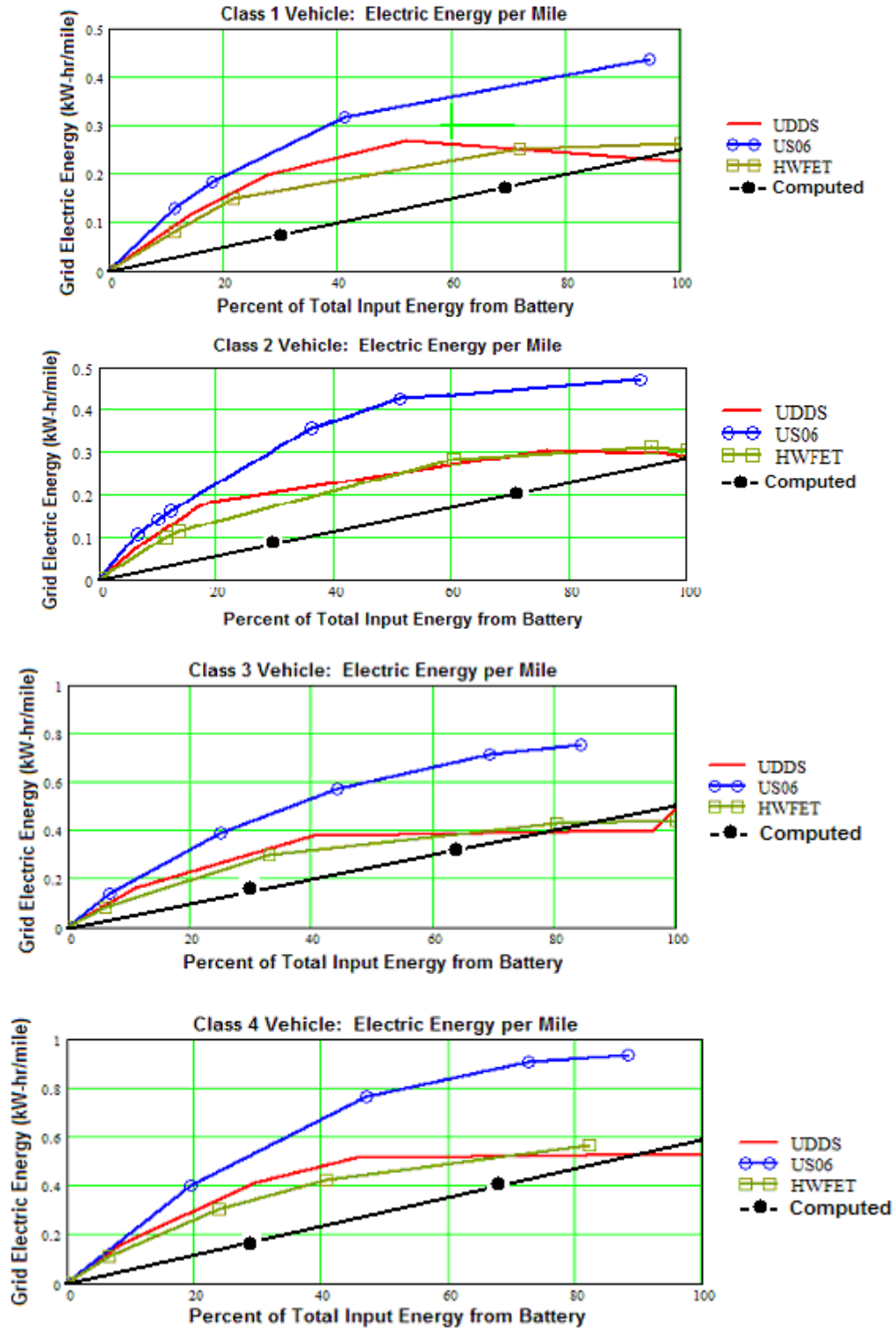


Figure 3.6: Energy-per-mile that would be required from the grid by the four vehicle classes as a function of k_{PHEV} , the fraction of the total input energy from the battery.

3.7 Fuel Efficiency

Using the EPA miles-per-gallon values in Table 3.9, the following calculation in Figure 3.7 gives an estimate of the miles-per-gallon of gasoline that a PHEV achieves as a function of k_{PHEV} that is the fraction of the input energy supplied by the battery. This approximate calculation simply assumes that the gallons of gasoline decreases linearly as k_{PHEV} increases. These computed results are shown as the computed line in Figure 3.8 for each vehicle class.

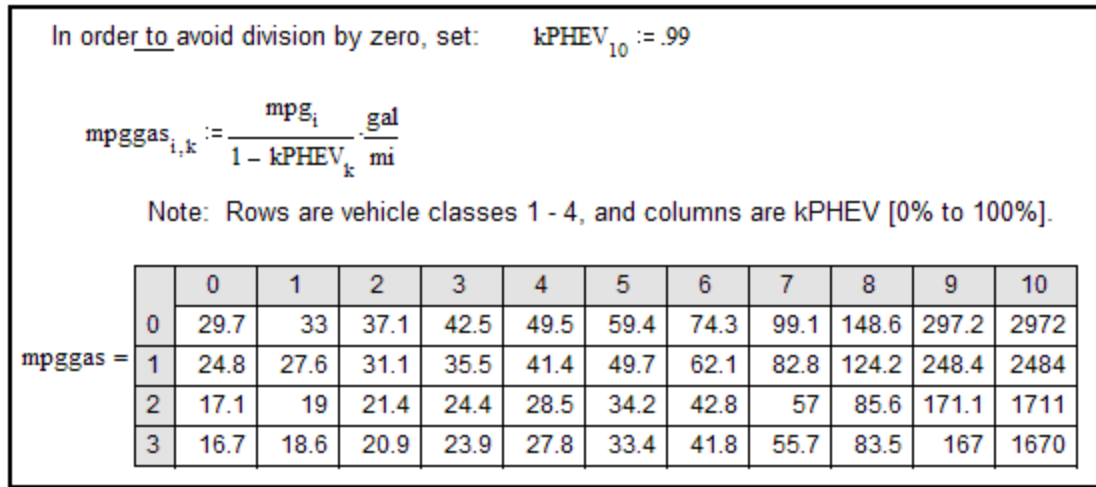


Figure 3.7: Calculation of miles per gallon of gasoline for the four vehicle classes.

A more accurate estimate of the fuel efficiency coming from the PSAT simulation data is also shown in Figure 3.7. Again, the miles-per-gallon of gasoline used to drive each of the three driving schedules are plotted as a function of k_{PHEV} . All plots show that as more of the energy to drive the vehicle comes from grid-supplied electric energy, the miles-per-gallon of gasoline greatly increases. For a value of $k_{PHEV} \geq 0.7$, Figure 3.8 shows that the three schedules UDDS, HWFET, and US06 would be driven in excess of 100 miles-per-gallon of gasoline for all four vehicle classes. These results clearly show the significant potential that PHEVs have to reduce oil consumption far beyond diesel engine technology or even currently available charge-sustaining hybrid-electric vehicles (HEVs).

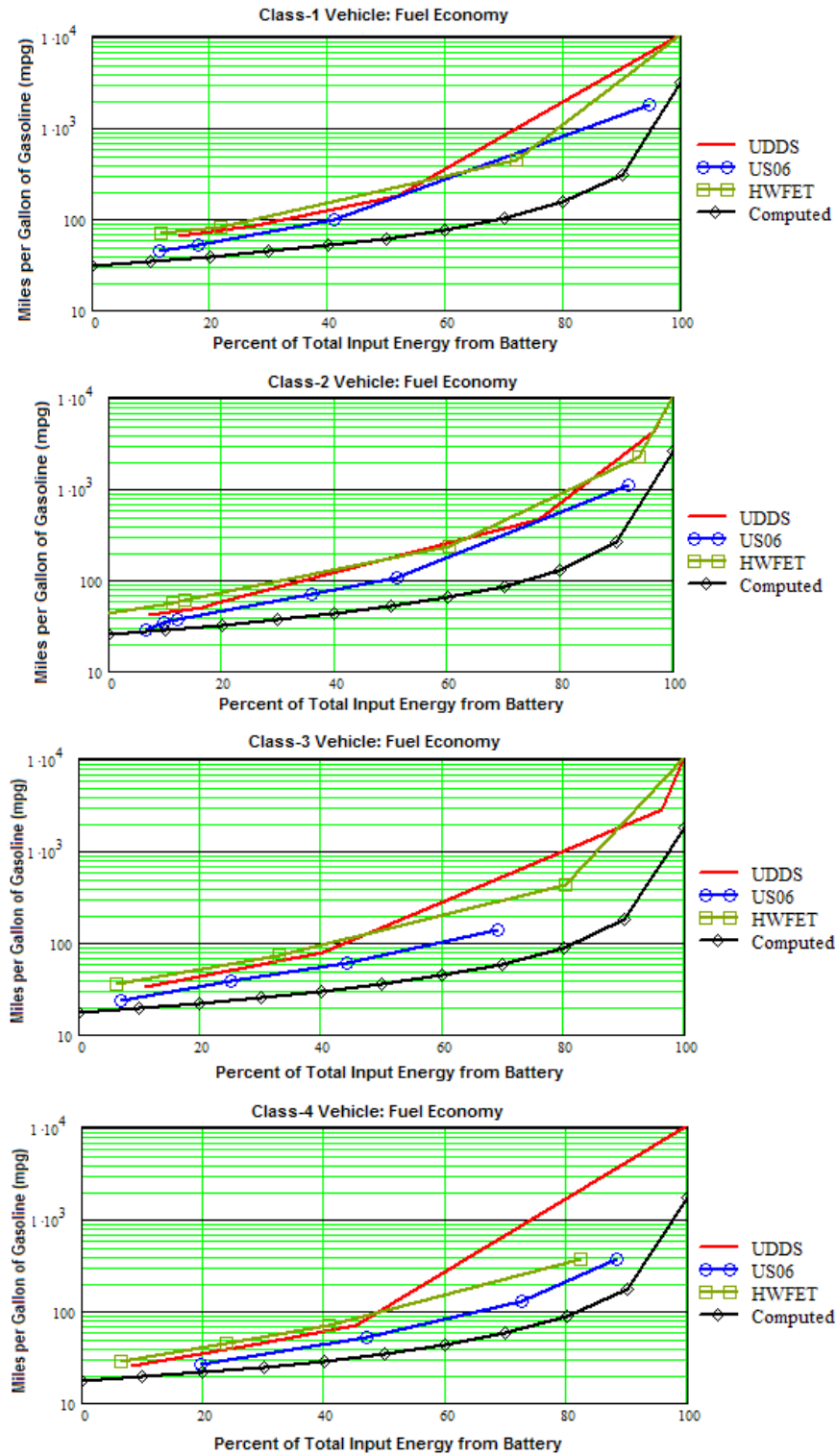


Figure 3.8: Miles-per-gallon of gasoline as a function of the percentage of the total input energy from the battery.

4. Regulated Emissions and Greenhouse Gas Emissions for PHEVs

4.1 Introduction

Plug-in hybrid electric vehicles (PHEVs) are to be designed to substitute grid-supplied electric energy for the motive energy now supplied by a petroleum-based fuel, gasoline or diesel. The result of this fuel substitution is that there will be less tailpipe emissions of regulated emissions and greenhouse gases with an increase in emissions from the electric power plants in producing the energy required to recharge these PHEVs. This section defines the emissions regulated by the Environmental Protection Agency (EPA), and then presents an analysis to see which way the balance between emissions for conventional vehicles and PHEVs swings. This key question is simply will we have more or less regulated emissions and greenhouse gasses with PHEVs as part of our light-duty vehicle fleet as compared to the present fleet with no PHEVs?

4.2 Regulated Tailpipe Emissions

We start by considering tailpipe regulated emission standards for conventional vehicles. These standards date back to 1970, and have undergone a series of revisions to reduce what is allowed. The latest standard passed in 2000 to be implemented by 2004 is known as the *Tier2 Standard for Passenger Cars and Light Trucks*. These latest standards apply to light-duty vehicles that are defined as vehicles having a curb weight less than 6000 lbs. These Standards are defined to limit the following emissions that are known as *Regulated Emissions*:

- Nitrogen Oxides (NO_x), including NO nitrogen monoxide, and NO₂ nitrogen dioxide.
- Non-Methane Organic Gases (NMOG) consisting primarily of hydrocarbons such as carbon monoxide (CO).
- Volatile Organic Compounds (VOCs).
- Particulate Matter (PM) in the case of diesel engines.

NO_x and NMOG contribute to the formation of ozone that is a prime contributor to smog. Smog and PM cause serious health risks, particularly with persons having respiratory conditions. Another aspect of this newest Tier2 Standard is that for the first time the Standard would apply identically to both passenger vehicles and light-duty trucks.

Along with two earlier Standards, Tier 1, and National Low Emission Vehicle (NLEV), the latest Tier2-Bin 5 Standard is summarized in Table 4.1. Note in Table 4.1 how the emission standards have been steadily tightened since the mid 1990s. In fact, the statement often heard in California where the drive towards lower emissions has been consistent is that the older 10% of their vehicle fleet account for 90% of the regulated emissions.

Table 4.1: Regulated exhaust emission standards in (grams per mile) [4.1].

Standard	NO _x	NMOG	HC	PM
Tier 1 (1996)	0.60	0.320	4.400	0.10
NLEV (1999)	0.40	0.100	2.200	0.05
Tier2 (2004)	0.07	0.090	0.01	0.01

In Table 4.1 the NO_x value for the NLEV standard is taken to be the average value between Cars at 0.3 gm/mi and SUVs, Minivans, and Trucks < 6000 lbs at 0.5 gm/mi.

4.3 Comparison of NO_x Emissions Conventional Vehicles and PHEVs

NO_x emissions are produced in energy conversion processes at higher temperatures and pressures, particularly with diesel engines. A basic thermodynamic principle is that the efficiency of any process converting heat energy to mechanical energy has higher efficiency (i.e. more mechanical energy output per unit of fuel burned) if this process burns fuel at the highest possible temperature. In Europe, diesel engines are more common than the spark ignited engines in the U.S., as fuel is much more expensive than in our country, and diesels use less fuel. Diesel engines in passenger cars in the U.S. market are not very common partially because they cannot meet our NO_x emission standards. The German manufacturers, Volkswagen, BMW and Mercedes, have made much progress in producing what are termed “clean diesels” that will meet Tier2 NO_x standard levels. By 2007 all new passenger and light-duty trucks must meet the Tier2 – Bin5 level for NO_x of 0.07 grams/mile. A phase-in period from 2004 to 2007 was allowed, but now (in 2009) the Standard should be met by all new vehicles. In preparing the newest Tier2 Standard, the EPA realized that the fuel used must also be altered. In particular, the sulfur content of gasoline and diesel fuels produced by domestic refiners, and also sold by gasoline importers, must meet an average sulfur standard of 30 ppm (parts per million) and a cap of 80 ppm. This requirement is the basis for diesel fuel selling at a higher price than all gasoline grades, even premium.

Figure 4.1 below presents a calculation that compares the NO_x emissions from conventional vehicles to the total NO_x emissions from PHEVs plus the powerplant emissions due to the added generated electric energy needed to recharge these PHEVs. The recharge energy uses the electric energy per mile values computed in Figure 3.5 for our four vehicle classes. This Figure 4.1 assumes that the PHEV engine in each class meets the Tier2 NO_x Standard and receives $(1 - k_{PHEV})$ of its drive energy-per-mile from these engines. Then using the May, 2005 Clean Air Interstate Standard for NO_x emissions from power plants of 0.15 lbs of NO_x per MMBTU (MMBTU = 10⁶ BTU), the additional NO_x emissions-per-mile for the powerplant recharging energy that is k_{PHEV} of the drive energy is added to give the total NO_x emissions from PHEV tailpipes per mile. These emission totals are then compared to the Tier2 standard.

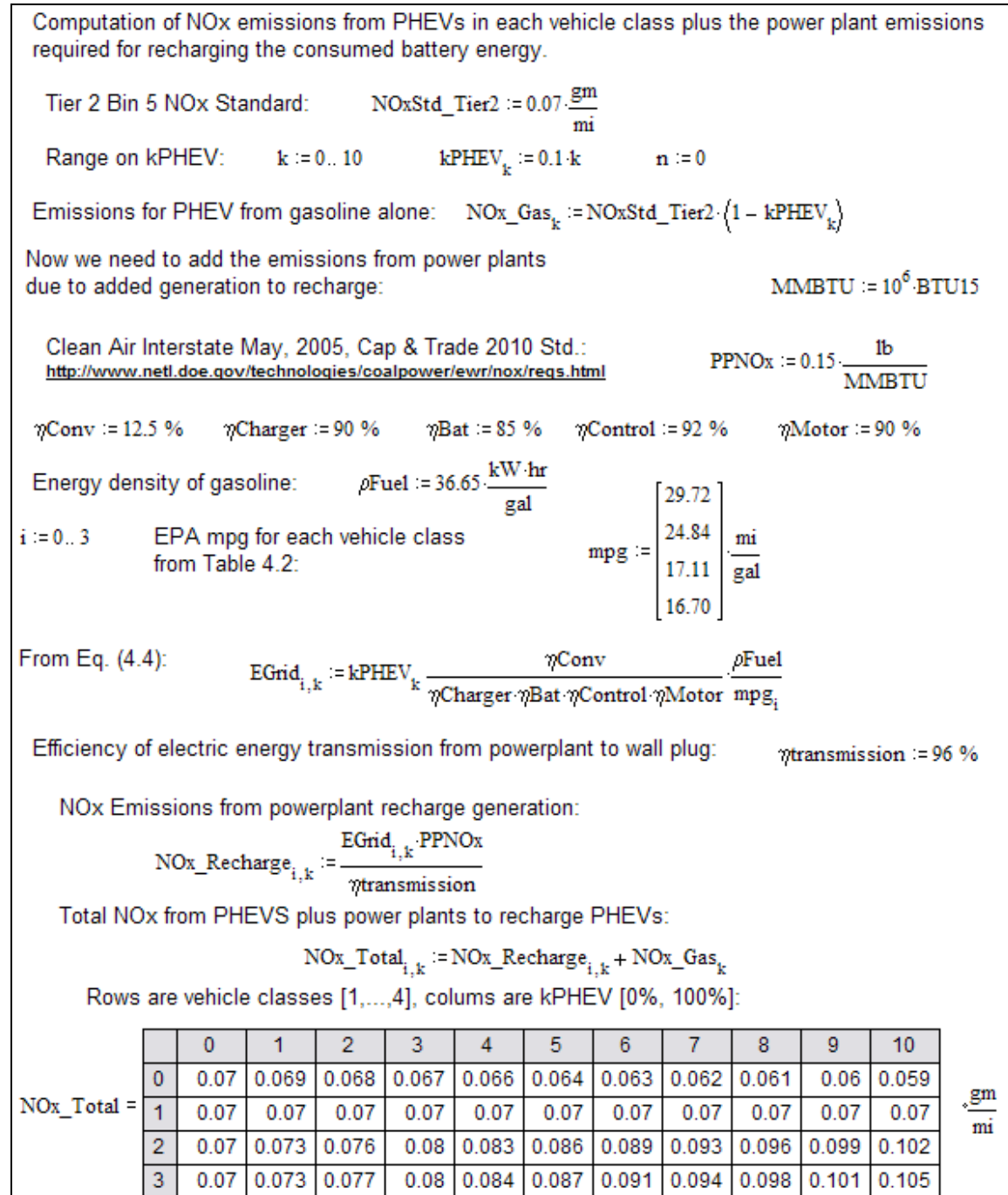


Figure 4.1: Regulated NO_x emissions for PHEVs.

Note in Figure 4.1 that this simple calculation indicates a reduction of total NO_x emissions for PHEV Classes 1 and 2 with total emissions decreasing as k_{PHEV} increases to 1.0 representing a Zero Emission Vehicle (ZEV) battery-electric powertrain. However, for the two larger Classes 3 and 4 the NO_x emissions increase as k_{PHEV} increases to 1.0. This calculation is based on the assumption that in each vehicle class the IC engine in a conventional powertrain meets the Tier2-Bin5 NO_x standard of 0.07 grams/mile. If electric powerplants can meet the prescribed 0.15 lbs/MMBtu NO_x

emission standard, then the introduction of Class 1 and 2 PHEVs will result in a net reduction of NO_x emissions, while Classes 3 and 4 would require further powerplant NO_x reductions to avoid net increases in NO_x emissions. In fact, a powerplant NO_x emission standard of approximately 0.010 lbs/MMBtu is required to have a net NO_x reduction for all PHEV vehicle classes for k_{PHEV} over its entire range.

4.4 PHEV NO_x Emissions from PSAT Simulations

Using the NO_x data from the simulation results Tables 3.5 – 3.8, Figure 4.2 is drawn for Classes 1 and 2, and Figure 4.3 is drawn for Classes 3 and 4. The straight-line computed curve is a plot of $[\text{NO}_x_{\text{Gas}}]$ from Figure 4.1. This is the NO_x produced by the PHEV vehicle itself, in each class, without accounting for the powerplant NO_x emissions. The powerplant emissions are not included in the PSAT vehicle simulations.

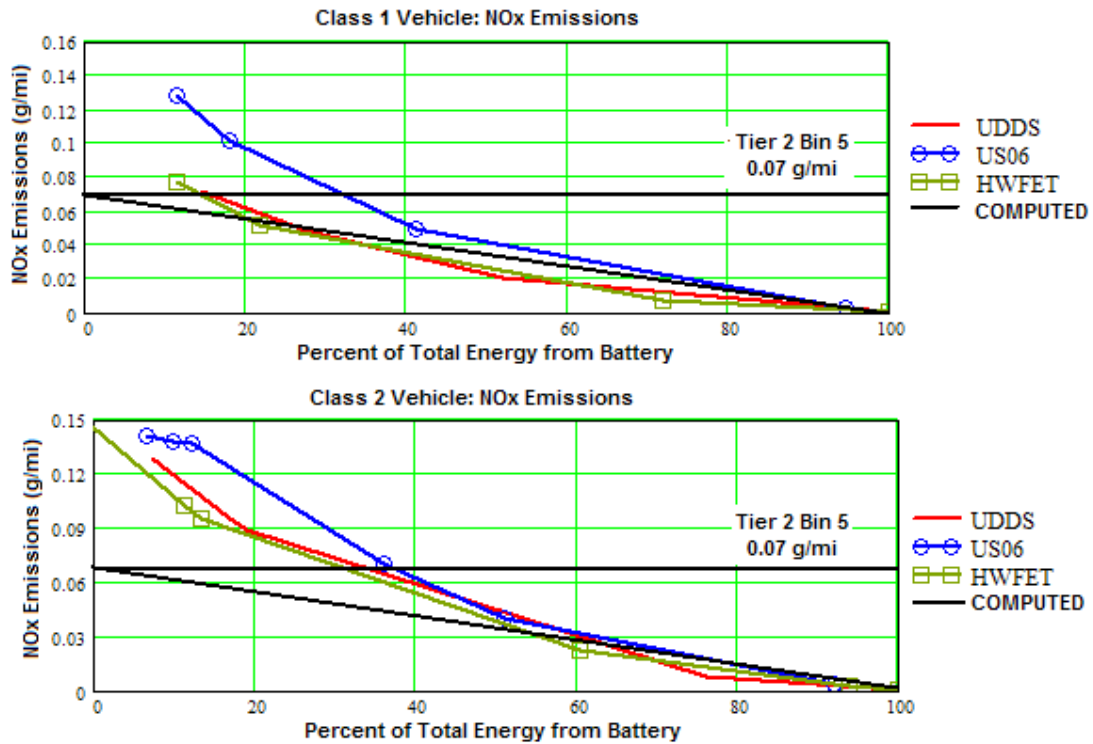


Figure 4.2: NO_x emissions for Class 1 and 2 vehicles as a function of the percent of the total input energy from the battery.

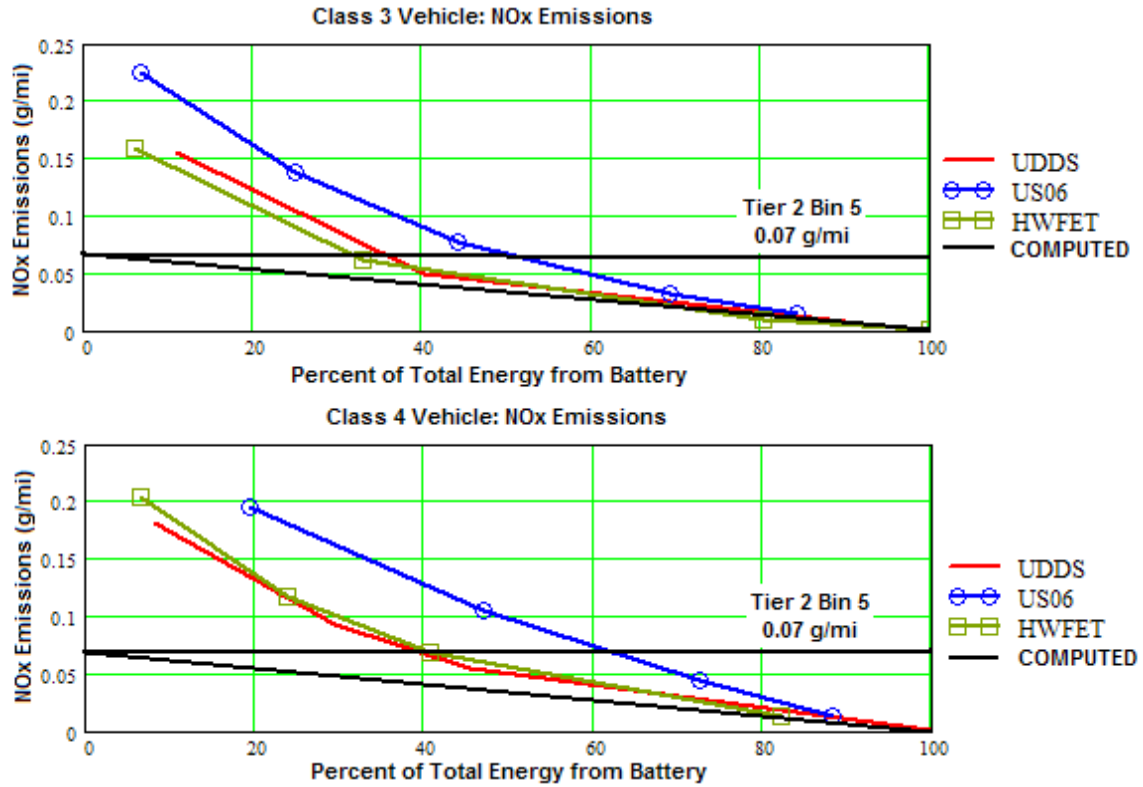


Figure 4.3: NO_x emissions for Class 3 and 4 vehicles as a function of the percent of the total input energy from the battery.

Figures 4.2 and 4.3 show, as would be expected, that meeting the Tier2-Bin5 standard of 0.07 grams/mile for NO_x emissions, the US06 driving schedule requires the largest value for k_{PHEV} , the fraction of the total input energy that comes from the battery. Table 4.2 lists the minimum value of k_{PHEV} required for meeting the Tier2-Bin5 standard over each of the three driving schedules for each of the four vehicle classes.

Table 4.2: Minimum value of k_{PHEV} , the fraction of the total input energy that comes from the battery, required to meet the Tier2 Bin5 standard on each of the three driving schedules.

Vehicle Class	UDDS	HWFET	US06
1	0.15	0.14	0.31
2	0.33	0.30	0.37
3	0.35	0.31	0.49
4	0.40	0.40	0.62

The results in Table 4.2 indicate that all classes of vehicles can meet this latest Tier2-Bin5 standard if $k_{PHEV} \geq 0.62$.

4.5 Introduction to Greenhouse Gas Emissions

The Kyoto Protocol was agreed upon on December 11, 1997 and entered into force on February 16, 2005 [4.2]. Both the U.S. and Australia are two major countries that have

not ratified this Protocol. However, many individual states and cities in the U.S. have made commitments to the spirit of the Protocol. The objective of this agreement is

“to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. [4.3]”

Here anthropogenic refers to processes that are derived by human activity as opposed to those occurring in natural environments without human influences. As of June, 2007, 172 parties have ratified the Protocol. Of these, the Annex I signers include 36 countries plus the EU (European Union). This Annex I group that emits 61.6% of the world’s greenhouse gas emissions is required by 2008 – 2012 to reduce their green house gas (GHG) emissions by a collective average of 5% below their 1990 levels. For the collective EU countries this reduction corresponds to a 15% reduction below their expected GHG emissions in 2008. There are six greenhouse gases in the Protocol that are as follows: carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). The discussion below concentrates on the emission of carbon dioxide as this is a non-regulated emission common to power plants and to vehicles burning fossil fuels. As a matter of interest China has now surpassed the U.S. in GHG emissions, and is not included in the Annex I group that has stated requirements on reducing emissions. See the Kyoto Protocol website reference [4.2] for the reasoning behind this anomaly.

4.6 Comparison of CO₂ Emissions from Conventional Vehicles and PHEVs

Recent studies show that the CO₂ being released into the earth’s atmosphere by the burning of carbon-based fossil fuels is a major contributing factor causing global warming. All fossil fuels contain carbon, and when these fuels are burned, the carbon combines with the oxygen in the air that supports combustion to form carbon dioxide. If there is not enough air when the fuel is burned, then CO is formed. This happens in an IC engine when the mixture of fuel to air is too high that is too rich. The key point here is that CO₂ is a natural product formed by burning all fossil fuels such as gasoline, diesel, coal, natural gas, etc. We assume that PHEVs are designed, at least initially, to use a combination of gasoline or diesel fuel with electric energy. Now we need to compare the emission of CO₂ from a conventional vehicle to the sum of the CO₂ produced by the IC engine in the PHEV plus the CO₂ produced by the electric power plants in producing the added electric energy to recharge these PHEVs. For convenience, we consider that the liquid fuel used by a conventional vehicle, and as one of the two fuels in a PHEV, is gasoline. Thus, diesel fuel is initially not included since very few light-duty vehicles in the U.S. have diesel engines.

Two key parameter values are needed to make this comparison. The first involves the pounds (lbs) of CO₂ produced by burning 1 gallon of gasoline. The mass of carbon in gasoline is known to be 2421 grams/gal = 5.337 lbs/gal [4.4]. The molecular weight of carbon is 12, and the molecular weight of CO₂ is 44. In addition, it is customary to assume that 99% of the carbon is oxidized, (i.e. combines with oxygen in the air to form CO₂). Therefore the pounds of CO₂ formed when burning one gallon of gasoline is given by

$$CO_{2,Gas} = 5.377 \cdot 99\% \cdot \frac{44}{12} = 19.375 \frac{\text{lbs}}{\text{gal}}$$

The second key parameter involves the pounds of CO₂ emitted from electric power plants per kWh of generated electric energy. This value depends on the fuel mix used to produce this electric energy. If the power plant is either nuclear or hydro, then no CO₂ is emitted. However, if the power plant burns coal, natural gas, or fuel oil then CO₂ is emitted. In short, the amount of CO₂ per kWh of output is dependent on the generation mix of the system being considered. For simplicity, the value we initially use is the average for the power plants of the largest 100 electric utility companies in the U.S. This value is 1.350 lbs of CO₂/kWh [4.5]. Now Figure 4.3 below presents this comparison between the CO₂ emissions from conventional vehicles to PHEVs as a function of the PHEV design parameter, k_{PHEV} , that is the fraction of the total input energy supplied by the battery.

In Figure 4.3 the total CO₂ emissions from PHEV tailpipes plus powerplant increased emissions due to the added generation for recharging in our four vehicle classes are given in the [CO2PHEV_Total] table. The first column in this table gives the CO₂ emissions for a charge sustaining vehicle with $k_{PHEV} = 0$. The second table [CO2_Reduction_Factor] gives the factor by which CO₂ is reduced as a function of k_{PHEV} . For example, with $k_{PHEV} = 0.7$, CO₂ emissions are reduced by a factor of 33.3%.

Calculation of CO2 emissions from Conventional Vehicles and PHEVs.

Reference: <<http://www.epa.gov/otaq/climate/420f05001.htm>> pg.2:

Carbon content of gasoline: $\text{CarbonGasoline} := 2421 \frac{\text{gm}}{\text{gal}}$ $\text{Mol_Wt_Carbon} := 12$

CO2 emissions with 99% oxidation: $\text{Mol_Wt_CO2} := 44$

$$\text{CO2Gasoline} := \text{CarbonGasoline} \cdot 99 \% \cdot \frac{\text{Mol_Wt_CO2}}{\text{Mol_Wt_Carbon}} \quad \text{CO2Gasoline} = 19.375 \frac{\text{lb}}{\text{gal}}$$

EPA combined conventional vehicle mpg for each Class-i from Table 4.9:

$$i := 0..3 \quad \text{mpg} := \begin{bmatrix} 29.72 \\ 24.84 \\ 17.11 \\ 16.70 \end{bmatrix} \frac{\text{mi}}{\text{gal}}$$

CO2 emissions from conventional vehicle:

$$\text{CO2Conv}_i := \frac{\text{CO2Gasoline}}{\text{mpg}_i} \quad \text{CO2Conv} = \begin{bmatrix} 0.652 \\ 0.78 \\ 1.132 \\ 1.16 \end{bmatrix} \frac{\text{lb}}{\text{mi}}$$

Now let's compute CO2 from PHEVs and the powerplants for recharging. Start by calculating the recharging energy from the grid per mile driven for the four vehicle classes using Eq. (5.4):

Efficiencies of: Conventional powertrain, Battery turn-around, Battery charger, Motor controller, Motor.

$$\eta_{\text{Conv}} := 12.5 \% \quad \eta_{\text{Bat}} := 85 \% \quad \eta_{\text{Charger}} := 90 \% \quad \eta_{\text{Controller}} := 92 \% \quad \eta_{\text{Motor}} := 90 \%$$

$$\text{Energy density of gasoline:} \quad \rho_{\text{Fuel}} := 36.65 \frac{\text{kW} \cdot \text{hr}}{\text{gal}} \quad k := 0..10 \quad \text{kPHEV}_k := 0.1 \cdot k$$

$$\text{EGrid}_{i,k} := \text{kPHEV}_k \cdot \frac{\eta_{\text{Conv}}}{\eta_{\text{Charger}} \cdot \eta_{\text{Bat}} \cdot \eta_{\text{Controller}} \cdot \eta_{\text{Motor}}} \cdot \frac{\rho_{\text{Fuel}}}{\text{mpg}_i}$$

Efficiency of electric energy transmission from powerplant to wall plug: $\eta_{\text{transmission}} := 96 \%$

1999 Average U.S. CO2 powerplant output from "Electric Power in the U.S.", DOE/EPA, July, 2000:

$$\text{CO2Gen} := 1.350 \frac{\text{lb}}{\text{kW} \cdot \text{hr}}$$

CO2 caused by additional powerplant energy generation to recharge PHEVs:

$$\text{CO2PHEV_Elec}_{i,k} := \frac{\text{EGrid}_{i,k} \cdot \text{CO2Gen}}{\eta_{\text{transmission}}}$$

CO2 caused by PHEV engine in burning gasoline:

$$\text{CO2PHEV_Gasoline}_{i,k} := \frac{\text{CO2Gasoline} \cdot (1 - k_{\text{PHEV}_k})}{\text{mpg}_i}$$

Total CO2 for PHEV: $\text{CO2PHEV_Total}_{i,k} := \text{CO2PHEV_Elec}_{i,k} + \text{CO2PHEV_Gasoline}_{i,k}$

Rows are for each vehicle class [1,...,4], columns are for kPHEV [0%, 10%, ..., 100%].
First column is therefore a conventional powertrain with kPHEV = 0%.

	0	1	2	3	4	5	6	7	8	9	10	
CO2PHEV_Total =	295.7	281.7	267.6	253.6	239.5	225.5	211.4	197.4	183.3	169.3	155.2	gm mi
1	353.8	337	320.2	303.4	286.6	269.8	253	236.1	219.3	202.5	185.7	
2	513.6	489.2	464.8	440.4	416	391.6	367.2	342.8	318.4	294	269.6	
3	526.2	501.2	476.2	451.2	426.2	401.2	376.2	351.2	326.2	301.3	276.3	

$$\text{CO2_Reduc_factor}_{i,k} := \frac{\text{CO2PHEV_Total}_{i,0} - \text{CO2PHEV_Total}_{i,k}}{\text{CO2PHEV_Total}_{i,0}}$$

	0	1	2	3	4	5	6	7	8	9	10
CO2 Reduc factor =	0	0.048	0.095	0.143	0.19	0.238	0.285	0.333	0.38	0.428	0.475

NOTE: CO2 Reduction factor is independent of Vehicle Class!

Figure 4.4: PHEV emission of the greenhouse gas, CO₂.

The CO₂ Reduction Factor in the last table in Figure 4.4 can be directly computed from

$$\text{CO2_Reduc_Factor} = k_{\text{PHEV}} \cdot \left(1 - \frac{\text{CO2Gen}}{\text{CO2Gasoline}} \cdot \eta_{\text{Total}} \cdot \rho_{\text{Fuel}}\right)$$

where the efficiency η_{Total} is defined by

$$\eta_{\text{Total}} = \eta_{\text{Conv}} \eta_{\text{Charger}} \cdot \eta_{\text{Bat}} \cdot \eta_{\text{Controller}} \cdot \eta_{\text{Motor}} \cdot \eta_{\text{Transmission}}$$

4.7 PHEV CO₂ Emissions from PSAT Simulations

Using the CO₂ data from the simulation results Tables 3.5 – 3.8, Figure 4.5 is drawn for Classes 1 and 2, and Figure 4.6 is drawn for Classes 3 and 4. The computed line is a plot of [CO2PHEV_Gasoline] in Figure 4.4. This is the computed value of the CO₂ emissions for the vehicle in each class without the emissions from the powerplants. Note in all cases that this calculation gives higher CO₂ emission levels than were actually obtained from the PSAT simulations. The value of powerplant CO₂ emissions used in Figure 4.4 is 1.350 lbs of CO₂/kWh from year 2000 and may be high. The net conclusion is that PHEVs will give a substantial reduction in CO₂ emissions in addition to substantially reducing gasoline consumption.

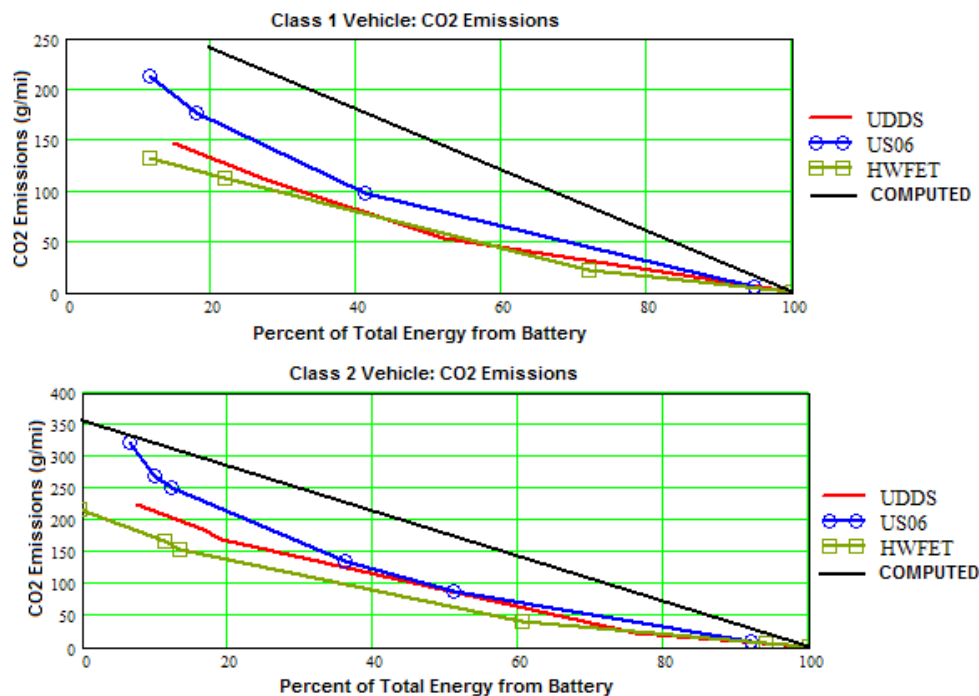


Figure 4.5: CO₂ emissions for Class 1 and 2 vehicles as a function of the percent of the total input energy from the battery.

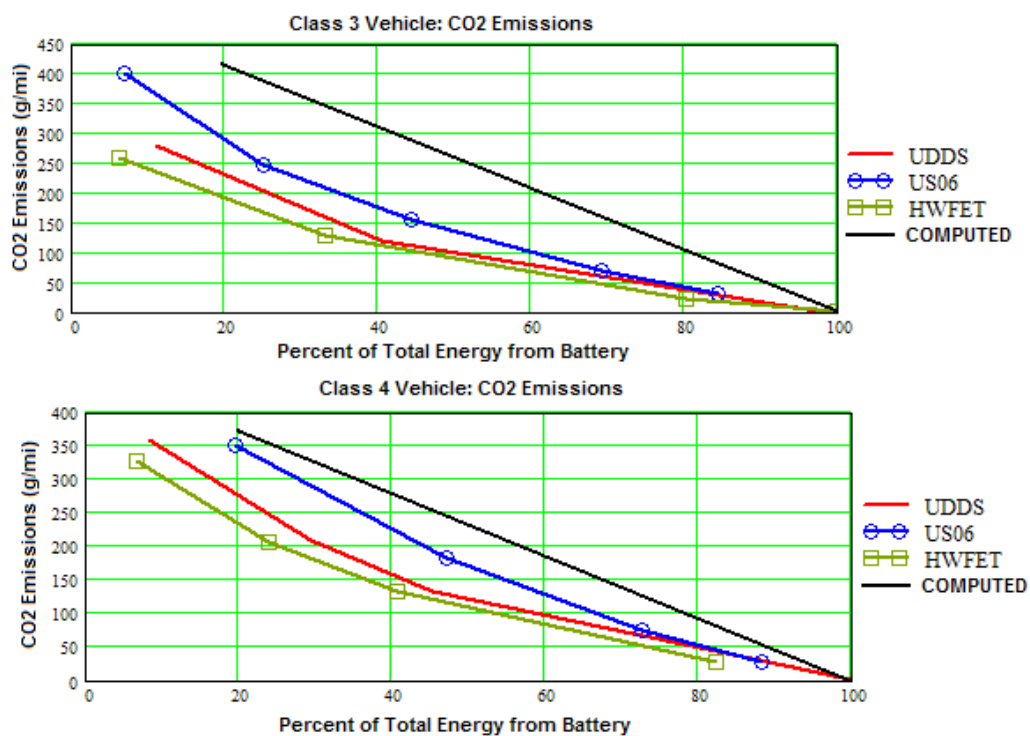


Figure 4.6: CO₂ emissions for Class 3 and 4 vehicles as a function of the percent of the total input energy from the battery.

5. Household Supply Requirements and PHEV Vehicle / Grid Interface Design

5.1 Introduction

In order to require minimal infrastructure changes for the recharging of Plug-in Hybrid Electric Vehicles (PHEVs), a standard 120 V three-prong grounded outlet is to be used. The connection to the vehicle could then be made using a standard extension cord with the proper current rating. All recharging power-electronic circuitry would be on-board the vehicle. This rectifying circuitry could then be matched to the specific battery chemistry used in the PHEV. Thus, no stand-alone chargers would be needed, and the driver could plug into any electric power outlets within reach of his/her extension cord. The nominal rated current draw for each vehicle class is computed starting with the result in Equation 3.2 that gives the grid-supplied recharge energy per mile driven for each vehicle class- i . This rated current draw is determined starting with the energy per mile driven given by E_{Grid-i} for a given k_{PHEV} from Equation 3.2. Now specifying the total distance driven, the time for recharging, and outlet voltage, the rated current draw is given by

$$I_{Recharge-i} = \frac{E_{Grid-i}(k_{PHEV}) \cdot d}{T_{Charge} \cdot V_{Outlet}} \quad (5.1)$$

where d is the driving distance (miles), T_{Charge} is the recharging time (hr). and V_{Outlet} is the wall outlet-socket voltage.

Using Equation 5.1, Table 5.1 gives the current rating for a 120 V circuit required to recharge a PHEV having driven a distance $d = 20, 40$, and 60 miles in each of our four vehicle classes with the control algorithm maintaining $k_{PHEV} = 0.7$. Thus, these driving distances are not driven on the batteries alone as a ZEV.

Table 5.1: Current rating in (A) for a 120 V circuit with a recharge time interval of 6 hours with $k_{PHEV} = 0.7$.

Vehicle Class	20-Miles	40-Miles	60-Miles
1	4.73	9.46	14.20
2	5.66	11.32	16.99
3	8.22	16.44	24.66
4	8.42	16.84	25.26

As shown in Table 5.1, a 120 V branch circuit rated at 20 A is adequate for a 20 and 40 mile drive for all four vehicle classes. This same branch circuit could also handle a 60 mile drive in classes 1 and 2 only. For a 60 mile drive for classes 3 and 4, either the circuit must be wired to a 30 A rating (i.e. AWG-No. 10 wire) or the circuit voltage should be raised to 240 V, thus halving the current values given in Table 5.1. Note in Equation 5.1 that if the branch-circuit voltage is doubled, then the recharge time could be halved to 3 hrs. and the same current ratings in Table 5.1 would be obtained.

5.2 Feasibility of Battery Packs for PHEVs

As previously pointed out, there is at present no production PHEVs on the market. However, we can get some idea of what probable designs will be produced by considering the required battery pack rated energy storage for a PHEV operating at a $k_{PHEV} = 0.7$ value. Thus, for each vehicle class we want to compute the kWh and Ah ratings of the battery pack that would give the three ZEV ranges in Table 5.1 with this preferred value of k_{PHEV} . This computation must include a factor that specifies the allowable SOC-range. This factor, ΔSOC involves the minimum SOC that is allowed during battery-only charge-depleting operation before the control algorithm switches to charge-sustaining operation. Thus, for example, a $\Delta SOC = 80\%$ would allow charge depletion from an SOC = 100% down to an SOC = 20%. The minimal battery rating can be determined from Equation 3.2 that gives the required recharging energy per mile for each vehicle class. Thus, the minimal battery energy rating is given by

$$E_{Bat.Rating-i} = \frac{E_{Grid-i}(0.7) \cdot d \cdot \eta_{Charger}}{\Delta SOC} \quad (5.2)$$

The Ah rating is a common way of normalizing the battery-pack energy storage rating by dividing the energy in Equation 5.2 by the rated voltage of the battery pack. The value of a battery cells Ah rating, in effect, gives the charge that each individual cell can store.

Now using Equation 5.2, Table 5.2 is computed for each vehicle class over our three driving distances, assuming that $k_{PHEV} = 0.7$, and $\Delta SOC = 80\%$. A nominal pack voltage of 336 V is arbitrarily chosen in the computation of Ah's. Note that if we choose a higher nominal voltage, then the Ah rating of each cell is reduced, but we need more cells in series to achieve this higher pack terminal voltage. So the weight and volume of the battery pack tends to stay constant. However, a higher pack voltage reduces controller and motor losses.

Table 5.2: Battery pack rating for each vehicle class over the three driving distances (kWh / Ah).

Vehicle Class	20-Miles	40-Miles	60-Miles
1	3.83 / 11.41	7.7 / 22.82	11.50 / 34.22
2	4.59 / 13.65	9.17 / 27.30	13.76 / 40.95
3	6.66 / 19.82	13.32/39.63	19.97 / 59.44
4	6.82 / 20.30	13.64 / 40.60	20.46 / 60.90

The battery chemistry presently considered the best choice for PHEVs is Lithium-Ion (Li-Ion). This chemistry has the highest energy and power densities of all chemistries. Table 5.3 contains data on three currently available Li-Ion cells from SAFT, a major producer of Li-Ion batteries for hybrid vehicles that look reasonable for a PHEV design.

Table 5.3: Data for available SAFT Li-Ion battery cells.

Cell Type	VL 41M	VL 30P	VL 12V
Nominal Voltage (V)	3.6	3.6	3.6
Avg. Capacity (Ah)	41 (C/3)	28 (C/1)	12 (C1)
Specific Power (W/kg)	794	1136	5000 (18 sec)
Specific Energy (Wh/kg)	136	97	74
Energy Density (Wh/liter)	285	209	175
Peak Current (A)	300 (30 sec)	500 (10 sec)	3200 (2 sec)
Cell Weight (kg)	1.07	1.1	0.64
Cell Diam. / Ht. (mm)	54.3 / 222	54 / 222	47 / 173
Cell Volume (dm ³ =liter)	0.51	0.51	0.27

In Table 5.3 the (C/3) indicates that the battery is discharged at a constant current = (1/3 its Ah value) over a time period of 3 hours. Thus a cell rated for C/3 at 60 Ah could deliver 20 A for 3 hours. Note that its C/1 rating would be less than 60 Ah as the current it could deliver for 1 hour is less than 60 A, so the C/x value must be specified when an Ah rating is given. Battery manufacturers often quote a C/20 rating as that gives a much higher Ah value than C/1 or C/3.

The VL 41M cell is a medium energy cell that represents a compromise between peak power and energy storage, and is reasonable for a PHEV design. The VL 30P and VL12V cells are more suitable for charge sustaining HEVs that need high power output but much less energy storage. Notice that the VL 41M has an Ah capacity (41 Ah) sufficient for all vehicle classes for charge depleting operation with $k_{PHEV} = 0.7$ over driving distances of 20 and 40 miles. For a 60 mile charge depleting drive, at this same k_{PHEV} value, the VL-41M cell is only suitable for vehicles in class 1 and 2. For a 60 mile charge depleting drive in classes 3 and 4, a cell with more energy storage is needed or charge depleting operation would start short of 60 miles.

If we assume a battery pack nominal terminal voltage of 336 V, then 94 cells in series would be needed. Using VL 41M cells, the weight of the 94 cells would be $(94 \cdot 1.07) = 100.6$ kg (221 lbs). For the volume calculation, a packing factor $4/\pi$ is needed for these cylindrical cells. Thus, the minimum volume for 94 cells is $((4/\pi) \cdot 94 \cdot 0.51) \approx 61$ liters (2.2 ft³). Both the weight and volume are reasonable values. The conclusion here is that a 40 mile charge depleting operation is a reasonable design target with the control algorithm aimed at maintaining an average $k_{PHEV} = 0.7$.

5.3 Introduction to Vehicle / Grid Interface Design

This section considers the design issues for the connection of a PHEV to the electrical distribution system. The basic thesis of the designs to be considered here is that all of the electronics for electric energy flow control and communication should be on-board the vehicle and not in a special charging station in a customer's garage or other plug-in location. This specification for on-board electronics is proposed so that there is essentially no special house rewiring needed after a PHEV is purchased. The only exception might be to have a 240 V, 30 A outlet installed in the garage to allow for more rapid electric energy interchange. This higher voltage receptacle has the same specifications as an ordinary electric clothes dryer or an electric oven outlet, and in new homes could be readily installed during construction. For older homes, such an outlet

could usually be installed with minimal difficulty. Thus, the only equipment external to the vehicle needed by the driver of a PHEV would be an extension cord of suitable rating with a male plug at one end for the 120 V or 240 V wall receptacle and a female plug at the other end to plug into a mating male receptacle under an access door on the vehicle. If two extension cords were supplied, one with a 120 V male end and the other with a 240 V male end, then the vehicle could be plugged into any receptacle in any location convenient for the driver using the appropriate extension cord.

5.4 On-Board Electronic Requirements

Now let us consider the requirements for the on-board electronics. These requirements are grouped into four levels in order to allow for increasing functionality.

5.4.1 Level-0

All electric drives require a power electronic controller between the battery pack and the electric-drive motor. This electric motor is either an induction motor or a permanent-magnet field synchronous or brushless-dc motor. For either motor type, the controller must have power-electronic circuitry that inverts the dc-electric energy from the battery into ac-electric energy for the stator of these electric motors. This same power-electronic circuitry can also be used to rectify the ac-electrical energy from a wall receptacle into dc-electrical energy to recharge the battery pack. Thus, the level-0 interface would simply include the following features:

1. A control for the controller circuitry that would modulate the charging electrical energy injected into the battery pack. Generally, this energy is applied at a constant current until some specified battery pack terminal voltage is reached. Then the charging energy is supplied at constant voltage until a specified higher battery pack terminal voltage is reached whereupon charging is discontinued. This constant voltage charging is known as a *finish charge*. The advantage of having this charging control on-board the vehicle is that it can be matched to the specific battery chemistry used in the battery pack.
2. A sensor that would not allow the vehicle to be operated if the female plug on the extension cord were inserted into the vehicle charging port. This sensor could also be on the charging port access door, as this door could not close if the extension cord plug were not removed.

All battery pack cooling and cell equalization would be designed into the battery pack for proper operation during both recharging and normal vehicle operation. The level-0 interface would supply recharge electric energy whenever the connection to the wall receptacle was established.

5.4.2 Level-1

The level-1 interface would include the features of the level-0 interface with the addition of time-of-day restrictions. The simplest form of this enabling circuitry would be to have a clock on-board the vehicle that would only allow recharging between some set off-peak hours. If the vehicle were connected to the wall receptacle outside of this off-peak window, then no recharging would occur. Because the cost of electric energy for

powering the vehicle is so much less than the cost of an equivalent amount of gasoline, there may be no need to give a special reduced rate for this off-peak recharging energy. Therefore, this time-of-day reduced rate is not included in the level-1 interface.

5.4.3 Level-2

The level-2 interface includes the features of the level-0 and level-1 interfaces with a two-way wireless communications capability that is enabled when connection to a wall receptacle is established. This two-way communication would allow for a great many features of great value to the electric utility, as now the PHEV would appear as both a controllable load and a store of electric energy for emergency generation during a peak power situation. The envisioned features of this two-way communication are as follows:

1. Upon being plugged into a wall-receptacle, the vehicle would report this fact to the utility including the vehicles identification and a GPS location of the receptacle. The exact receptacle identification is probably not needed, just its approximate location in the distribution system.
2. The utility can then decide when it wants to supply an enabling signal to allow the recharging to proceed. This enabling signal could be turned on and off depending on the state of the utility's system and the location of the vehicle. The location of the vehicle in the distribution system is important, as transmission bottleneck problems may exist that make charging not desirable.

The charging energy with a level-2 interface would be billed to the location where the vehicle is receiving charging energy. The utility does not know the exact wall receptacle being used, only its general location in the distribution system. Generally, PHEV charging will be at the driver's home location, so his/her electric bill will include charges for this charging energy.

5.4.4 Level-3

The Level-3 interface assumes that there are dedicated wall receptacles that are used for PHEV connection to the power grid. These special receptacles include the capability of transmitting to the utility their identification. So now, upon connection of the PHEV to this special receptacle, the utility knows both the vehicle identification and the exact wall receptacle being used. With this added information on the specific wall receptacle, the level-2 interface can be extended such that billing will always be transferred to the driver's electric bill, and not to the bill of the remote location where the charging energy was actually obtained. Here the term "remote location" refers to a wall receptacle different from a receptacle connected to the meter that produces the driver's monthly bill. Thus, the added energy recorded by the remote location meter due to this PHEV charging energy must be debited from this remote location meter. The vehicle circuitry has the capability to keep track of the charging energy received. The utility after enabling charging to proceed can then monitor the recorded energy and make the correct billing adjustments debiting the remote location meter and adding energy to the driver's meter.

If level-3 interfaces are being used, then the added feature where energy could be extracted from the vehicle and injected into the wall receptacle can be included. This vehicle-to-grid (V2G) operation would proceed only if the driver had given prior

permission. This permission would be accessible by the utility once the vehicle identification was received. As with the charging operation, V2G operation, if permitted by the driver, would proceed after an enabling signal was received from the utility. Now the billing information would require adding energy to the remote location meter, and debiting energy from the driver's home meter. As an incentive to the driver to allow V2G operation, the energy debited from the driver's meter could be the actual energy injected into the grid multiplied by some agreed upon factor greater than unity. A very important design requirement of V2G operation is that no electric energy can be transmitted to the grid if the grid is not active. This requirement means that if the wall receptacle had no voltage due to a power failure, the vehicle would not back-feed the line. Back-feeding a distribution circuit presents a serious hazard to utility line maintenance personnel.

Reference [5.1] defines what the author terms "The CashBack Car". This reference views PHEVs as a dispatchable generation resource similar to those generators in the system that can be used for frequency regulation. These PHEVs can perform this ancillary function beyond what a generator can do as follows. A generator can inject more or less power into the system, but cannot absorb power. The PHEV can both inject power and also absorb power. An actual demonstration of this regulation capability of PHEVs as a dispatchable load is described in [5.2]. The dollar value of this ancillary capability to the electric utility is high enough that the PHEV, according to [5.1], can pay back to the owner most if not all of the vehicle's fuel costs for gasoline and recharging electric energy.

6. PHEV Infrastructure Impact

Distribution systems are typically designed for specific load carrying capability based on typical load consumption patterns. When plug-in hybrid electric vehicles (PHEVs) are deployed (consumers acquire PHEVs and use the existing electric system in houses and commercial building for charging the PHEVs) the patterns of electric power demand will change. It is possible that the electric power system may be adequate to handle the new patterns and levels of demand or it is possible that periods of overloads on this system may increase. Both circuits and transformers are vulnerable to these overloads with the transformer being more susceptible to overloads.

To quantify the impact PHEV charging could have on distribution transformers a loss of life calculation will be utilized. This method involves three steps:

1. Center-tapped single phase distribution transformer simulation.
2. Electro-thermal transformer simulation.
3. Loss-of-life (LOL) calculation.

In the first step random electric loads will be assumed (the probabilistic model of electric loading is described fully in Volume II of this report) and the resulting transformer currents will be calculated using a center-tapped single phase distribution transformer model. From these currents the electro-thermal transformer model will be utilized to compute the transformer winding temperatures and hourly hot-spot temperature. From the hot-spot temperature a percent LOL can be computed.

Two experiments will be performed to quantify the impact of PHEV charging on distribution transformers. The first varies the number of PHEVs charged from a single 15 kVA transformer (one, two, and three PHEVs in the distribution system). The second varies the size of the distribution transformer used to charge three PHEVs (10 kVA, 15 kVA, and 25 kVA). In all scenarios the same base case electric load is assumed and two limiting ambient conditions are used, Figure 2.1 shows the daily ambient temperature for both cases (Tucson Arizona and Fairbanks Alaska on July 1, 2008).

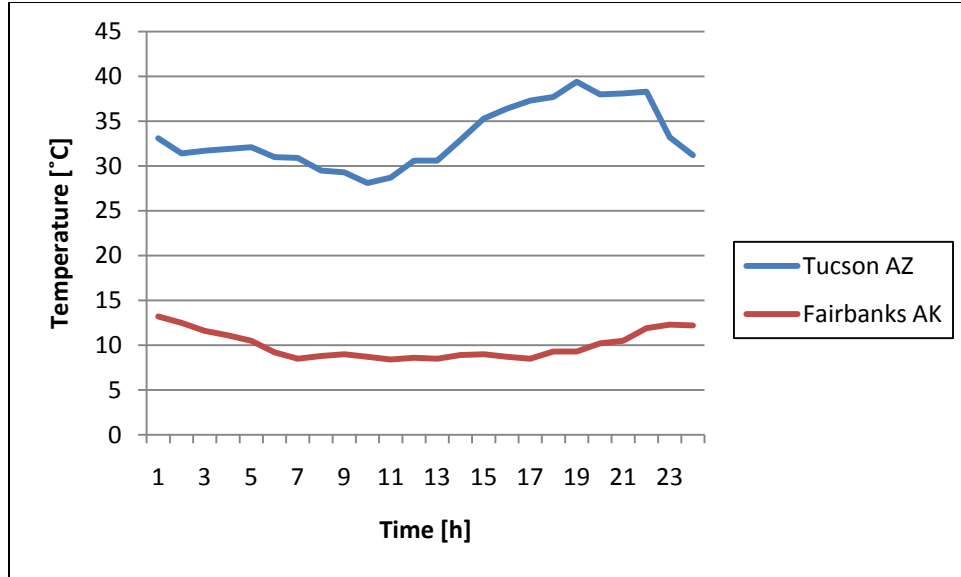


Figure 6.1: Daily ambient temperature profiles used as limiting case scenarios [6.1].

Repeated simulations in each scenario will be performed, resulting in a histogram of percent LOL for each scenario. A maximum likelihood estimation of each scenarios mean percent LOL will be used as an estimate of the expected percent LOL, from which percent increase in LOL will be computed.

6.1 Distribution System Model

The model, shown in Figure 6.2, is fully described in [6.2]. This model for our purposes is a single phase distribution transformer feeding three typical houses. The transformer is a 7.960 kV to 120/240 V transformer. The transformer has series resistance R_A and reactance X_A .

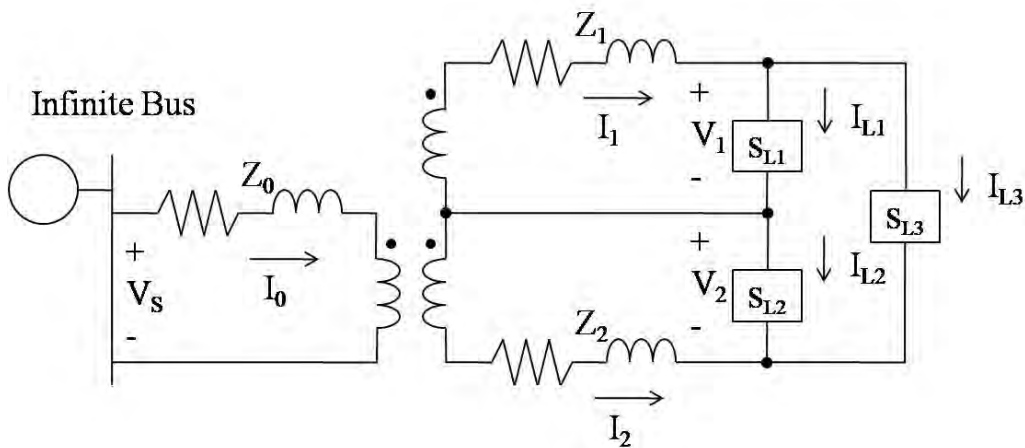


Figure 6.2: Center-tapped single phase distribution transformer model [6.2].

To compute the winding impedances (Z_0 Z_1 Z_2) the interlaced transformer design equations were used [6.2]

$$Z_{p.u.0} = 0.5 \cdot R_A + j \cdot 0.8 \cdot X_A$$

$$Z_{p.u.1} = Z_{p.u.2} = R_A + j \cdot 0.4 \cdot X_A$$

To convert the per-unit impedance values to actual units the base impedances must be computed.

$$Z_{\text{base high voltage}} = \frac{V_s^2}{S_{\text{transformer rated}}}$$

$$Z_{\text{base low voltage}} = \frac{240^2}{S_{\text{transformer rated}}}$$

Thus,

$$Z_0 = Z_{\text{base high voltage}} \cdot Z_{p.u.0}$$

$$Z_1 = Z_2 = Z_{\text{base low voltage}} \cdot Z_{p.u.1}$$

The turns ratio (n_t) is the ratio of the primary and secondary voltages

$$n_t = \frac{7960}{120} = 66.3333$$

Finally, the total complex power is distributed between the two 120 V circuits and the 240 V circuit assuming that 60% of the power demand in typical household loads is 120 V (split evenly between the two 120 V lines) and 40% 240 V. Thus,

$$S_{L1} = S_{L2} = 0.3 \cdot (P^{(h)} + j \cdot Q^{(h)})$$

$$S_{L3} = 0.4 \cdot (P^{(h)} + j \cdot Q^{(h)})$$

The method outlined in [6.2] to compute the transformer currents is an iterative process consisting of a forward sweep and a backward sweep.

The electro-thermal transformer model, described next, computes the expected transformer winding temperature based on the transformer current results from the center-tapped single phase transformer model.

6.2 Transformer Electro-Thermal Model

Simplified electro-thermal model of a center tapped convection cooled distribution transformer [6.3] is shown in Figure 6.3.

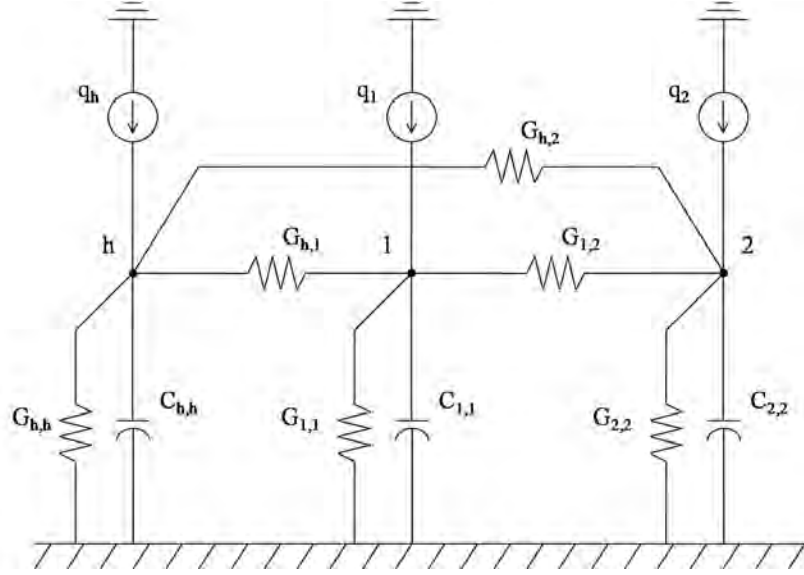


Figure 6.3: Electro-thermal transformer model.

Each node in Figure 6.3 represents:

- The high voltage winding (node h).
- The low voltage winding center tap 1 (node 1).
- The low voltage winding center tap 2 (node 2).

In Figure 6.3, each circuit element represents a thermal phenomenon: the conductance components represent heat transfer within and between the transformer windings (estimated from temperature gradients between transformer windings [6.3]); the capacitive components represent transformer winding thermal inertia (computed from volume and specific heat constants of the transformer windings [6.3]); and the current sources represent heat sources in the form of ohmic losses in each of the transformer windings.

The dynamics of the transformer winding temperatures [6.3] are described by the following differential equation

$$\mathbf{C} \cdot \frac{d\vec{T}}{dt} = -\mathbf{G} \cdot \vec{T} + \vec{Q} \quad (6.1)$$

where $\mathbf{C}$ is the thermal capacitance matrix

$$\mathbf{C} = \begin{bmatrix} C_{h,h} & 0 & 0 \\ 0 & C_{1,1} & 0 \\ 0 & 0 & C_{2,2} \end{bmatrix}$$

$\vec{T}$ is the components temperature vector

$$\vec{T} = [T_h \quad T_1 \quad T_2]^T$$

$\vec{Q}$ is the heat input vector

$$\vec{Q} = [Q_h \quad Q_1 \quad Q_2]^T$$

which represent ohmic losses in the transformer windings and as such can be modeled as a function of the currents in the transformer windings and resistance of the windings

$$\vec{Q} = [\text{Real}(Z_0) \cdot I_h^2 \quad \text{Real}(Z_1) \cdot I_{1,1}^2 \quad \text{Real}(Z_2) \cdot I_{1,2}^2]^T$$

and $\mathbf{G}$ is the thermal conductance matrix, which represents the thermal conductance among the three windings

$$\mathbf{G} = \begin{bmatrix} G_{h,h} + G_{h,1} + G_{h,2} & -G_{h,1} & -G_{h,2} \\ -G_{h,1} & G_{1,1} + G_{h,1} + G_{1,2} & -G_{1,2} \\ -G_{h,2} & -G_{1,2} & G_{2,2} + G_{h,2} + G_{1,2} \end{bmatrix}$$

The winding capacitive circuit parameters $C_{h,h}$, $C_{1,1}$, and $C_{2,2}$ are functions of the mass density ρ_W , specific heat c_W , and volume V (in³) of the respective windings that they represent [6.4], where $C_* = \rho_W \cdot c_W \cdot V_*$, C_* is used as a general terms for the individual winding capacitive results, and V_* is used as a general term for the volume of the particular winding. For copper the mass density $\rho_w = 8.93 \text{ g/cm}^3$ and specific heat $c_w = 0.385 \text{ J/(g}\cdot^\circ\text{C)}$ are physical constant values.

To estimate the volume of typical transformer windings a number of transformers physical dimensions and volumetric quantity of oil data was utilized. The data utilized included transformer dimension and transformer oil volume values for a range of Power Partner overhead distribution transformers [6.5]. The specific data utilized is shown in Table 6.1.

Table 6.1: Transformer dimension and oil volume data [6.5].

kVA	Height h [in]	Radius r [in]	Oil Volume [gal]
10	34	6.625	11
15	36	6.625	12
25	41	7.625	18

The numeric values of the circuit parameters utilized for the 15 kVA model were analytical computed and experimentally verified [6.6], the circuit parameters for the 10 kVA and 25 kVA transformer were computed from the first. Verification of these circuit parameters is ongoing work. The circuit parameter values utilized are shown in Table 6.3 for each of the three transformer sizes utilized.

From the height and diameter data the transformer volume was computed, using the common volume of a cylinder formula $V = \pi \cdot r^2 \cdot h$. The height was reduced by five inches to account for the transformers bushing included in the height dimension. Next, the oil volume was subtracted from the transformer volume resulting in an approximation of the transformer less oil volume, representing the total volume for transformer core and windings. Finally, the primary winding volume was assumed to be 0.553% of the total core and winding volume and the secondary winding was assumed to 0.874% of the total core and winding volume. These percentages were selected so that the 15 kVA results would approximate previously verified electro-thermal circuit parameter values [6.6].

This method resulted in the transformer less oil volume, primary winding volume, secondary winding volume, $C_{1,1}$, $C_{2,2}$ and $C_{3,3}$ results shown in Table 6.2.

Table 6.2: Electro-thermal transformer capacitance results.

kVA	Transformer Less Oil Volume [cm ³]	Primary Winding Volume [cm ³]	Secondary Winding Volume [cm ³]	$C_{1,1}$	$C_{2,2}$ and $C_{3,3}$
10	23892.1	132.1	208.8	454.2	359.0
15	24626.2	136.2	215.2	468.2	370.0
25	39624.0	219.1	346.3	753.3	595.3

The conductance circuit parameters are solved for assuming (as the standard [9] requires) the nameplate transformer rating full load should result in a 65°C winding temperature increase. Specifically, in Equation 6.1: $\frac{d\vec{T}}{dt}$ was set to zero (indicating steady state conditions), $\vec{T}$ was set to $[65 \ 65 \ 65]^T$, and $\vec{Q}$ was set to $[R_h \cdot I_{P,R}^2 \ R_1 \cdot I_{S,R}^2 \ R_2 \cdot I_{P,R}^2]^T$ where $I_{P,R} = S_{Rated}/V_{Primary}$ and $I_{S,R} = S_{Rated}/V_{Secondary}$. Thus, Equation 1 simplifies to

$$\mathbf{G} \cdot \vec{T} = \vec{Q}$$

which after substitution is equivalently

$$\begin{bmatrix} G_{h,h} + G_{h,1} + G_{h,2} & -G_{h,1} & -G_{h,2} \\ -G_{h,1} & G_{1,1} + G_{h,1} + G_{1,2} & -G_{1,2} \\ -G_{h,2} & -G_{1,2} & G_{2,2} + G_{h,2} + G_{1,2} \end{bmatrix} \cdot \begin{bmatrix} 65 \\ 65 \\ 65 \end{bmatrix} = \begin{bmatrix} R_h \cdot I_{P,R}^2 \\ R_1 \cdot I_{S,R}^2 \\ R_2 \cdot I_{S,R}^2 \end{bmatrix}$$

which can be separated into three algebraic equations and after some simplification are

$$G_{h,h} \cdot 65 = R_h \cdot I_{P,R}^2$$

$$G_{1,1} \cdot 65 = R_1 \cdot I_{S,R}^2$$

$$G_{2,2} \cdot 65 = R_2 \cdot I_{S,R}^2$$

Finally, it is assumed that

$$G_{h,h} = 0.1 \cdot (G_{h,1} + G_{h,2})$$

$$G_{1,1} = 0.1 \cdot (G_{h,1} + G_{1,2})$$

$$G_{2,2} = 0.1 \cdot (G_{h,2} + G_{1,2})$$

which results in an analytic set of functions for the conductance values in terms of the winding resistance and rated transformer currents. The three modeled transformers resulting circuit parameters are shown in Table 6.3.

Table 6.3: Electro-thermal model circuit parameters.

	10 kVA	15 kVA	25 kVA
Z_0	$22.1766 + j \cdot 177.4125$	$14.7844 + j \cdot 118.2750$	$8.8706 + j \cdot 70.9650$
Z_1, Z_2	$0.0403 + j \cdot 0.0806$	$0.0269 + j \cdot 0.0538$	$0.0161 + j \cdot 0.03226$
$C_{1,1}$	454.2	468.2	753.3
$C_{2,2}, C_{3,3}$	359.0	370.0	595.3
$G_{h,h}$	0.5385	0.8077	1.3462
$G_{h,1}, G_{h,2}$	2.6923	4.0385	6.7308
$G_{1,1}, G_{2,2}$	1.0769	1.6154	2.6923
$G_{1,2}$	8.0769	12.1154	20.1923

A trapezoidal integration method is used to calculate the solution of Equation 6.1. In particular, integration within the time interval $[t - u, t]$ is

$$\vec{T}(t) = \left(\mathbf{C} + \mathbf{G} \cdot \frac{u}{2} \right)^{-1} \cdot \left(\mathbf{C} - \mathbf{G} \cdot \frac{u}{2} \right) \cdot \vec{T}(t - u) + \left(\mathbf{C} + \mathbf{G} \cdot \frac{u}{2} \right)^{-1} \cdot \vec{Q} \cdot u$$

where u is the time step of the integration.

The input to the above model is the transformer currents (I_h $I_{l,1}$ $I_{l,2}$) over a specific time period, e.g. one day. The result from the trapezoidal integration is the estimated transformer temperature over the simulated time span. The transformer temperature is with respect to ambient temperature.

6.3 Loss of Life Calculations

The process of insulation degradation, for oil filled transformer, is a function of three phenomenon (1) temperature, (2) moisture, and (3) oxygen content [6.7]. The second two consist of water and oxygen contamination of the transformer oil and can be controlled through “oil preservation systems” [6.7] and thus are not considered in this analysis. The following method outlined in [6.7] is used to compute the percent LOL.

The percent LOL P_L is a function of the equivalent life E_L (hr) and the normal insulation life N_L (hr)

$$P_L = \frac{E_L \cdot 100}{N_L}$$

where the equivalent life E_L is computed as a function of the aging acceleration factor θ_u

$$E_L = \sum_{u=1}^U \theta_u \cdot \Delta t_u$$

and the aging acceleration factor θ_u is computed as a function of the aging rate constant B and the transformer hot-spot temperature $\tilde{T}_u$ ($^{\circ}\text{C}$) at time u (hr)

$$\theta_u = \exp \left\{ \frac{B}{383} - \frac{B}{\tilde{T}_u + 273} \right\}$$

The percent LOL calculations is computed for a typical summer day based on hourly increments, thus U is 24 and Δt_u is 1 hour. Thus, the percent LOL calculation variables E_L and θ_u will be computed for each hour of the simulated day based on the simulated hot-spot temperature $\tilde{T}_u$ in that hour (the maximum simulated transformer temperature for a given hour).

The percent LOL constants N_L and B are selected based on historically accepted values. The historical perspective on the insulation life values and LOL calculations is quite interesting, the values in Table 6.4 for normal insulation life and in Table 6.5 for aging rate constant are surrounded in ambiguity; however, in [6.7] a conclusion is drawn that the “chemical test measurement of degree of polymerization is a much better indication of cellulosic insulation mechanical characteristics than loss of tensile strength,” therefore the normal insulation life used is 150,000 hours (17.1 years) and aging rate constant used is 14,580.

Table 6.4: Normal insulation life times [6.7].

Basis	Normal Insulation Life [hr]
50% retained tensile strength of insulation (former IEEE Std. C57.92-1981)	65,000
25% retained tensile strength of insulation	135,000
200 retained degree of polymerization in insulation	150,000
Interpretation of distribution transformer functional life test (former IEEE std. C57.91-1981 criterion)	180,000

Table 6.5: Aging rate constant [6.7].

Basis	Aging rate constant
50% retained tensile strength of insulation (former IEEE Std. C57.92-1948)	14,830
50% retained tensile strength of insulation (former IEEE Std. C57.92-1981)	16,054
DT life tests (former IEEE Std. C57.92-1981)	14,594
250 retained degree of polymerization in insulation	14,580

6.4 Results

It is expected that the repeated LOL results should follow a normal distribution due to the law of large numbers. Thus each scenario is repeated 100 times and the simulation results are characterized using the common normal distribution maximum likelihood estimator (MLE)

$$\hat{\mu} = \frac{1}{N} \sum_{i=1}^N x_i$$

this result is valid assuming that the percent LOL results will follow normally distributed. From the mean MLE results for each of the scenarios simulated a percent change in average LOL can be determined for both experiments conducted. The results from the first experiment, varying the number of PHEVs in the distribution system, are shown in

Table 6.6. The results from the second experiment, varying the size of the transformer charging three PHEVs, are shown in Table 6.7.

Table 6.6: Base case and PHEV scenario percent LOL for Tucson AZ and Fairbanks AK varying the number of PHEVs charged using a 15kVA transformer.

# of PHEVs	1		2		3	
Scenario	Base Case	PHEV Scenario	Base Case	PHEV Scenario	Base Case	PHEV Scenario
Tucson AZ	3.2725E-06	3.4741E-06	3.2701E-06	3.6875E-06	3.2737E-06	3.9566E-06
Fairbanks AK	5.6455E-08	6.1380E-08	5.6867E-08	6.7451E-08	5.6422E-08	7.3125E-08

Table 6.7: Base case and PHEV scenario percent LOL for Tucson AZ and Fairbanks AK varying the size of the transformer used to charge three PHEVs.

Xfmer. Size	10 kVA		15 kVA		25 kVA	
Scenario	Base Case	PHEV Scenario	Base Case	PHEV Scenario	Base Case	PHEV Scenario
Tucson AZ	9.6593E-06	1.4412E-05	3.2921E-06	3.9510E-06	1.9133E-06	2.0532E-06
Fairbanks AK	1.7916E-07	3.0089E-07	5.6383E-08	7.3226E-08	3.3069E-08	3.6528E-08

Using the normal insulation life and aging rate constant selected for operation at a constant 110 °C for 24 hours is 0.016%. Intuitively, this indicates that a transformer that withstood a 24 hour period with hot-spot temperature of 110 °C aged the equivalent of 0.016% of its useful life. Notice, 24 hours is 0.016% of 150,000 hours.

Notice that, the effect of ambient temperature is significant; most of the results show the percent loss of life in Tucson AZ being two orders of magnitude larger than the similar experiment and scenario in Fairbanks AK.

The amplitude of the percent LOL is not the focus of this study. Rather the relative increase in percent LOL. This increase is the increase in transformer degradation caused by the additional electrical load caused by PHEV charging. Figure 6.4 shows the percent increase in percent LOL for the first experiment and Figure 6.5 shows the percent increase in percent LOL for the second experiment.

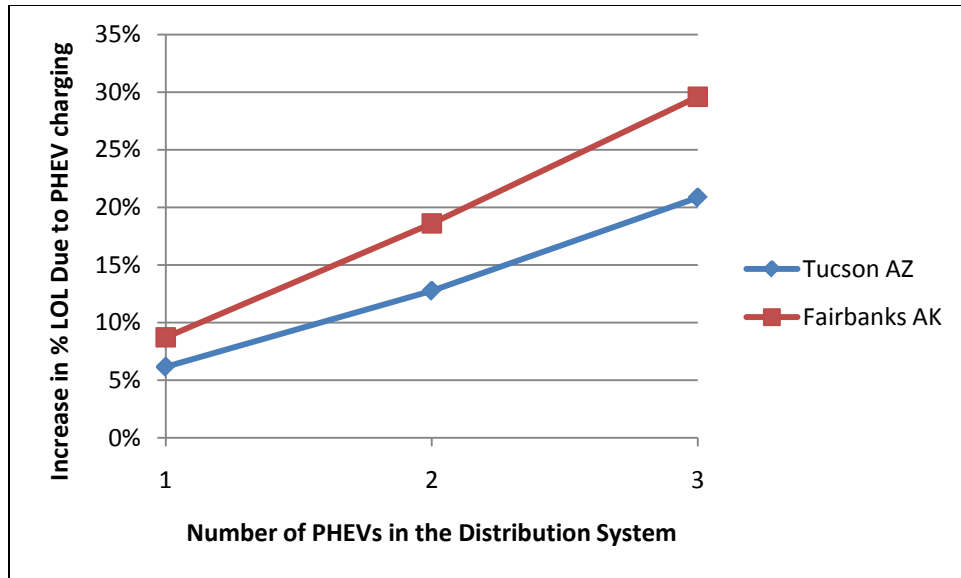


Figure 6.4: Increase in percent LOL for Tucson AZ and Fairbanks AK for a varying number of PHEVs included in the distribution system.

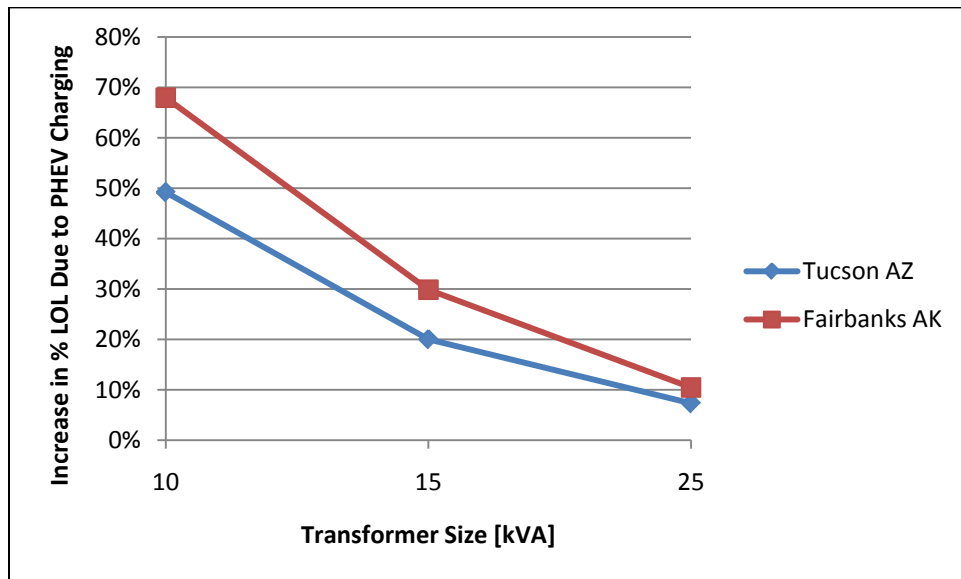


Figure 6.5: Increase in percent LOL for Tucson AZ and Fairbanks AK charging three PHEVs using different transformer sizes.

In the first experiment the percent LOL is computed for a 15 kVA transformer when the electric load is increased for one, two and three PHEVs. As expected the percent increase in LOL increased as the number of PHEVs in the distribution system increased. Because the Fairbanks AK results are so small the relative percent increase for these results is larger than the Tucson AZ results.

In the second experiment the percent LOL is computed for a 10 kVA, 15 kVA and 25 kVA transformer when the electric load is increased due to three PHEVs in the

distribution system. The percent increase in LOL is significant for both scenarios using a 10 kVA transformer. Notice that, the average peak load was 11.1 kW, thus the 10 kVA transformer is undersized by 11% with no additional load due to PHEV charging.

6.5 Conclusion

The electric load was a random variable computed with and without PHEV charging. Repeated simulations of both the base case and PHEV scenarios were used to compute an average LOL result for both scenarios, and from this a percent reduction of LOL was computed.

The transformer life results indicate that adding the additional electric load demand to distribution transformers has a measurable effect on the longevity of the transformer. The impact is expounded as the number of PHEVs which are applied to the transformer increases and when the transformer loading is increased beyond the nameplate rating of the transformer.

On average it was assumed that the average daily electric demand seen by a distribution transformer for three typical houses is 150 kWh. The average added electric load due to PHEVs is on average 16 kWh. The added average electric load demand seen at the transformer and resulting average LOL are shown in Table 6.8, computed as the average percent LOL for the Tucson AZ and Fairbanks AK results.

Table 6.8: Increase in average electric load and resulting average transformer LOL.

	Percent Increase	
	Average Electric Load	Transformer LOL
One PHEV	10.67%	7%
Two PHEVs	21.33%	16%
Three PHEVs	32.00%	25%

If the failure rate of a specific hypothetical utility company with a fleet of 3 million transformers was originally 10% per year. Then assume that as the penetration of PHEVs reaches significant levels the failure rate of transformers increases to 17% per year (on average all transformers load increases due to one PHEV) the impact on the entire utility companies transformer fleet would increase significantly. Specifically, originally 10% failure rate indicates 300,000 transformers would fail in a single year. Increasing this failure rate to 17% would indicate 510,000 transformers would fail in a typical year with the added electric load due to PHEV.

In economic terms, consider an assumption that purchasing and installing a new transformer costs \$750. Then replacing the original failed transformers required an annual budget of \$225 million. Whereas, the increased number of failures including the PHEV electrical load would cost \$382.5 million. This increase in utility company expenditures would be offset utility company added revenue generated by the added electric load demand created by the added PHEV. Assuming 3 million PHEVs each adding 16 kWh per day charge 8 cents per kWh represents added annual revenue of \$1,401.6 million, indicating approximately, \$1,019.1 million in net profit.

Potential avenues for future work quantifying the impact of PHEV charging on distribution transformers is in the process, which includes further analytic modeling of distribution transformers. Opportunities for this work to continue are numerous; specifically, data on specific power system feeder loading, transformer fleet specifics, and economic cost data would provide significant validation of the developed methodology.

7. PHEV Energy Utilization

To quantify where the electric energy used to charge plug-in hybrid electric vehicles (PHEVs) is generated, a probabilistic simulation program was developed. Two key steps of this simulation program include a vehicle fleet simulation and a power system simulation. The vehicle fleet simulation computes: the amount of added electric load demand to charge the PHEV fleet, the amount of gasoline used by both an internal combustion (IC) vehicle fleet and vehicle fleet comprised of both IC vehicles and PHEVs, and the amount of environmental air pollution (EAP) generated by both vehicle fleets. The power system simulation computes how much fuel usage and subsequent EAP is generated by each generator in a specific power system. The power system simulation is based on the Probabilistic Production Costing (PPC) [7.1] algorithm.

7.1 Vehicle Simulations

The vehicle simulation utilize vehicle operational metrics computed using the results from Powertrain System Analysis Toolkit (PSAT) simulations. The PSAT results were used to compute IC vehicle and PHEV performance metrics. The IC vehicle metrics include

- Fuel efficiency.
- NO_x and CO₂ generated per mile.

The PHEV performance metrics include

- Required grid electric energy required per mile.
- Fuel efficiency.

Using the developed performance metrics three vehicle simulation results are computed: the amount of added electric load demand to charge a PHEV fleet, the amount of gasoline utilized, and the amount of EAP generated. The methods used to calculate these three results are described next.

First, a few variables will be defined: N_T is the total number of light duty vehicles in the power system area, N_{PHEVs} is the number of PHEVs in the light duty vehicle fleet, and P_{PHEV} is the percent penetration of PHEVs.

$$P_{PHEV} = \frac{N_{PHEVs}}{N_T}$$

Thus the number of IC vehicles in the light duty vehicle fleet is $(1 - P_{PHEV}) \cdot N_T$.

To compute the additional energy required to charge the PHEV fleet five calculations are required:

1. Compute the daily required grid energy, $D_E^{(v,d,c)}$.
2. Compute the daily recharge length, $C_T^{(v,d)}$.
3. Generate the recharge voltage, $V^{(v,c)}$.
4. Compute the recharge current, $I^{(v,d,c)}$.

5. Compute the total recharge power, p_v , per hour.

The superscripts in these variables indicate that the variables represent the quantity in question for vehicle- v on day- d and the vehicle is a vehicle of class- c . Where, vehicle- v is a particular vehicle sampled randomly from the total vehicle fleet N_T , the total number of vehicles in the sample population is n , day- d is a particular day of the simulation, the total number of days simulated is D , and class- c is one of the four defined vehicle classes.

First, $D_E^{(v,d,c)}$ is computed. This value depends on the random value, $M^{(v,d)}$, which represents the daily driving distance for vehicle- v on day- d , and the PHEV design value, $M_E^{(c)}$, which represents the distance a PHEV in class- c can drive in charge sustaining mode. If $M^{(v,d)}$ is greater than or equal to $M_E^{(c)}$ the required grid energy is the entire usable fraction of the PHEV battery capacity. Otherwise $D_E^{(v,d,c)}$ is the produce of the daily driving distance times $E^{(c)}(k_{PHEV})$

$$D_E^{(v,d,c)} = \begin{cases} BC^{(c)} & M^{(v,d)} \geq M_E^{(c)} \\ M^{(v,d)} \cdot E^{(c)}(k_{PHEV}) & M^{(v,d)} < M_E^{(c)} \end{cases}$$

where $BC^{(c)}$ is a random value representing the usable fraction of the PHEVs battery capacity for a PHEV in class- c and $E^{(c)}(k_{PHEV})$ a PHEV performance metric function representing the required grid electric energy rate for a PHEV in class- c with design variable k_{PHEV} .

Second, $C_T^{(v,d)}$ is computed. This value is the number of hours the vehicle will be plugged in

$$C_T^{(v,d)} = (24 - A_T^{(v,d)}) + D_T^{(v,d+1)}$$

where $A_T^{(v,d)}$ is a random value representing the arrival time of vehicle- v on day- d and $D_T^{(v,d)}$ is a random value representing the departure time of vehicle- v on day- d . Thus, $C_T^{(v,d)}$ is the number of hours between arriving home on day- d , and leaving on day- $d + 1$.

Third, $V^{(v,c)}$ is generated. This value is a discrete random value is set to 120 volts for 70% of the PHEVs in the vehicle fleet and 240 volts for 30% of the PHEVs in the vehicle fleet.

Fourth, $I^{(v,d,c)}$ is computed.

$$I^{(v,d,c)} = \min \left\{ \frac{D_E^{(v,d,c)} \cdot 1000}{V^{(v,c)} \cdot C_T^{(v,d)}}, I^* \right\}$$

This value is limited by the maximum current available, I^* , from the charging circuit. Where I^* is 15 A from 120 V service and 30 A from 240 V service. Thus, $I^{(v,d,c)}$ cannot exceed the service capacity.

Finally, the required recharge power, p_v , is the energy required every hour of the charging period

$$p_v = \frac{N_{PHEV}^{(c)} \cdot V^{(v,c)} \cdot I^{(v,d,c)}}{n \cdot 10^6}$$

where $N_{PHEV}^{(c)}$ is the number of PHEVs in class- c .

Next, the method used to compute the amount of gasoline consumed by a fleet of IC vehicles and a fleet of vehicles with P_{PHEV} penetration of PHEVs is described.

To compute of the amount of gasoline for a vehicle fleet with a specified level of PHEV penetration three steps are required:

1. Compute the amount of gasoline a fleet of N_T IC vehicles would consume, G_{IC} .
2. Compute the amount of gasoline a fleet of $N_T \cdot P_{PHEV}$ PHEVs would consume, G_{PHEV} .
3. Compute the total gasoline usage, G .

The total gasoline used by a fleet of N_T IC vehicles is computed assuming the average used by the vehicle sample population, $\overline{G_{IC}^{(c)}}$, is equal to the population average.

$$\overline{G_{IC}^{(c)}} = \frac{1}{n} \sum_{v=1}^n \frac{T^{(v)}}{IC_{MPG}^{(c)}}$$

where $T^{(v)}$ is the total distance driven by vehicle- v and $IC_{MPG}^{(c)}$ is the fuel efficiency of the IC vehicles in class- c .

Thus, G_{IC} is the sum of the product of the total number of vehicles in class- c times the average gasoline used per vehicle in class- c for each vehicle class

$$G_{IC} = N_T \sum_{c=1}^4 p_c \cdot \overline{G_{IC}^{(c)}}$$

where p_c is the percentage of vehicles in class- c .

To calculate the amount of gasoline a fleet of PHEVs uses is more complicated because the rate, at which PHEVs use fuel (in the assumed control strategy), depends on the daily driving distance. If $M_E^{(c)}$ is greater than or equal to $M^{(v,d)}$ the entire daily driving distance will be performed in charge depleting mode. Under this condition the daily required gasoline, $D_G^{(v,d,c)}$, is

$$D_G^{(v,d,c)} = \frac{M^{(v,d)}}{MPG^{(c)}(k_{PHEV})}$$

where $MPG^{(c)}(k_{PHEV})$ is the performance metric function representing the fuel efficiency of PHEVs in class- c with vehicle design variable k_{PHEV} in the charge depleting mode. However, if $M_E^{(c)}$ is strictly less than $M^{(v,d)}$ then the distance $(M^{(v,d)} - M_E^{(c)})$ must be completed in charge sustaining mode, and $D_G^{(v,d,c)}$ is

$$D_G^{(v,d,c)} = \frac{M_E^{(c)}}{MPG^{(c)}(k_{PHEV})} + \frac{M^{(v,d)} - M_E^{(c)}}{MPG^{(c)}(0)}$$

where $MPG^{(c)}(0)$ is the fuel efficiency of a PHEV in class- c in the charge sustaining mode. The first term in this sum represents gasoline used in charge depleting mode and the second term represents gasoline used in charge sustaining mode.

From $D_G^{(v,d,c)}$ the yearly gasoline usage, $Y_G^{(v,c)}$, is computed summing over each day in the simulation

$$Y_G^{(v,c)} = \sum_{d=1}^D D_G^{(v,d,c)}$$

Next, the sample vehicle population average gasoline usage, $\overline{Y_G^{(c)}}$, is computed

$$\overline{Y_G^{(c)}} = \frac{1}{n} \sum_{v=1}^n Y_G^{(v,c)}$$

Then, G_{PHEV} is the sum of the product of the number of vehicles in each class times the average gasoline usage per vehicle for each vehicle class

$$G_{PHEV} = N_T \cdot P_{PHEV} \sum_{c=1}^4 p^{(c)} \cdot \overline{Y_G^{(c)}}$$

assuming that the sampled PHEV population average gasoline usage is equal to the PHEV population gasoline usage average.

Finally, G is the sum of the gasoline used by the IC vehicles and the gasoline used by the PHEVs.

$$G = (1 - P_{PHEV}) \cdot G_{IC} + G_{PHEV}$$

The vehicle EAP is computed in a parallel fashion to that of the gasoline consumption, replacing the fuel efficiency with EAP rates. To simplify the description $P^{(c)}(k_{PHEV})$ will be used as a general term for either $NO_x^{(c)}(k_{PHEV})$ or $CO_2^{(c)}(k_{PHEV})$. These functions are the EAP performance metric functions for a PHEV in class- c with design variable k_{PHEV} . Additionally, $IC_{EAP}^{(c)}$ will be used as a general term for either $IC_{NOx}^{(c)}$ or $IC_{CO2}^{(c)}$. These values are the EAP rates for the IC vehicles in class- c .

First, the total EAP generated by the fleet of IC vehicles is described, followed by the description of the EAP generated by the fleet of PHEVs.

The total EAP generated by a fleet of N_T IC vehicles is computed, assuming the vehicle population average, $\overline{EAP_{IC}^{(c)}}$, is equal to the average generated by the sample population

$$\overline{EAP_{IC}^{(c)}} = \frac{1}{n} \sum_{v=1}^n \frac{T^{(c)}}{IC_{EAP}^{(c)}}$$

Thus, the total fleet EAP generated, EAP_{IC} , is the sum of the product of the total number of vehicles in class- c times the average EAP generated per vehicle in class- c for each vehicle class

$$EAP_{IC} = N_T \sum_{c=1}^4 p^{(c)} \cdot \overline{EAP_{IC}^{(c)}}$$

The method used to compute the total EAP generated by a fleet of PHEVs is described next.

First, the daily amount of EAP generated, $D_{EAP}^{(v,d,c)}$, is computed. If $M_E^{(c)}$ is greater than or equal to $M^{(v,d)}$ then

$$D_{EAP}^{(v,d,c)} = M^{(v,d)} \cdot P^{(c)}(k_{PHEV})$$

however, if $M_E^{(c)}$ is strictly less than $M^{(v,d)}$ then

$$D_{EAP}^{(v,d,c)} = M_E^{(c)} \cdot P^{(c)}(k_{PHEV}) + (M^{(v,d)} - M_E^{(c)}) \cdot P^{(c)}(0)$$

where the first term in the sum represents EAP produced in charge depleting mode and the second term is EAP produced in charge sustaining mode.

Second, the yearly EAP generated, $Y_{EAP}^{(v,c)}$, is computed summing over each day in the simulation

$$Y_{EAP}^{(v,c)} = \sum_{d=1}^D D_{EAP}^{(v,d,c)}$$

Third, the sample vehicle population average yearly EAP generated, $\overline{Y_{EAP}^{(c)}}$, is computed

$$\overline{Y_{EAP}^{(c)}} = \frac{1}{n} \sum_{v=1}^n Y_{EAP}^{(v,c)}$$

Next, the total EAP generated by a fleet of PHEVs, EAP_{PHEV} , is described. This value is the sum of the product of the number of vehicles in each class times the average EAP generated per vehicle class over each vehicle class

$$EAP_{PHEV} = N_T \cdot P_{PHEV} \sum_{c=1}^4 p^{(c)} \cdot \overline{Y_{EAP}^{(c)}}$$

Finally, the total EAP generated, EAP , is the sum of the EAP produced by both the IC vehicles and the PHEVs

$$EAP = (1 - P_{PHEV}) \cdot EAP_{IC} + EAP_{PHEV}$$

Additional details regarding the vehicle simulation can be found in Volume II of this report. The vehicle simulation results of the added electric load demand created by including PHEVs into the light duty vehicle fleet are used by the PPC simulation to calculate the power system results with and without the added electric load due to PHEV charging.

7.2 PPC Simulation

The problem of electric power system simulation may be defined as follows. Given the forecasted electric load demand for the time period under consideration and a list of available generating units in the system, simulate the operation of the system in order to forecast energy generated by units, cost, required fuel and environmental pollution, taking into account the effects of scheduling functions within the time period considered and the random forced outages of the units.

Historically a very successful probabilistic simulation technique has been developed [7.2], [7.3]. This technique will be briefly discussed.

The methodology is based on appropriate probabilistic models for generating units and the electric power demand. The probabilistic model of a generating unit of capacity c MW is shown in Figure 7.1. This is known as the up and down state model. This model can be interpreted as follows. With probability p the unit is available for production and with probability $q = 1 - p$ it is unavailable. The quantity q is known as the forced outage rate (FOR) of the unit.

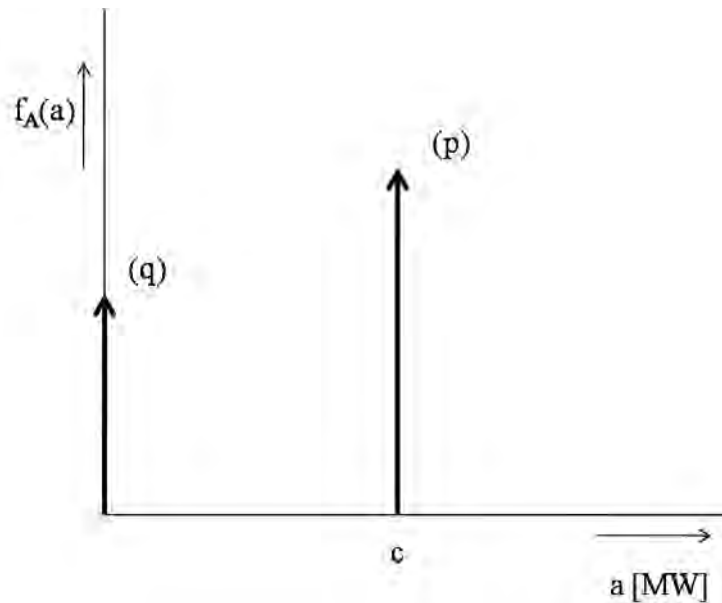


Figure 7.1: Probability density function of the available capacity of a generating unit.

The electric power demand probabilistic model is developed as follows. The electric power demand of a system is plotted as a function of time to obtain the chronological load demand curve. From the chronological load curve, another curve can be constructed which describes the length of time for which the load was greater than a specified value. In addition, the time axis is normalized by the duration T of the time period considered and it is shown in Figure 7.2. The generated curve can be interpreted as follows. Consider point A on the curve with coordinates $(t/T, l)$. Over the period T the load on the system is greater than l for a time period equal to t . Therefore, if the frequency

theory of probability is used and the load duration curve is referred to the future, the definition in Equation 7.1 follows.

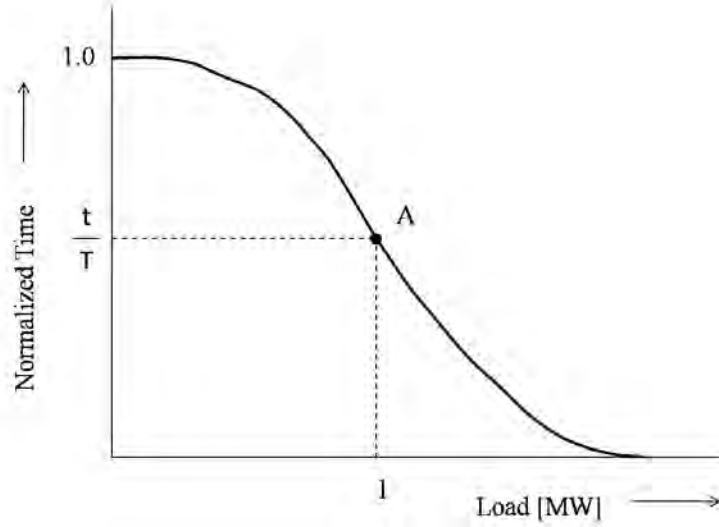


Figure 7.2: Normalized inverted load duration curve

$$L(l) = \Pr\{\text{load} \geq l\} = \frac{t}{T} \quad (7.1)$$

It is apparent that the normalized time axis can be interpreted as probability. Therefore we can define $L(l)$ to represent the normalized inverted load duration curve.

The function $F_L(l)$, is defined in Equation 7.2 describes the probability distribution function (or cumulative probability function) of the variable l , the total load on the system, which is interpreted as a random variable

$$F_L(l) = \Pr\{\text{load} \leq l\} = 1 - L(l) \quad (7.2)$$

The functions $L(l)$ and $F_L(l)$ describe the same thing, the statistics of the variable l . The function $F_L(l)$ is the usual probability distribution function (PDF) which $L(l)$ is called the inverted probability distribution function (IPDF).

Given the above models the following quantities can be computed.

1. Probability of operation of unit 1:
 $\Pr\{\text{Unit 1 in operation}\} = \Pr\{\text{Unit 1 output} > 0\}.$
2. Expected value of produced energy from the unit.
3. Expected value of cost of operation of unit- i .
4. Expected fuel amount required of unit- i .
5. Expected pollutant amounts to be emitted from unit- i .

The aforementioned quantities can be computed as follows. Consider the n units of the system operated at level $x_1, x_2, \dots, x_n$. If unit- k is not in operation, then obviously

$x_k = 0$. Since there is a finite probability that any unit can be forced out, the output of unit- j , x_j , can be considered to be a random variable with probability of forced outage equal to q_j . This derivation results

$$\Pr\{A_j = x_j\} = \begin{cases} 1 - q_j & x_j \neq 0 \\ q_j & x_j = 0 \end{cases}$$

where A_j is a random variable representing the available capacity of unit- j . This relationships states that the probability that the output of generator- j is x_j equals $1 - q_j$, and the probability that the same output is zero equals q_j .

Further assume that the electric load equals l . The probability distribution function is determined with the load duration curve defined in Equation 7.2. For the condition that has been considered, the apparent load l_a is defined

$$l_a = l - x_1 - x_2 - \dots - x_n$$

Since $l, x_1, \dots, x_n$ are not deterministically known, the above equation can be replaced with its equivalent equation in terms of corresponding random variables

$$L_a = L - A_1 - A_2 - \dots - A_n$$

where L is a random variable representing the electric load and A_i is a random variable representing the output of unit- i . Since the PDFs of the random variables $L, A_1, \dots, A_n$ are known and since these random variables are independent, the probability distribution function of the random variable L_a can be easily computed with a series of convolutions [7.2], [7.3], [7.4].

If we assume that $l_a > 0$, load exceeds generation, then another unit should be brought into operation or one or more of the operating units should increase their output. Assume that unit- i is operating at x_i and that it is selected according to an arbitrary dispatch criterion to respond to any increases in the load. This arbitrary dispatch criterion will be qualified later. Without loss of generality x_i may be equal to zero. In general, if $l_a > 0$ the output of unit- i will increase from x_i to $x_i + \Delta x_i$ where Δx_i is a small increment (1-2 MW). We shall refer to this increment as the block Δx_i . It should be obvious that if $x_i = 0$, the increment Δx_i may not be small. In this case unit- i will be brought into operation at a level at least equal to minimum allowable operating level. With the described formulation and application of basic probability theory, it is easy to derive expressions for the expected energy to be produced, cost of operation, required fuel, and pollutant emission from the Δx_i increase in the output of generator- i . The results are summarized as follows:

Step 1: Compute the probability distribution function of random variable $L' = L_a + A_i$.

Let it be $F_L'(z)$. If $x_i = 0$, skip this step and assume $F_L'(z) = F_L(z)$.

Step 2: Compute

$$E(\Delta x_i) = (1 - q_i) \cdot T \cdot \int_{x_i}^{x_i + \Delta x_i} (1 - F_L'(z)) dz$$

$$C(\Delta x_i) = (1 - q_i) \cdot T \cdot f_i(0) \cdot (1 - F_L(0)) \cdot \delta(x_i) + (1 - q_i) \cdot T \cdot \int_{x_i}^{x_i + \Delta x_i} \frac{df(z)}{dz} (1 - F_L(z)) dz$$

Where:

- $\delta(x_i) = \begin{cases} 1 & \text{if } x_i = 0 \\ 0 & \text{if } x_i \neq 0 \end{cases}$,
- $f(z)$ is the heat rate curve of unit- i ,
- $\frac{df(z)}{dz}$ is the incremental heat rate of unit- i ,
- $E(\Delta x_i)$ is the expected energy to be produced from block Δx_i , and
- $C(\Delta x_i)$ is the expected heat consumed by block Δx_i .

Plant pollution output can be computed similarly. If the pollution curve for the plant is known as a function of power output $g(z)$, the expected amount of pollutants to be produced from block Δx_i is

$$G(\Delta x_i) = (1 - q_i) \cdot T \cdot g(0) \cdot (1 - F_L(0)) \cdot \delta(x_i) + (1 - q_i) \cdot T \cdot \int_{x_i}^{x_i + \Delta x_i} \frac{dg(z)}{dz} (1 - F_L(z)) dz$$

where $G(\Delta x_i)$ is the expected amount of pollutants from block Δx_i .

The cost of operation of block Δx_i is computed

$$\text{cost}(\Delta x_i) = C(\Delta x_i) \cdot \frac{p_f}{h_f}$$

where p_f is the price (\$/kg) of fuel and h_f is the heat content of fuel (cal/kg). The fuel required for the operation of block Δx_i is computed

$$\text{fuel}(\Delta x_i) = \frac{C(\Delta x_i)}{h_f}$$

Once the above computations have been completed, the apparent load, after loading of block Δx_i , will be

$$l_a = l - x_i - x_2 - \dots - (x_i + \Delta x_i) - \dots - x_n$$

The probability distribution function of L_a can be easily computed

$$l_a = l - (x_i + \Delta x_i)$$

In this case a convolution between the probability density function of variable L with the probability density function of variable $x_i + \Delta x_i$ with suffice to determine the statistics of variable L_a .

The application of above procedure for the computation of expected production quantities is obvious. Each generating unit is partitioned into a number of blocks. The procedure is then applied on each one of the blocks.

On a basic level the impact of PHEV charging in terms of primary energy source utilization and EAP production can be computed comparing PPC results with no electric load demand representing PHEV charging with PPC results where the computed electric load demand has been increased due to PHEV charging. Specifically, because the vehicle simulation includes random values repeated iterations of both the vehicle simulation and the power system simulation so that average results could be computed.

Three experiments were conducted using the probabilistic simulation of an integrated power system with distributed PHEVs methodology to quantify the impact charging PHEVs will have on primary energy source utilization.

7.3 Results

In the first two experiments the level of PHEV penetration is increased from 0% (Base Case), to 5%, 10%, 20% and 40%.

In the first experiment the power system used to charge the vehicles is the 1979 Reliability Test System (RTS) [7.5]. In the second experiment the power system is the average generating mix used in the United States. The third experiment keeps the number of PHEVs constant and varies the RTS generating mix. The RTS generating mix is changed such that the total generating capacity is constant but the ratio of clean generating capacity is increased.

In each experiment the results include primary fuel utilization shifts and pollution shifts. The total cost for consumers is computed for the first experiment only. The generating capacity mixes for both power systems simulated are shown in Figure 7.3 and Figure 7.4.

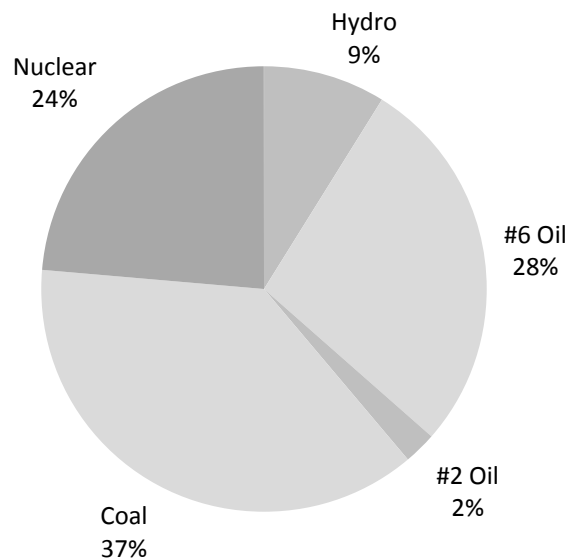


Figure 7.3: RTS generating capacity [7.5].

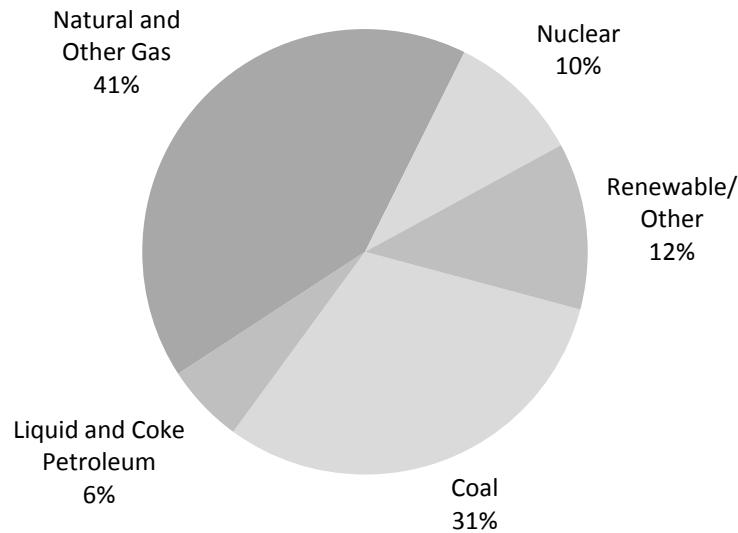


Figure 7.4: U.S. total generating capacity [7.6].

The expected energy production from each fuel for the base case, no added electric load demand representing PHEV charging, and a scenario where 5% of the light duty vehicle fleet in the power system area is replaced with a fleet of PHEVs are shown in Table 7.1. In Table 7.1 the percent change was calculated

$$\text{Percent Change} = \frac{5\% \text{ PHEV} - \text{Base Case}}{\text{Base Case Total}} \cdot 100\%$$

the total amount of generated energy is used to normalize the percent change so that the relative size of each fuels contribution to the total energy generated is accounted for. Without this normalization the percent increase in the RTS simulation #2 oil percent increase would be 17.71% increase and #6 oil percent increase would be 9.67% improperly indicating higher increase in #2 oil over #6 oil because the contribution of #2 oil is so small compared to all other fuels.

Table 7.1: Change in primary energy source utilization.

		Base Case [GWh]	5% PHEV Penetration [GWh]	Percent Increase
RTS Simulations	#6 Oil	924	1,014	0.59%
	#2 Oil	5	6	0.01%
	Coal	7,988	8,212	1.47%
	Nuclear	6,167	6,167	0%
	Hydro	194	194	0%
U.S. Power System Simulations	Coal	2,000,000	2,013,547	0.33%
	Liquid and Coke Petroleum	45,533	45,881	0.01%
	Natural and Other Gas	882,840	889,230	0.16%
	Nuclear	808,630	812,525	0.09%
	Renewables/Others	377,920	380,657	0.07%
Modified RTS Simulations	#6 Oil	1014	862	-0.97%
	#2 Oil	6	11	0.03%
	Coal	8,212	6,052	-13.85%
	Nuclear	6,167	8,384	14.22%
	Hydro	194	217	0.15%

In the RTS simulations #6 oil and coal are utilized to meet the additional load due to PHEV charging. In the RTS the nuclear and hydro energy are fully utilized thus no increase in energy utilization is possible. In the U.S. power system simulations coal is significantly utilized followed next by natural gas and next by both nuclear and renewable energy sources. Very little added energy is provided by petroleum sources. The modified RTS simulations introduced additional nuclear and hydro generation capacity. This change resulted in significant increase in nuclear energy generation and slight increase in hydro energy generation.

In addition to the expected energy production, expected NO_x and CO₂ EAP production were also calculated. Total system EAP results are shown in Table 7.2. The total system EAP is the total EAP produced by both the electric power system and the light duty vehicle fleet in the power system area. Table 7.2 shows EAP results for each experiments base case and 5% PHEV penetration simulations. Here the percent decrease is normalized by the base case results, as is standard.

Table 7.2: Total system EAP.

		Base Case [kg]	5% PHEV Penetration [kg]	Percent Decrease
RTS Simulations	NO _x	4.4316E+07	4.4724E+07	-0.92%
	CO ₂	1.7361E+10	1.7200E+10	0.93%
U.S. Power System Simulations	NO _x	2.9589E+10	2.9577E+10	0.04%
	CO ₂	2.0974E+13	2.0946E+13	0.14%
Modified RTS Simulations	NO _x	4.4724E+07	4.1982E+07	6.13%
	CO ₂	1.7200E+10	1.6454E+10	4.34%

In the RTS simulations, an increase of 0.92% of NO_x represents an annual increase of 0.4986 million kg of NO_x; whereas, a decrease of 0.93% of CO₂ represents a decrease of 160.6 million kg of CO₂. Similarly in the U.S. simulations, a decrease of 0.04% of NO_x represents an annual decrease of 12.40 million kg of NO_x; further, a decrease of 0.14% of CO₂ represents a decrease of 28,900 million kg of CO₂. In the modified RTS simulations significant EAP reduction were simulated, a decrease of 6.13% of NO_x represents an annual decrease of 2.742 million kg of NO_x; further, a decrease of 4.34% of CO₂ represents a decrease of 745.9 million kg of CO₂.

The fuel cost of a PHEV includes gasoline and electricity purchasing. The average annual fuel cost was compared for PHEV versus IC vehicles in the RTS simulations. Assuming constant gasoline price of \$3.00 per gallon and electricity rate of 8 cents per kWh all year long it was found that PHEV fuel costs were 65% less expensive than IC vehicle fuel costs. Additional results from the three experiments can be found in Volume II of this report.

7.4 Conclusion

The results from this research indicate that for the US and the modified RTS system PHEVs offer cleaner transportation with decreased gasoline utilization at a lower cost to consumers.

The outlined methodology has been integrated into a simulation program with graphical user interface. Thus, the ground work has been performed for further analysis of an actual power system and the impact that the added electric load would have on primary energy source utilization, environmental air pollution, and cost to consumers in both electricity rates and transportation fuel costs. Specific details of the power system data required are outlined in Volume II of this report.

8. An Evaluation of PHEV Contributions to Power System Disturbances and Economics

This section of the report is based on the material in [8.1] and will focus on the support plug-in hybrid electric vehicles (PHEVs) can provide to grid security and possible economic benefits for grid operation. PHEVs also have a large potential to save money for those that own one. An analysis of the economic benefit to individual owners will be described. An in-depth formulation of how much power PHEVs can provide will also be shown. To show the economic benefit of grid connection, the IEEE 24, IEEE 118, and a utility 2,574 bus test system will demonstrate costs associated with PHEVs. These systems with several different levels of support will be simulated to see what potential cost benefits and increased grid security can be achieved.

8.1 Literature Review

8.1.1 Justification for Integrating PHEVs to the Power Grid

The concept of vehicle-to-grid (V2G) connections started in 1997 with Professor Willett Kempton [8.2], exploring the potential economic and system potential of electric cars connected to the power grid. To show the potential power of untapped energy, look at the capacities of the grid and electric vehicles.

According to the 2007 EIA Energy Outlook, the total generation capacity of U.S. electric utilities is almost 920 GW (0.92 TW) [8.3]. Let us assume a grid connection of all light duty vehicles (cars, SUVs, and small trucks) to a standard 120-V 15-A electrical outlet (1.8 kW of output power). According to the 2005 statistics, there were approximately 238.3 million light duty vehicles [8.4]. This represents a total possible output power of 429 GW, nearly half the current capacity of all U.S. generators combined with only a standard outlet connection. With improved outlet connections, this number could be even larger.

Another false rumor is that the majority of this potential power would not be available to the grid. According to a 2001 survey, the average car is only used 62.32 min per day; in other words, the average vehicle is idle for 96% of the time [8.5]. Studies have shown that even during peak travel hours, 90% of the vehicle fleet is not in use [8.6]. This shows that during peak load a large majority of the electric vehicle capacity will be ready for control room operators to use.

8.1.2 Evaluation of Potential Grid Uses for PHEVs

PHEVs have been envisioned to help the power grid in several different ways. Such methods include: base load generation, peak demand, spinning reserves, regulation, reactive power, and grid security improvement. Some of these ideas show promise, while others do not show much potential.

One method that does not show promise is base load generation [8.6]. Currently nuclear power stations constitute the majority of base load generation and produce very cheap electricity, often 3 to 5 ¢/kWh, much lower than the cost to operate a PHEV to supply base load power.

Peak demand generation, on the other hand, has much different potential. During peak demand period, around 3-6 pm, electricity prices can spike to well over 30 ¢/kWh. This is because of where the last few megawatts of power are generated. Often small, very expensive generation units come online to supply peak power. These units are often powered by natural gas or oil and can also be highly polluting.

If PHEVs were charged at night when electric rates are low, then sold its stored energy back onto the grid during the peak, a profit could be made. The drawback to this method is the percentage of time this event occurs. It may only be possible to use this method a couple hundred hours a year [8.6]. This would not earn much money for consumers and may not be worth their effort.

One large potential for PHEVs is their use in regulation. Grid operators at an independent system operator (ISO) are constantly adjusting the amount of power generation to closely match the amount of power consumption at any one time. This method of adjustment, called regulation or automatic generation control (AGC), can be very costly. For example, California ISO typically spends up to 80% of their ancillary service expenditures on regulation [8.7].

Another potential use of PHEVs is the supply of reactive power to the grid. Current technology in power electronic converters can change the power factor of the alternating current to the grid to supply real and reactive power support [8.8]. In the future, most ISOs are planning reactive power markets. Once this happens this could be a great additional source of revenue for PHEV owners.

A final proposed use for PHEV is use in improving grid security. During a system disturbance, generators are quickly asked to increase or decrease output to suppress the effects of the change in the system. A PHEV's inverter has a much faster response time than a turbo-generator governor's and could react rapidly to a disturbance. This would improve overall reliability of the system and potentially allow the grid to run at a lower overall cost with this rapid response [8.9]. This paper will explore the use of PHEVs for grid security and cost reduction in much greater detail.

8.1.3 Beginnings of Vehicle-to-Grid Connections

Several cities and states are already taking the initiative to push the idea of plug-in hybrid electric vehicles. One example is Austin Energy, a city owned utility, in central Texas. They have launched a recent campaign – called Plug-In Partners – to line up potential buyers once PHEVs are in production. So far they have had over 8,000 pledges from residents and organizations. Their own city council has already set aside \$1 million in rebates for the first 1,000 customers and also plans to change city building codes to require plugs available in parking lots [8.10].

The Michigan Public Service Commission (MPSC) also initiated a pilot program to integrate PHEVs to the Michigan power grid. Their location near some of the largest auto makers in the world will put them in a unique position to be a leader in V2G testing and connections. They will study the effects on the grid at low, medium and high levels of PHEVs and how that fits in with current smart grid projects [8.11].

8.2 Case for Converting Vehicle Fleet to PHEVs

8.2.1 Personal Savings Over Current Vehicles

By increasing the battery capacity of the current HEV, the PHEV becomes a dual-fuel vehicle. The electric utility can supply off-peak energy during the night to replace gasoline for daily commuting. This new source of energy has the potential to be very attractive to the consumer.

For example, gasoline has an energy content of 124,000 BTU per gallon or 36.36 kWh per gallon [8.12]. Taking a US average of \$3.84 per gallon [8.13], the cost of energy from gasoline is about 10.56 cents per kWh. Considering the average price of electricity of 8.90 cents per kWh for 2006 [8.14], there does not seem to be a large advantage until one considers the energy conversion efficiencies.

Moving energy from the wall socket to a battery pack and an electric motor has an average efficiency of around 61% [8.15]. This is vastly higher than the efficiency of the current internal combustion engine of 12.6% (see Figure 8.1). Hence, taking efficiencies into account, it costs 83.8 cents per usable kWh for gasoline but only 14.6 cents per usable kWh using electricity or the equivalent of buying gasoline at \$0.67 per gallon. In addition, cars would mainly be charged during the nighttime off-peak hours when spot electricity prices are usually much lower. Utilities could set up programs for PHEV owners to give discounted rates or real-time pricing to take advantage of this cheaper electricity.

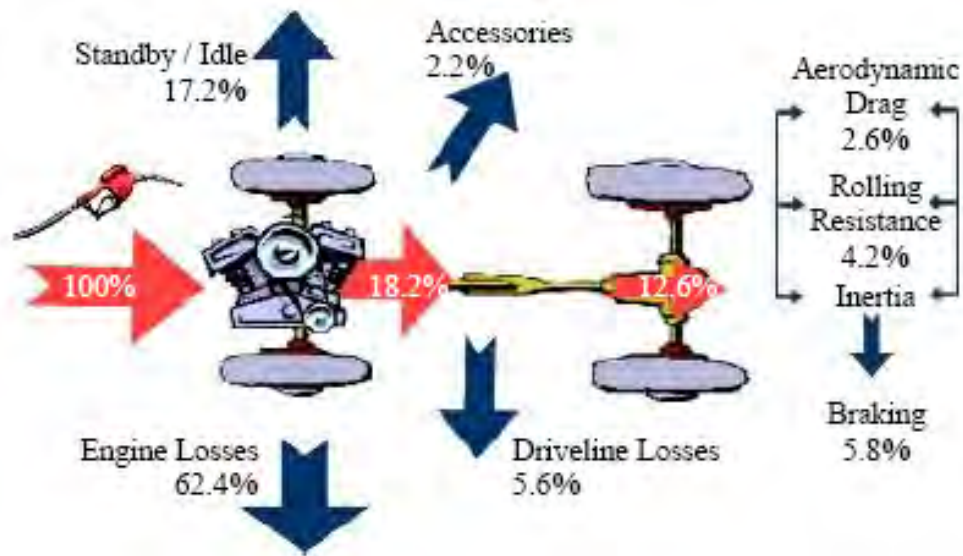


Figure 8.1: Internal combustion powertrain energy losses [8.16].

To see the potential to the US economy, look at the nation-wide fleet of vehicles. If each vehicle drives an average of 11,800 miles per year [8.17] and makes an average 22.9 mpg [8.18], a typical vehicle will use about 515 gallons of gas per year. This translates to an annual savings of over \$1,600 per PHEV. As mentioned earlier, with 238.3 million light duty vehicles (passenger cars, SUVs and small trucks), if only 20% of the current fleet is

replaced by plug-in hybrids, it would save \$78 billion annually. These savings will only increase as oil and gasoline prices continue to rise.

8.2.2 Greenhouse Gas Reduction

Another large benefit of the PHEV is its beneficial impact on the environment. The current light duty vehicle fleet consumes approximately 6.5 million barrels of oil equivalent per day, or 52% of the entire nation's oil imports [8.19]. All of this gasoline is burned and produces harmful greenhouse gas emissions nationwide. Switching this fuel consumption to the production of electricity, more efficient and advanced technologies can remove those harmful gases from the emissions.

A November 2007 study performed a nationwide simulation of this theory to see how much it would impact emissions. The study concluded that greenhouse gases, mainly carbon dioxide (CO₂), are expected to reduce by 27%. This varied by as much as 40% for the ERCOT region, which has a large number of natural gas plants, to slightly negative for the Midwest with a large amount of coal generation. The largest impact is seen with volatile organic compounds (VOCs) and carbon monoxide (CO) emissions having a reduction of 93% and 98%, respectively. This number could be exaggerated since it is assumed that all PHEVs will only run on electric mode and does not take into effect longer trips that will use the internal combustion engine. Nitrogen oxide (NO_x) emissions are also projected to decrease 31% mainly due to reduced refining of gasoline [8.19].

Not all emissions will have a positive effect. Particulate emissions (PM₁₀) and sulfur oxide (SO_x) emissions are expected to increase by 18% and 125%, respectively. This is largely due to the increase in coal-fired power generation. The positive side will be that the most harmful emissions will be removed from urban areas to a few hundred generation sites across the country. This can add pressure to increase funding in carbon sequestration technologies to further reduce emissions [8.19].

It should be noted that these values could be reduced even further with the increased use of wind energy, which produces zero greenhouse gases during generation. Wind also generally blows more during the nighttime hours, which is when most plug-in vehicles will be charging and storing more power from the grid.

8.3 US Vehicle and Grid Connection Information

8.3.1 Estimation of PHEV Penetration

Besides the obvious individual economic benefit PHEVs can provide, they also have a large potential for the electric power grid because they represent a large amount of energy storage. To analyze the benefits to the grid, an estimate of the amount of support from PHEVs needs to be determined.

As of July 2006, the US population is 299.398 million people [8.20]. The peak load during the same time period was 789,475 MW [8.21]. This equates to 2.637 kW per person or 379.24 people per MW. According to the 2006 Census, there were 111.6 million occupied houses in the US and 91.2% of these houses have at least one vehicle [8.22].

Using these numbers, there is an average of 2.68 people per house, 141.5 houses per MW of peak load, and 129.05 houses with vehicles per MW of peak load. If we estimate 20% of houses own a PHEV, this translates to 25.8 plug-in hybrids per MW of peak load.

To analyze how much power can be delivered by PHEVs, one must consider the amount of “energy flow” that can be achieved. The main constraint is the connection to the grid. Current technology of bidirectional converters and practical limits of residential service could support a maximum power transfer of about 10 kW. Commercial installations could theoretically take maximum power straight from the electric motor in the range of 100 kW. This amount of power transfer cannot be achieved in the standard home or business without a major change to the wiring and circuit breakers and a large cost to consumers. This would be a large deterrent to potential PHEV buyers.

The PHEV power inverters could also adjust the power factor coming from the vehicle to allow reactive power support to the grid. This study, however, will only look at real power support since consumers are not charged for reactive power and would not see a monetary benefit from this type of support. In the future, reactive power markets could be created, giving incentive to users to provide reactive support.

We will examine what can be achieved with minimal or no upgrade to a house’s wiring. If the hybrid was plugged into a standard 120-V, 15-A wall outlet, it would be able to provide a power transfer of 1.8 kW. Using the number of PHEVs per MW of peak load, they can provide 46.45 kW per MW or 4.6% of relief. This paper will also take a look at other possible connections to see the wide range of possible support available from PHEVs.

8.4 Test Cases

To show the benefits of plug-in hybrids, a typical power system needs to be analyzed. For the purposes of this research, three different test cases were examined: IEEE 24 bus, IEEE 118 bus, and a utility 2,574 bus case. To see the cost benefits of PHEV support, a steady-state power flow will be run for the case to determine the system state and costs associated with generation.

8.4.1 Solving an Optimal Power Flow for a Test Case

The first step was to evaluate the operating cost of the system using optimal power flow (OPF). OPF can trace its origins back to 1962 [8.23]. The goal is to schedule the generation of a system to minimize an objective function while not violating any constraints on the system. Common constraints on the system can include power balance, voltage profiles for buses, and thermal constraints on transmission lines. Usually the objective is to minimize cost, but it could also be to minimize losses or minimize control shifts.

To formulate the OPF problem [8.24], we define $\underline{x}$ as the vector of state variables and $\underline{u}$ as the vector of control variables. The objective function is defined as $f(\underline{x}, \underline{u})$. The equality constraints such as the power flow equations and total power generation equaling power consumption plus losses, are defined as $g(\underline{x}, \underline{u})$. The inequality constraints including voltage profiles and thermal constraints, are defined as $h(\underline{x}, \underline{u})$.

$$\begin{aligned}
& \min f(\underline{x}, \underline{u}) \\
& s. t. g(\underline{x}, \underline{u}) = \underline{0} \\
& h(\underline{x}, \underline{u}) \leq \underline{0}
\end{aligned} \tag{8.1}$$

The function $f(\underline{x}, \underline{u})$ for this OPF will be to minimize the overall operating cost of the power generation, shown in Equation 8.2 where G is the set of all generators and PHEV support for the power system

$$f(\underline{x}, \underline{u}) = \sum_{i \in G}^n \alpha_{gen,i} + \beta_{gen,i} \cdot P_{gen,i} + \gamma_{gen,i} \cdot P_{gen,i}^2 \tag{8.2}$$

The generator coefficients for the cost function are given in Table 8.2, ($\alpha = a, \beta = b, \gamma = c$). The function $g(\underline{x}, \underline{u})$ contains the power flow equations

$$\begin{aligned}
P_i(\underline{x}) &= |\tilde{V}_i| \cdot \sum_{k \in C_i} \{ |\tilde{V}_k| [G_{ik} \cos(\theta_i - \theta_k) + B_{ik} \sin(\theta_i - \theta_k)] \} + P_{load,i} - P_{gen,i} \\
&= 0 \\
Q_i(\underline{x}) &= |\tilde{V}_i| \cdot \sum_{k \in C_i} \{ |\tilde{V}_k| [G_{ik} \sin(\theta_i - \theta_k) + B_{ik} \cos(\theta_i - \theta_k)] \} + Q_{load,i} - Q_{gen,i} \\
&= 0
\end{aligned}$$

and the power balance equation

$$\sum P_{gen} - \sum P_{loss} - \sum P_{load} = 0$$

where $\tilde{Y}_{ik} = G_{ik} + j \cdot B_{ik}$ is the complex admittance from bus i to bus k and C_i is the set of all buses connected to bus_i .

The function $h(\underline{x}, \underline{u})$ contains all the inequality constraints for the problem. These include voltage constraints at each bus, generator constraints, and thermal constraints on transmission lines. The equations are given

$$\begin{aligned}
V_i^{\min} &\leq V_i \leq V_i^{\max} \quad \forall i \in H \\
P_{gen,i}^{\min} &\leq P_{gen,i} \leq P_{gen,i}^{\max} \quad \forall i \in G \\
Q_{gen,i}^{\min} &\leq Q_{gen,i} \leq Q_{gen,i}^{\max} \quad \forall i \in G \\
|S_{flow,ij}| &\leq |S_{flow,ij}^{\max}| \quad \forall ij \in L
\end{aligned}$$

where H is the set of all buses in the system, G is the set of all generators, L is the set of all lines and transformers, and $|S_{flow,ij}|$ is the magnitude of the complex power flowing from bus i to j .

Using all of these equations we construct the Langrangian of the minimization problem defined in (8.1):

$$\mathcal{L}(\underline{x}, \underline{u}, \underline{\lambda}, \underline{\mu}) = f(\underline{x}, \underline{u}) + \underline{\lambda}^T \cdot g(\underline{x}, \underline{u}) + \underline{\mu}^T \cdot h(\underline{x}, \underline{u})$$

The variables $\underline{\lambda}$ and $\underline{\mu}$ are defined as the Lagrange multipliers. To minimize this function we set the gradient to zero and solve for the control variables and multipliers.

$$\nabla \mathcal{L}(\underline{x}, \underline{u}, \underline{\lambda}, \underline{\mu}) = 0$$

8.4.2 Solving a Security Constrained OPF for a Test Case

Security constrained OPF (SCOPF) takes the original OPF problem and adds additional constraints. The OPF solves a system optimally for $N - 0$ contingencies, or the system at steady state with all lines and generators in service. The SCOPF solves the system to minimize cost while also making the system secure for $N - 1$ contingencies, or the system with any one transmission line or generator out of service. Since the SCOPF has more constraints it will always be equal to or more expensive than the OPF. The SCOPF problem formation is

$$\begin{aligned} \min f(\underline{x}^{(0)}, \underline{u}) \\ \text{s.t. } \left. \begin{aligned} g(\underline{x}^{(j)}, \underline{u}) &= 0 \\ h(\underline{x}^{(j)}, \underline{u}) &\leq 0 \end{aligned} \right\} \quad j = 1, 2, \dots, C \end{aligned}$$

where $j = 0$ is the base case and $j = 1, 2, \dots, C$ is each $N - 0$ contingency case.

8.4.3 IEEE 24 Bus Test Case

To test the theories of PHEV support, a test case is needed. For this we choose the IEEE 24-bus Reliability Test System (see Figure 8.2) [8.25]. This system contains 34 generation units with a total capacity of 3,405 MW, 17 loads totaling 2,850 MW and 580 Mvar, and 38 transmission lines. At peak load, this system has several contingencies and high congestion which will show larger impacts versus an extremely secure system.

Since this case was created in 1979, the cost data for generators has become extremely outdated. To fix this, updated cost figures for different fuel types were found and can be seen in Table 8.1 and Table 8.2 [8.26].

Table 8.1: Fuel cost figures for generators.

Fuel Type	Fuel Energy Density [kcal/kg]	Fuel Costs [\$ /kg]	Fuel Costs [\$ /kcal]	Fuel Costs [\$ /MBtu]
#6 Oil	11,200	0.6	5.35 E-05	13.50
#2 Oil	12,000	0.65	5.41 E-05	13.65
Coal	6,000	0.05	8.33 E-06	2.10
Nuclear	2.00 E+21	60,000	3.00 E-17	~0.00

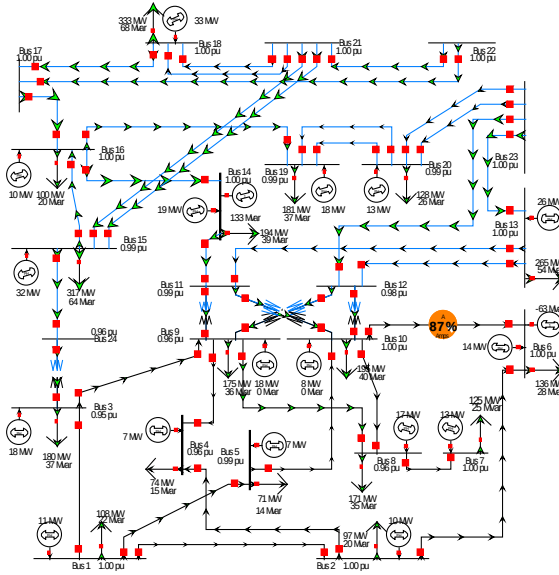


Figure 8.2: IEEE 24 bus test system.

Table 8.2: Cost curve values for generator types.

Size MW	Gen Type	Fuel Type	a [MBtu/kWh]	b [MBtu/kWh]	c [MBtu/kWh]
12	Fossil Steam	#6 Oil	18.24	-1.25 E-06	6.09 E-14
20	Combustion Turbine	#2 Oil	17.00	-1.25 E-06	0.00
50	Hydro	Water	0.00	0.00	0.00
76	Fossil Steam	Coal	18.24	-1.97 E-07	1.52 E-15
100	Fossil Steam	#6 Oil	15.94	-1.39 E-07	8.06 E-16
155	Fossil Steam	Coal	13.63	-5.58 E-08	1.97 E-16
197	Fossil Steam	#6 Oil	12.40	-3.02 E-08	8.25 E-17
350	Fossil Steam	Coal	11.96	-1.63 E-08	2.67 E-17
400	Nuclear Steam	LWR	14.84	-2.71 E-08	3.78 E-17

Currently all fixed costs are set to zero and hydro units are assumed to have no fuel costs. For this study, we will only consider the system under peak load conditions. To simulate the support of PHEVs, a “generator” was inserted at every load bus. This would represent the entire amount of support available from all PHEVs in a city with a corresponding MW load value. After running an OPF and contingency analysis on the system before the addition of PHEVs, there are numerous problems.

An initial OPF, with no plug-in support, produced an overall cost of \$139,068 per hour. Checking all $N - 1$ contingencies for lines and generators, the system has 9 insecure contingencies. An initial SCOPF had a cost of \$167,089 per hour with 2 unenforceable contingencies and 1 binding contingency, an increase in cost of 20% and a 78% reduction in violating contingencies.

Some trouble spots during contingencies include low voltage violations on the left side of the grid and line overloads on the right side.

8.4.4 IEEE 118 Bus Test Case

The next system to be examined is the standard IEEE 118 bus case [8.27]. This system contains 54 standard generation units with a total capacity of 7,220 MW, 91 loads totaling 5,318 MW and 2,085 MVAR, and 186 transmission lines. Generation cubic cost coefficients, generator limits, and transmission line power limits were taken from a previous paper concerning unit commitment [8.28], [8.29]. Fuel cost figures were matched similarly to the generators in the IEEE 24 bus case based upon their maximum output. As with the 24 bus case, a PHEV “generator” was added to every load bus and set to produce or consume the specified amount of support.

After running an initial OPF with no plug-in support, there were 26 separate $N-1$ contingency violations with an overall cost of \$330,823 per hour. The initial SCOPF produced 3 unenforceable contingencies, 4 binding contingencies, and a cost of \$443,552 per hour. This was an increase in costs of 34% and a reduction in violating contingencies of 85%.

8.4.5 Utility 2,574 Bus Test Case

The final test system used for this simulation was a 2,574 bus case from a region of a North American utility. This system is much larger and was taken during a peak load day in 2007. It contains 220 generation units totaling 27,725 MW of capacity, 622 load buses with a total load of 20,823 MW and 3,166 MVAR, 95 switched shunts, and 3,315 transmission lines. Generator, transmission line, and interface limits were included along with 851 predefined contingencies. Cost figures for the generators were not included, so based upon the generator’s upper limit, the units were classified similar to the 24 bus test case and given corresponding cost figures.

Starting with the base case and no plug-in support, an initial OPF was run and produced 588 $N-1$ contingency violations (mostly interface overloads) and a total cost of \$1,096,327 per hour. The initial SCOPF produced 9 unenforceable contingencies and 9 binding contingencies at a total cost of \$1,812,126 per hour, 65% more costly than the OPF but a 98% reduction of the original violating contingencies.

8.5 Test Scenarios Using PHEVs

8.5.1 Amount of PHEV Support for Simulations

To see a wide range of possibilities of the potential support PHEVs could provide, several factors were varied to view their impacts. Future penetration of plug-ins in society is highly uncertain. Several factors can determine future use including the availability of plug-ins from manufacturers, the amount of government incentives to consumers, and the future price of fossil fuels.

For the purposes of this study, penetration levels of 10% to 25% were examined. Also the type of vehicle connection can have a large impact on the available support. We looked at connecting the vehicle to both 120-V and 240-V circuits with circuit breakers of 15 A, 20 A, and 40 A. Amounts of PHEV support are shown in Table 8.3.

Table 8.3: PHEV support in percent of peak load.

10% PHEV	120V	240V	15% PHEV	120V	240V
15A	2.3229%	4.6458%	15A	3.4844%	6.9687%
20A	3.0972%	6.1944%	20A	4.6458%	9.2916%
40A	6.1944%	12.3888%	40A	9.2916%	18.5832%

20% PHEV	120V	240V	25% PHEV	120V	240V
15A	4.6458%	9.2916%	15A	5.8073%	11.6146%
20A	6.1944%	12.3888%	20A	7.7430%	15.4860%
40A	12.3888%	24.7776%	40A	15.486%	30.9720%

Since potential support can range from as low as 2% to just below 31%, SCOPF simulations of the three test systems will be run with support from 1% to 31% in 1% increments. All PHEV “generators” were given a piece-wise linear cost function. If the PHEVs were absorbing power they would pay a price of 5 ¢/kWh and would supply power to the grid for a price of 20 ¢/kWh.

8.6 Results

8.6.1 IEEE 24 Bus Test Case

As expected, larger vehicle penetrations and upgraded outlet connections have a larger effect on the support PHEVs can achieve. The support was not linear, however. For the first 10% of support, the cost had a steep decrease. With only a little more than 4% of PHEV support, the SCOPF became the same operating cost as the OPF. After a support level of 10-15%, any additional support had only a small incremental effect on the cost of the system. This can all be seen in Figure 8.3.

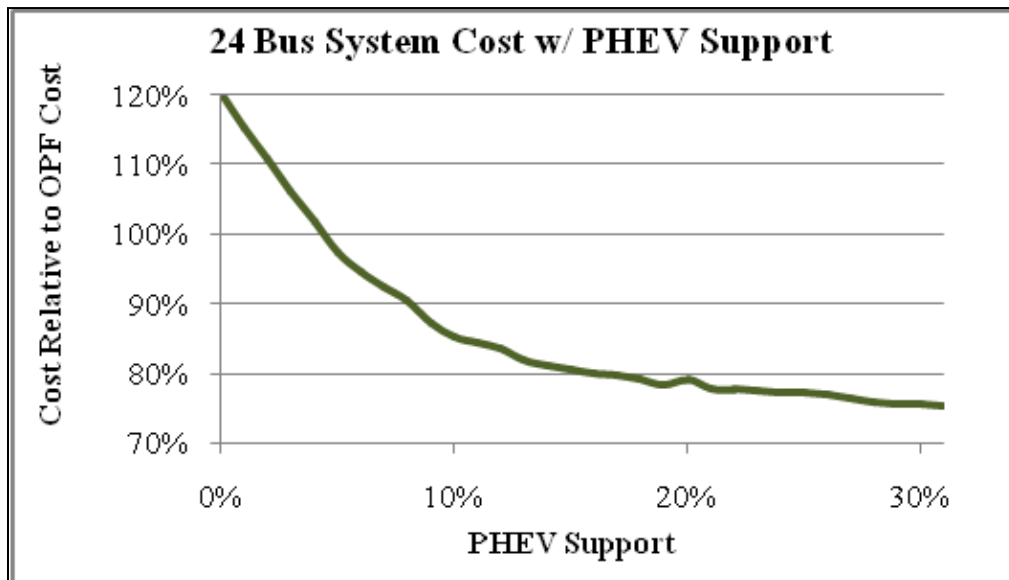


Figure 8.3: Bus system cost vs. PHEV support normalized to OPF cost.

Contingencies did not see as immediate an effect as the system cost. The system still had two unenforceable contingencies until after 10% of support and the final unenforceable contingency was eliminated after 16% of PHEV support. Results can be seen in Figure 8.4.

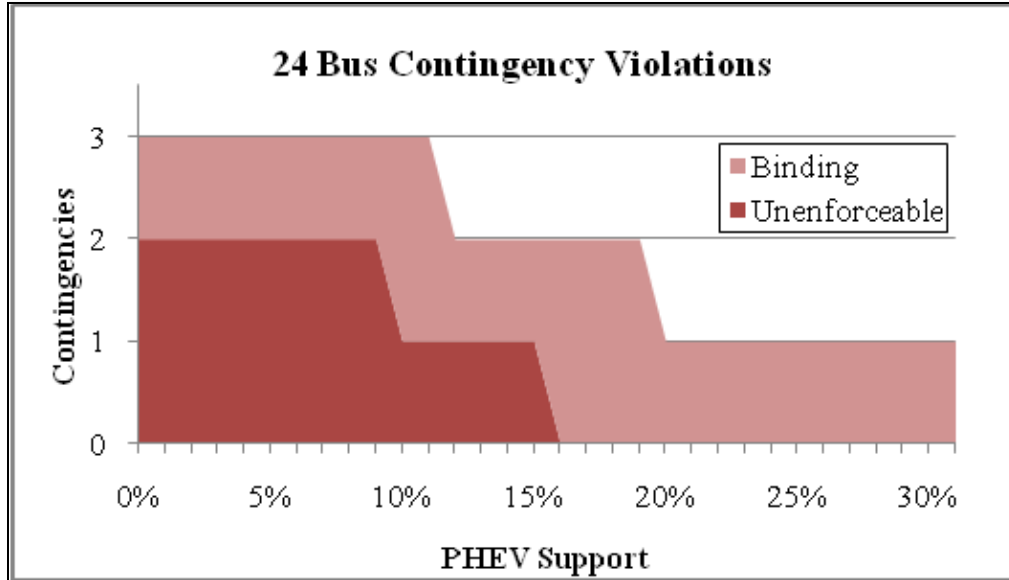


Figure 8.4: 24 Bus contingency violations vs. PHEV support.

The maximum line overload had similar results. During the period of support from 0% to 16%, the overloads steadily decreased overall and after 16% when all unenforceable contingencies were eliminated the system was $N - 1$ secure so every line was at or less than 100% of its limit.

It should be noted that the unenforceable contingencies and maximum line overloads might be larger than it should be due to the charging on the transmission line from bus 6 to 10. It is abnormally high causing a large amount of MVAR on the line and the overload.

8.6.2 IEEE 118 Bus Test Case

The 118 bus test case had similar results. For the first 10% of support the system cost had a sharp decrease and began to have a smaller effect larger than 20% (see Figure 8.5). For this system it took a larger amount of support to reduce the cost to the base case OPF, a little more than 12%.

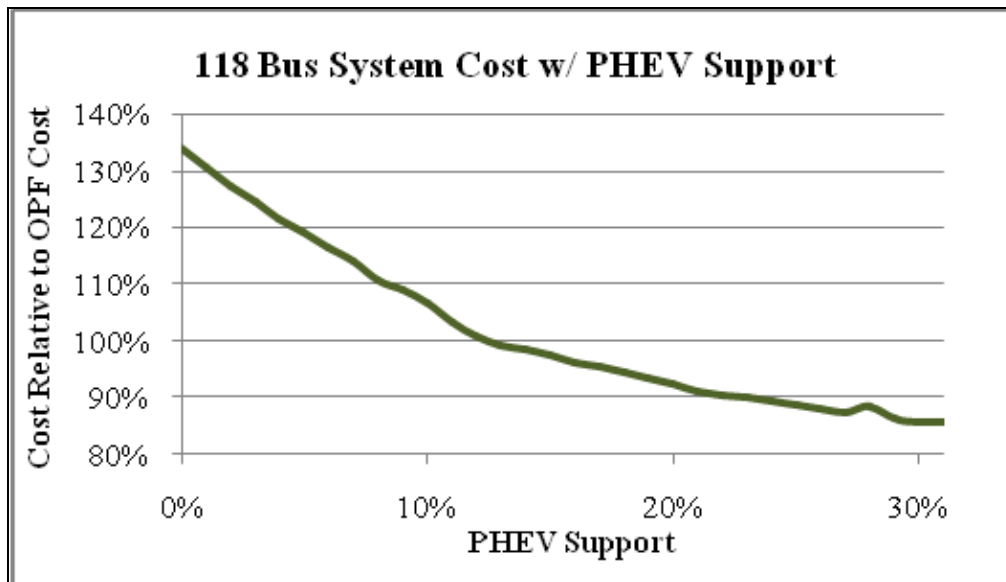


Figure 8.5: 118 Bus system cost vs. PHEV support.

Unenforceable contingencies experienced an immediate benefit with only 1% of support reducing the overall number to two violations. From 12% to 14% of support, the remaining two unenforceable contingencies were eliminated, making the system $N - 1$ secure (see Figure 8.6). The number of binding contingencies fluctuated throughout the region of support but was not a large issue since the system cost continued to decrease as discussed earlier.

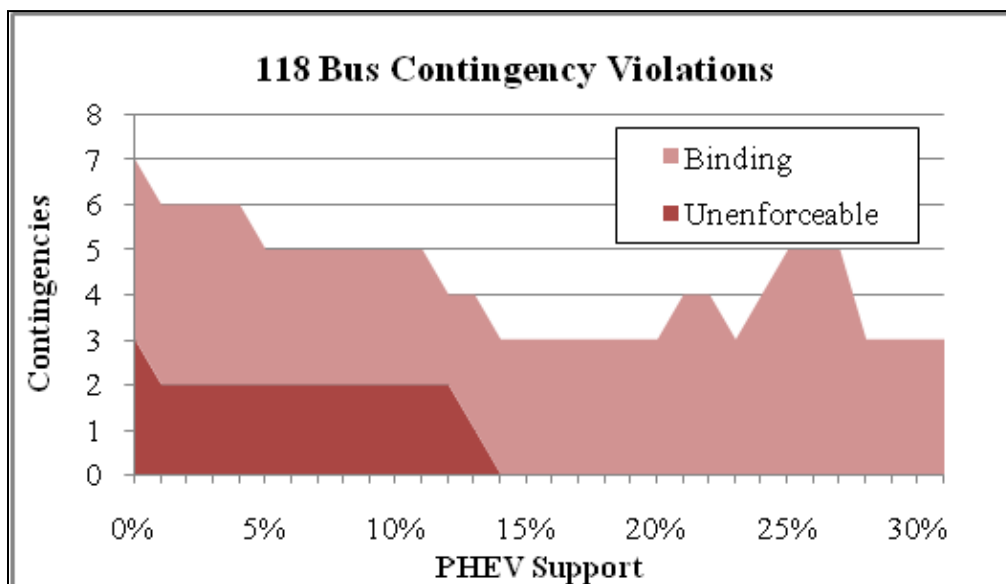


Figure 8.6: 118 Bus contingency violations vs. PHEV support.

Maximum line overloads had a similar result as the previous case. They continued to decrease and reached 100% at the same time the system became completely secure. The overloads experienced a small bump around 25% of support coinciding with a small

increase in binding contingencies. This is most likely due to tolerances in the algorithm and the system can still be considered $N - 1$ secure.

8.6.3 Utility 2,574 Bus Test Case

The much larger utility system has some different results than the previous two IEEE test cases. The initial SCOPF with no plug-in support had a much higher cost, 165% of the base case OPF system cost. As PHEV power increased, it had a continually large effect on overall system cost (see Figure 8.7).

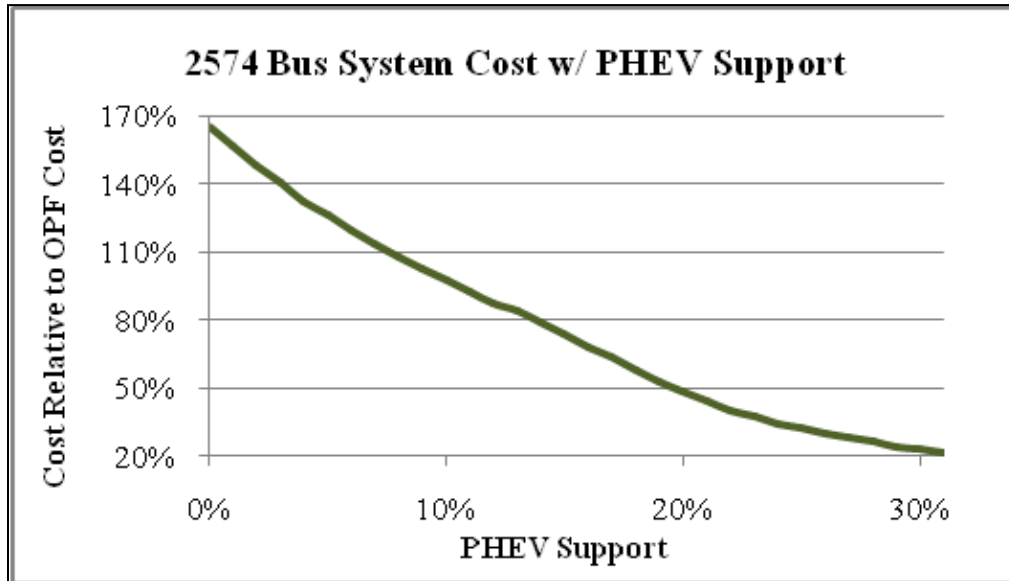


Figure 8.7: 2,574 Bus System Cost vs. PHEV Support.

After 9% of support, the SCOPF became cheaper than the original OPF and continued to decline to only 22% with 30% of PHEV power. This is largely due to the inclusion of interface limits with the utility case. The initial maximum interface overload was over 400% of its stated limit with the OPF and greatly reduced to 100% with over 20% of support.

Contingency violations had a similar result as the other two cases. Unenforceable contingency violations decreased from 9 to 5 after only 4% of support. From 7% to 8%, 2 more contingencies were eliminated and the final 3 were eliminated after 22% of support making the system $N - 1$ secure (see Figure 8.8).

Maximum line flows continued to decrease steadily from over 116% to around 102% over the first 12% of PHEV support. From about 12% to 21% of support there was little change in the line overloads. This was most likely due to the SCOPF algorithm first eliminating the interface violations before satisfying every limit violation. During emergency situations a line violation of 102% may be acceptable if costs are being greatly reduced by eliminating interface overloads first.

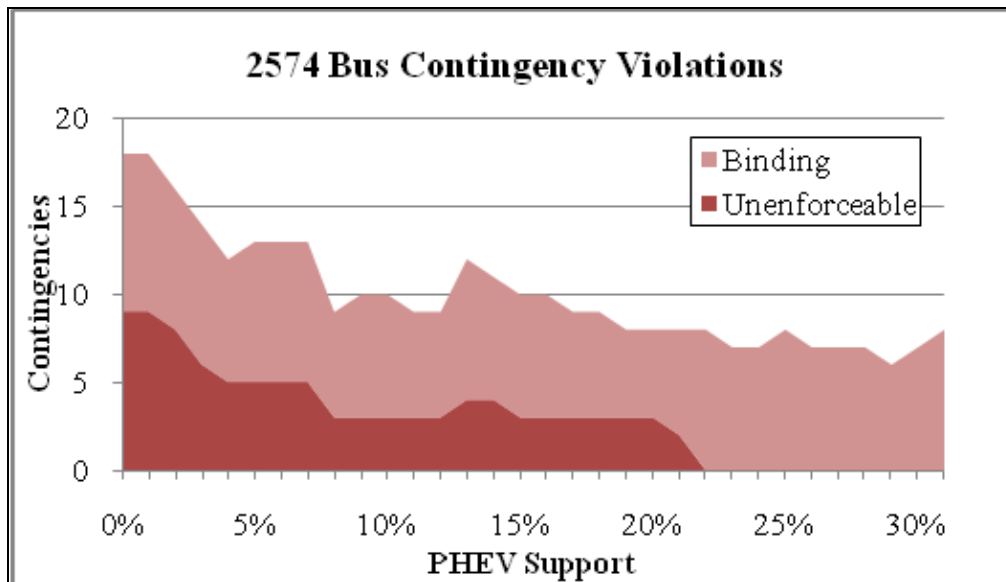


Figure 8.8: 2,574 Bus contingency violations vs. PHEV support.

8.7 Conclusion

Plug-in hybrids have been shown to be a promising advancement toward meeting our future personal transportation needs. They can save the typical consumer over \$1,600 annually, reduce our nation's dependence on foreign oil imports, and reduce overall pollution. They have also demonstrated great potential when simply parked in the home garage or at work plugged into an outlet providing grid support.

As we can see from the three test systems, plug-in hybrids have a great potential to save grid operating costs and reduce contingencies. It is interesting to note for the test systems that after 10% - 15% of support, the PHEVs have a minimal effect on the grid. This can be a good situation since it will take time for the pool of hybrids to grow and we can still see significant impacts very quickly as the penetration grows.

Plug-in hybrids had a significant effect on unenforceable SCOPF contingencies and maximum line overloads, but the contingencies required a larger amount of support. All test systems were made completely $N - 1$ secure after PHEV support from 14% to 22%. It should be noted that plug-ins might have a larger effect on contingencies if they were also providing reactive support.

It will be crucial to the future of the transportation and energy industries as well as the environment to push the development and implementation of PHEVs. Currently at least 14 automakers are pursuing the development of the first line of pluggable hybrid vehicles [8.30].

General Motors is the most advanced of the American Big 3 in the process to develop a PHEV. They officially unveiled the Chevrolet Volt concept car at the North American International Auto Show on January 7, 2007, in Detroit, Michigan. This series electric vehicle is set for production as early as 2010-2012, once the batteries are fully developed and tested, currently underway as of February 2008 [8.31]. Some groups such as the

Electric Auto Association have already taken it upon themselves to convert current HEVs like the Prius into a PHEV [8.32].

This technology has the potential to reduce and even eliminate our dependence on foreign oil, greatly reduce greenhouse gas emissions, and save large amounts of money for transportation. This issue needs to stay at the top of the list and is critical to our future energy independence.

References

- [1.1] Energy Information Administration, "U.S. Crude Oil Supply and Disposition," http://tonto.eia.doe.gov/dnav/pet/pet_sum_crdsnd_adc_mbbl_m.htm, accessed September 2008.
- [1.2] Energy Information Administration, "Weekly Inputs, Utilization & Production," http://tonto.eia.doe.gov/dnav/pet/pet_pnp_wiup_dcu_nus_w.htm, accessed September 2008.
- [1.3] Energy Information Administration, "World Crude Oil Prices," http://tonto.eia.doe.gov/dnav/pet/pet_pri_wco_k_w.htm, accessed June 2009.
- [1.4] Lucy Sanna, "Driving the Solution the Plug-In Hybrid Electric Vehicle", EPRI Journal, pp. 8-17, Fall 2005.
- [1.5] www.fueleconomy.gov, "Where Does the Energy Go?," <http://www.fueleconomy.gov/feg/atv.shtml>, accessed June 2008
- [1.6] Energy Information Administration, "U.S. Weekly Product Supplied," http://tonto.eia.doe.gov/dnav/pet/pet_cons_wpsup_k_w.htm, accessed August 2008.
- [1.7] Energy Information Administration, "Net Internal Demand, Capacity Resources, and Capacity Margins by North American Electric Reliability Council Region," <http://www.eia.doe.gov/cneaf/electricity/epa/epat3p2.html>, accessed August 2008.
- [2.1] J. Meisel, "An Analytic Foundation for the Toyota Prius Powertrain with a Comparison to a Strong Parallel Hybrid Electric Powertrain", SAE Paper 2006-01-0666, SAE World Congress, April, 2006.
- [2.2] J. Meisel, "An Analytic Foundation for the Two-Mode Hybrid-Electric Powertrain with a Comparison to the Single Mode Toyota Prius THS-II Powertrain", SAE Paper 2009-01-1321, 2009 SAE World Congress, April, 2009.
- [2.3] Powertrain Group, Understanding GM Hybrid Electric Vehicles, General Motors Corporation, foldout p. 45, July 2006.
- [2.4] National Research Council's Standing Committee, Review of the Research Program of the Partnership for a New Generation of Vehicles, National Academy Press, Washington D.C.
- [3.1] P. Sharer, R. Leydier, A. Rousseau, "Impact of Drive Cycle Agressiveness and Speed on HEVs Fuel Consumption Sensitivity", Argonne National Lab presentation, April, 2007.
- [3.2] M. Kintner-Meyer, K. Schneider, and R. Pratt, "Impacts Assessment of Plug-In Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids; Part 1: Technical Analysis", September 2008, <http://www.ferc.gov/>.
- [3.3] Argonne National Lab, "Powertrains System Analysis Toolbox (PSAT)," <http://www.anl.gov/techtransfer/pdf/PSAT.pdf>, accessed July 2008.
- [4.1] The National Academies Press, State and Federal Standards for Mobile-Source Emissions, National Academy of Science, 2006.
- [4.2] UNFCCC, "Kyoto Protocol," http://unfccc.int/kyoto_protocol/items/2830.php, accessed April 2009.

- [4.3] UNFCCC, “Full Text of the convention Article 2: Objective,” http://unfccc.int/essential_background/convention/background/items/1353.php, accessed April 2009.
- [4.4] Environmental Protection Agency, “Emission facts: Average carbon dioxide emissions resulting from gasoline and diesel fuel”, <http://epa.gov/otaq/climate/420f05001.htm#calculating>, accessed February 2005.
- [4.5] EPA/DOE, “Carbon Dioxide Emissions from the Generation of Electric Power in the United States”, National Energy Information Center, (202-586-8800), Table 1.1, July 2000.
- [5.1] D.B. Sandalow (ed.), “Plug-In Electric Vehicles, What Role For Washington?”, Brookings Institution Press 2009 c. 240pp, Chapter 4, J. Wellington, “The CashBack Car”, pp. 65 – 85.
- [5.2] W. Kemton, “V2G Vehicle to Grid Power,” Center for Carbon-Free Power Integration, University of Delaware, April 2007, www.udel.edu/V2G/.
- [6.1] National Climatic Data Center, “US Climate Reference Network,” <http://www.ncdc.noaa.gov/crn>, accessed May 2009.
- [6.2] W. H. Kersting, Distribution System Modeling and Analysis. CRC Press: Taylor & Francis Group, 2007.
- [6.3] “Electric Power Quality” class notes for ECE 4833 Electric Power Quality, School of Electrical and Computer Engineering at the Georgia Institute of Technology, Fall 2007.
- [6.4] J. F. Lindsay, "Temperature rise of an oil-filled transformer with varying load," IEEE Transactions on Power Apparatus and Systems, vol. PAS-103, no. 9, pp. 2530-36, September 1984.
- [6.5] Power Partners, “Overhead Distribution Transformers,” www.powerpartners-usa.com/resouces/381.pdf, accessed May 2009.
- [6.6] A. P. Meliopoulos, (private communication), 2009.
- [6.7] ANSI/IEEE C57.91-1995, Guide for Loading Mineral-Oil-Immersed Transformers.
- [7.1] A. P. Meliopoulos, "Computer aided instruction of energy source utilization problems," IEEE Transactions on Education, vol. E-24, no. 3, pp. 204-9, August 1981.
- [7.2] R.R. Booth, “Power system simulation model based on probability analysis,” IEEE Trans. Power App. Syst., vol. PAS-91, pp. 62-69, Jan./Feb. 1972.
- [7.3] M.A. Sager et al., “A new generation production cost program to recognize forced outages,” IEEE Trans. Power App. Syst., vol. PAS-91, PP. 2114-2142, Sept./Oct. 1972.
- [7.4] A.P. Meliopoulos, “Power system planning...Class notes,” Georgia Institute of Technology, Atlanta GA.
- [7.5] Reliability Test System Task Force of the Application of Probability Methods Subcommittee, “IEEE reliability test system” IEEE Transactions on Power Apparatus and Systems, vol. PAS-98, no. 6, pp. 2047-54, November 1979.

- [7.6] Energy Information Administration, "Existing Capacity by Energy Source," May 2009, <http://www.eia.doe.gov/cneaf/electricity/epa/epat2p2.html>, accessed September 2009.
- [8.1] S.L. Judd and T.J. Overbye, "An Evaluation of PHEV Contributions to Power System Disturbances and Economics," presented at North American Power Symposium, Calgary, Canada, 2008.
- [8.2] W. Kempton and S. E. Letendre, "Electric vehicles as a new power source for electric utilities," *Transportation Research*, vol. 2, no. 3, pp. 157-175, 1997.
- [8.3] J. Conti, "Annual energy outlook 2007, with Projections to 2030," Energy Information Administration, U.S. Department of Energy, Washington, DC, p. 135, 150, 153, February 2007.
- [8.4] Bureau of Transportation Statistics, U.S. Department of Transportation, "Table 1-11: Number of U.S. aircraft, vehicles, vessels and other conveyances," December 2007, http://www.bts.gov/publications/national_transportation_statistics/html/table_01_11.html
- [8.5] P. S. Hu and T. R. Reuscher, Federal Highway Administration, U.S. Department of Transportation, "Summary of travel trends: 2001 national household travel survey," p. 30, December 2004, <http://nhts.ornl.gov/2001/pub/STT.pdf>.
- [8.6] W. Kempton, J. Tomić, S. Letendre, A. Brooks, and T. Lipman, "Vehicle-to-grid power: Battery, hybrid, and fuel cell vehicles as resources for distributed electric power in California," Davis, CA, Institute for Transportation Studies Report #UCD-ITS-RR-01-03, pp. i-v, June 2001, <http://www.udel.edu/V2G>.
- [8.7] A. Brooks and T. Gage, AC Propulsion, "Integration of electric drive vehicles with the electric power grid – A new value stream," in 18th Electric Vehicle Symposium, Berlin, Germany, October 2001, pp. 2-3, 9-1, http://www.acpropulsion.com/reports/ACP_V2G_EVS18.pdf.
- [8.8] S. De Breucker, P. Jacqmer, K. De Brabandere, J. Driesen, and R. Belmans, "Grid power quality improvements using grid-coupled hybrid electric vehicles," in *Power Electronics, Machines, and Drives*, 2006, pp. 505-509.
- [8.9] D. Sutanto, "Alternative energy resource from electric transportation," in *Proceedings of the Power Electronics Systems and Applications Conference*, November 2004, pp. 150-151.
- [8.10] J. J. Fialka, "In quest for cleaner energy, Texas city touts plug-in car," in *Wall Street Journal*, March 26, 2007, p. A1.
- [8.11] Michigan Public Service Commission, Michigan Department of Labor & Economic Growth, "MPSC initiates pilot program to integrate plug-in hybrid electric vehicles into the electric grid, positioning state to become a technology and jobs leader," March 11, 2008, <http://michigan.gov/mpsc/0,1607,7-159--187335--,00.html>.
- [8.12] Energy Information Administration, U.S. Department of Energy, "EIA – Energy basics – Converting energy units," March 2008, http://www.eia.doe.gov/basics/conversion_basics.html.

- [8.13] Energy Information Administration, U.S. Department of Energy, "Gasoline and diesel fuel update," May 19, 2008,
<http://tonto.eia.doe.gov/oog/info/gdu/gasdiesel.asp>.
- [8.14] Energy Information Administration, U.S. Department of Energy, "Electric power annual, average retail price of electricity to ultimate customers by end-use sector," October 2007. [Online] Available:
<http://www.eia.doe.gov/cneaf/electricity/epa/epat7p4.html>.
- [8.15] Professor J. Meisel, Georgia Institute of Technology (private communication), 2008.
- [8.16] FuelEconomy.gov, U.S. Department of Energy & Environmental Protection Agency, "Advanced technologies & energy efficiency," 2008,
<http://www.fueleconomy.gov/feg/atv.shtml>.
- [8.17] Bureau of Transportation Statistics, U.S. Department of Transportation, "Table 1-32: U.S. vehicle-miles," December 2007,
http://www.bts.gov/publications/national_transportation_statistics/html/table_01_32.html.
- [8.18] Bureau of Transportation Statistics, U.S. Department of Transportation, "Table 4.23: Average fuel efficiency of U.S. passenger cars and light trucks," December 2007,
http://www.bts.gov/publications/national_transportation_statistics/html/table_04_23.html.
- [8.19] Same as [3.2]
- [8.20] U.S. Census Bureau, "Annual population estimates 2000-2007," 2007,
<http://www.census.gov/popest/states/NST-ann-est.html>.
- [8.21] Energy Information Administration, U.S. Department of Energy, "Electric power annual," October 2007,
http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html.
- [8.22] U.S. Census Bureau, "United States - Selected housing characteristics: 2006," 2006 Census, http://factfinder.census.gov/servlet/ADPTable?_bm=y&-geo_id=01000US&-_name=ACS_2006_EST_G00_DP4&s_name=ACS_2006_EST_G00_&-_lang=en&-_sse=on.
- [8.23] J. Carpienter, "Contribution e l'étude do dispatching économique," Bulletin Society Française Electriciens, vol. 3, August 1962.
- [2.24] A. J. Wood and B. F. Wollenberg, Power Generation Operation and Control, 2nd ed. New York: John Wiley & Sons, Inc., 1996.
- [8.25] Same as [7.5]
- [8.26] Professor A. P. Meliopoulos, Georgia Institute of Technology (private communication), 2007.
- [8.27] University of Washington Electrical Engineering, "Power systems test case archive: 118 bus power flow test case," December 1962,
http://www.ee.washington.edu/research/pstca/pf118/pg_tca118bus.htm.

- [8.28] Y. Fu, M. Shahidehpour, and Z. Li, "Long-term security-constrained unit commitment: Hybrid Dantzig-Wolfe decomposition and subgradient approach," IEEE Transactions on Power Systems, vol. 20, no. 4, pp. 2093-2106, November 2005.
- [8.29] Electrical and Computer Engineering Department, Illinois Institute of Technology, "Data for 118 bus test case," April 2007, http://motor.ece.iit.edu/Data/SCUC_118/.
- [8.30] CalCars, The California Cars Initiative, "How carmakers are responding to the plug-in hybrid opportunity," February 2008, <http://www.calcars.org/carmakers.html>.
- [8.31] GM Media Online, General Motors, "Chevrolet Volt – GM's concept electric vehicle – Could nearly eliminate trips to the gas station," January 2007, <http://media.gm.com/servlet/GatewayServlet?target=http://image.emerald.gm.com/gmnews/viewmonthlyreleasedetail.do?domain=74&docid=31656>.
- [8.32] Electric Auto Association – Plug-In Hybrid Electric Vehicle, "Plug-in hybrids," December 2007, http://www.eaa-phev.org/wiki/Plug-In_Hybrids.
- [A.1] J. Wise, "The truth about hydrogen," Popular Mechanics, vol. 183, no. 11, pp. 82-129, November 2006.
- [A.2] U. Bossel, "Efficiency of hydrogen fuel cell, diesel-SOFC-hybrid, and battery electric vehicles," www.efcf.com/reports/E04.pdf, accessed April 2009.
- [B.1] ThermoAnalytics, Inc., "Battery Types and Characteristics," <http://thermoanalytics.com/support/publications/batterytotypesdoc.html>, accessed May 2009.
- [B.2] L. Brooke, "Spearheading the EV Revolution," Automotive Engineering International, May 2009.
- [B.3] Better Place website: <http://www.betterplace.com/>
- [C.1] Same as [7.5].
- [C.2] Energy Information Administration, "Existing Capacity by Energy Source," <http://www.eia.doe.gov/cneaf/electricity/epa/epat2p2.html>, accessed May 2009.
- [C.3] Energy Information Administration, "Net Generation by Energy Source: Total (All Sectors)," http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html, accessed May 2009.
- [C.4] Energy Information Administration, "U.S. Electric Power Industry Estimated Emissions by State (EIA-767 and EIA-906)," <http://www.eia.doe.gov/cneaf/electricity/epa/epat5p1.html>, accessed May 2009.
- [C.5] Tennessee Valley Authority, "TVA reservoirs and power plants," http://www.tva.gov/sites/sites_ie2.htm, accessed July 2008.
- [C.6] Energy Information Administration, "Net Internal Demand, Capacity Resources, and Capacity Margins by North American Electric Reliability Council Region," <http://www.eia.doe.gov/cneaf/electricity/epa/epat3p2.html>, accessed May 2009.
- [C.7] U.S. Department of Transportation Federal Highway Administration, "State Motor-Vehicle Registration," <http://www.fhwa.dot.gov/policy/ohim/hs03/mv.htm>, accessed May 2009.

Project Publications

C. Roe, F. Evangelos, J. Meisel, A.P. Meliopoulos, and T. J. Overbye, "Power System Level Impacts of PHEVs," *42nd Hawaii International Conference on System Sciences (HICSS)*, 2009.

C. Roe, J. Meisel, A.P. Meliopoulos, and T. J. Overbye, "Power System Level Impacts of Plug-In Hybrid Electric Vehicles Using Simulation Data," *IEEE Conference on Global Sustainable Energy Infrastructure (Energy 2030)*, 2008.

S. L. Judd and T. J. Overbye "An Evaluation of PHEV Contributions to Power System Disturbances and Economics," in *40th North American Power Symposium, Calgary, Alberta, Canada*, 2008.

Appendix A: Hydrogen Fuel as a Competing Technology to Charge-Depleting PHEVs

A.1 Introduction

On May 7, 2009, Energy Secretary Steven Chu announced that hydrogen research will be “zeroed out” in the 2010 federal budget. In recent years there has been great deal of federal funding towards using hydrogen as an automotive fuel either in a fuel cell producing on-board electric energy for an electric drive or by injecting the hydrogen directly into an internal combustion engine instead of a petroleum-based fuel. The production of this hydrogen would require grid-supplied electric energy, and would have a substantial impact on the electric utility companies. Thus, hydrogen represents a potential automotive fuel that needs some consideration by the electric utility industry even though knowledgeable experts say that real hydrogen-fueled vehicles are at least “20 years in the future”. This 20-year figure appears to stay constant no matter when the question of availability is posed.

A.2 Four Main Hurdles for Hydrogen as an Automotive Fuel

There are four main hurdles towards the realization of hydrogen as a replacement for petroleum as an automotive fuel. These hurdles are [A.1]:

1. Production
2. Storage
3. Distribution
4. Use

A.2.1 Production:

The leading method for producing hydrogen in the U.S. involves using fossil fuels particularly natural gas. High pressure and temperature are used to break the hydrocarbons into hydrogen and carbon oxides, particularly CO₂. Therefore, even though hydrogen fueled vehicles produce no CO₂, this particular production process does add this greenhouse gas to the atmosphere. Presently 95% of the hydrogen used in the U.S. comes from this process using natural gas as the base fuel. The U.S. has great reserves of natural gas that could serve as a source for hydrogen as a transportation fuel provided the production facilities to do this conversion could be built and the emission problems (particularly CO₂) handled. Here the emissions are moved from vehicle tailpipes to these hydrogen production plants, a fact that fuel-cell proponents often fail to mention. A second method to produce hydrogen is electrolysis, where an electric current passing between two plates immersed in water splits the water into its hydrogen and oxygen components. Now, as with PHEVs, emissions are moved from vehicle tailpipes to the electric powerplants. There are sufficient water supplies, and off-peak electric energy could be used for this electrolysis process. In summary, with substantial investment, the U.S. could produce the hydrogen needed for use as an automotive fuel. The hurdle of production can be overcome.

A.2.2 Storage:

At present there are two ways of storing hydrogen on-board a vehicle; either as a liquid or as a gas. In particular, BMW has been working on liquid storage of hydrogen. The energy density (kWh/liter) of liquid hydrogen is about one-third that of gasoline. However, the major problem involves two factors. The first relates to the large amount of energy needed to convert gaseous hydrogen to its liquid form. The second major issue involves the extremely low temperature (20° Kelvin or -253° C) required to maintain hydrogen in its liquid state. At room temperatures, hydrogen is in its gaseous state holding about one-three-hundredth the energy of an equivalent volume of gasoline. Therefore, in order to store hydrogen in a reasonably sized containment tank, gaseous hydrogen must be compressed. To store enough hydrogen for a 350-mile range, a tank pressure on the order of 10,000 psi is required. A recent announcement from Honda concerning their FCX Clarity fuel-cell powered vehicle, shown in Figure A.1, claims a range of 270 miles with a charging pressure of only 5000 psi, thus representing a significant reduction in storage pressure. However, these pressures represent a serious safety hazard in vehicles subject to everyday collisions. In addition, these high-pressure storage tanks take up four to five times the space of a gasoline tank giving an equivalent driving range. Perhaps the fuel cell and the electric drive may take less space than a conventional IC engine powertrain, thus compensating for the larger tank volume.



Figure A.1: The Honda Clarity fuel cell vehicle.

A.2.3 Distribution:

In general, hydrogen is a difficult substance to transport since it tends to make metals brittle to the point of fracture. The current methods of transporting hydrogen are either as a liquid in special tankers or as a compressed gas in high-pressure cylinders in truck trailers. Both methods are not very efficient, particularly when compared to the transmission of electric energy. One way to avoid these expensive transportation methods is to use a hydrogen pipeline with the hydrogen transported as a gas. These pipes must have special treatment to avoid the problem of becoming brittle, and to withstand the very high pressures that are required. Another approach is to make the hydrogen where vehicles are to be refueled. This is what is being done at about half of the 36 refueling stations now in operation using natural gas as the feedstock with CO₂ being released. If electric energy could be generated with much reduced emission levels, then an electrolysis process could be used at these refueling stations. Efforts to use renewable energy sources for electric energy generation with an electrolysis-based hydrogen refueling station would now eliminate all emissions.

A.2.4 Use:

Hydrogen can be injected directly into the cylinders of an internal combustion engine (ICE) with minor modifications needed for the engine. This is a relatively straightforward approach to using hydrogen as a transportation fuel. In particular, BMW has been exploring this approach since the 1970s. However, the major thrust is to use hydrogen in a fuel cell that produces electric energy as long as hydrogen is supplied. Many hurdles need to be overcome in order to have a production ready fuel cell suitable for a passenger vehicle. If we assume that all these hurdles can be overcome, we can zero in on other key reasons that fuel-cell technology makes little sense. As shown in Figure A.2, the fuel-cell approach starts with the production of hydrogen, as discussed above, by either breaking it free using a fossil fuel or by electrolysis. Let us here assume that electrolysis of water is the method of choice. In this case electric energy is used to split water into its hydrogen and oxygen components. The storage and transportation problems now come into play in order to have the hydrogen on-board the vehicle for the fuel cell conversion back to electric energy.

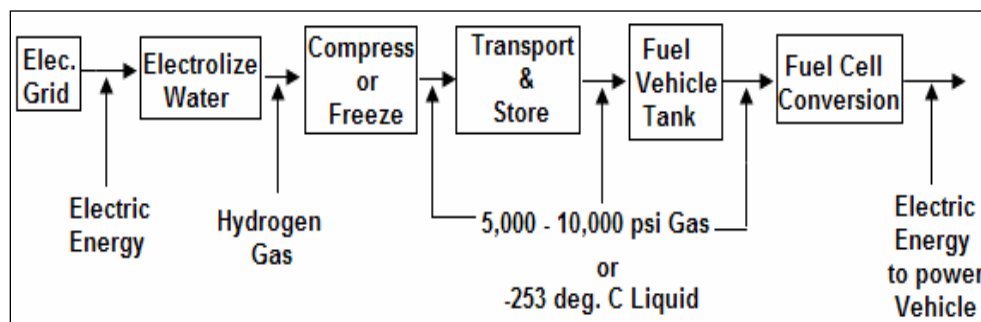


Figure A.2: The fuel-cell cycle for using hydrogen as an automotive fuel, whereby the electric energy from the grid uses hydrogen as an energy transport medium to provide electric energy onboard the vehicle.

With the plug-in hybrid electric vehicle (PHEV) approach, shown in Figure A.3, the power plant electric energy is transported over an existing grid transmission network directly to the PHEV. This energy is then stored on-board in battery packs that have an ever-increasing capability.

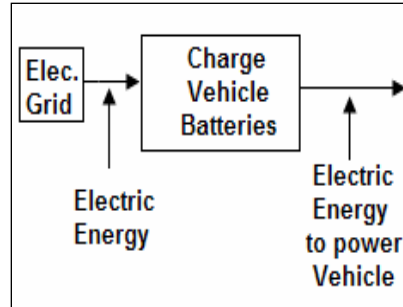


Figure A.3: The PHEV stores the electric energy directly from the grid.

The key point is that the use of hydrogen in fuel cells requires a double conversion from electric energy to hydrogen and then back to electric energy onboard the vehicle. The onboard storage of hydrogen requires either cryogenic or high-pressure tanks whereas batteries operate nominally at ambient temperatures and pressures. It is this double conversion along with the problems associated with the transmission of the hydrogen fuel and its on-board storage that makes the PHEV a much more practical approach to minimizing reliance on petroleum-based fuels. Note that, this discussion has made the leap-of-faith assumption that a production feasible fuel cell can be developed. The conclusion is that hydrogen as an automotive fuel is certainly not a near-term option.

A.3 Fuel-Cell Vehicle vs. PHEV Efficiency

Finally, let us consider how much of the electric energy out of an electric power plant ends up as electric energy on-board both a fuel-cell vehicle and a PHEV. Approximate efficiencies for a fuel-cell vehicle are as follows [A.2]:

A.3.1 Efficiency of process component in a Fuel-Cell Vehicle:

1. Electrolysis of water, power plant to hydrogen 70%
2. Compression of hydrogen 90%
3. Transportation of compressed gaseous hydrogen 90%
4. Fuel-cell conversion of hydrogen back into electric energy 50%
5. Parasitic losses for the fuel-cell system are about 10%, so efficiency is 90%

Multiplying these efficiency factors gives an overall cascaded value of $0.7 \cdot 0.9 \cdot 0.9 \cdot 0.5 \cdot 0.9 = 25.5\%$. Thus 25.5% of the electric energy out of an electric power plant ends up being available on-board the fuel-cell vehicle to supply energy for the electric drive train.

A.3.2 Efficiency of process component in a Plug-in Hybrid Electric Vehicle (PHEV):

1. Electric grid transmission system power plant to home wall plug 96%
2. Battery charger (rectifier, ac to dc) 90%
3. Turn-around efficiency of the battery (electric energy out / electric energy in) 85%

Again multiplying these efficiency factors gives an overall value of $0.96 \cdot 0.9 \cdot 0.85 = 73.4\%$. Thus, the transfer of electric energy from an electric power plant to the point where this energy is available at the electric motor controller onboard a vehicle is more efficient by a factor of $73.4\%/25.5\% = 2.88$ for a PHEV compared to a fuel-cell vehicle. If hydrogen is produced by a process that uses electric energy, then it is much more efficient simply to transmit the electric energy over the grid into a vehicle battery storage system, and not to use hydrogen as an energy transport medium.

Appendix B: Battery-Electric Powertrains as an Alternative to PHEV Powertrains

B.1 Introduction

Recently there is renewed interest in battery-electric powertrains that are known as ZEVs (Zero Emission Vehicles). This reconsideration of ZEVs is due mainly to the increased energy storage capability of batteries, particularly Lithium-Ion (Li-Ion) batteries. In the 1990s, there was substantial interest in ZEVs driven mainly by a mandate in California that was passed in 1990 by the California Air Resources Board (CARB). This mandate essentially required that by 1998, 2% of all vehicles sold in California by the seven major auto manufacturers must be ZEVs. The origin of this mandate came originally from GMs demonstration of a prototype ZEV known as the *Impact*. Under the direction of Roger Smith, GMs President at the time, GM mounted a significant R&D program to convert the *Impact* into a production vehicle that became the EV-1. Starting in 1997, EV-1s were being leased in California and Arizona using Delco/Delphi Lead-Acid (Pb-Acid) batteries. Approximately 700 such vehicles were manufactured and leased. These early EV-1s were very efficient vehicles in terms of their low rolling and aerodynamic resistances. However, the batteries were quite erratic often limiting the driving range to 35 miles before recharging was required. Approximately 500 second generation EV-1s were produced, using Nickel-Metal Hydride (Ni-MH) batteries that increased the range to approximately 100 miles. Also, some of these second generation EV-1s used more reliable Panasonic Pb-Acid batteries. Other manufacturers in this same time frame produced ZEVs, including Honda (EV+, 1997), Toyota (RAV4), Nissan (Altra EV), Ford (Ranger-EV), and Daimler-Chrysler (EPIC). So clearly there was substantial effort by many auto manufacturers to produce ZEVs to meet the California mandate. The auto industry requested more time for development, so the mandate was modified such that the 1998 deadline for 2% ZEVs was extended to 2003 with the percentage of ZEV sales raised to 10%.

Under intense pressure by elected officials and the oil and auto industries, CARB eventually eliminated the mandate in exchange for a "good faith effort" by the big 7 to market real-world ZEVs. A "Memorandum of Agreement" was signed that committed the auto manufacturers to:

- Produce ZEVs in quantities consistent with public demand.
- Have public demonstration programs to increase this demand.
- Continue research into battery powered ZEVs.
- Support infrastructure development and rebates for purchasing ZEVs.
- Support fleet usage of ZEVs.

The net result has been that efforts to produce ZEVs by the major auto manufacturers declined (essentially ended) in favor of hybrid electric vehicles (HEVs), particularly by Toyota, and hydrogen fueled vehicles with substantial funding by the Bush administration. In summary, the use of electric energy to displace petroleum-based fuels has not been advanced until the recent spike in oil prices.

B.2 Specific Energy and Power Ratings for Batteries and Gasoline.

The sole energy source in a ZEV is the battery, and since the time of Thomas Edison the battery has limited the utility of ZEVs. Table B.1 shows the maximum specific energy and power ratings of the three most common battery chemistries, and also the specific heat energy for gasoline.

Table B.1: Specific energy and power for common battery chemistries and gasoline [B.1].

Energy Source	Specific Energy (Wh/kg)	Specific Power (W/kg)
Advanced Lead-Acid	42	412
Nickel-Metal Hydrid	80	250
Lithium-Ion	150	300
Gasoline	11,543	N/A

The improvement in battery specific energy in recent years has been significant with Li-Ion having nearly four times the specific energy of Advanced Pb-Acid batteries. However, note that the specific power of Advanced Pb-Acid batteries is highest of the three batteries. This means that a Pb-Acid battery pack can provide for the best acceleration performance, but with a serious weight penalty due to its low specific energy. Li-Ion batteries are the current preferred choice for ZEVs, giving the highest range per unit weight with adequate power for performance. Also note that, the specific energy of gasoline dwarfs all of the batteries in energy storage by almost two-orders of magnitude.

B.3 Energy Requirements of ZEVs and PHEVs

From Figure 3.6 the required energy per mile from the grid for ZEVs and PHEVs is tabulated in Table B.2 for the US06 driving schedule. A value of $k_{PHEV} = 0.7$, is assumed for the PHEV control algorithm design. The value of k_{PHEV} is the fraction of the total input energy that comes from the battery. Thus, using $k_{PHEV} = 1.0$ in **Error! Reference source not found.** we have an estimate of the grid supplied recharging energy for ZEVs. The last column in Table B.2 is taken from Table 3.4 for a conventional powertrain in each vehicle class over the US06 driving schedule.

Table B.2: Recharging energy for ZEVs and PHEVs on the US06 driving schedule with the mpg for a conventional powertrain in each vehicle class.

Vehicle Class	ZEV (kWh/mi)	PHEV (kWh/mi)	Conv. Veh. (mi/gal)
Class-1 Compact	0.45	0.38	25.82
Class-2 Full-size	0.48	0.44	21.26
Class-3 Medium SUVs & Pickup Trucks	0.78	0.72	14.21
Class-4 Large SUVs & Pickup Trucks	0.96	0.89	11.16

B.4 Estimate of ZEV and PHEV Driving Range

A key aspect of vehicle operation involves the range that can be driven before requiring refueling. For a ZEV, this refueling involves recharging of its battery pack from grid supplied electric energy. For PHEVs, there exists an option based on the fact that vehicle operation can be maintained even if the battery state of charge (SOC) is at its lower limit as long as there is gasoline in the fuel tank. Thus for a PHEV, the range is similar to a conventional vehicle. The PHEV range calculation involves the range achieved during charge-depleting operation until reaching the lower SOC limit and then adding the range achieved during charge-sustaining operation using the remaining fuel in the gas tank. In order to arrive at some estimate of vehicle range driving repeated US06 cycles, we assume the Li-Ion battery masses shown in Figure B.1. The ZEV battery mass of 430 kg (950 lbs.) for the Class-1 vehicle corresponds to the Li-Ion battery pack being used in the Tesla Motors Roadster, consisting of 6,831 Li-Ion 18650 type individual cells wired in series and parallel [B.2]. Each of these cylindrical cells is 18.3 mm (0.72 in.) in diameter and 64.9 mm (2.56 in.) long. Larger battery packs are assumed for the larger vehicle classes 2, 3, and 4. For the PHEVs, all battery packs are assumed to be half the size of the corresponding size in the ZEVs. For the PHEVs, the sizes of the gas tanks for each vehicle class are shown in Figure B.1. The calculations in Figure B.1 assume that 80% of the battery stored energy can be used (Bat_factor = 80%) and that the PHEV mpg is increased by a factor of 1.25 over a conventional powertrain when driven charge sustaining (PHEV_factor = 1.25). Table B.3 summarizes the key range determining parameters and the range results obtained from the calculations in Figure B.1.

Table B.3: Summary of battery sizes and range for ZEVs and PHEVs.

Class	ZEV Bat. (kg)	ZEV Range (miles)	PHEV Bat. (kg)	PHEV Fuel (gal)	PHEV Range (miles)
1	430	150	215	12	443
2	450	147	225	15	449
3	700	141	350	23	456
4	850	139	425	29	451

Large battery packs were selected for the ZEVs in order to give a reasonable driving range. The range of the PHEVs is on the order of conventional non-hybrid powertrains.

B.5 Recharging / Refueling Times

The above section shows that a reasonable driving range, on the order of 150 miles, can be realized for ZEVs using large (i.e. heavy) Li-Ion battery packs. However, the most serious negative aspect of ZEVs is their required recharging times. This calculation is shown in Figure B.2, wherein a grid supply of 30 A at 240 V is assumed to be used. These times are summarized as follows:

- Class-1: 7.5 hrs.
- Class-2: 7.8 hrs.
- Class-3: 12.2 hrs.
- Class-4: 14.8 hrs.

In order to realize a reasonable driving range large batteries need to be used, that in turn require significant recharging times even with a 240 V, 30 A supply. Clearly a ZEV is only a practical vehicle when used for daily driving not exceeding a range of 150 miles. Continued driving then requires substantial time for recharging. This long recharging time is due to the commonly available grid supply power capability not the battery chemistry. With a PHEV there is no such recharging limitation as the vehicle can be driven charge sustaining in the same manner as HEVs now on the market. Refueling on a long trip simply involves refilling the gas tank.

B.6 Summary

The case for ZEVs reduces down to the following advantages and disadvantages:

B.6.1 ZEV Advantages:

- Simpler less expensive powertrain than PHEVs.
- Minimal maintenance with only an electric drive.
- Zero vehicle tailpipe emissions.
- Fueled only with electric energy that could be produced with renewable non-carbon sources.

B.6.2 ZEV Disadvantages:

- Requires large battery packs to get a reasonable driving range.
- Recharging these large battery packs requires a long time interval making their use for longer trips not practical. These recharging times are long due to the limited electric power that can be supplied in a non-industrial grid connection.

The case for PHEVs reduces down to the following advantages and disadvantages:

B.6.3 PHEV Advantages:

- Appreciable amounts of the energy driving the vehicle comes from an electrical source that could be produced with renewable non-carbon sources.
- Longer trips are still practical as the powertrain is fully operational in a charge-sustaining hybrid mode.
- Vehicle tailpipe emissions are greatly reduced.
- The battery pack can be much smaller than a ZEV battery pack, and also the IC engine can be smaller than a conventional engine-only vehicle in the same class.

B.6.4 PHEV Disadvantages:

- The powertrain has both an IC engine and an electric drive, thus increasing cost and control complexity.
- Some petroleum based fuel will still be used (at least in the near term).
- Vehicle tailpipe emissions are not zero.

The case for ZEVs is now being made on the basis that most daily driving is well within the range of present battery technology. However, from a consumer's viewpoint, ZEVs represent a vehicle that does not have the full utility of engine-only conventional vehicles, charge-sustaining HEVs, or charge-depleting PHEVs. The main negative aspect of ZEVs is the issue of refueling (i.e. recharging) time that is limited by the power available on the electric distribution system. This is not a battery limit, but rather a power system limit. One recent suggestion for ZEVs by Better Place is to swap a discharged battery for a charged battery [B.3]. We can do this for battery operated hand tools, so why not for ZEVs? One can only wonder if Better Place has any concept of the weight of ZEV batteries as listed in Table B.3.

This means that a ZEV would generally be purchased as a second vehicle used only where the intended planned range is well within its capability. No one wants to constantly be concerned that he/she will be stranded, so a consideration of the length of each trip needs to be made. A ZEV, compared to a conventional vehicle, would be like driving with the gas gauge never higher than 25%, a point where most people head for a gas station.

Calculation of vehicle range for ZEVs and PHEVs:

$$i := 0..3 \quad kPHEV := 0.7 \quad \eta_{Charger} := 90 \% \quad \eta_{Bat} := 85 \% \quad Bat_factor := 80 \% \quad PHEV_factor := 1.25$$

$$\text{Specific Energy of Li-Ion battery: } \rho_{Li_Ion} := 150 \cdot \frac{W \cdot hr}{kg} \quad \text{Gasoline energy: } \rho_{fuel} := 36.65 \cdot \frac{W \cdot hr}{gal}$$

Energy from the grid for each class vehicle-i from simulations:

$$E_{Grid_ZEV} := \begin{bmatrix} 0.45 \\ 0.48 \\ 0.78 \\ 0.96 \end{bmatrix} \cdot \frac{W \cdot hr}{mi} \quad E_{Grid_PHEV} := \begin{bmatrix} 0.38 \\ 0.44 \\ 0.72 \\ 0.89 \end{bmatrix} \cdot \frac{W \cdot hr}{mi}$$

Energy from the battery:

$$E_{Bat_ZEV_i} := E_{Grid_ZEV_i} \cdot \eta_{Charger} \cdot \eta_{Bat} \quad E_{Bat_PHEV_i} := E_{Grid_PHEV_i} \cdot \eta_{Charger} \cdot \eta_{Bat}$$

$$\text{Battery mass: } M_{ZEV} := \begin{bmatrix} 430 \\ 450 \\ 700 \\ 850 \end{bmatrix} \cdot kg \quad M_{PHEV_i} := (50 \%) \cdot M_{ZEV_i}$$

$$Range_ZEV_i := \frac{M_{ZEV_i} \cdot \rho_{Li_Ion} \cdot Bat_factor}{E_{Bat_ZEV_i}}$$

$$Range_ZEV = \begin{bmatrix} 150 \\ 147 \\ 141 \\ 139 \end{bmatrix} \cdot mi$$

Range of PHEV while running charge depleting:

$$Range_PHEV_Depl_i := \frac{M_{PHEV_i} \cdot \rho_{Li_Ion} \cdot Bat_factor}{E_{Bat_PHEV_i}} \quad Range_PHEV_Depl = \begin{bmatrix} 88.751 \\ 80.214 \\ 76.253 \\ 74.906 \end{bmatrix} \cdot mi$$

Fuel used while running charge depleting with (1-kPHEV) of wheel energy from IC engine:

$$E_{CONV} := \begin{bmatrix} 25.82 \\ 21.26 \\ 14.21 \\ 11.16 \end{bmatrix} \cdot \frac{mi}{gal} \quad Q_{Depl_i} := \frac{Range_PHEV_Depl_i}{E_{CONV_i}} \cdot (1 - kPHEV) \quad Q_{Depl} = \begin{bmatrix} 1.031 \\ 1.132 \\ 1.61 \\ 2.014 \end{bmatrix} \cdot gal$$

$$\text{Fuel tank capacity: } Q_{Tank} := \begin{bmatrix} 12 \\ 15 \\ 23 \\ 29 \end{bmatrix} \cdot gal \quad Q_{Remaining_i} := Q_{Tank_i} - Q_{Depl_i}$$

$$Range_PHEV_Sustaining_i := Q_{Remaining_i} \cdot E_{CONV_i} \cdot PHEV_factor$$

$$Total_Range_PHEV_i := Range_PHEV_Depl_i + Range_PHEV_Sustaining_i$$

$$Total_Range_PHEV = \begin{bmatrix} 443 \\ 449 \\ 456 \\ 451 \end{bmatrix} \cdot mi$$

Figure B.1: Calculation of ZEV and PHEV driving range.

Recharging time for ZEV:

Energy required from grid: $E_{\text{Recharge}_i} := \text{Range_ZEV}_i \cdot E_{\text{Grid_ZEV}_i} \cdot \text{Bat_factor}$

Recharge Voltage: $V := 240 \cdot \text{volt}$ Recharge Current: $I := 30 \cdot \text{amp}$

Recharge time: $\text{Recharge_Time}_i := \frac{E_{\text{Recharge}_i}}{V \cdot I}$

Recharge_Time	=	$\begin{bmatrix} 7.5 \\ 7.8 \\ 12.2 \\ 14.8 \end{bmatrix} \text{hr}$
---------------	---	--

Figure B.2: Battery-Electric ZEV recharging times from a 240 V, 30 A receptacle.

Appendix C: Power System Data Utilized in the Primary Energy Source Utilization Experiments

In the primary energy source utilization (Chapter 7) two power systems are utilized. Both systems are described next. The first system, described first, is the 1979 reliability test system (RTS), a standard hypothetical power system developed by the Reliability Test System Task Force of the Application of Probability Methods Subcommittee [D1]. The second system, described second, is based on the generating mix [D2], energy production [D3], and environmental air pollution [D4] for the entire US. All simulations were performed using the load data, described last, defined in [D1] with corresponding peak power levels.

C.1 RTS System Data

The RTS system modeled utilized five types of fuel: #6 oil, #2 oil, coal, nuclear, and hydro. The cost and heat content of each fuel, Table C.1, is based on data in [C.1]. The cost data has been updated to typical current prices. The hydro energy generation is treated a bit differently. The hydro energy generation is utilized based on 100% availability. As such it is treated as negative load when calculating the load demand curve for the system. The relative cost of each fuel is of significant importance because the generating unit dispatching is ordered based on economic ranking.

Table C.1: Fuel data [C.1].

Fuel Type	Fuel Costs [\$ /kg]	Fuel Energy Density [kcal/kg]
#6 Oil	0.6	11,200
#2 Oil	0.65	12,000
Coal	0.05	6,000
Nuclear	60,000	200-1019
Hydro	--	--

The RTS system modeled utilized 32 different generators. These 32 generators are comprised of nine different generator types. Generator unit reliability data, Table C.2, includes mean time to failure (MTTF) and mean time to repair (MTTR) and resulting forced outage rate (FOR)

$$\text{FOR} = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}}$$

Table C.2: Generating unit reliability data [C.1].

Size of Unit [MW]	FOR	MTTF [h]	MTTR [h]
12	0.02	2,940	60
20	0.1	450	50
50	--	--	--
76	0.02	1,960	40
100	0.04	1,200	50
155	0.04	960	40
197	0.05	950	50
350	0.08	1,150	100
400	0.12	1,100	150

Unit reliability for the hydro units is considered in the calculations of the hydro availability data.

Generator generating capacity data, Table C.3, includes generator fuel type, maximum generating capacity, and minimum generating capacity.

Table C.3: Generating unit generation capacity data [C.1].

Fuel	Capacity [MW]	
	Maximum	Minimum
#6 Oil	12	2.4
#2 Oil	20	16
Hydro	50	--
Coal	76	15.2
#6 Oil	100	25
Coal	155	54.25
#6 Oil	197	68.95
Coal	350	140
Nuclear	400	100

Again, the hydro capacity is treated as negative load and as such no minimum capacity is required.

The generator heat rate function

$$h(P) = a_h + b_h \cdot P + c_h \cdot P^2$$

is used as a cost function modeling the amount of fuel needed to meet a specific power demand for each generator. Where $h(P)$ is the required heat rate (kcal/h), P represents the generated power, and the coefficients a_h , b_h , and c_h are the heat rate coefficients computed for each generator type in the system. Each generator type heat rate coefficients are shown in Table C.4.

Table C.4: Generating unit heat rate coefficients [C.1].

Size [MW]	$a_h \left[\frac{kcal}{h} \right]$	$b_h \left[\frac{kcal}{MWh} \right]$	$c_h \left[\frac{kcal}{(MW)^2 h} \right]$
12	3,330,369	2,550,425	15,047.24
20	10,080,000	3,150,000	0
50	--	--	--
76	21,092,334	2,550,425	2,375.881
100	31,362,044	1,963,834	2,413.314
155	43,407,948	1,946,828	1,401.447
197	33,003,505	2,193,793	328.5092
350	81,532,894	1,873,123	822.2852
400	90,962,133	2,244,962	116.0031

In Table C.4 the zero c_h coefficient for the 20 MW units is because only two heat rate data points are published. The resulting heat rate curve is linear. Again, the hydro units were treated as negative load and as such required no heat rate equation.

The generator emission rate function

$$e(P) = a_e + b_e \cdot P$$

is used as a cost function modeling the amount of environmental air pollution (EAP) generated at a specific power level. Where $e(P)$ is the emission rate [kg/h], P represents the generated power, and the coefficients a_e and b_e are the emission rate coefficients computed for each generator type in the system.

Due to the lack of published emission data for the RTS generators. Published EAP statistics [C.5] were utilized to compute general generator pollution cost functions in this study. The published data is reproduced in Table C.5 and the resulting emission rate coefficients are shown in Table C.6. The method utilized to compute both the heat rate coefficients and the EAP rate coefficients can be found in Volume II of this report.

Table C.5: TVA generator statistics [C.5].

Plant	Energy Produced [billions of kWh]	NOx [thousands of tones/year]	CO2 [millions of tones/year]
Allen	4.9	17.4	5.7
Bull Run	6	28	4.6
Cumberland	18.97	18.4	19
Gallatin	4.7	23.4	7.7
John Saviers	5.25	30.1	5.1
Johnsonville	5.68	86.8	9
Kingston	10	55.5	35.8

Table C.6: Generating unit emission rate coefficients.

Size [MW]	NO _x		CO ₂	
	$a_e \left[\frac{kg}{h} \right]$	b_e	$a_e \left[\frac{kg}{h} \right]$	b_e
12	19.7155	0.4832	6,458.5234	158.2971
20	7.6205	3.8102	1,251.936	625.968
50	--	--	--	--
76	179.8726	0.6961	37,417.1151	144.8031
100	45.8303	0.1467	47,324.7232	151.4391
155	374.4125	0.9381	123,204.126	308.6856
197	547.9919	1.0803	92,849.1186	183.0351
350	2,604.0367	3.2348	270,003.8028	335.4085
400	--	--	--	--

In Table C.6 the hydro (50 MW) and nuclear (400 MW) generators produced no EAP, thus the emission rate coefficients are both zero.

The environmental air pollutants NO_x and CO₂ were selected based on the availability of both power plant emission data and PSAT result data. Both were necessary so that a comparison could be made in terms of total system EAP. The total system EAP is the EAP produced by both the power system and vehicle fleets for scenarios with and without PHEV charging.

Further, the peak electric load demand utilized was 2,850 [MW] [C.1]. The number of vehicles in the power system test area was set to 1.539 million (computed via average power system utilization and vehicle ownership assumptions outlined in Volume II of this report).

C.2 US System Data

Based on publicly available total U.S. generating capacity, Table C.7, total U.S. generated energy production per fuel source, Table C.8, and total U.S. power system EAP generated, Table C.9, Probabilistic Production Costing (PPC) input data was generated so that the base case results closely matched the results in Tables C.8 and C.9.

Table C.7: Total U.S. generating capacity by energy source [C.2].

Fuel Source	Generator Nameplate Capacity [MW]
Coal	336,040
Liquid and Coke Petroleum	62,394
Natural and Other Gas	452,052
Nuclear	105,764
Renewable/Other	131,541

Table C.8: Net U.S. energy generating by source [C.3].

Fuel Source	Net Generation By Fuel Source [GWh]
Coal	1,994,385
Liquid and Coke Petroleum	45,354
Natural and Other Gas	888,521
Nuclear	808,972
Renewable/Other	377,648

Table C.9: Estimated EAP by each fuel source in 2007 for the entire U.S. [C.4].

Fuel	CO₂ [kg]	NO_x [kg]
Coal	16,018,807,896,000	22,956,252,000
Liquid and Coke Petroleum	536,895,358,000	1,258,970,000
Natural and Other Gas	3,458,905,616,000	3,402,814,000
Renewable/Other	118,031,404,000	1,582,196,000

Further, the peak electric load demand utilized was 764,476 [MW] [C.6]. The number of vehicles in the power system test area was set to 135,669,897 [C.7].

C.3 Load Data

The base case load demand data was generated taking the product of the weekly peak (Table C.10), daily peak (Table C.11), and hourly peak (Table C.12) data to create hourly load demand data for one year (8760 hours).

Table C.10: Weekly peak load in percent of annual peak [C.1].

Week	Peak Load [%]	Week	Peak Load [%]	Week	Peak Load [%]
1	86.2	19	87	37	78
2	90	20	88	38	69.5
3	87.8	21	85.6	39	72.4
4	83.4	22	81.1	40	72.4
5	88	23	90	41	74.3
6	84.1	24	88.7	42	74.4
7	83.2	25	89.6	43	80
8	80.6	26	86.1	44	88.1
9	74	27	75.5	45	88.5
10	73.7	28	81.6	46	90.9
11	71.5	29	80.1	47	94
12	72.7	30	88	48	89
13	70.4	31	72.2	49	94.2
14	75	32	77.6	50	97
15	72.1	33	80	51	100
16	80	34	72.9	52	95.2
17	75.4	35	72.6		
18	83.7	36	70.5		

Table C.11: Daily peak load in percent of weekly peak [C.1].

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Peak Load [%]	93	100	98	96	94	77	75

Table C.12: Hourly peak load in percent of daily peak [C.1].

Hour	Winter Weeks [%]		Summer Weeks [%]		Spring/Fall Weeks [%]	
	1-8 and 44-52		18-30		9-17 and 31-43	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
12(midnight)-1a	67	78	64	74	63	75
1a-2a	63	72	60	70	62	73
2a-3a	60	68	58	66	60	69
3a-4a	59	66	56	65	58	66
4a-5a	59	64	56	64	59	65
5a-6a	60	65	58	62	65	65
6a-7a	74	66	64	62	72	68
7a-8a	86	70	76	66	85	74
8a-9a	95	80	87	81	95	83
9a-10a	96	88	95	86	99	89
10a-11a	96	90	99	91	100	92
11a-12noon	95	91	100	93	99	94
12noon-1p	95	90	99	93	93	91
1p-2p	95	88	100	92	92	90
2p-3p	93	87	100	91	90	90
3p-4p	94	87	97	91	88	86
4p-5p	99	91	96	92	90	85
5p-6p	100	100	96	94	92	88
6p-7p	100	99	93	95	96	92
7p-8p	96	97	92	95	98	100
8p-9p	91	94	92	100	96	97
9p-10p	83	92	93	93	90	95
10p-11p	73	87	87	88	80	90
11p-12midnight	63	81	72	80	70	85

The RTS system also includes six 50 MW hydro electric generating units. The hydro units are utilized 100% based on availability. The power available from the hydro units

$$H_P^{(q)} = \frac{E_A^{(q)} \cdot C_A^{(q)} \cdot H_E}{2190 \cdot 1000}$$

is treated in effect as negative load. Thus, each hourly load in calendar quarter- q is decreased by the hydro power available $H_P^{(q)}$ in quarter- q , where $E_A^{(q)}$ and $C_A^{(q)}$ are defined in Table C.13 and represent the energy and maximum capacity available in quarter- q respectively, and H_E is 100% of the available energy from the hydro units (200 GWh).

Table C.13: Hydro energy per calendar quarter [C.1].

Quarter	Energy Availability [%]	Capacity Availability [%]
1	35	100
2	35	100
3	10	90
4	20	90

Power System Impacts of Plug-in Hybrid Electric Vehicles

Volume II

Information about this volume

For information about this project contact:

Sakis Meliopoulos
Georgia Power Distinguished Professor
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0250

Power Systems Engineering Research Center

The Power Systems Engineering Research Center (PSERC) is a multi-university Center conducting research on challenges facing the electric power industry and educating the next generation of power engineers. More information about PSERC can be found at the Center's website: <http://www.pserc.org>.

For additional information, contact:

Power Systems Engineering Research Center
Arizona State University
577 Engineering Research Center
Tempe, Arizona 85287-5706
Phone: 480-965-1643
Fax: 480-965-0745

Notice Concerning Copyright Material

PSERC members are given permission to copy without fee all or part of this publication for internal use if appropriate attribution is given to this document as the source material. This report is available for downloading from the PSERC website.

© 2009 Georgia Institute of Technology and University of Illinois at Urbana-Champaign. All rights reserved.

Table of Contents

1. Introduction.....	1
2. Literature Review.....	3
2.1 First Focus	3
2.2 Second Focus.....	11
3. Impact of PHEV charging on Primary Energy Source Utilization	13
3.1 Probabilistic Simulation of an Integrated Power System with Distributed PHEVs Methodology.....	13
3.1.1 Vehicle Simulation.....	14
3.1.1.2 Vehicle Operation Distributions.....	23
3.1.2 Calculate Load Curves	28
3.1.3 Power System Simulation Using the Probabilistic Production Costing (PPC) Power System Simulation Procedure	31
3.1.4 Calculate EAP Statistics.....	31
3.2 Primary Energy Source Utilization Experiments	33
3.2.1 Reliability Test System (RTS) Experiment.....	33
3.2.2 United States System Experiment	48
3.2.3 Modified Reliability Test System	53
3.3 Conclusion.....	56
4. Impact of PHEV charging on Distribution Transformers.....	61
4.1 Random Feeder Electrical Load	61
4.2 PHEV Electrical Load	62
4.3 Center-Taped Single-Phase Distribution Transformer Model	63
4.4 Electro-Thermal Transformer Model	67
4.5 Transformer Loss-of-Life (LOL) Calculation	69
4.6 Transformer Impact Simulation Procedure	70
4.7 Transformer Impact Results	77
4.8 Conclusion.....	79
5. Conclusion	80
References.....	81
Appendix A: PSAT Simulation Results.....	84

List of Figures

Figure 1.1: Energy mix used in transportation [1.5].	1
Figure 1.2: Energy mix used in the electric utility industry [1.5].	2
Figure 2.1: 2005 electric power system generation capacity by fuel type for Colorado [2.4].	6
Figure 2.2: 2005 electric power system energy generation by fuel type for Colorado [2.4].	6
Figure 2.3: Generator type used to charge PHEV in the Xcel service area [2.4].	7
Figure 2.4: Projected power generating capacity in 2020 [2.5].	8
Figure 2.5: Computed base case energy generated in 2020 [2.5].	8
Figure 2.6: Projected power generating capacity in 2030 [2.5].	9
Figure 2.7: Computed base case energy generated in 2030 [2.5].	9
Figure 2.8: Computed increase in energy per fuel type for 2020 [2.5].	10
Figure 2.9: Computed increase in energy per fuel type for 2030 [2.5].	10
Figure 3.1: Simulation overview block diagram.	13
Figure 3.2: Simulation sub-steps block diagram.	14
Figure 3.3: Class 2 PSAT discrete data and weighted average for the required grid energy performance metric.	17
Figure 3.4: Class 2 PSAT discrete data and weighted average for the fuel efficiency performance metric.	18
Figure 3.5: Class 2 PSAT discrete data and weighted average for the NOx rate performance metric.	18
Figure 3.6: Class 2 PSAT discrete data and weighted average for the CO2 rate performance metric.	19
Figure 3.7: Average PHEV grid energy per mile approximation for each PHEV class.	20
Figure 3.8: Average PHEV fuel efficiency approximations for each PHEV class.	20
Figure 3.9: Average PHEV NOx rate approximation and for each PHEV class.	21
Figure 3.10: Average PHEV CO2 rate approximation and for each PHEV class.	21
Figure 3.11: PHEV required grid energy calculation block diagram.	30
Figure 3.12: 12 MW unit heat rate data [3.8] and approximation.	36
Figure 3.13: Pollution normalization justification.	39
Figure 3.14: Typical vehicle design parameter scatter plot.	43
Figure 3.15: Increase in max and min power demand for each RTS scenario.	44
Figure 3.16: Primary energy generated for each RTS scenario.	45

Figure 3.17: Increase in primary energy for each RTS PHEV penetration scenario	45
Figure 3.18: RTS percent change of EAP as a function of PHEV penetration.	47
Figure 3.19: RTS gasoline utilization as a function of PHEV penetration.....	47
Figure 3.20: Increase in max and min power demand for each U.S. scenario.....	50
Figure 3.21: Primary energy generated for each U.S. scenario.	51
Figure 3.22: Increase in primary energy for each U.S. PHEV penetration scenario.	51
Figure 3.23: U.S. percent change of EAP as a function of PHEV penetration.....	52
Figure 3.24: U.S. gasoline utilization as a function of PHEV penetration.	53
Figure 3.25: Clean energy experiment scenario generation capacities.....	54
Figure 3.26: Clean energy experiment scenario generated energy.....	55
Figure 3.27: Clean energy experiment scenario increase in primary energy.....	55
Figure 3.28: Clean energy experiment change in EAP for each simulated scenario.....	56
Figure 3.29: RTS generating capacity [3.8].....	57
Figure 3.30: U.S. total generating capacity [3.10].....	58
Figure 4.1: Hourly mean peak real power.	62
Figure 4.2: Center-tapped single phase transformer model [4.1].	64
Figure 4.3: Electro-thermal transformer model.	67
Figure 4.4: Transformer impact simulation block diagram.	70
Figure 4.5: Sample scenario feeder load data.	72
Figure 4.6: Sample scenario winding currents.....	73
Figure 4.7: Sample scenarios winding temperatures.	74
Figure 4.8: Sample scenarios hot-spot temperature.	75
Figure 4.9: Base case LOL histogram.....	77
Figure 4.10: Single PHEV charging LOL histogram.....	78

List of Tables

Table 2.1: Vehicle assumptions made in penetration level papers.	3
Table 2.2: Vehicle MPG [2.4].....	4
Table 2.3: Vehicle performance results [2.4].....	5
Table 3.1: PSAT IC results for each vehicle class.....	15
Table 3.2: PHEV grid energy per mile function parameters for each vehicle class.	16
Table 3.3: PHEV fuel efficiency (1/MPG) function parameters for each vehicle class. ...	16
Table 3.4: PHEV NO _x generated per mile function parameters for each vehicle class. ...	16
Table 3.5: PHEV CO ₂ generated per mile function parameters for each vehicle class. ...	17
Table 3.6: Battery capacity range for each vehicle class [kWh].....	22
Table 3.7: Computed kPHEV range for each vehicle class.	23
Table 3.8: IC vehicle class distribution [3.3].	23
Table 3.9: Vehicle departure and arrival time distribution parameters.	25
Table 3.10 Fuel type data [3.8].	33
Table 3.11: Generating unit reliability data [3.8].	33
Table 3.12: Generating unit generation capacity data [3.8].....	34
Table 3.13: Generating unit heat rate coefficients [3.8].	36
Table 3.14: TVA generator statistics [3.9].....	37
Table 3.15: Generating unit emission rate coefficients.	38
Table 3.16: Weekly peak load in percent of annual peak [3.8].	40
Table 3.17: Daily peak load in percent of weekly peak [3.8].	40
Table 3.18: Hourly peak load in percent of daily peak [3.8].	41
Table 3.19: Hydro energy per calendar quarter [3.8].....	41
Table 3.20: Number of vehicles for each RTS simulation.....	42
Table 3.21: Energy statistics for each simulated RTS scenario.....	46
Table 3.22: Added RTS power system revenue.....	46
Table 3.23: RTS annual fuel cost.....	48
Table 3.24: Total U.S. generating capacity by fuel type [3.10].....	49
Table 3.25: Net U.S. energy generating by fuel type [3.11].....	49
Table 3.26: Estimated EAP by each fuel type in 2007 for the entire U.S. [3.12].....	49
Table 3.27: Number of vehicles for each U.S. simulation.....	50
Table 3.28: Clean energy capacity and generated energy summary.....	54

Table 3.29: Change in primary energy source utilization.....	59
Table 3.30: Total system EAP.	60
Table 4.1: PHEV timing distribution parameters.	63
Table 4.2: Normal insulation life times [4.8].....	69
Table 4.3: Aging rate constant [4.8].	70
Table 4.4: Hot-spot temperature results and LOL calculation.....	76
Table 4.5: LOL MLE results.....	78
Table 4.6: Increase in average electric load and resulting average transformer LOL.	79
Table A.1: Vehicle class 1 PHEV PSAT results.....	84
Table A.2: Vehicle class 2 PHEV PSAT results.....	85
Table A.3: Vehicle class 3 PHEV PSAT results.....	85
Table A.4: Vehicle class 4 PHEV PSAT results.....	85
Table A.5: IC PSAT results.	85

Nomenclature

α_p	PHEV population variance coefficient
θ_u	Transformer insulation aging acceleration factor
$\vec{\mu}$	PHEV vehicle design parameters mean vector
μ_{BC}	PHEV usable battery capacity mean [kWh]
$\mu^{(c)}$	PHEV class- c population mean
$\mu_P^{(h)}$	Feeder real power demand mean in hour- h [W]
μ_m	Vehicle daily driving distance distribution mean [mi.]
$\mu_T^{(p)}$	Vehicle timing distribution- p mean [h]
ρ	PHEV k_{PHEV} usable battery capacity correlation
Σ	PHEV vehicle design parameters covariance matrix
σ_{BC}	PHEV usable battery capacity standard deviation [kWh]
$\sigma^{(c)}$	PHEV class- c population standard deviation
$\sigma_P^{(h)}$	Feeder real power demand standard deviation in hour- h [VA]
σ_{kPHEV}	PHEV k_{PHEV} standard deviation
σ_m	Vehicle daily driving distance distribution standard deviation [mi.]
$\sigma_T^{(p)}$	Vehicle timing distribution- p standard deviation [h]
$\mathbf{A}$	Linear least square known observation matrix
$A_{CO_2}^{(c)}$	PHEV CO ₂ rate function parameter [kg/mi.]
$A_E^{(c)}$	PHEV grid electric energy function parameter [kWh/mi.]
$A_{GPM}^{(c)}$	PHEV MPG function parameter [gal./mi.]
$A_{NOx}^{(c)}$	PHEV NO _x rate function parameter [kg/mi.]
ADVISOR	Advanced Vehicle Simulator
AEC	Average Electricity Cost
a_h	Generator heat rate function parameter [kcal/h]
a_p	Generator emission rate function parameter [kg/h]
A_T^*	A particular value generated for the random daily arrival time [h]
$A_T^{(v,d)}$	RV representing the daily arrival time for vehicle- v on day- d [h]
$\mathbf{B}$	Lower triangle matrix computed using the Cholesky decomposition
B	LOL calculation aging rate constant [K]
BC	RV representing the useable battery capacity of PHEV [Wh]
$BC^{(c)}$	RV representing a PHEV in class- c usable battery capacity [kWh]
$BC_{\max}^{(c)}$	Maximum usable battery capacity for PHEV in class- c [kWh]
$BC_{\min}^{(c)}$	Minimum usable battery capacity for PHEV in class- c [kWh]
$B_{CO_2}^{(c)}$	PHEV CO ₂ rate function parameter
$B_E^{(c)}$	PHEV grid electric energy function parameter
$B_{GPM}^{(c)}$	PHEV MPG function parameter
$B_{NOx}^{(c)}$	PHEV NO _x rate function parameter
BEV	Battery Electric Vehicle
b_h	Generator heat rate function parameter [kcal/MWh]

b_p	Generator emission rate function parameter [kg/MWh]
c	Vehicle class- c , represents a group of vehicles of comparable sizes
$\mathbf{C}$	Electro-thermal transformer model thermal capacitance matrix [joules/°C]
CC	Combined Cycle generation plant
c_h	Generator heat rate function parameter [kcal/(MW) ² h]
$CO_2^{(c)}(0)$	PHEV charge sustaining CO ₂ rate [kg/mi.]
$CO_2^{(c)}(k_{PHEV})$	PHEV performance metric CO ₂ rate function [kg/mi.]
$C_A^{(q)}$	Hydro generator percent capacity available in quarter- q [%]
CT	Combustion Turbine
$C_T^{(v,d)}$	RV representing the daily recharge time for PHEV- v on day- d [h]
d	Day- d , a particular day in the simulation
D	Total number of days in the simulation
D_T^*	A particular value generated for the random daily depart time [h]
$D_E^{(v,d,c)}$	The daily recharge energy required by PHEV- v on day- d in class- v [kWh]
$D_{EAP}^{(v,d,c)}$	Daily EAP generated by PHEV- v on day- d in class- c [kg]
$D_G^{(v,d,c)}$	Daily gasoline consumed by PHEV- v on day- d in class- c [gal.]
$D_T^{(v,d)}$	RV representing the daily departure time for vehicle- v on day- d [h]
e	Iterative load flow error tolerance
EAP	Environmental Air Pollution
EAP	Total EAP generated by N_T vehicles with P_{PHEV} penetration of PHEVs [kg]
$\overline{EAP}_{IC}^{(c)}$	Average EAP generated by IC vehicles in class- c [kg/veh.]
EAP_{IC}	Total EAP generated by N_T IC vehicles [kg]
EAP_{PHEV}	Total EAP generated by a fleet of $N_T \cdot P_{PHEV}$ PHEVs [kg]
$E^{(c)}(k_{PHEV})$	PHEV performance metric grid electric energy rate function [kWh/mi.]
EIA	Energy Information Agency
E_L	Transformer insulation equivalent life [h]
$e(P)$	Generator emission rate as a function of demanded power level P [kg/h]
EPRI	Electric Power Research Institute
$E_A^{(q)}$	Hydro generator percent energy available in quarter- q [%]
FOR	Forced Outage Rate
G	Total gasoline consumed by N_T vehicles with P_{PHEV} penetration of PHEVs [gal.]
$\mathbf{G}$	Electro-thermal transformer model conductance matrix [W/°C]
$\overline{G}_{IC}^{(c)}$	IC vehicle in class- c sample population average gasoline consumed [gal./veh.]
GE	Total Generated Energy
G_{IC}	Total gasoline consumed by a fleet of N_T IC vehicles [gal.]

G_{PHEV}	Total gasoline consumed by a fleet of $N_T \cdot P_{PHEV}$ PHEVs [gal.]
GPS	Global Positioning Satellite
GUI	Graphical User Interface
h_c	Hour when PHEV- v on day- d in class- c is charging [h]
H_E	Full energy available from hydro generators [MWh]
HEV	Hybrid Electric Vehicle
$h(P)$	Generator heat rate as a function of demanded power level P [kcal/h]
$H_p^{(q)}$	Hydro generator power available in quarter- q [MW]
HWFET	Highway Fuel Economy Test
I^*	Maximum current available from the charging circuit [A]
I_0	Transformer high voltage winding current [A]
I_1	Transformer 120 V winding line 1 current [A]
I_2	Transformer 120 V winding line 2 current [A]
$\bar{I}_0$	Transformer average high voltage winding current [A]
$\bar{I}_1$	Transformer average 120 V winding line 1 current [A]
$\bar{I}_2$	Transformer average 120 V winding line 2 current [A]
IC	Internal Combustion
$IC_{CO_2}^{(c)}$	Internal combustion vehicle CO ₂ rate for class- c [kg/mi.]
$IC_{MPG}^{(c)}$	Internal combustion vehicle MPG for class- c [mi./gal.]
$IC_{NO_x}^{(c)}$	Internal combustion vehicle NO _x rate for class- c [kg/mi.]
IID	Independent and Identically Distributed
$\bar{I}_{L1}$	Transformer average 120 V load 1 current [A]
$\bar{I}_{L2}$	Transformer average 120 V load 2 current [A]
$\bar{I}_{L3}$	Transformer average 240 V load current [A]
$I^{(v,d,c)}$	The required recharge current for vehicle- v in class- c [A]
k_{PHEV}	PHEV amount of driving energy derived from electricity [%]
$k_{PHEV}^{(c)}$	RV representing the PHEV in class- c k_{PHEV} [%]
$k_{PHEV,max}^{(c)}$	Maximum k_{PHEV} value for PHEV in class- c [%]
$k_{PHEV,min}^{(c)}$	Minimum k_{PHEV} value for PHEV in class- c [%]
$LDC[h_c]$	Load demand array of the required power for all PHEVs in hour- h_c [MW]
LOL	Loss-of-Life
LOLP	Loss-of-Load Probability
$M_E^{(c)}$	PHEV charge depleting distance for PHEV in class- c [mi.]
M_E^*	Optimal trip length, i.e. X in PHEV-X [mi.]
MLE	Maximum Likelihood Estimator
MPG	Miles per Gallon
$MPG^{(c)}(0)$	PHEV in class- c charge sustaining MPG performance [mi./gal.]
$MPG^{(c)}(k_{PHEV})$	PHEV performance metric MPG function [mi./gal.]
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
$M^{(v,d)}$	RV representing the daily distance driven by vehicle- v on day- d [mi.]
n	Sample size of the vehicles simulated

N	Standard normal distributed RV
$\vec{N}$	Vector of IID standard normal RVs
$N_{PHEV}^{(c)}$	Number of PHEVs in class- c
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Corporation
NESSIE	National Electric System Simulation Integrated Evaluator
NILDC	Normalized Inverted Load Duration Curve
N_L	Transformer insulation normal life span [h]
$NO_x^{(c)}(0)$	PHEV charge sustaining NO_x rate [kg/mi.]
$NO_x^{(c)}(k_{PHEV})$	PHEV performance metric NO_x rate function [kg/mi.]
n_t	Center-tapped single phase transformer turns ratio
N_T	Total number of vehicle in the power system area
ORCED	Oak Ridge Competitive Electricity Dispatch
p	Distribution- p , the particular distribution from the daily timing distributions
P	Added real power demand due to PHEV [W]
$\bar{P}$	Average feeder real power demand [W]
$p^{(c)}$	Percentage of vehicles in class- c
$\overline{P^{(c)}(k_{PHEV})}$	Generic term for $NO_x^{(c)}(k_{PHEV})$ or $CO_2^{(c)}(k_{PHEV})$ [kg/mi.]
$p.f.$	Expected feeder power factor
$p.f.^{(h)}$	Discrete RV representing the feeder power factor in hour- h
$p^{(h)}$	RV representing the household electric load real power demand in hour- h [W]
PHEV	Plug-In Hybrid Electric Vehicle
P_L	Transformer insulation percent loss of life [%]
PPC	Probabilistic Production Costing
P_{PHEV}	Percentage penetration of PHEV into the light-duty vehicle fleet
PROSYM	Proprietary Hourly Power System Evaluation Model
PSAT	Powertrain System Analysis Toolkit
p_v	PHEV power demand per hour [MW]
q	Quarter- q , calendar quarter
Q	Added reactive power due to PHEV [VAR]
$\bar{Q}$	Average feeder reactive power demand [VAR]
$\vec{Q}$	Electro-thermal transformer model heat input vector [W]
$Q^{(h)}$	Household electric load reactive power demand in hour- h [VA]
R_A	Transformer series resistance [p.u.]
RTS	Reliability Test System
RV	Random Variable
S_{L1}	Center-tapped single phase transformer 120 V complex load 1 [VA]
S_{L2}	Center-tapped single phase transformer 120 V complex load 2 [VA]
S_{L3}	Center-tapped single phase transformer 240 V complex load [VA]
$\bar{S}_{L1}$	Average 120 V complex load 1 [VA]
$\bar{S}_{L2}$	Average 120 V complex load 2 [VA]
$\bar{S}_{L3}$	Average 240 V complex load [VA]

ST	Steam Turbine
t	Trapezoidal integration method current time [sec]
$\vec{T}$	Electro-thermal transformer model temperature vector [$^{\circ}\text{C}$]
$\tilde{T}_h$	Transformer hot-spot temperature [$^{\circ}\text{C}$]
T^m	Total distance driven in the simulation period for vehicle- v [mi.]
TFC	Total Fuel Cost
TVA	Tennessee Valley Authority
u	Trapezoidal integration method time step length [sec]
U_1	Uniformly distributed (0,1] IID pseudo random number
U_2	Uniformly distributed (0,1] IID pseudo random number
UDDS	Urban Dynamometer Driving Schedule
UE	Unserviced Energy
US06	Updated federal test driving cycle
v	Vehicle- v , a particular vehicle sampled from the total vehicle population
$\bar{V}_1$	Average 120 V load 1 voltage [V]
$\bar{V}_2$	Average 120 V load 2 voltage [V]
V_s	Center-tapped single phase transformer model source voltage [V]
$V^{(v,c)}$	RV representing the recharge voltage for vehicle- v in class- c [V]
$\vec{X}$	Linear least square unknown vector
X_A	Transformer series reactance [p.u.]
$\vec{X}_{VD}$	Vector of generated random vehicle design parameters
$\vec{Y}$	Linear least square known data vector
$\overline{Y_{EAP}^{(c)}}$	PHEV sample population average EAP generated per vehicle in class- c [kg/veh.]
$\overline{Y_G^{(c)}}$	PHEV sample population average gasoline consumed per vehicle in class- c [gal./veh.]
$Y_{EAP}^{(v,c)}$	Yearly EAP generated by PHEV- v in class- c [kg]
$Y_G^{(v,c)}$	Yearly gasoline usage consumed by PHEV- v in class- c [gal.]
Z_0	Center-tapped single phase transformer high voltage winding impedance [Ω]
Z_1	Center-tapped single phase transformer low voltage winding 1 impedance [Ω]
Z_2	Center-tapped single phase transformer low voltage winding 2 impedance [Ω]
$Z_{\text{base high voltage}}$	High voltage per-unit base impedance value [Ω]
$Z_{\text{base low voltage}}$	Low voltage per-unit base impedance value [Ω]
$Z_{p.u.0}$	Center-tapped single phase transformer high voltage winding impedance [p.u.]
$Z_{p.u.1}$	Center-tapped single phase transformer low voltage winding 1 impedance [p.u.]
$Z_{p.u.2}$	Center-tapped single phase transformer low voltage winding 2 impedance [p.u.]

1. Introduction

Presently, the U.S. is importing crude oil at the rate of 10.0 Mb/day [1.1]. Additionally, approximately 5.1 Mb/day of crude oil are produced domestically [1.1]. Two-thirds (62.9%) of this oil is refined into gasoline and diesel fuel to power U.S. passenger vehicles and trucks [1.2]. Thus, the majority of U.S. passenger vehicles and trucks are fueled by imported oil. A number of options have been proposed to reduce the use of imported oil including: finding more oil, increasing vehicle fuel economy, using ethanol as a vehicle fuel, using conventional hybrid electric vehicles (HEVs), and using plug-in HEVs (PHEVs).

Aftermarket conversion of a currently available HEV into a PHEV is possible today [1.3], suggesting that PHEV technology is feasible for significant levels of market penetration in the near future. PHEVs represent a potentially lucrative new semi-dispatchable load for the electric utility industry.

The key potential benefit to the electric utility industry is the possible addition of a large controllable load. Just under 400 million gallons of gasoline a day are used in the U.S. [1.4]. If PHEV drivers were to charge off peak this additional load would be added with minimal increased need for added generation.

Displacing petroleum usage with electric energy would diversify the transportation sector energy usage. The energy mix used in transportation (Figure 1.1) is 96% petroleum [1.5]. Displacing a small portion of this energy distribution with the energy mixture used in the electric power system (Figure 1.2) has the potential to add three new fuel types to the transportation sector energy mix.

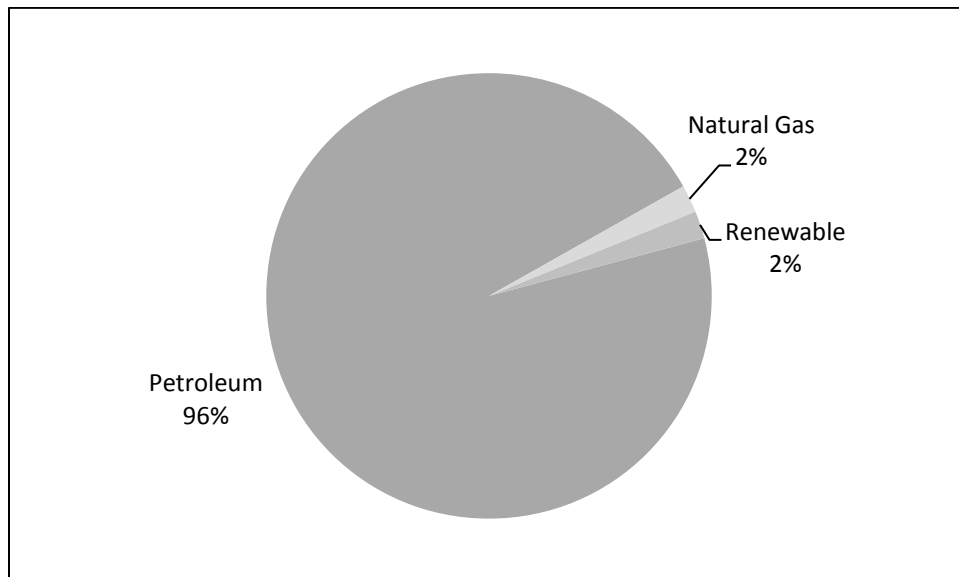


Figure 1.1. Energy mix used in transportation [1.5].

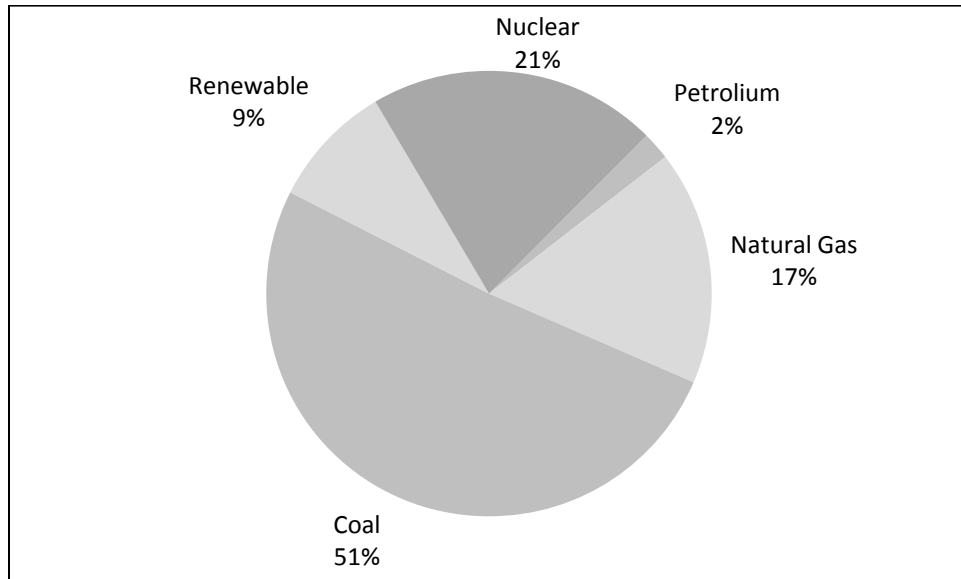


Figure 1.2. Energy mix used in the electric utility industry [1.5].

The remainder of this thesis is organized as follows:

- Related published literature is examined and the context which this thesis fits into the broader research is evaluative (Chapter 2).
- Research into the impact of diversifying the transportation energy mix is described in terms of primary energy source utilization, environmental air pollution (EAP), and gasoline consumption (Chapter 3).
- Research into the potential impact of increased loading on an aging infrastructure is described utilizing a loss-of-life indication on distribution transformers (Chapter 4).
- A summary of the results are included in the conclusion (Chapter 5).

2. Literature Review

Two foci of this research are (1) which power system fuel types will be utilized to meet the added electric energy demand used to charge plug-in hybrid electric vehicles (PHEVs) and (2) what will be the impact of the increased electricity demand on pole top distribution transformers. The first focus includes two related considerations of (1) how many vehicles an existing power system can accommodate and (2) the total system environmental air pollution (EAP) which includes EAP from both the vehicle fleet and from the power system.

2.1 First Focus

The first focus of this research has received much attention in currently available literature. The second focus has received only minimal attention in currently available literature. First, a subset of the currently available literature related to focus number one is introduced. Second, a single document is introduced related to focus number two. Finally, the contribution provided by the present work is summarized.

What impact will charging PHEVs have on the electric power system? This question has been investigated by many research groups, in many different ways, focusing on a number of implications. The questions answered by others include:

- How many vehicles can a power system accommodate?
- Which fuel types will the added load utilize?
- What added EAP will be generated by this new load?
- Can the electric utility infrastructure withstand the potential additional load?

Two investigations which computed the number of vehicles that existing power systems could support found that the percentage of the U.S. light duty vehicle fleet that could be supported was 34% (charging the vehicle between 22:00 and 08:00) [2.1], 43% (charging between 18:00 and 06:00) and 73% (charging all day) [2.2]. The calculations in both reports are quite similar.

Key PHEV assumptions made in both investigations, including vehicle energy required per mile and total miles driven per year, shown in Table 2.1.

Table 2.1. Vehicle assumptions made in penetration level papers.

Report	Total Miles Driven [mi.]	Grid energy required per mile [kWh/mi.]
[2.1]	14,300	0.41
[2.2]	12,000	0.26 – Compact sedan
		0.30 – Mid-size sedan
		0.38 – Mid-size SUV
		0.46 – Full-size SUV

Clear reasons for the discrepancy between these results include more conservative charging time limits in [2.1] then [2.2], more miles driven per year in [2.1] then [2.2], and higher grid energy requirements in [2.1] over every vehicle size in [2.2] except the full size SUV. Each of these factors leads to a lower percentage penetration result in [2.1] then [2.2].

In [2.3] an optimal dispatch charging procedure is outlined and results conclude that 50% penetration of the light duty vehicle fleet, where vehicles derived 40% of their miles from electricity, could be met by existing generation capacity. In this report the vehicle assumptions include an average grid electric energy demand of 0.34 kWh per mile and different average daily driving distances depending on different U.S. regions, from 29.8 miles per day in the southwestern study region to 42.2 miles per day in the central study region. This level of penetration is clearly within the ranges indicated in the first two reports discussed ([2.1], and [2.2]).

Additional research has focused on the impact that charging PHEVs will have on primary energy source utilization, where primary energy source utilization refers to which power system fuel type/s will be utilized to meet the added demand due to PHEV charging. Specifically, investigations have been performed using the Xcel power system [2.4] and the 13 regions specified by the North American Electric Reliability Corporation (NERC) [2.5].

In [2.4], three vehicle types were modeled: conventional vehicles (CVs), HEVs, and PHEV-20s, where PHEV-X indicates a PHEV which is capable of driving X miles using the battery alone. Each vehicles equivalent miles per gallon (MPG) is shown in Table 2.2. The PHEV fuel efficiency was computed using Advanced Vehicle Simulator (ADVISOR) [2.6].

Table 2.2. Vehicle MPG [2.4].

	CV	HEV	PHEV-20
MPG [mi./gal.]	26	36	37

In [2.4] vehicle assumptions include an annual driving distance of 13,900 miles per year, a PHEV grid electric energy demand of 0.36 kWh per mile, and a PHEV battery capacity of 7.2 kWh. Further, in [2.4] four vehicle charging cases were defined:

- Case 1. Uncontrolled charging, which meant each vehicle charged at a rate of 1.4 kW where charging started whenever the vehicle arrived home and charged only at home.
- Case 2. Delayed charging, which meant all vehicles from case 1 are delayed until 10 pm to start charging.
- Case 3. Off-peak charging, which meant utility control of vehicle charging times at a rate of 3.2 kW (providing a least cost scenario).

- Case 4. Continuous charging, which meant each vehicle charged at a rate of 1.4 kW where mid-day charging is capable (providing a maximum amount of electric drive mileage and minimum gasoline case).

Finally, vehicle fleet daily driving performance was based on global positioning satellite (GPS) recorded vehicle data of 227 vehicles in St. Louis, Missouri [2.4]. Results of electricity usage, gasoline consumed, and total fuel costs are shown in Table 2.3. In these results fuel cost is the cost of only gasoline purchasing for CVs and HEVs where as this cost includes both gasoline and electric energy purchasing for the PHEV cases.

Table 2.3. Vehicle performance results [2.4].

	CV	HEV	PHEV Cases 1-3 (Charging once per day)	PHEV Case 4 (Continuous charging)
Electricity Required [kWh] (Daily / Annual)	0	0	5.3 / 1,944	9.4 / 3,530
Annual Gasoline Use [gal.]	535	386	237	145
Annual Fuel Cost [\$]	1,375	993	778	614

The annual fuel cost was computed using \$2.57 per gallon of gasoline and 8.6 cents per kWh electricity rates [2.4]. From the results in Table 2.3, it is clear that total gasoline consumption and annual fuel cost are reduced in all PHEV cases over the CV and HEV operation. Regardless of charging method the annual reduction in gasoline utilization, driving PHEVs versus CV, would be at least 298 gallons of gasoline per vehicle and at least \$597 saved in fuel costs per vehicle.

The primary energy source utilization results in [2.4] include the impact of PHEV charging on the total system load, the EAP emissions (vehicle and power system), and the marginal cost of electricity. This study considered a penetration level of 500,000 vehicles, or equivalently 30% of the light-duty vehicle fleet in the Xcel Energy, Inc. service territory. The power system simulations were computed using Proprietary Hourly Power System Evaluation Model (PROSYM). The PROSYM software computed generator dispatching, on an hourly basis, and generated EAP for each of the four charging cases [2.4].

The 2005 power system generating mix and energy generated for all of Colorado based on fuel type is shown in Figures 2.1 and 2.2. Xcel Energy, Inc. serves approximately 55% of the total Colorado population and supports 55% of the total Colorado annual electricity demand.

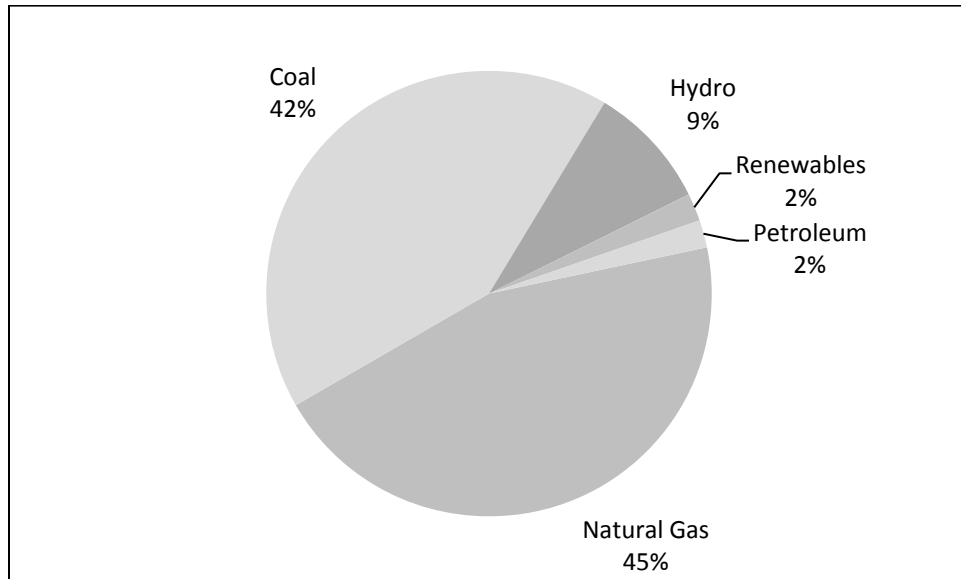


Figure 2.1. 2005 electric power system generation capacity by fuel type for Colorado [2.4].

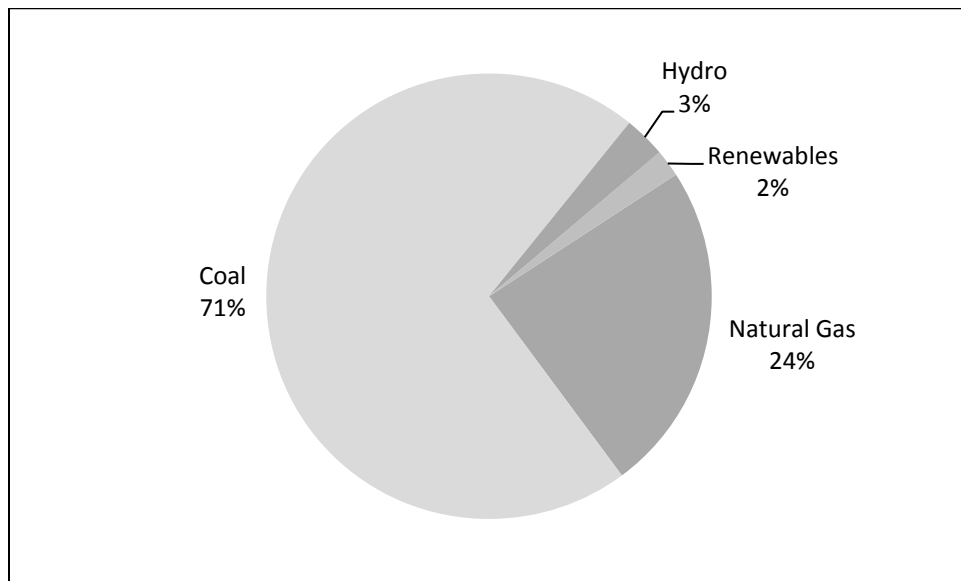


Figure 2.2. 2005 electric power system energy generation by fuel type for Colorado [2.4].

In [2.4] results showed the percent of energy from each generator type for the four charging cases. The three generator types considered were simple cycle and other gas (reciprocating and steam units); combined cycle gas; and coal. The percentage of energy produced from each generator type for each charging scenario is shown in Figure 2.3.

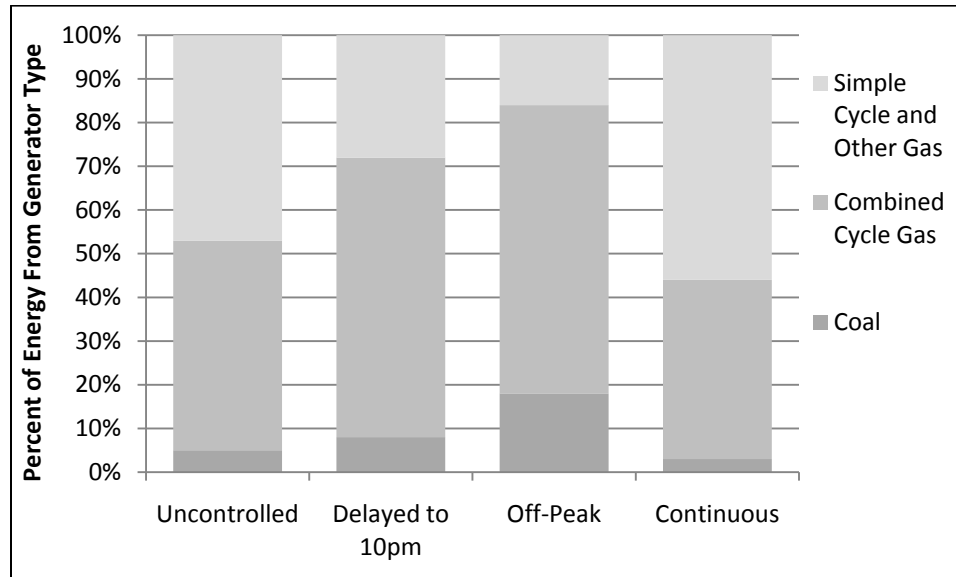


Figure 2.3. Generator type used to charge PHEV in the Xcel service area [2.4].

This analysis showed that natural gas is utilized to meet the majority of the PHEV charging load. Also, as the PHEV charging load is shifted later in the evening and off peak the coal utilization increased. Further results drawn in this work include a small decrease in total NO_x generated and a significant reduction in total CO_2 . Next, the investigation of the 13 regions specified by the NERC in terms of PHEV primary energy source utilization [2.5] is described.

In [2.5] an analysis is provided of primary energy source utilization due to PHEV charging for each of the 13 NERC regions of the U.S. This analysis utilized the Oak Ridge Competitive Electricity Dispatch (ORCED) model to compute primary energy source utilization and power system EAP generated. This analysis included two different charging time considerations and three different charging rates. The first charging time was called “evening” and was defined by PHEV charging starting at 5 pm and the second charging time scenario was called “night” and was defined by PHEV charging starting at 10 pm. The three charging rates were 120V/15A (1.4kW), 120V/20A (2kW), and 220V/30A (6kW). All PHEV charging included nine hours of charging. Two future time frames were simulated. The first time frame was in the year 2020 and the second in the year 2030. The projected level of PHEV penetration in 2020 was estimated to be 19.58% and in 2030 was estimated to be 50.39%.

This report [2.5] documented results for all 13 NERC regions. The results summarized here are the sum of the results for all 13 regions. The *power* generating capacity for the 13 regions projected to 2020 is shown in Figure 2.4. The base case *energy* generated for the 13 regions in 2020 is shown in Figure 2.5. Comparable figures for 2030 are Figures 2.6 and 2.7. In each of these figures ST, CT, and CC represent steam turbines, combustion turbines and combined cycle generation plants respectively.

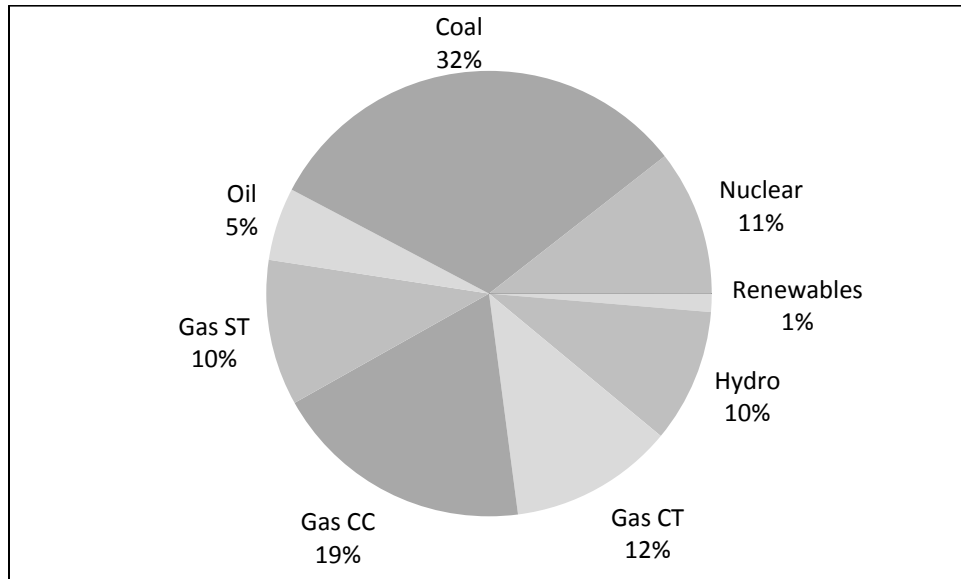


Figure 2.4. Projected power generating capacity in 2020 [2.5].

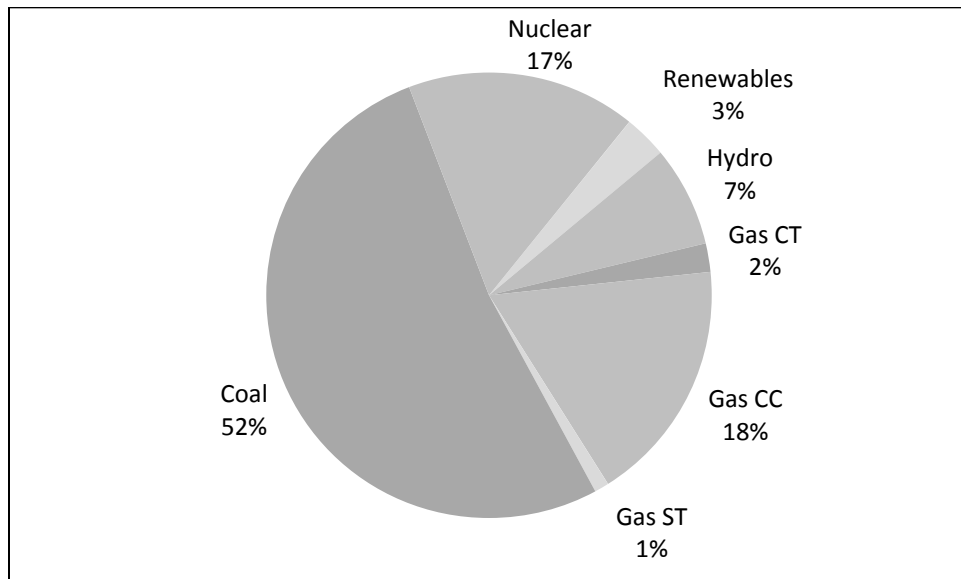


Figure 2.5. Computed base case energy generated in 2020 [2.5].

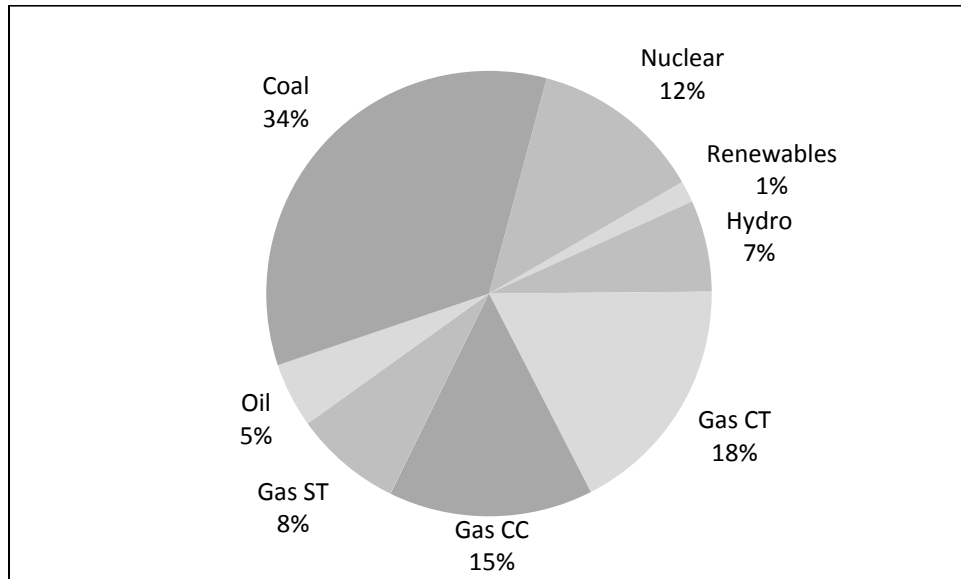


Figure 2.6. Projected power generating capacity in 2030 [2.5].

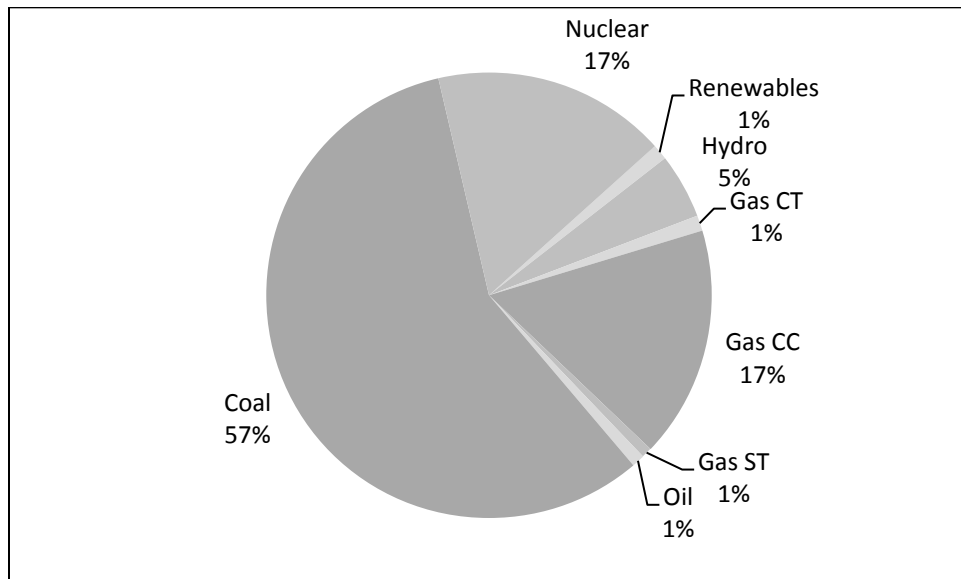


Figure 2.7. Computed base case energy generated in 2030 [2.5].

This investigation [2.5] compared the projected primary energy source utilization and EAP generated with and without PHEV penetration in the years 2020 and 2030 for each charging scenario. Vehicle assumptions included daily driving distance of 20 miles per day, PHEVs operated in an all electric driving mode, and a HEV fuel efficiency of 40 MPG. The primary energy source utilization results from this investigation for each charging scenario are summarized in Figures 2.8 and 2.9 for the 2020 and 2030 results

respectively. In each of these figures the projected increase in energy generated for each fuel type is shown.

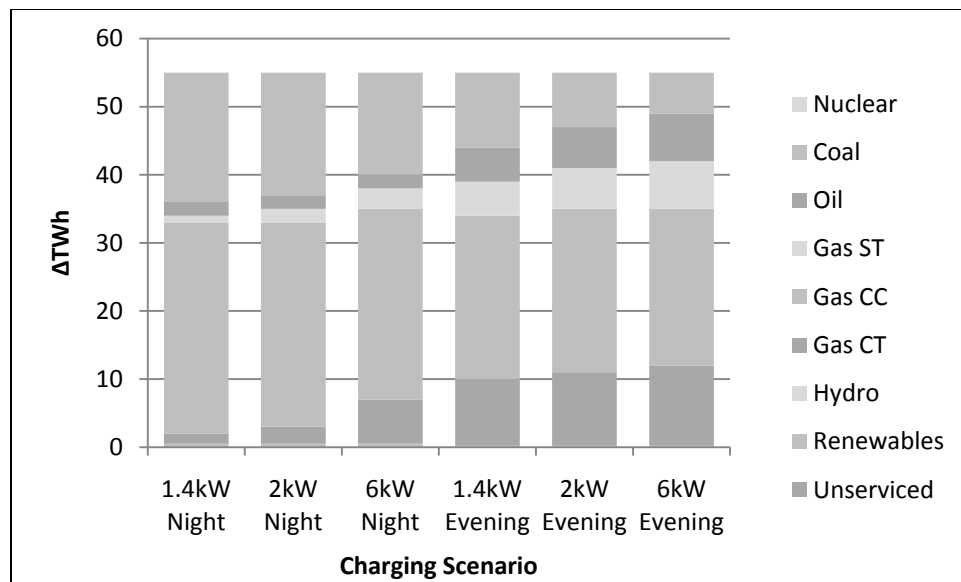


Figure 2.8. Computed increase in energy per fuel type for 2020 [2.5].

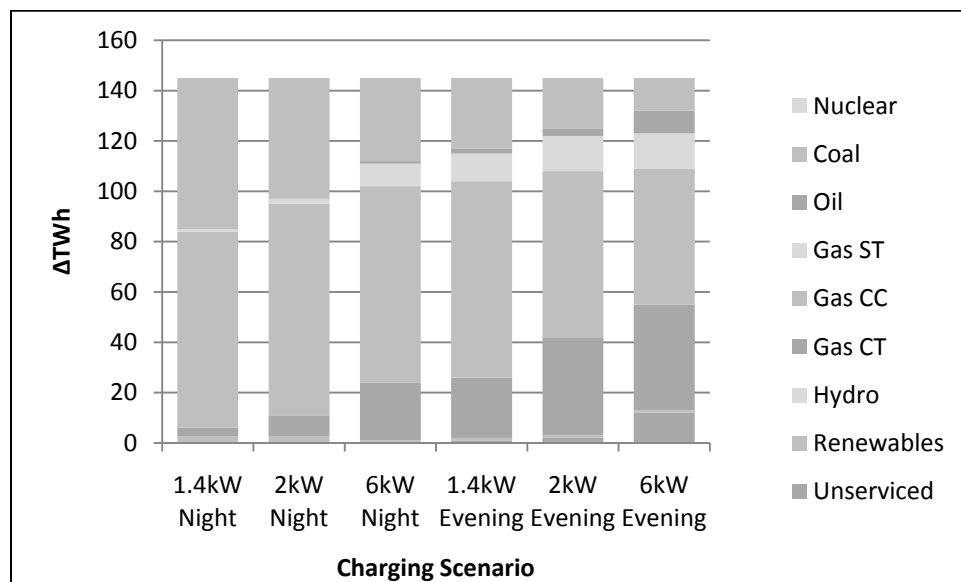


Figure 2.9. Computed increase in energy per fuel type for 2030 [2.5].

In both time frames 2020 and 2030 and all charging scenarios, the three most utilized fuel types were gas CC, gas CT and coal. Emission results showed CO₂ emissions slightly higher in most NERC regions, contradicting the CO₂ results in [2.4]. The generation of the other two pollutants considered, NO_x and SO₂, were limited by regulation caps. This

limitation invalidates any comparison of emission results between studies for NO_x and SO₂. Next, an additional study of EAP effects of PHEV use is summarized.

In [2.7] nine scenarios of annual CO₂ emission scenarios were simulated. The nine scenarios were all possible combinations of three levels of power system CO₂ emission intensity and three levels of PHEV penetration levels. From the nine scenarios the following conclusions were drawn:

- CO₂ emissions decreased significantly in each of the nine scenarios.
- The maximum of CO₂ reduction was achieved with the combination of high PHEV penetration and the low power system CO₂ intensity.
- Cumulative CO₂ emission reductions were simulated in the range of 3.4 to 10.3 billion tons. The simulation operated in the time span of 2010 through 2050.
- Regionally each area of the country will have CO₂ reductions.
- The common reduction in CO₂ for each regional area was contradicted in [2.5] where emission levels did not follow any consistent pattern.

The modeling in [2.7] simulated the evolution of the power system and transportation utilization over the 2010 to 2050 time span. The power system model was a combination of the Energy Information Agency's (EIA) National Energy Modeling System (NEMS) [2.8] and the Electric Power Research Institute (EPRI) National Electric System Simulation Integrated Evaluator (NESSIE). The transportation utilization modeled both vehicle emissions and market adoption of PHEVs.

Additional research literature which investigated the impact that PHEV operation will have on EAP production includes [2.9], [2.10], and [2.11]. These investigations lack an analysis of EAP produced from the electric power system, thus missing half of the picture when comparing the operation of PHEVs with the use of CVs. Next, literature documenting the impact of PHEV charging on the electric infrastructure is introduced.

2.2 Second Focus

Thus far, the mentioned research has focused on (1) the number of vehicles an existing power system idle generation capacity can accommodate, (2) the primary energy source utilization of PHEV charging, and (3) the EAP produced by PHEV utilization. The question remains what, if any, impact will PHEV charging have on the electric power infrastructure itself? The potential impact was quantified in [2.12].

An advantage of a higher utilization factor of the electric power utility, achievable with the use of PHEVs [2.1], [2.2], and [2.3], is "an efficiency gain, distributing average costs over a greater number of kilowatt-hours" [2.12]. However, oil-cooled transformers rely on common utilization patterns to avoid the detrimental effects of overheating. In [2.12] the transformers temperature and life expectancy were modeled using a Montsinger equation. Further, a sensitivity analysis of the modeled transformer temperature indicated that, "the current transformer designs may represent a significant constraint with respect to integration PHEVs into central-station power systems" [2.12].

In summary, a review of the literature shows that existing reserve capacity is capable of supporting a sizable portion of the light duty vehicle fleet replaced by PHEVs, the added electric energy will be met by primary energy sources depending on the generating mix, mixed EAP results, and oil-cooled transformers may represent a constraint on integrating PHEVs into the existing infrastructure.

This thesis adds to the existing body of research by (1) developing a probabilistic analysis of the well documented topic of PHEV primary energy source utilization, (2) quantifying the loss-of-life of pole top transformers using probabilistic simulations.

The impact of PHEV charging on primary energy source utilization is described next.

3. Impact of PHEV charging on Primary Energy Source Utilization

To quantify where the electric energy used to charge plug-in hybrid electric vehicles (PHEVs) is generated, a probabilistic simulation program was developed. Two key steps of this simulation program include vehicle fleet simulations and power system simulations. The vehicle fleet simulations compute the amount of added electric load demand to charge the PHEV fleet, the amount of gasoline used by both internal combustion (IC) vehicles and PHEVs, and the amount of environmental air pollution (EAP) generated by both IC vehicles and PHEVs. The power system simulations simulate how much fuel usage and subsequent EAP are generated by a specific power system. The specific power system simulation is based on the Probabilistic Production Costing (PPC) [3.1] power system simulation procedure.

3.1 Probabilistic Simulation of an Integrated Power System with Distributed PHEVs Methodology

A top level block diagram of the probabilistic simulation program is shown in Figure 3.1.

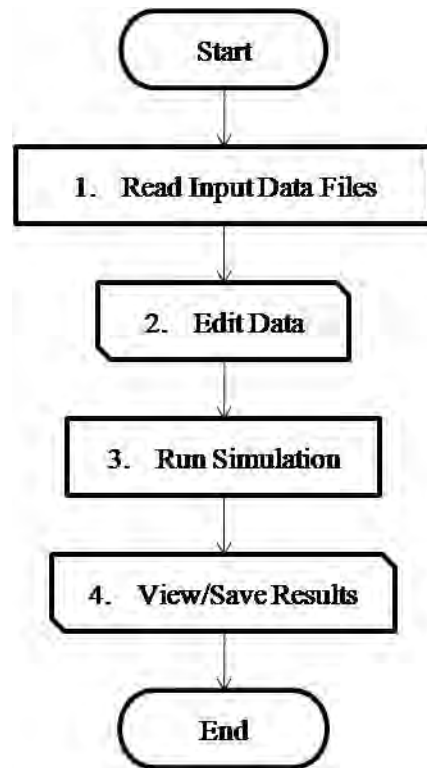


Figure3.1. Simulation overview block diagram.

In Figure 3.1 step 1 is initiated when an input file is opened, step 2 is an optional step where the program user may or may not edit the input data, step 3 is broken into four sub-steps shown in Figure 3.2, and step 4 is an optional step where the program user may or may not view or save the simulation results.

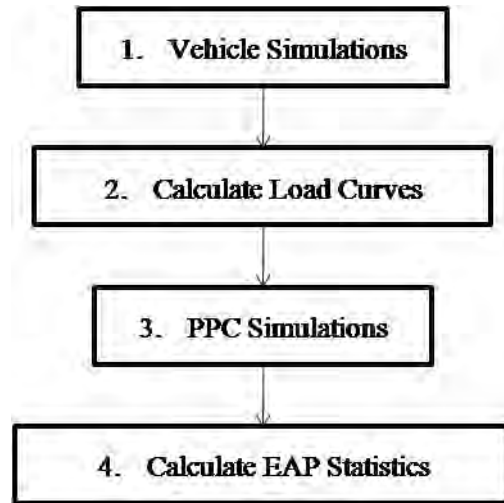


Figure 3.2. Simulation sub-steps block diagram.

Each sub-step in Figure 3.2 is used to perform the probabilistic simulation. Specifically, sub-step 1 initializes the vehicle fleet performance metrics, generates the vehicle operation distributions, and computes the gasoline usage statistics. Sub-step 2, computes the chronological load demand curves and the normalized inverted load duration curves (NILDCs). Sub-step 3, performs the PPC power system simulation procedure. Sub-step 4, computes the IC vehicle EAP and PHEV EAP statistics.

In the reminder of this section:

- The vehicle fleet simulations are fully described.
- The power system load curve calculation method is fully described.
- The power system simulations are fully described.

3.1.1 Vehicle Simulation

In the first sub step of Figure 3.2 the vehicle fleet parameters are computed based on vehicle simulations performed using Powertrain System Analysis Toolkit (PSAT) version 6.2, developed by DOE's Argonne National Labs [3.2]. In PSAT the simulation of IC and hybrid powertrains generate vehicle operational data from which IC vehicle and PHEV models are developed. Full PSAT results are shown in Appendix 1, and this data is utilized to compute the results below.

Four vehicle classes were arbitrarily selected to provide a diverse vehicle fleet representative of what a real vehicle fleet could look like in the future. The following vehicles were used as inspiration for each class:

- Class 1: Honda Civic and Ford Focus.
- Class 2: Honda Accord and Ford Taurus.
- Class 3: Ford Explorer and Ford F-150.
- Class 4: Chevrolet Suburban and Chevrolet Silverado.

Once the complete vehicle models had been selected, PSAT simulated the operation of the modeled vehicles over specified driving schedules. Three drive schedules Highway Fuel Economy Test (HWFET), Urban Dynamometer Driving Schedule (UDDS), and the updated federal test driving cycle (US06) were selected to generate varied results representative of an entire vehicle fleet. First the PSAT IC vehicle results are described followed by the PSAT PHEV results.

3.1.1.1 Vehicle Fleet Performance Metrics

The PSAT IC vehicle simulations resulted in fuel efficiency, NO_x generated per mile driven, and CO₂ generated per mile driven for each vehicle class over each of the three drive cycles (Table A.5). To compute a single estimate, for each of the performance metrics (fuel efficiency, NO_x generated per mile driven, and CO₂ generated per mile driven), for each vehicle class (classes 1-4) a weighted average of the results for each drive cycle is computed. The US06 drive cycle represents more modern driving and as such is weighted 50%. The remaining 50% is split 55% UDDS and 45% HWFET analogous to the comprehensive EPA fuel efficiency. The resulting weighted average performance metric for each class is shown in Table 3.1.

Table 3.1. PSAT IC results for each vehicle class.

Class	1	2	3	4
MPG [mi./gal.], $IC_{MPG}^{(c)}$	27.58	23.52	15.17	11.89
NO _x generated per mile [kg/mi.], $IC_{NOx}^{(c)}$	1.643E-04	1.904E-04	2.778E-04	3.253E-04
CO ₂ generated per mile [kg/mi.], $IC_{CO2}^{(c)}$	0.3300	0.3884	0.6016	0.7656

Next, the PHEV PSAT results are described. No mass production PHEVs are currently available thus the performance metrics including energy required per mile, gasoline efficiency, and EAP generated per mile are approximated based on PSAT simulation results.

PSAT simulations were performed for each vehicle class over each drive cycle and varying the amount of drive energy supplied from the vehicles battery. The variable amount of driving energy supplied from the vehicles battery was defined as k_{PHEV} ($k_{PHEV} \in [0,1]$). This parameter is defined such that, $k_{PHEV} = 0$ represented a charge sustaining hybrid i.e. on average all of the drive energy came from gasoline and $k_{PHEV} = 1$ represented a pure battery electric vehicle (BEV) i.e. all of the drive energy came from electricity.

The vehicle simulation methodology utilizes randomly generated vehicle design parameters including k_{PHEV} . To facilitate simulating PHEV operation without a priori knowledge of the exact value of k_{PHEV} performance metric functions (3.1 - 3.4) are approximated based on the discrete PSAT results (Tables A.1 - A.4). The method to compute the functional relations is described next.

$$E^{(c)}(k_{PHEV}) = A_E^{(c)} \cdot (k_{PHEV})^{B_E^{(c)}} \quad (3.1)$$

$$1/MPG^{(c)}(k_{PHEV}) = A_{GPM}^{(c)} \cdot (1 - k_{PHEV})^{B_{GPM}^{(c)}} \quad (3.2)$$

$$NO_x^{(c)}(k_{PHEV}) = A_{NOx}^{(c)} \cdot (1 - k_{PHEV})^{B_{NOx}^{(c)}} \quad (3.3)$$

$$CO_2^{(c)}(k_{PHEV}) = A_{CO2}^{(c)} \cdot (1 - k_{PHEV})^{B_{CO2}^{(c)}} \quad (3.4)$$

Each performance metric function is a function of the vehicle design parameter k_{PHEV} and the vehicle class- c . In (3.1), $E^{(c)}(k_{PHEV})$ is the required energy per mile driven [kWh/mi.] and values of the function parameters $A_E^{(c)}$ [kWh/mi.] and $B_E^{(c)}$ are given in Table 3.2. In (3.2), $MPG^{(c)}(k_{PHEV})$ is the fuel efficiency [mi./gal.] and values of the function parameters $A_{GPM}^{(c)}$ [gal./mi.] and $B_{GPM}^{(c)}$ are given in Table 3.3. In (3.3), $NO_x^{(c)}(k_{PHEV})$ is the generated NOx per mile driven [kg/mi.] and values of the function parameters $A_{NOx}^{(c)}$ [kg/mi.] and $B_{NOx}^{(c)}$ are given in Table 3.4. In (3.4), $CO_2^{(c)}(k_{PHEV})$ is the generated CO2 per mile driven [kg/mi.] and values of the function parameters $A_{CO2}^{(c)}$ [kg/mi.] and $B_{CO2}^{(c)}$ are given in Table 3.5.

Table 3.2. PHEV grid energy per mile function parameters for each vehicle class.

Class	A_E [kWh/mi.]	B_E
1	0.3790	0.4541
2	0.4288	0.4179
3	0.6720	0.4040
4	0.8180	0.4802

Table 3.3. PHEV fuel efficiency (1/MPG) function parameters for each vehicle class.

Class	A_{GPM} [gal./mi.]	B_{GPM}
1	0.0268	1.901
2	0.0329	1.892
3	0.0505	1.884
4	0.0547	1.844

Table 3.4. PHEV NO_x generated per mile function parameters for each vehicle class.

Class	A_{NOx} [kg/mi.]	B_{NOx}
1	1.341E-04	1.752
2	1.642E-04	2.113
3	2.209E-04	1.751
4	2.500E-04	1.501

Table 3.5. PHEV CO₂ generated per mile function parameters for each vehicle class.

Class	A_{CO_2} [kg/mi.]	B_{CO_2}
1	0.2423	1.916
2	0.2954	1.895
3	0.4555	1.875
4	0.4907	1.839

The function parameters (Tables 3.2 - 3.5) are estimated from the discrete PSAT results (Tables A.1 - A.4) using a weighted nonlinear least squares approximation method. Specifically, MATLABs function *lsqnonlin* [3.3] is used to compute the approximation function parameters.

Each drive cycle PSAT data and resulting weighted average performance metric function for the Class 2 data is shown in Figure 3.3 for the grid electric energy, in Figure 3.4 for the fuel efficiency, in Figure 3.5 for the NO_x generated per mile, and in Figure 3.6 for the CO₂ generated per mile. In Figures 3.3 - 3.6 the discrete drive cycle data is shown with data markers and dashed lines, the weighted continuous approximations are shown with a solid line.

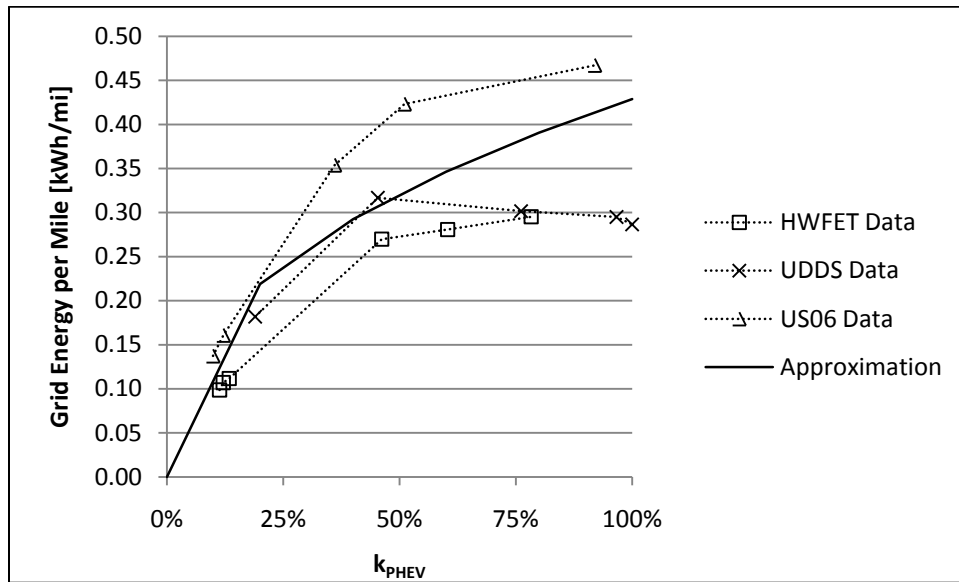


Figure 3.3. Class 2 PSAT discrete data and weighted average for the required grid energy performance metric.

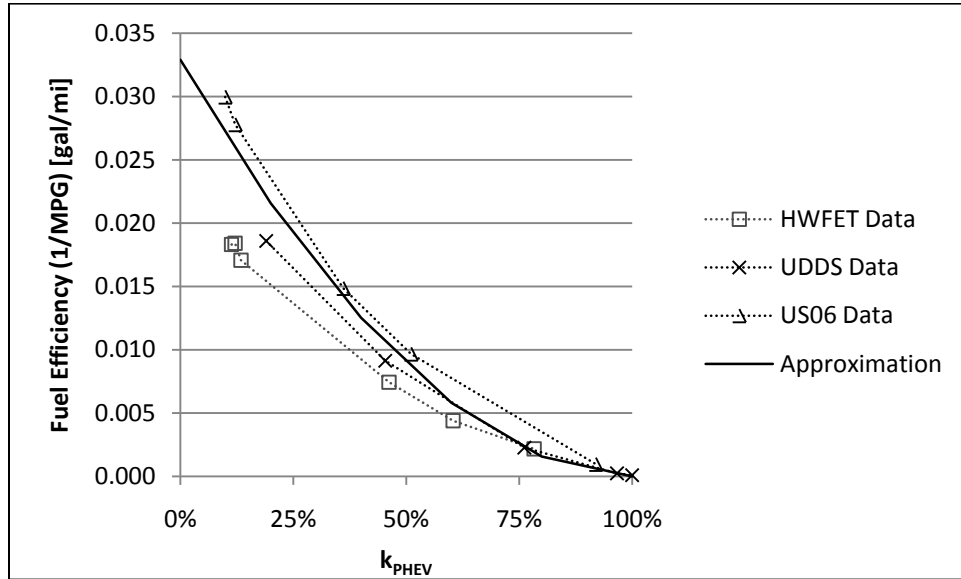


Figure 3.4. Class 2 PSAT discrete data and weighted average for the fuel efficiency performance metric.

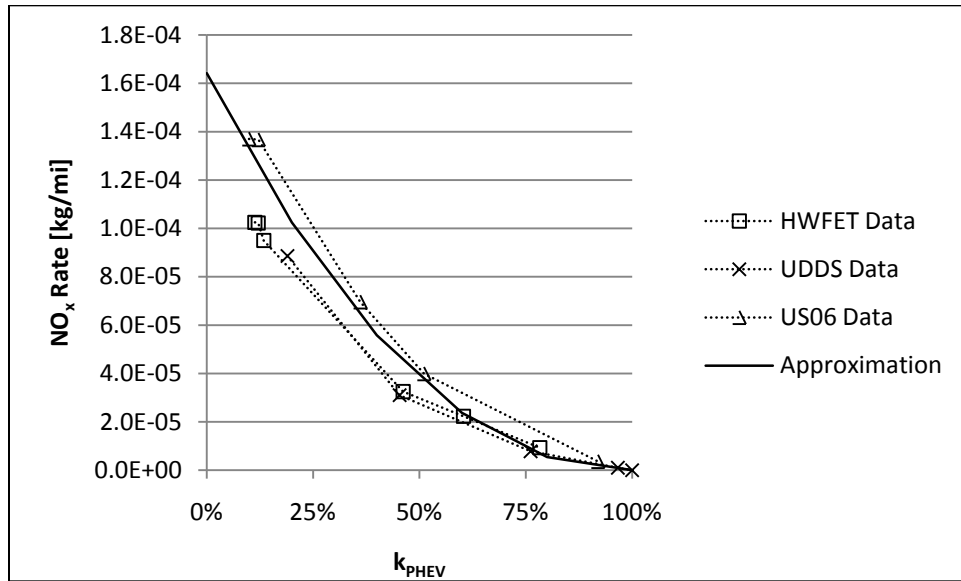


Figure 3.5. Class 2 PSAT discrete data and weighted average for the NO_x rate performance metric.

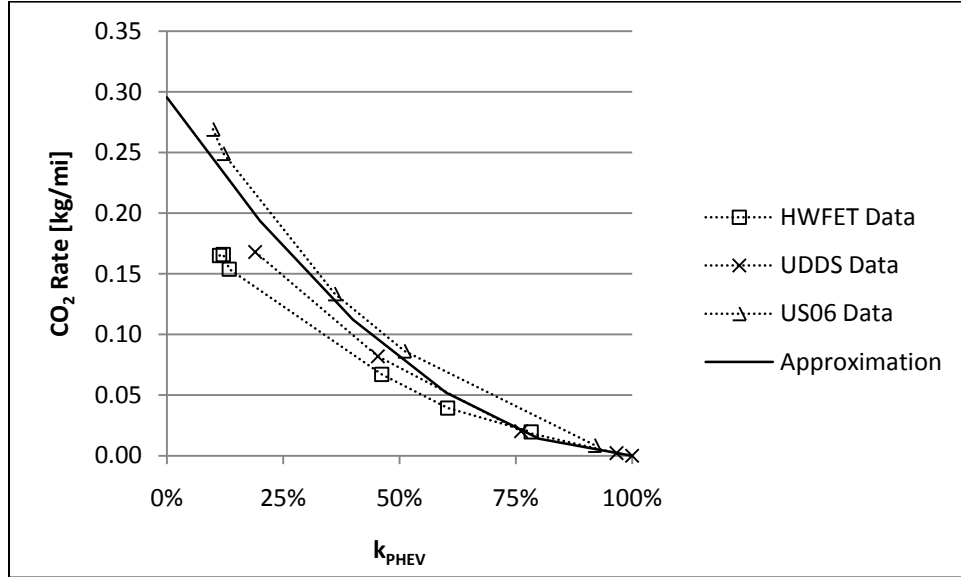


Figure 3.6. Class 2 PSAT discrete data and weighted average for the CO₂ rate performance metric.

The weighted average performance metric functions (3.1 - 3.4) are computed with the same weighting as the IC data results (50% US06, 27.5% UDDS, and 22.5% HWFET). The most accurate approximation of the PHEV energy per mile (3.1) for each class is a power trend line. In Figure 3.3 the approximated power function (3.1) closely matches the PSAT discrete data over the entire range of k_{PHEV} and when evaluated at $k_{PHEV} = 0$ evaluates to zero electrical energy required per mile driven as expected for a charge sustaining HEV. All other performance metrics are approximated with shifted power functions. In figures 3.4 through 3.6 the shifted approximation functions closely match the PSAT discrete data over the entire range of k_{PHEV} . These approximation functions (3.2 - 3.4) are shifted so that at $k_{PHEV} = 1$, and these functions then evaluate to zero. Thus, a BEV ($k_{PHEV} = 0$) requires no gasoline per mile driven (3.2) and produces no NO_x (3.3) nor CO₂ (3.4) per mile driven.

The weighted average performance metric function (3.1 - 3.4) for each vehicle class are shown in Figure 3.7 for the grid energy per mile approximations (3.1), in Figure 3.8 for the fuel efficiency approximations (3.2), in Figure 3.9 for the NO_x rate approximations (3.3), and in Figure 3.10 for the CO₂ rate approximations (3.4).

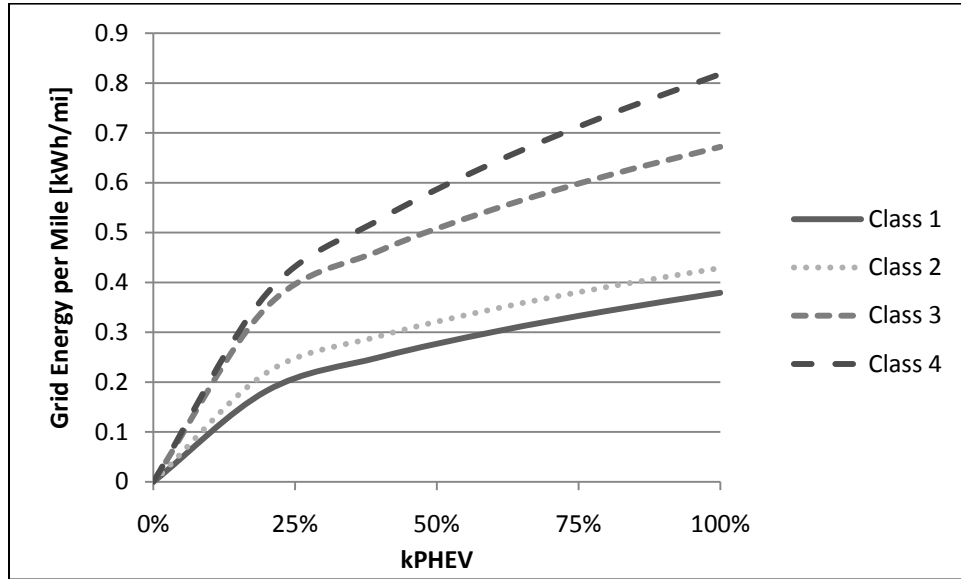


Figure 3.7. Average PHEV grid energy per mile approximation for each PHEV class.

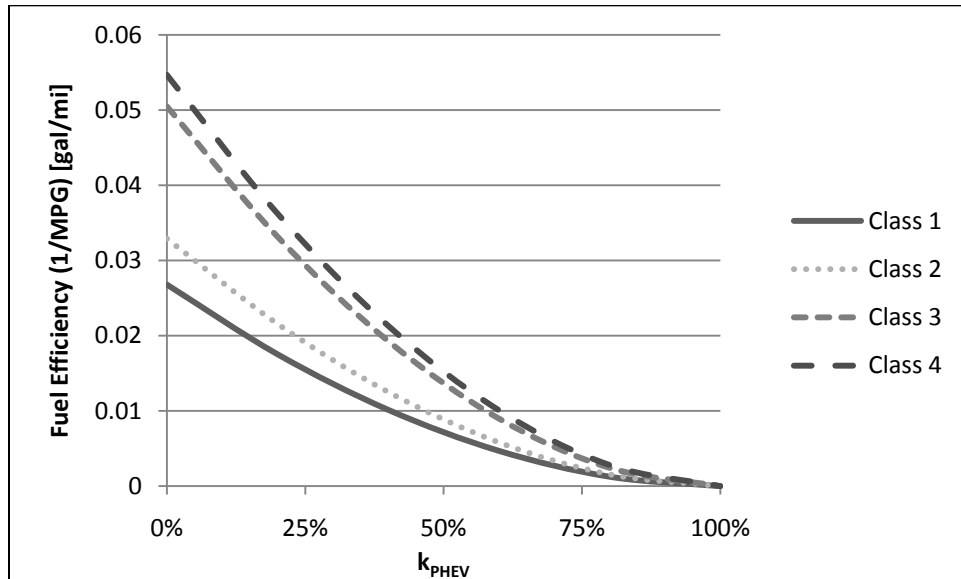


Figure 3.8. Average PHEV fuel efficiency approximations for each PHEV class.

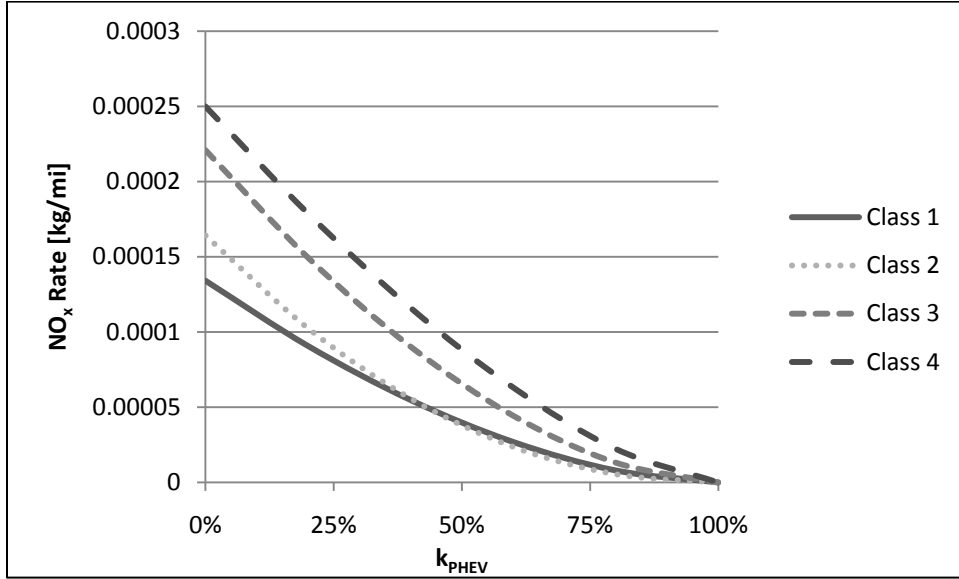


Figure 3.9. Average PHEV NO_x rate approximation and for each PHEV class.

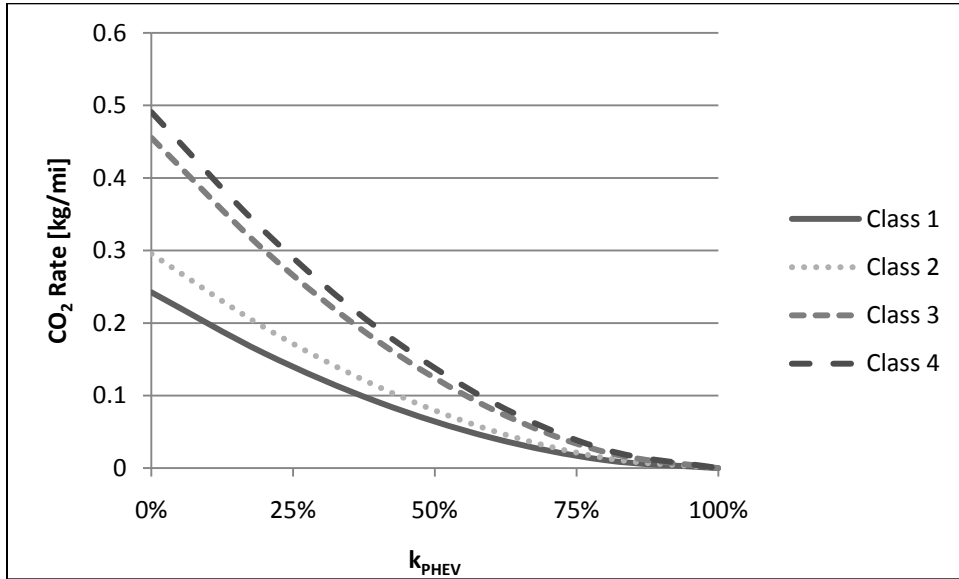


Figure 3.10. Average PHEV CO₂ rate approximation and for each PHEV class.

In figures 3.7 through 3.10 all of the weighted approximations follow a strict ranking by class, except the NO_x rate approximation functions (Figure 3.9) for PHEV classes 1 and 2. There is a crossover between these two classes of NO_x rate approximation functions at approximately 50% k_{PHEV} . This result is realistic because the two vehicle classes are similar in size and performance.

The two-mode PHEV control strategy is optimized to maximize the benefits of PHEVs for an optimal trip length of M_E^* miles. The two modes are a charge depleting mode and a

charge sustaining mode ($k_{PHEV} = 0$). The charge depleting mode is used initially when the vehicles battery is relatively fully charged. On trips (times between charging) longer than M_E^* , after the battery is depleted (to a specified lower level) the charge sustaining mode is utilized. The charge sustaining mode relies on gasoline to maintain a constant average state-of-charge where on average all the energy used to drive the PHEV comes from gasoline. The driving distance in the charge depleting mode is called the charge depleting distance $M_E^{(c)}$ (miles). The charge depleting distance for each vehicle class- c ($c \in \{1,2,3,4\}$), $M_E^{(c)}$, is calculated, in (3.5), as a function of the useable battery capacity, $BC^{(c)}$ [kWh], assumed to be a random variable (RV) within the battery capacity ranges defined in Table 3.6 for each vehicle class, and the vehicles required grid energy per mile, $E^{(c)}(k_{PHEV})$.

$$M_E^{(c)} = BC^{(c)} / E^{(c)}(k_{PHEV}) \quad (3.5)$$

Table 3.6. Battery capacity range for each vehicle class [kWh].

Class	$BC_{\max}^{(c)}$ [kWh]	$BC_{\min}^{(c)}$ [kWh]
1	12	8
2	14	10
3	21	17
4	23	19

From $BC^{(c)}$ (Table 3.6) and M_E^* a formula for the vehicle design parameter k_{PHEV} can be derived. Substituting (3.1) into (3.5) results in

$$M_E^{(c)} = BC^{(c)} / \left[A_E^{(c)} \cdot \left(k_{PHEV}^{(c)} \right)^{B_E^{(c)}} \right] \quad (3.6)$$

which can be rearranged to solve for $k_{PHEV}^{(c)}$ as

$$k_{PHEV}^{(c)} = \left[BC^{(c)} / \left(A_E^{(c)} \cdot M_E^* \right) \right]^{1/B_E^{(c)}} \quad (3.7)$$

The ranges of $k_{PHEV}^{(c)}$ for each vehicle class can be computed from (3.7), an M_E^* value of 40 miles, and the battery capacity ranges in Table 3.6. An M_E^* value of 40 is selected to provide typical results for approximately 75% of average U.S. driver's daily commutes [3.4]. The computed ranges of k_{PHEV} are shown in Table 3.7. The parameter $k_{PHEV}^{(c)}$ represents the percentage of energy per mile on average which comes from a PHEV in class- c battery in the assumed vehicle control strategy during the charge depleting mode.

Table 3.7. Computed k_{PHEV} range for each vehicle class.

Class	$k_{PHEV,max}^{(c)}$	$k_{PHEV,max}^{(c)}$
1	0.5976	0.2447
2	0.6151	0.2750
3	0.5428	0.3217
4	0.4800	0.3224

The values in Tables 3.6 and 3.7 form the basis of one of the three random vehicle fleet parameters described next.

3.1.1.2 Vehicle Operation Distributions

The following three vehicle parameters are based on random distributions.

1. PHEV vehicle class populations.
2. PHEV design parameters k_{PHEV} and battery capacity.
3. Daily driving distance, departure time, and arrival time.

This section of the thesis introduces the RV distributions for each of the vehicle parameters, motivates why the particular distribution type and parameters are selected, and describes the method used to generate the RVs in the simulation program.

The vehicle fleet is distributed into the four vehicle classes based on the assumed vehicle class distribution $p^{(c)}$. The number of vehicles in each vehicle class is the total number of vehicles in the power system area, N_T , times the percentage of vehicles in each class, $p^{(c)}$, shown in Table 3.8.

Table 3.8. IC vehicle class distribution [3.3].

Class 1	Class 2	Class 3	Class 4
0.20	0.30	0.30	0.20

The first RV distribution is the number of PHEVs in each vehicle class. The level of PHEV penetration is defined as P_{PHEV} . The total number of PHEVs with P_{PHEV} penetration is $N_T \cdot P_{PHEV}$. The number of PHEVs in each vehicle class is normally distributed with mean $\mu^{(c)}$ and variance $(\sigma^{(c)})^2$. Where $\mu^{(c)}$ is $N_T \cdot P_{PHEV} \cdot p^{(c)}$ and $(\sigma^{(c)})^2$ is $\alpha_p \cdot \mu^{(c)}$ (by default $\alpha^{(c)}$ is 1%). The normal distribution is selected because normal distributions often occur naturally. Thus, this distribution realistically models random consumer behavior. The specific values for mean and variance are arbitrarily selected.

The Box-Müller method, in (3.8) is used to compute normally distributed RVs [3.5]

$$N = \sqrt{-2 \cdot \ln(U_1)} \cos(2 \cdot \pi \cdot U_2) \quad (3.8)$$

where, N is a standard normal value (a normal RV with a mean of zero and a variance of one), U_1 and U_2 are independent and identically distributed (IID) pseudo random numbers distributed uniformly over the range (0,1]. U_1 and U_2 are generated using the C function $rand()$. The vehicle class population is then computed

$$N_{PHEV}^{(c)} = \mu^{(c)} + \sigma^{(c)} \cdot N \quad (3.9)$$

where the result $N_{PHEV}^{(c)}$ is normally distributed with mean $\mu^{(c)}$ and standard deviation $\sigma^{(c)}$.

The next set of RV distributions is the vehicle design parameters $k_{PHEV}^{(c)}$ and usable battery capacity $BC^{(c)}$ [kWh]. The random vehicle design parameters are assumed to be distributed according to a bivariate normal distribution with mean vector $\vec{\mu}$ and covariance matrix Σ . The bivariate normal distribution is selected because of the ability to include parameter correlation. Using the specified ranges of k_{PHEV} and $BC^{(c)}$, given in Tables 3.6 and 3.7, $\vec{\mu}$ and Σ are calculated. The correlation between $k_{PHEV}^{(c)}$ and $BC^{(c)}$ ρ is arbitrarily set to 0.8. This correlation represents the intuitive relationship between the design parameters $k_{PHEV}^{(c)}$ and $BC^{(c)}$. The correlation coefficient is arbitrarily selected with added consideration that Σ be positive definite so that a Cholesky decomposition [3.6] of Σ can be computed.

As an example of how the bivariate normal values are generated, the calculations for the Class 2 vehicle design parameters are shown below in detail. First, the bivariate distribution parameters $\vec{\mu}^{(2)}$ and $\Sigma^{(2)}$ are calculated

$$\vec{\mu}^{(2)} = \begin{bmatrix} (k_{PHEV,max}^{(2)} + k_{PHEV,min}^{(2)})/2 \\ (BC_{max}^{(2)} + BC_{min}^{(2)})/2 \end{bmatrix} \quad (3.10)$$

$$= \begin{bmatrix} (0.6151 + 0.2750)/2 \\ (14 + 10)/2 \end{bmatrix} = \begin{bmatrix} 0.4451 \\ 12 \end{bmatrix}$$

$$\sigma_{kPHEV}^{(2)} = (k_{PHEV,max}^{(2)} - k_{PHEV,min}^{(2)})/4 \quad (3.11)$$

$$= 0.6151 - 0.2750/4 = 0.0850$$

$$\sigma_{BC}^{(2)} = (BC_{max}^{(2)} - BC_{min}^{(2)})/4 \quad (3.12)$$

$$= (14 - 10)/4 = 1 \text{ kWh}$$

$$\Sigma^{(2)} = \begin{bmatrix} \sigma_{kPHEV}^2 & \rho \cdot \sigma_{kPHEV} \cdot \sigma_{BC} \\ \rho \cdot \sigma_{kPHEV} \cdot \sigma_{BC} & \sigma_{BC}^2 \end{bmatrix} \quad (3.13)$$

$$= \begin{bmatrix} 0.0882^2 & 0.8 \cdot 0.0882 \cdot 1 \\ 0.8 \cdot 0.0882 \cdot 1 & 1^2 \end{bmatrix}$$

$$= \begin{bmatrix} 0.0072 & 0.0680 \\ 0.0680 & 1 \end{bmatrix}$$

Next, the Cholesky decomposition is used to decompose the covariance matrix into a lower triangular matrix $\mathbf{B}$, where

$$\Sigma = \mathbf{B} \cdot \mathbf{B}^T \quad (3.14)$$

and specifically, for Class 2

$$\mathbf{B}^{(2)} = \begin{bmatrix} 0.0850 & 0 \\ 0.8 & 0.6 \end{bmatrix}$$

Then, a vector of two standard normal values $\vec{N}$ is generated using (3.8). Finally, the desired multivariate normal distribution is calculated

$$\vec{X}_{VD} = \begin{bmatrix} k_{PHEV}^{(2)} \\ BC^{(2)} \end{bmatrix} = \vec{\mu} + \mathbf{B} \cdot \vec{N} \quad (3.15)$$

Similar calculations are performed for each vehicle class.

The last set of RVs is those associated with the daily vehicle performance: miles driven per day $M^{(v,d)}$ [mi], vehicle departure time $D_T^{(p)}$ [h], and vehicle arrival time $A_T^{(p)}$ [h]. The miles driven per day are distributed log-normal RVs with mean μ_m of 3.37 and standard deviation σ_m of 0.5 [3.7], the vehicle timing distributions are normally distributed RVs with parameters shown in Table 3.9. The parameter p in the distribution parameters mean $\mu_T^{(p)}$ [h] and variance $(\sigma_T^{(p)})^2$ [h] indicates one of the four possible daily timing distributions: weekday departure, weekend departure, weekday arrival, or weekend arrival.

Table 3.9. Vehicle departure and arrival time distribution parameters.

	Departure		Arrival	
Parameter	Weekday	Weekend	Weekday	Weekend
$\mu_T^{(p)}$ [h]	7	9	18	15
$(\sigma_T^{(p)})^2$ [h]	3	6	3	6

The log normal distribution is selected because of the correlation between the shape of a log normal histogram and the author's intuition. This intuition has been verified comparing sample generated results with known driving pattern statistics. The known driving statistics are average yearly total miles driven of 12,000 miles, 50% of drivers drive 25 miles per day or less, and 75% of drivers drive 45 miles or less [3.4]. Sample results computed by MATLAB using 328,500 log normal RVs ($\mu_m = 3.37$ and $\sigma_m = 0.5$) show that the total yearly driving distance average is 12,018 miles, 48% of the vehicles drive 25 miles or less each day, and 83% of the vehicles drive 45 miles or less each day, which closely approximate the driving performance results from [3.4].

In the probabilistic simulation program the log normal RVs are generated using a standard normal RV, N , generated using (3.8). Then, the value $M^{(v,d)}$ is computed from

$$M^{(v,d)} = e^{(\mu_m + \sigma_M \cdot N)} \quad (3.16)$$

where $M^{(v,d)}$ is a RV representing the total miles vehicle- v on day- d drove and is distributed log normal with mean μ_m and standard deviation σ_M . Vehicle- v is a

particular vehicle sampled randomly from the total vehicle fleet N_T . The total number of vehicles in the sample population is n , where n is much less than N_T , because generating data for N_T vehicles for the entire simulation period is computationally prohibitive. Day- d is a particular day of the simulation. The total number of days simulated is D .

For the time performance parameters, departure time and arrival time Gaussian distributions are selected as a best estimate of random consumer behavior. Different timing distributions are used to model the potential different consumer behaviors on weekdays versus weekends.

As before a standard normal value, N , is computed using (3.8). Then, the value $X_T^{(p)}$ is computed

$$X_T^{(p)} = \left\lfloor \mu_T^{(p)} + \sigma_T^{(p)} \cdot N \right\rfloor \quad (3.17)$$

where the result $X_T^{(p)}$ is a normally distributed integer with mean $\mu_T^{(p)}$ and standard deviation $\sigma_T^{(p)}$. The value $X_T^{(p)}$ represents either the arrival time $A_T^{(p)}$ or the departure time $D_T^{(p)}$ depending on the values used for the mean and standard deviation.

The arrival time $A_T^{(v,d)}$ for vehicle- v on day- d must occur after the departure time $D_T^{(v,d)}$ for vehicle- v on day- d . To achieve this specification, an acceptance-rejection method is used. Let A_T^* be a particular generated arrival time and D_T^* be a particular generated departure time. Each generated pair (A_T^*, D_T^*) is checked, and if $A_T^* \leq D_T^*$ then a new pair is generated. The process is repeated until $A_T^* > D_T^*$ and the generated pair is accepted.

3.1.1.3 Gasoline Usage Statistics

Three steps are required to compute of the amount of gasoline for a vehicle fleet with a specified level of PHEV penetration:

1. Compute the amount of gasoline which a fleet of N_T IC vehicles will consume, G_{IC} [gal.].
2. Compute the amount of gasoline which a fleet of $N_T \cdot P_{PHEV}$ PHEVs will consume, G_{PHEV} [gal.].
3. Compute the total gasoline usage, G [gal.].

The total gasoline G_{IC} used by a fleet of N_T IC vehicles is computed assuming the average gasoline used by the vehicle sample population, $\overline{G_{IC}^{(c)}}$ [gal./veh.], is equal to the average gasoline used by the population average, so that

$$\overline{G_{IC}^{(c)}} = 1/n \cdot \sum_{v=1}^n \left(T^{(v)} / IC_{MPG}^{(c)} \right) \quad (3.18)$$

where $T^{(v)}$ is the total number of miles driven by vehicle- v over the simulation period and $IC_{MPG}^{(c)}$ is the fuel efficiency of an IC vehicle in class- c . Thus, G_{IC} is the sum of the product of the total number of vehicles in class- c times the average gasoline used per vehicle in class- c for each vehicle class. Hence

$$G_{IC} = N_T \cdot \sum_{c=1}^4 \left(p^{(c)} \cdot \overline{G_{IC}^{(c)}} \right) \quad (3.19)$$

To calculate the amount of gasoline a fleet of PHEVs uses is more complicated because the rate at which PHEVs use fuel, in the assumed control strategy, depends on the daily driving distance. If $M_E^{(c)}$ is greater than or equal to $M^{(v,d)}$, then the entire daily driving distance is performed in charge depleting mode. Under this condition the daily required gasoline, $D_G^{(v,d,c)}$ [gal.], is

$$D_G^{(v,d,c)} = M^{(v,d)} / MPG^{(c)}(k_{PHEV}) \quad (3.20)$$

Where $MPG^{(c)}(k_{PHEV})$ is the fuel efficiency of a PHEV with design variable k_{PHEV} in class- c in the charge depleting mode. However, if $M_E^{(c)}$ is strictly less than $M^{(v,d)}$ then the distance $(M^{(v,d)} - M_E^{(c)})$ must be completed in charge sustaining mode, and $D_G^{(v,d,c)}$ is

$$D_G^{(v,d,c)} = M_E^{(c)} / MPG^{(c)}(k_{PHEV}) + (M^{(v,d)} - M_E^{(c)}) / MPG^{(c)}(0) \quad (3.21)$$

where the first term in the sum represents gasoline used in charge depleting mode and the second term represents gasoline used in charge sustaining mode (where $MPG^{(c)}(0)$ is the fuel efficiency of a PHEV in class- c in the charge sustaining mode).

From $D_G^{(v,d,c)}$ the yearly gasoline usage, $Y_G^{(v,c)}$ [gal.], is computed by summing over each day in the simulation

$$Y_G^{(v,c)} = \sum_{d=1}^D D_G^{(v,d,c)} \quad (3.22)$$

Next, the sample vehicle population average gasoline usage, $\overline{Y_G^{(c)}}$ [gal./veh.], is computed

$$\overline{Y_G^{(c)}} = 1/n \cdot \sum_{v=1}^n Y_G^{(v,c)} \quad (3.23)$$

Then, the total gasoline G_{PHEV} used by a fleet of $N_T \cdot P_{PHEV}$ PHEVs is the sum of the product of the number of vehicles in each class times the average gasoline usage per vehicle for each vehicle class

$$G_{PHEV} = N_T \cdot P_{PHEV} \cdot \sum_{c=1}^4 (p^{(c)} \cdot \overline{Y_G^{(c)}}) \quad (3.24)$$

assuming, again, that the sampled PHEV population average gasoline usage is equal to the total PHEV population gasoline usage.

Finally, the total gasoline usage, G , is the sum of the gasoline used by the IC vehicles and the gasoline used by the PHEVs, G_{PHEV} . The gasoline used by the IC vehicles is the percentage of IC vehicles in the total vehicle fleet times G_{IC} . The percentage of IC vehicles in the population is $(1 - P_{PHEV})$. Thus,

$$G = (1 - P_{PHEV}) \cdot G_{IC} + G_{PHEV} \quad (3.25)$$

Thus far, the described methodology computes the performance of a fleet of N_T vehicles with a penetration percentage of P_{PHEV} . The next step in the probabilistic simulation program is to compute the load curves used in the power system simulation algorithm.

3.1.2 Calculate Load Curves

Two forms of load curves are used, namely the chronological load curve and the NILDC [3.1]. The chronological form depicts the load as a function of time. The second form, computed from the first, depicts a probabilistic description of the electric load. First the chronological load curve is computed using the base case electric load and the additional electric load due to PHEV charging. Second the chronological load curve is converted into the NILDC.

In each simulated experiment the base case electric load demand is based on data in [3.8] and the peak electric load of the power system in the experiment. The data in [3.8] describes the electric load demand as a percentage of the peak for each hour of a year. The electric load representing PHEV charging is added to the base case electric load. Next, the method to calculate the added electric load demand due to PHEV charging is described.

To compute the additional energy required to charge the PHEV fleet requires five calculations:

1. Compute the daily recharge energy required by the PHEV from the grid, $D_E^{(v,d,c)}$ [kWh].
2. Compute the daily recharge length, $C_T^{(v,d)}$ [h].
3. Generate the recharge voltage, $V^{(v,c)}$ [V].
4. Compute the recharge current, $I^{(v,d,c)}$ [A].
5. Compute the total recharge power, p_v [MW], per hour.

First, $D_E^{(v,d,c)}$ is computed. This value depends on $M^{(v,d)}$ and $M_E^{(c)}$. If $M^{(v,d)}$ is greater than or equal to $M_E^{(c)}$ then the required grid energy is $BC^{(c)}$. Otherwise $D_E^{(v,d,c)}$ is the product of $M^{(v,d)}$ and $E^{(c)}(k_{PHEV})$.

$$D_E^{(v,d,c)} = \begin{cases} BC^{(c)} & M^{(v,d)} \geq M_E^{(c)} \\ M^{(v,d)} \cdot E^{(c)}(k_{PHEV}) & M^{(v,d)} < M_E^{(c)} \end{cases} \quad (3.26)$$

Second, $C_T^{(v,d)}$ is computed. This value is the number of hours between arriving home on day- d and leaving on day- $d + 1$ (note that on day- D , the last day of the simulation, the arrival time on day- D and the departure time on day-1 is used).

$$C_T^{(v,d)} = (24 - A_T^{(v,d)}) + D_T^{(v,d+1)} \quad (3.27)$$

Third, $V^{(v,c)}$ is generated. This value is a discrete RV, and is set at 120 volts for 70% of the vehicles and is set at 240 volts for 30% of the vehicles.

Fourth, $I^{(v,d,c)}$ is computed. This value is limited by the maximum current available, I^* [A], from the charging circuit, where I^* is 15 A from a 120 V service and 30 A from a 240 V service.

$$I^{(v,d,c)} = \min \left\{ \left(D_E^{(v,d,c)} \cdot 1000 \right) / \left(V^{(v,c)} \cdot C_T^{(v,d)} \right), I^* \right\} \quad (3.28)$$

where $D_E^{(v,d,c)} \cdot 1000$ is the energy [Wh] required by the PHEV- v on day- d in class- c , and $V^{(v,c)} \cdot C_T^{(v,d)}$ is the charging voltage [V] for the PHEV- v in class- c times the number of hours the PHEV- v on day- d will be charged. The charging voltage is held constant for each vehicle in the simulation period assuming that PHEV owners will not change their charging circuit over the simulation period. The charging time is held constant for each class for simplicity. Thus, the quotient

$$\left(D_E^{(v,d,c)} \cdot 1000\right) / \left(V^{(v,c)} \cdot C_T^{(v,d)}\right)$$

is the current demanded for the required energy at the charging voltage level for the number of hours the PHEV will be charging. Additionally, using the $\min\{\cdot\}$ function results in $I^{(v,d,c)}$ not exceeding the service capacity.

Finally, the required recharge power is the energy required every hour of the charging period and is stored in an array, $LDC[h_c]$, where h_c is the simulation hour. The array is initialized to all zeros and computed by looping through each vehicle in the sampled population and each vehicle class adding the product of the number of vehicles in the present class times the required grid power in MW for each charging hour for each day of the simulation.

$$p_v = \left(N_{PHEV}^{(c)} \cdot V^{(v,c)} \cdot I^{(v,d,c)}\right) / (n \cdot 10^6) \quad (3.29)$$

This procedure is outlined in Figure 3.11.

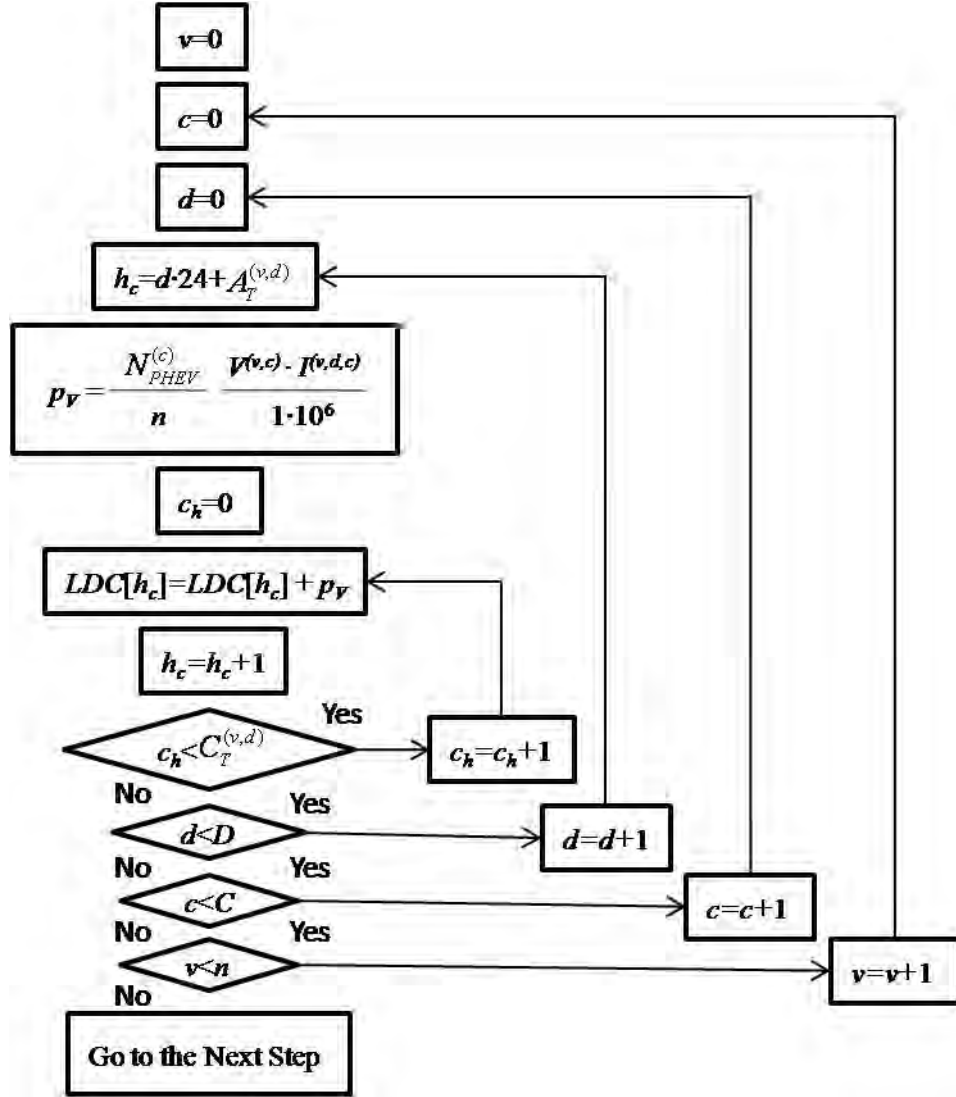


Figure 3.11. PHEV required grid energy calculation block diagram.

The chronological electric load model is converted into a probability distribution function (inverted) of the load for the purposes of the probabilistic simulation method. In general, a NILDC describes the length of time for which the load is greater than a specified value, which ranges from the system minimum load to the maximum load [3.1].

To convert from the chronological load demand curve to the NILDC requires that the range of possible load levels from the system minimum to the system maximum load be broken up into a specified number of increments. For each increment the number of hours during which the load is greater than or equal to that level is counted. Then, the resulting count for each increment is normalized by the total length of the simulation in hours. The resulting curve has horizontal axis units of power and vertical axis units of probability. The vertical axis probability is the probability that the load is greater than or equal to the horizontal axis power level.

3.1.3 Power System Simulation Using the Probabilistic Production Costing (PPC) Power System Simulation Procedure

PPC power system simulation procedure provides the following functionality, “Given the forecasted electric load demand for the time period under consideration and a list of available generating units of the system, simulate the operation of the system in order to forecast energy generated by units, cost, and required fuel, taking into account the effects of scheduling functions within the time period considered and the random forced outages of the units” [3.1], where units indicates generators in power plants.

The forecasted electric load demand is the NILDC introduced in the last section. The list of available generating units is described below. The forced outage rate (FOR) of the available generating units is defined as a function of the mean time to failure (MTTF) and mean time to repair (MTTR)

$$\text{FOR} = \text{MTTF}/(\text{MTTF} + \text{MTTR}) \quad (3.30)$$

Given a forecasted electric load demand and list of available generators, the expected value of each of the following quantities can be computed for each available generating unit:

1. Total energy produced.
2. Total fuel cost.
3. Total amount of fuel utilized.
4. Total EAP generated.

The calculation of the above power system quantities is based on a probabilistic methodology fully developed in [3.1]. In [3.1] the “arbitrary dispatch criterion“ utilized is an economic dispatch criterion. Thus, when additional load needs to be met the generator selected to meet the demand is chosen by the least expensive option available.

The PPC power system simulation procedure is utilized to compute both the base case power system results and the PHEV scenario results. Because the electric load due to PHEV charging is based on RVs repeated simulations of the PHEV scenarios is used to compute average system production results.

3.1.4 Calculate EAP Statistics

Next, the method used to compute the total system EAP results is described. The results from the vehicle and power system simulations are combined to compute the total system EAP.

The vehicle EAP is computed in a similar fashion to that of the gasoline consumption, replacing the fuel efficiency with EAP rates, denoted by $P^{(c)}(k_{PHEV})$, as a general term for either, $NO_x^{(c)}(k_{PHEV})$ or $CO_2^{(c)}(k_{PHEV})$, the NO_x and CO_2 emission rates of a PHEV utilizing design variable k_{PHEV} in class- c respectively. First, the total EAP generated by the fleet of IC vehicles is described, followed by a description of the EAP generated by the fleet of PHEVs.

The total EAP generated by a fleet of N_T IC vehicles is computed, assuming the sample vehicle population average EAP generated, $\overline{EAP_{IC}^{(c)}}$ [kg/veh.], is equal to the average EAP generated by the entire vehicle population

$$\overline{EAP_{IC}^{(c)}} = 1/n \cdot \sum_{v=1}^n \left(T^{(v)} / IC_{EAP}^{(c)} \right) \quad (3.31)$$

where $T^{(v)}$ is the total number of miles driven by vehicle- v over the simulation period and $IC_{MPG}^{(c)}$ is the fuel efficiency of an IC vehicle in class- c . Thus, the total vehicle fleet EAP generated, EAP_{IC} [kg], is the sum of the product of the total number of vehicles in class- c times the average EAP generated per vehicle in class- c for each vehicle class. Hence

$$EAP_{IC} = N_T \cdot \sum_{c=1}^4 \left(p^{(c)} \cdot \overline{EAP_{IC}^{(c)}} \right) \quad (3.32)$$

The method used to compute the total EAP generated by a fleet of PHEVs is described next. First, the daily amount of EAP generated, $D_{EAP}^{(v,d,c)}$ [kg], is computed. If $M_E^{(c)}$ is greater than or equal to $M^{(v,d)}$ then

$$D_{EAP}^{(v,d,c)} = M^{(v,d)} \cdot P^{(c)}(k_{PHEV}) \quad (3.33)$$

however, if $M_E^{(c)}$ is strictly less than $M^{(v,d)}$ then

$$D_{EAP}^{(v,d,c)} = M_E^{(c)} \cdot P^{(c)}(k_{PHEV}) + \left(M^{(v,d)} - M_E^{(c)} \right) \cdot P^{(c)}(0) \quad (3.34)$$

where the first term in the sum represents the EAP produced in charge depleting mode and the second term is the EAP produced in charge sustaining mode.

Second, the yearly EAP generated, $Y_{EAP}^{(v,c)}$ [kg], is computed by summing over each day in the simulation

$$Y_{EAP}^{(v,c)} = \sum_{d=1}^D D_{EAP}^{(v,d,c)} \quad (3.35)$$

Third, the sample vehicle population average yearly EAP generated, $\overline{Y_{EAP}^{(c)}}$ [kg/veh.], is computed

$$\overline{Y_{EAP}^{(c)}} = 1/n \cdot \sum_{v=1}^n Y_{EAP}^{(v,c)} \quad (3.36)$$

Next, the total EAP generated by a fleet of PHEVs, EAP_{PHEV} [kg], is calculated. This value is the sum of the product of the number of vehicles in each class times the average EAP generated per vehicle class over each vehicle class, and is given by

$$EAP_{PHEV} = N_T \cdot P_{PHEV} \sum_{c=1}^4 \left(p^{(c)} \cdot \overline{Y_{EAP}^{(c)}} \right) \quad (3.37)$$

Finally, the total EAP generated, EAP [kg], is the sum of the EAP produced by both the IC vehicles and the PHEVs

$$EAP = (1 - P_{PHEV}) \cdot EAP_{IC} + EAP_{PHEV} \quad (3.38)$$

The simulation methodology thus far described is facilitated with the use of a graphical user interface (GUI) with access to all the required input data and simulations results.

3.2 Primary Energy Source Utilization Experiments

This section describes how the three experiments are performed. The experiments are conducted using the probabilistic simulation of an integrated power system with distributed PHEVs methodology to quantify the impact which charging PHEVs will have on primary energy source utilization. In the first two experiments the level of PHEV penetration is increased from 0% (Base Case), to 5%, 10%, 20% and 40%. Here P_{PHEV} percent penetration is defined as

$$P_{PHEV} = N_{PHEVs}/N_T \quad (3.39)$$

where N_{PHEVs} is the total number of PHEVs in the simulation. In the first experiment the power system used to charge the vehicles is the 1979 Reliability Test System (RTS) [3.8]. In the second experiment the power system is the average generating mix used in the United States. The third experiment keeps the number of PHEVs constant and varies the RTS generating mix. The RTS generating mix is changed such that the total generating capacity is constant but the ratio of clean generating capacity (nuclear and hydro) is increased.

In each experiment the results include primary energy source utilization shifts and pollution shifts. The total cost for consumers is computed for the first experiment only.

3.2.1 Reliability Test System (RTS) Experiment

The RTS model was developed in [3.8] “to provide a basis for reporting on analysis methods”. It contains nearly all the power system data for the probabilistic simulation of an integrated power system with distributed PHEVs methodology; the only data not included in [3.8] is generator emission data. The remainder of this subsection describes the power system data used in the RTS experiment in this investigation and the results of the experiment.

3.2.1.1 RTS Experiment Data

The RTS system utilizes five fuel types (#6 oil, #2 oil, coal, nuclear, and hydro) and 32 different generators. These 32 generators consist of nine different generator types. The cost and heat content of each fuel type (Table 3.10) is based on data in [3.8]. The cost data has been updated to typical current prices.

Table 3.10. Fuel type data [3.8].

Fuel Type	Fuel Costs [\$/kg]	Fuel Energy Density [kcal/kg]
#6 Oil	0.6	11,200
#2 Oil	0.65	12,000
Coal	0.05	6,000
Nuclear	60,000	$200 \cdot 10^{19}$
Hydro	--	--

The hydro energy generation is treated as negative load when calculating the load demand curve. Thus, in Table 3.10 the hydro fuel cost and fuel energy density are not

included because hydro fuel is not included in the economic dispatch calculation. The relative cost of each fuel type is of significant importance because the generating unit dispatching is ordered based on economic ranking.

Generator unit reliability data (Table 3.11) includes MTTF, MTTR and resulting FOR.

Table 3.11. Generating unit reliability data [3.8].

Size of Unit [MW]	FOR	MTTF [h]	MTTR [h]
12	0.02	2,940	60
20	0.1	450	50
50	--	--	--
76	0.02	1,960	40
100	0.04	1,200	50
155	0.04	960	40
197	0.05	950	50
350	0.08	1,150	100
400	0.12	1,100	150

In Table 3.11 unit reliability for the hydro units is considered in the calculations of the hydro availability data.

Generator capacity data (Table 3.12) includes generator fuel type, maximum generating capacity, and minimum generating capacity.

Table 3.12. Generating unit generation capacity data [3.8].

Fuel	Capacity [MW]	
	Maximum	Minimum
#6 Oil	12	2.4
#2 Oil	20	16
Hydro	50	--
Coal	76	15.2
#6 Oil	100	25
Coal	155	54.25
#6 Oil	197	68.95
Coal	350	140
Nuclear	400	100

In Table 3.12, the hydro capacity is treated as negative load and as such no minimum capacity is required.

Additional data utilized in the PPC power system simulation procedure is heat and emission rate functions for all of the available generating units in the system. This data is described next.

The generator heat rate function (3.40), is used as a cost function modeling the amount of fuel needed to meet a specific power demand for each generator. A linear least square method is used to calculate the heat rate coefficients a_h , b_h , and c_h for each generator. In the heat rate function

$$h(P) = a_h + b_h \cdot P + c_h \cdot P^2 \quad (3.40)$$

P [MW] represents the generated power and $h(P)$ [kcal/h] is the required heat rate. The data used to compute each heat rate functions is found in [3.8]. The least square approximation solves the general matrix equation

$$\vec{Y} = \mathbf{A} \cdot \vec{X} \quad (3.41)$$

with solution

$$\vec{X} = (\mathbf{A}^T \cdot \mathbf{A}) \cdot \mathbf{A}^T \cdot \vec{Y} \quad (3.42)$$

where $\vec{Y}$ is a vector of known data (heat rate) [kcal/h], $\mathbf{A}$ is a known observation matrix (power levels) [MW], and $\vec{X}$ is a vector of unknown data (generator coefficients).

An example of how the heat rate coefficients are calculated is provided for the 12 MW generating units. For the 12 MW generators the heat rate input at four levels of output power levels (2.4 MW, 6.0 MW, 9.6 MW, 12.0 MW) are known [3.8]

$$\vec{Y} = \begin{bmatrix} \text{Heat Rate 1} \\ \text{Heat Rate 2} \\ \text{Heat Rate 3} \\ \text{Heat Rate 4} \end{bmatrix} = \begin{bmatrix} 9,434,880 \\ 19,504,800 \\ 28,788,480 \\ 36,288,000 \end{bmatrix} \quad (3.43)$$

$$\mathbf{A} = \begin{bmatrix} 1 & P_1 & P_1^2 \\ 1 & P_2 & P_2^2 \\ 1 & P_3 & P_3^2 \\ 1 & P_4 & P_4^2 \end{bmatrix} = \begin{bmatrix} 1 & 2.4 & 5.76 \\ 1 & 6 & 36 \\ 1 & 9.6 & 92.16 \\ 1 & 12 & 144 \end{bmatrix} \quad (3.44)$$

$$\vec{X} = \begin{bmatrix} a_h \\ b_h \\ c_h \end{bmatrix} \quad (3.45)$$

and the solution is computed

$$\begin{aligned} \vec{X} &= (\mathbf{A}^T \cdot \mathbf{A}) \cdot \mathbf{A}^T \cdot \vec{Y} \\ &= \left(\begin{bmatrix} 1 & 1 & 1 & 1 \\ 2.4 & 6 & 9.6 & 12 \\ 5.76 & 36 & 92.16 & 144 \end{bmatrix} \cdot \begin{bmatrix} 1 & 2.4 & 5.76 \\ 1 & 6 & 36 \\ 1 & 9.6 & 92.16 \\ 1 & 12 & 144 \end{bmatrix} \right) \\ &\quad \cdot \begin{bmatrix} 1 & 1 & 1 & 1 \\ 2.4 & 6 & 9.6 & 12 \\ 5.76 & 36 & 92.16 & 144 \end{bmatrix} \cdot \begin{bmatrix} 9,434,880 \\ 19,504,800 \\ 28,788,480 \\ 36,288,000 \end{bmatrix} \end{aligned}$$

$$= \begin{bmatrix} 303,340 \\ 355,040 \\ 15,047 \end{bmatrix}$$

Figure 3.12 shows the 12 MW generator discrete heat rate data and the continuous function computed using the results of linear least square method outlined above.

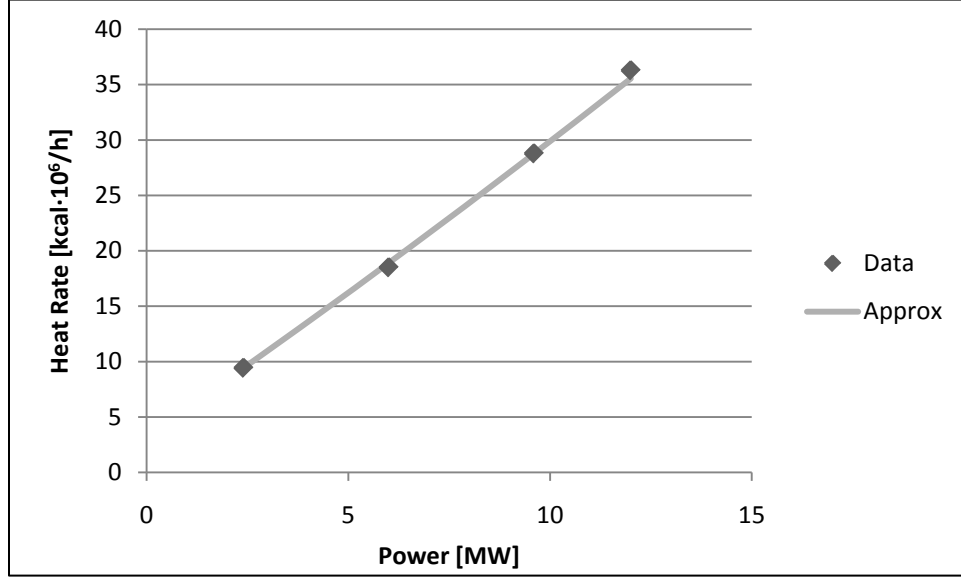


Figure 3.12. 12 MW unit heat rate data [3.8] and approximation.

Figure 3.12 shows a good agreement between the discrete data and the computed heat rate function. Similar linear least square calculations are performed for each generator using the discrete data outlined in [3.8] with results shown in Table 3.13. for all nine generator types.

Table 3.13. Generating unit heat rate coefficients [3.8].

Size [MW]	$a_h \left[\frac{kcal}{h} \right]$	$b_h \left[\frac{kcal}{MW h} \right]$	$c_h \left[\frac{kcal}{(MW)^2 h} \right]$
12	3,330,000	2,550,000	15,050
20	10,080,000	3,150,000	0
50	--	--	--
76	21,090,000	2,550,000	2,376
100	31,360,000	1,963,000	2,413
155	43,410,000	1,947,000	1,401
197	33,000,000	2,194,000	328.5
350	81,530,000	1,873,000	822.3
400	90,960,000	2,245,000	116.0

In Table 3.13, the c_h coefficient for the 20 MW units is zero because only two heat rate data points are published in [3.8]. The resulting heat rate curve is linear. Again, the hydro units are treated as negative load and as such require no heat rate equation in Table 3.13.

Next, the calculation of emission rate functions is described. The generator emission rate function (3.46) is used as a cost function modeling the amount of EAP generated at a specific power level. Again, a linear least square method is used to calculate the emission rate coefficients a_e and b_e for each generator.

$$e(P) = a_e + b_e \cdot P \quad (3.46)$$

In this equation, P [MW] represents the generated power and $e(P)$ [kg/h] is the emission rate.

Due to the lack of published emission data for the RTS generators in [3.8] the generator pollution statistics in [3.9], are utilized to approximate linear emission rate functions for each generator type in the RTS system (Table 3.14). From this data [3.9] the following procedure is utilized to compute the emission rate functions. First, the pollution statistics [3.9] are converted and normalized from thousands of tons per year (NO_x) and millions of tons per year (CO_2) to kg per MWh per year. Second, the average pollution, $R_{\text{Pollutant}}$ [kg/MWh], rate is scaled by the average power capacity, P_{ave} [MW], for each of the seven pollution generating plants utilized in the RTS power system (hydro and nuclear produce neither NO_x nor CO_2). Finally, assuming each plants pollution production would increase 20% from the minimum capacity, P_{min} [MW], to the maximum capacity P_{max} [MW], a linear emission rate function is approximated.

Table 3.14. TVA generator statistics [3.9].

Plant	Energy Produced [billions of kWh]	NO_x [thousands of tones/year]	CO_2 [millions of tones/year]
Allen	4.9	17.4	5.7
Bull Run	6	28	4.6
Cumberland	18.97	18.4	19
Gallatin	4.7	23.4	7.7
John Saviers	5.25	30.1	5.1
Johnsonville	5.68	86.8	9
Kingston	10	55.5	35.8

The environmental air pollutants NO_x and CO_2 are analyzed based on the availability of both power plant emission data and vehicle emission data. Both are necessary so that a comparison can be made in terms of total system EAP. The total system EAP is the EAP produced by both the power system and vehicle fleets for scenarios with and without PHEV charging.

An example of how the emission rate coefficients are calculated is provided for the 12 MW generating units below, where the linear least square variables $\vec{Y}$, $\mathbf{A}$, and $\vec{X}$ are

$$\vec{Y} = \begin{bmatrix} \text{Emission Rate 1} \\ \text{Emission Rate 2} \\ \text{Emission Rate 3} \end{bmatrix} = \begin{bmatrix} 0.9 \cdot R_{\text{Pollutant}} \cdot P_{\text{ave}} \\ R_{\text{Pollutant}} \cdot P_{\text{ave}} \\ 1.1 \cdot R_{\text{Pollutant}} \cdot P_{\text{ave}} \end{bmatrix} = \begin{bmatrix} 20.88 \\ 23.18 \\ 25.50 \end{bmatrix}$$

$$A = \begin{bmatrix} 1 & P_{\min} \\ 1 & P_{\text{ave}} \\ 1 & P_{\max} \end{bmatrix} = \begin{bmatrix} 1 & 2.4 \\ 1 & 7.2 \\ 1 & 12 \end{bmatrix}$$

$$\vec{X} = \begin{bmatrix} a_e \\ b_e \end{bmatrix}$$

Thus,

$$\vec{X} = (A^T \cdot A) \cdot A^T \cdot \vec{Y}$$

and the 12 MW units NO_x rate coefficients are

$$= \left(\begin{bmatrix} 1 & 1 & 1 \\ 2.4 & 7.5 & 12 \end{bmatrix} \cdot \begin{bmatrix} 1 & 2.4 \\ 1 & 7.2 \\ 1 & 12 \end{bmatrix} \right) \cdot \begin{bmatrix} 1 & 1 & 1 \\ 2.4 & 7.5 & 12 \end{bmatrix} \cdot \begin{bmatrix} 20.88 \\ 23.18 \\ 25.50 \end{bmatrix}$$

$$= \begin{bmatrix} 19.72 \\ 0.4832 \end{bmatrix}$$

Similar calculations are performed for each RTS generator, for both NO_x and CO₂ rate function coefficients, with results shown in Table 3.15.

Table 3.15. Generating unit emission rate coefficients.

Size [MW]	NO _x		CO ₂	
	$a_e \left[\frac{kg}{h} \right]$	b_e	$a_e \left[\frac{kg}{h} \right]$	b_e
12	19.72	0.4832	6,459	158.31
20	7.621	3.810	1,252	626.0
50	--	--	--	--
76	179.9	0.6961	37,420	144.8
100	45.83	0.1467	47,320	151.4
155	374.4	0.9381	123,200	308.7
197	548.0	1.080	92,850	183.0
350	2,604	3.235	270,000	335.4
400	--	--	--	--

In Table 3.15, the hydro (50 MW) and nuclear (400 MW) generators produced no EAP, thus the rate function coefficients are set to zero.

The accuracy of the emission rate functions is subject to question, having been obtained from emission statistics for seven different Tennessee Valley Authority (TVA) generators [3.9]. Pollution results from the RTS using the described power system simulation procedure, are plotted in Figure 3.13 and compared with the TVA plant data.

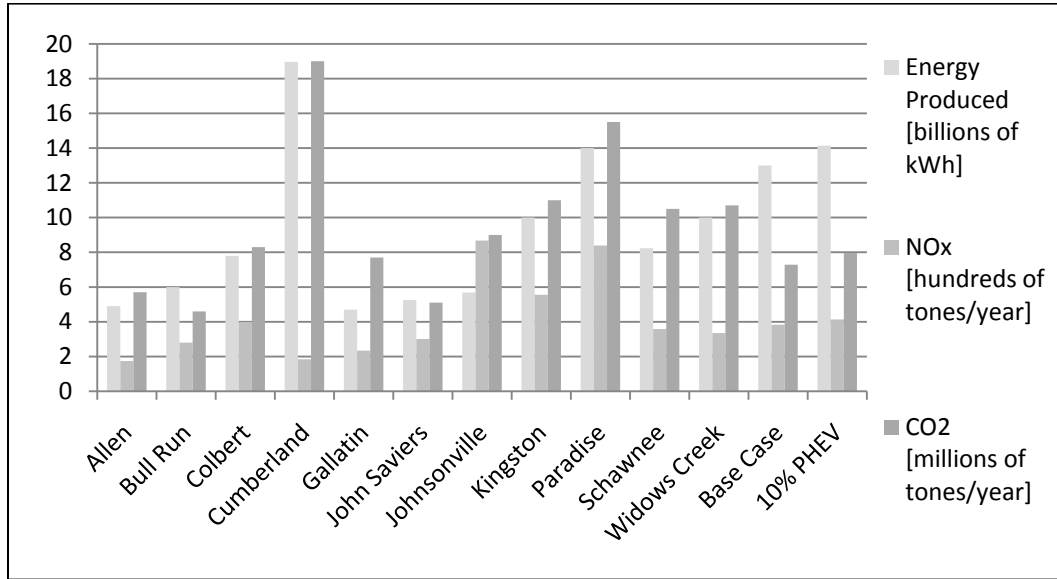


Figure 3.13. Pollution normalization justification.

Figure 3.13 shows the TVA generator statistics [3.9] and sample power system simulation procedure results. The sample power system simulation procedure results are shown for two scenarios the “Base Case” and “10% PHEV”. The “Base Case” scenario is RTS power system simulation procedure results with no additional electric load due to PHEV charging. Whereas, the “10% PHEV” scenario is RTS power system simulation procedure results with the added electric load from replacing 10% of the light duty vehicles in the RTS area with PHEVs. These results show that for comparable annual energy production, between the TVA generator energy production statistics and the “Base Case” and “10% PHEV” scenarios, the annual NO_x and CO₂ production, between these two sets of data, are on the same order of magnitude; suggesting that the approximated linear emission rate functions (Table 3.15) are realistic.

The base case load demand data is generated taking the product of the weekly peak (Table 3.16), daily peak (Table 3.17), and hourly peak (Table 3.18) data to create hourly load demand data for one year. The RTS system also includes six 50 MW hydro electric generating units. The hydro units are utilized 100% based on the availability (Table 3.19), thereby in effect treating the hydro generated energy as negative load. Thus, each hourly load is decreased by the hydro power available $H_p^{(q)}$ [MW] given by (3.47).

Table 3.16. Weekly peak load in percent of annual peak [3.8].

Week	Peak Load [%]	Week	Peak Load [%]	Week	Peak Load [%]
1	86.2	19	87	37	78
2	90	20	88	38	69.5
3	87.8	21	85.6	39	72.4
4	83.4	22	81.1	40	72.4
5	88	23	90	41	74.3
6	84.1	24	88.7	42	74.4
7	83.2	25	89.6	43	80
8	80.6	26	86.1	44	88.1
9	74	27	75.5	45	88.5
10	73.7	28	81.6	46	90.9
11	71.5	29	80.1	47	94
12	72.7	30	88	48	89
13	70.4	31	72.2	49	94.2
14	75	32	77.6	50	97
15	72.1	33	80	51	100
16	80	34	72.9	52	95.2
17	75.4	35	72.6		
18	83.7	36	70.5		

Table 3.17. Daily peak load in percent of weekly peak [3.8].

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Peak Load [%]	93	100	98	96	94	77	75

Table 3.18. Hourly peak load in percent of daily peak [3.8].

Hour	Winter Weeks [%]		Summer Weeks [%]		Spring/Fall Weeks [%]	
	1-8 and 44-52		18-30		9-17 and 31-43	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
12(midnight)-1a	67	78	64	74	63	75
1a-2a	63	72	60	70	62	73
2a-3a	60	68	58	66	60	69
3a-4a	59	66	56	65	58	66
4a-5a	59	64	56	64	59	65
5a-6a	60	65	58	62	65	65
6a-7a	74	66	64	62	72	68
7a-8a	86	70	76	66	85	74
8a-9a	95	80	87	81	95	83
9a-10a	96	88	95	86	99	89
10a-11a	96	90	99	91	100	92
11a-12noon	95	91	100	93	99	94
12noon-1p	95	90	99	93	93	91
1p-2p	95	88	100	92	92	90
2p-3p	93	87	100	91	90	90
3p-4p	94	87	97	91	88	86
4p-5p	99	91	96	92	90	85
5p-6p	100	100	96	94	92	88
6p-7p	100	99	93	95	96	92
7p-8p	96	97	92	95	98	100
8p-9p	91	94	92	100	96	97
9p-10p	83	92	93	93	90	95
10p-11p	73	87	87	88	80	90
11p-12midnight	63	81	72	80	70	85

Table 3.19. Hydro energy per calendar quarter [3.8].

Quarter	Energy Availability [%]	Capacity Availability [%]
1	35	100
2	35	100
3	10	90
4	20	90

$$H_P^{(q)} = (E_A^{(q)} \cdot C_A^{(q)} \cdot H_E) / (2190 \cdot 1000) \quad (3.47)$$

In (3.47) $H_p^{(q)}$ is the power available from the hydro generators in quarter- q , $E_A^{(q)}$ [MWh] is the energy available in quarter- q , $C_A^{(q)}$ [MW] is the maximum capacity available in quarter- q , and H_E is 100% of the available energy from the hydro units (200 GWh [3.8]).

As described in [3.8] the peak load demand of the RTS system is 2850 MW. From the peak load demand and a number of average statistical assumptions the total number of vehicles in the RTS area is derived below.

The number of customers is calculated from an average electric monthly demand of 1,500 kWh. Based on an average month of 30 days, the average power demand per customer is calculated to be $[1,500/(30 \cdot 24)] = 2.083$ kW. The peak system electric load demand is 2,850 MW [3.8] assuming 75% of this load is comprised of residential demand the number of customers in the power system area is calculated to be $(2,850,000 \cdot 75\%/2.083) = 1.026$ million. Finally, the number of vehicles per electric customer is assumed to be 1.5, which results in a total number of vehicles (N_T) of 1.539 million.

3.2.1.2 RTS Experiment Results

Four simulations are considered for varying the percentage of PHEV penetration. The levels simulated are 5%, 10%, 20% and 40%. For each RTS experiment scenario the number of IC vehicles (N_{IC}) and PHEVs (N_{PHEV}) are shown in Table 3.20.

Table 3.20. Number of vehicles for each RTS simulation.

Simulation	BC	5%	10%	20%	40%
N_{PHEV}	0	76,950	153,900	307,800	615,600
N_{IC}	1,539,000	1,462,000	1,385,000	1,231,000	923,400

In Table 3.20 notice that for each simulation the total number of vehicles remains 1.539 million.

For each PHEV penetration level the simulation is performed 30 times each, with a sample population of 100 vehicles. Thirty repeated simulations are performed so that a distribution of the expected results can be analyzed. Similarly, 100 vehicles are used as a sample vehicle population so that the impact of the vehicle assumption distribution can be observed; whereas simulating all of the vehicles in the power system areas is computationally prohibitive.

Vehicle assumptions including vehicle design parameters $k_{PHEV}^{(c)}$ and $BC^{(c)}$, are generated based on the probabilistic models described above. A scatter plot of 30 generated values is shown in Figure 3.14.

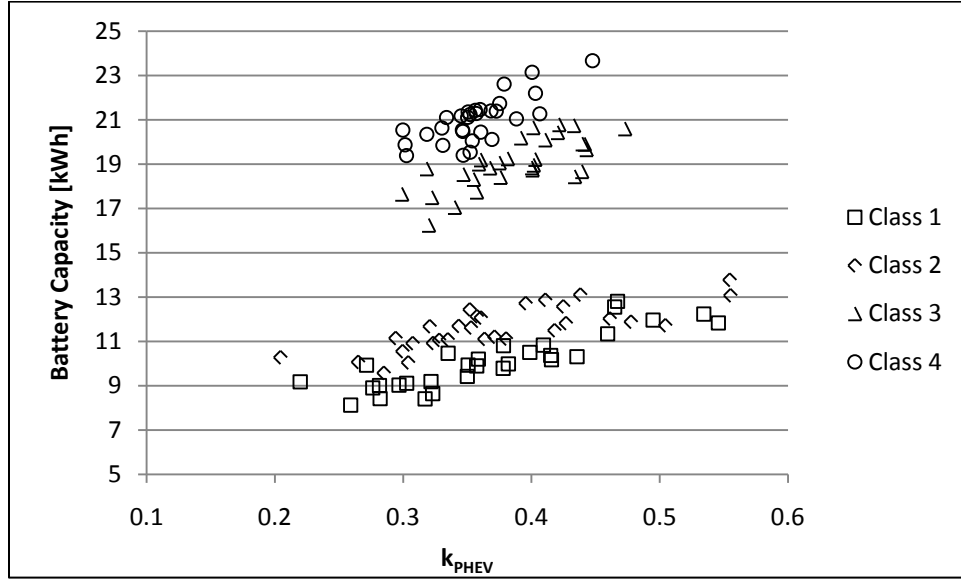


Figure 3.14. Typical vehicle design parameter scatter plot.

In Figure 3.14 two characteristics are apparent, namely the range of the vehicle design parameters and the correlation ($\rho = 0.8$) between the design parameters.

The base case electric load model [3.8] varies over the simulated year which is representative of typical electric load demand in a typical electric power system. Thus, the maximum power demand differs from the minimum power demand. The additional load due to PHEV charging is calculated with random charging times and random daily driving distances. One result of the probabilistic model of the added electric load due to PHEV charging is an increase in system maximum and minimum power demand. The increase in the maximum and minimum power demand is shown in Figure 3.15 for each of the simulated PHEV penetration levels. The maximum and minimum power demand for the PHEV scenarios are the average maximum and minimum power demand for the 30 PHEV penetration simulations.

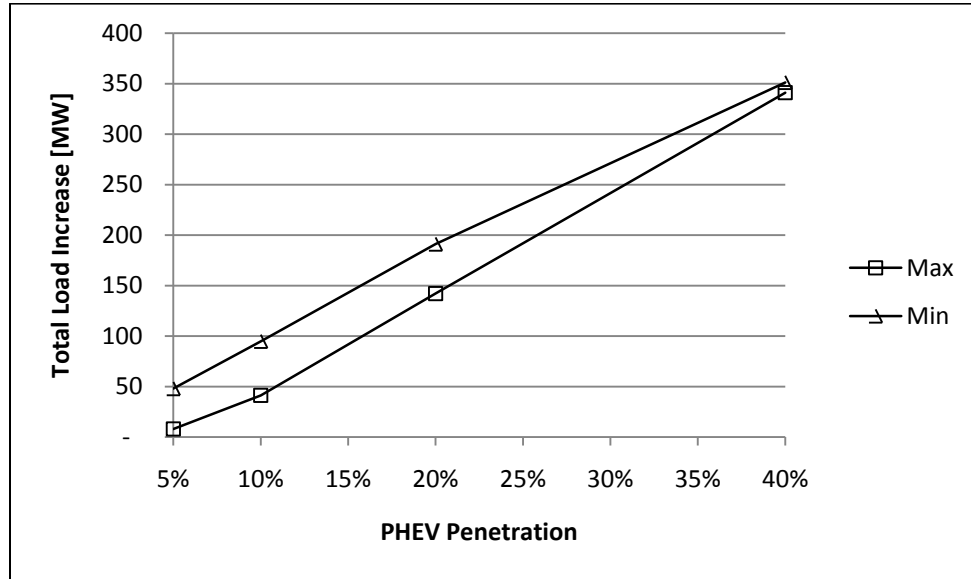


Figure 3.15. Increase in max and min power demand for each RTS scenario.

In Figure 3.15, the horizontal axis shows the percent of penetration of PHEVs and the vertical axis shows the *increase* in both maximum and minimum power demand for each percent PHEV penetration scenario simulated. Further, the base case result for maximum power demand is 2,834 MW and minimum power demand is 841 MW. Thus, the 5% PHEV penetration scenario maximum power demand is approximately $2834 + 10 = 2844$ MW. Where 2834 MW represents the base case maximum power demand and 10 MW (from Figure 3.15) represents the increase in maximum power demand for the 5% PHEV penetration scenario. Similarly, for the 5% PHEV penetration scenario minimum power demand is approximately $841 + 50 = 891$ MW. Where 841 MW represents the base case minimum power demand and 50 MW (from Figure 3.15) represents the increase in minimum power demand for the 5% PHEV penetration scenario.

The curves in Figure 3.15 show that the increase in system maximum load is smaller than the increase in system minimum load for each PHEV penetration scenario. This result indicates that the addition of PHEVs into a typical power system, with no control over when the vehicles are charged, will act to flatten the electric load demand curve.

The PPC power system simulation procedure computes the expected amount of energy generated by each fuel type to meet a projected electric load demand. Based on the developed projected electric load the energy generated by each fuel type is shown in Figure 3.16. For the “Base Case” scenario (no additional electric load due to PHEVs) the energy generated per fuel type is deterministic because the “Base Case” electric load demand is deterministic. Whereas, for the PHEV penetration scenarios the energy generated per fuel type is the average energy generated by each fuel type over the 30 repeated simulations for each penetration level.

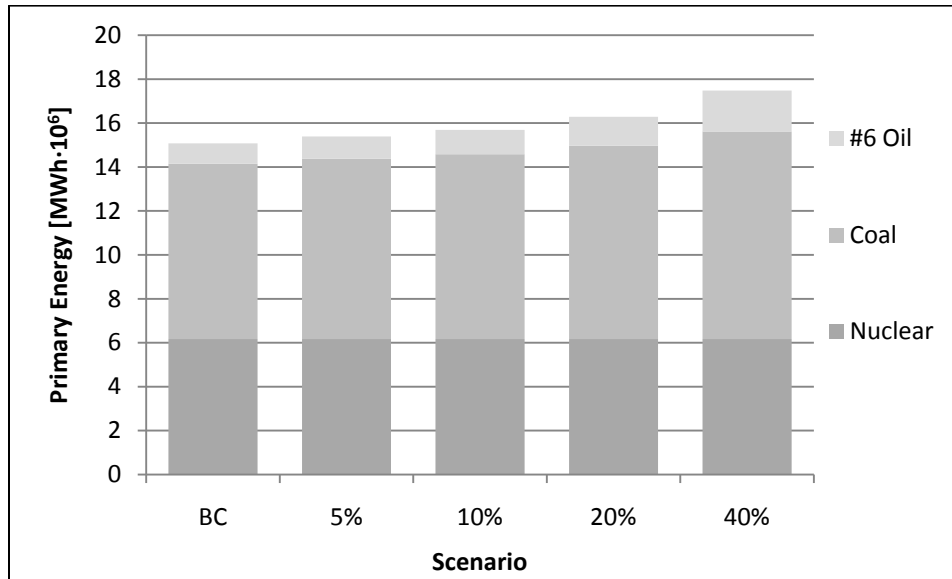


Figure 3.16. Primary energy generated for each RTS scenario.

In Figure 3.16, as expected the total generated energy increases as the penetration level of PHEVs increases. In Figure 3.16 the #2 oil, hydro, and unserved energy productions are negligible (i.e. very small contribution to the total energy production) and are removed from the list of fuel types. The specific increase in each fuel types energy production for each PHEV penetration level is shown in Figure 3.17.

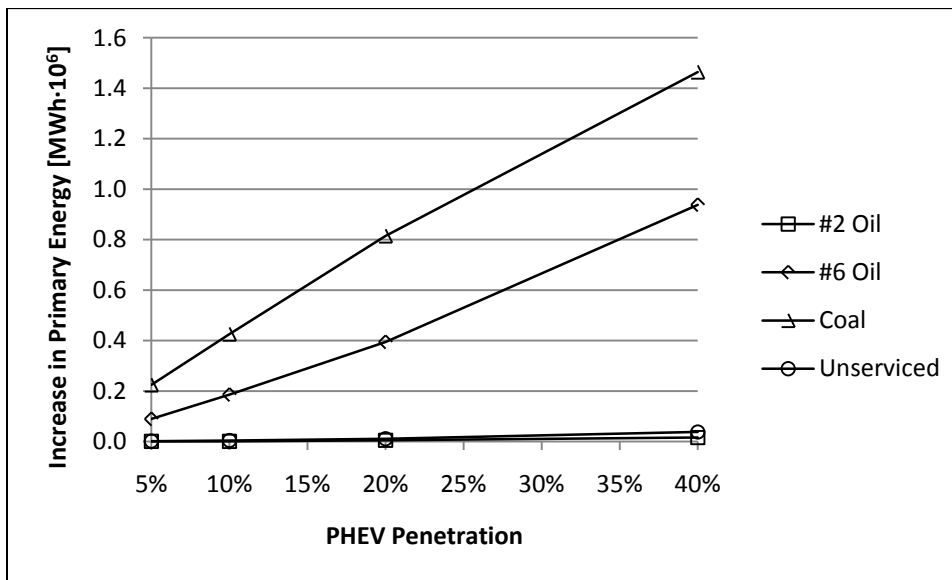


Figure 3.17. Increase in primary energy for each RTS PHEV penetration scenario.

In Figure 3.17, the increase in energy produced by each fuel type is computed by subtracting the base case fuel type energy production from the average PHEV scenario

fuel type energy production (Δ = PHEV Scenario – Base Case). The expected amount of nuclear and hydro energy production is constant, thus no increase in either is observed and both energy sources are removed from the list of power system fuel types in Figure 3.17. The significant increase in both #6 oil and coal indicates that these two fuel types are utilized to charge PHEVs for the particular power system generating mix studied.

The PPC power system simulation procedure computes expected energy statistics including loss of load probability (LOLP), total generated energy (GE), unserved energy (UE), total fuel cost (TFC), and average electricity cost (AEC) amount of energy generated by each fuel type to meet a project electric demand. For each PHEV scenario the energy statistic results are the average energy statistic over the 30 simulations, as shown in Table 3.21.

Table 3.21. Energy statistics for each simulated RTS scenario.

	Base Case	5%	10%	20%	40%
LOLP	0.0070	0.0083	0.0099	0.0142	0.0296
GE [MWh]	15,080,000	15,400,000	15,710,000	16,340,000	17,580,000
UE [MWh]	9,029	10,82	13,200	20,000	47,020
TFC [k\$]	202,700	215,100	228,1	256,500	323,000
AEC [¢/kWh]	1.34	1.40	1.45	1.57	1.84

In Table 3.21, each statistic increases proportionally with the number of PHEVs. From Tables 3.20 and 3.21 the added utility revenues can be calculated for each PHEV penetration level as shown in Table 3.22.

Table 3.22. Added RTS power system revenue.

Scenario	5%	10%	20%	40%
Increased Energy [MWh]	315,000	628,500	1,255,000	2,498,000
N_{PHEV}	76,950	153,900	307,800	615,600
Revenue [k\$]	25,210	50,280	100,400	199,900
Revenue [\$] per Vehicle per Year	327.60	326.70	326.20	324.70

The results shown in Table 3.22 are computed assuming that the retail electricity rate of 8 cents per kWh is constant all year long. In Table 3.22, the average power system revenue is \$326 per PHEV per year.

The impact of displacing gasoline usage with increased utilization of electric energy, for the RTS, causes a slight increase in NO_x and significant decrease in CO_2 for all PHEV penetration scenarios. The percent change in EAP is shown in Figure 3.18.

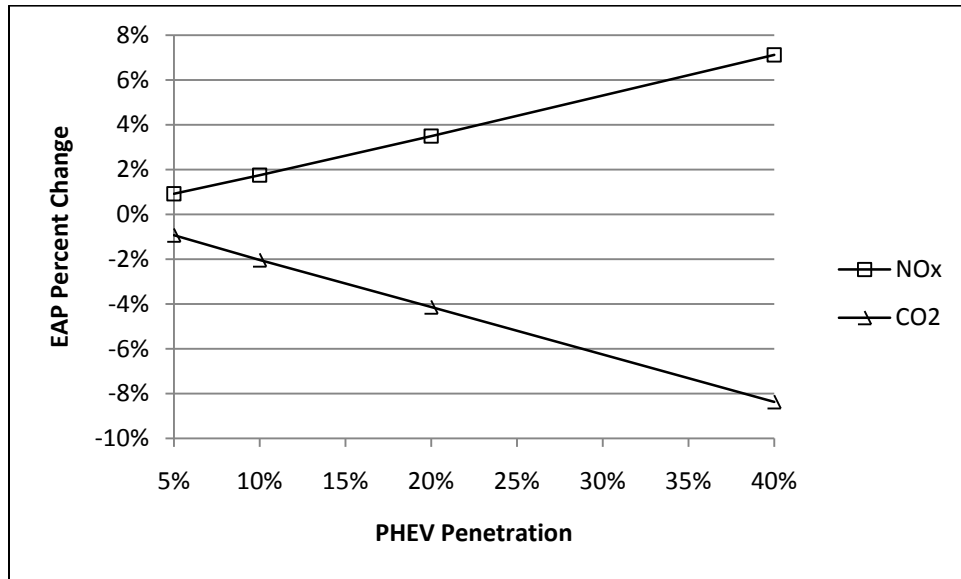


Figure 3.18. RTS percent change of EAP as a function of PHEV penetration.

The percent change at 5% PHEV penetration is 0.92% of NO_x and -0.93% of CO₂, which corresponds to an annual increase of 0.4986 million kg of NO_x and an annual decrease of 160.6 million kg of CO₂.

The gasoline utilization results reveal that the gasoline utilization decreases approximately linearly as PHEV penetration increases as shown in Figure 3.19.

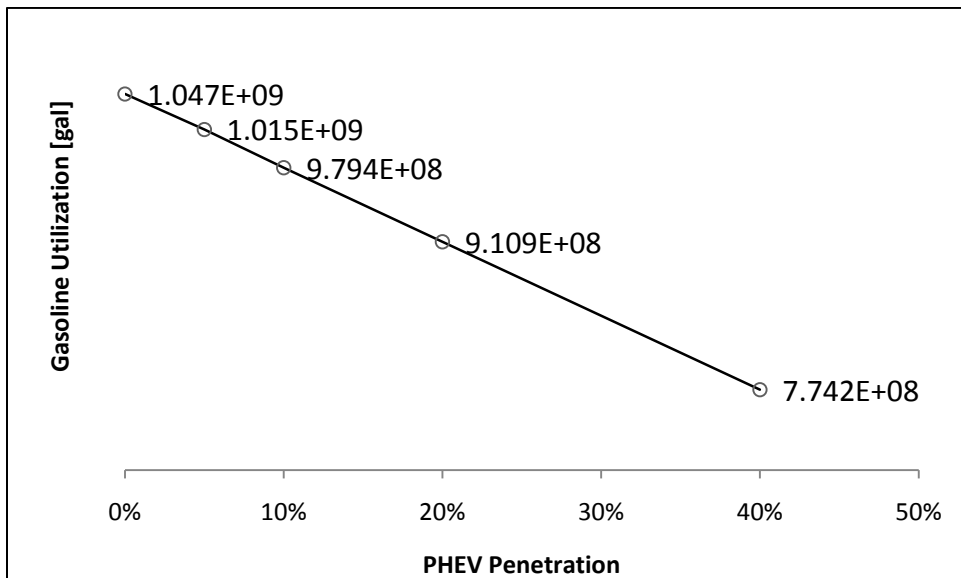


Figure 3.19. RTS gasoline utilization as a function of PHEV penetration.

Specifically, with a fleet of 1.539 million IC vehicles the average yearly gasoline utilization is 1,047 million gallons whereas with 40% of the vehicle fleet replaced with PHEV this utilization reduces to 774 million gallons, a reduction of 26.1%.

Based on the gasoline utilization (Figure 3.19) and the total generated energy (Table 3.21) the total fuel cost can be calculated for an average driver in each PHEV penetration level. The “Base Case” scenario yearly fuel cost consists of entirely gasoline purchases because no PHEVs are utilized, and the PHEV penetration scenarios total fuel cost includes electricity and gasoline purchases. It is assumed that gasoline costs \$3.00 per gallon and electricity rate is 8 cents per kWh all year long. Finally, the average gasoline utilization for the base case scenario is used to compute the amount of gasoline used per IC vehicle in the PHEV scenarios, the results are shown in Table 3.23.

Table 3.23. RTS annual fuel cost.

Scenario	Base Case	5%	10%	20%	40%
Annual Fuel Cost [\$]	2,042.00	1,089.00	1,041.00	1,037.00	1,035.00

In Table 3.23, a 65% reduction in fuel cost is achieved utilizing PHEVs over IC vehicles. This reduction in annual fuel cost is significantly influence by the cost effectiveness of electricity over gasoline.

3.2.2 United States System Experiment

Next, the second experiment, the U.S. experiment, is described. As with the RTS experiment the U.S. experiment varies the level of PHEV penetration. This experiment uses a generation mix representative of the entire U.S. Similarly, the peak electric load and number of vehicles in the power system area are set to values representing the entire U.S.

3.2.2.1 U.S. Experiment Data

Specifically, the data to generate PPC power system simulation procedure input data is the total U.S. generating capacity [3.10] (Table 3.24), the total U.S. generated energy production per fuel type [3.11] (Table 3.25), and the total U.S. power system EAP generated [3.12] (Table 3.26). PPC power system simulation procedure input data is composed so that the base case energy and EAP results match the statistics in Tables 3.25 and 3.26.

Table 3.24. Total U.S. generating capacity by fuel type [3.10].

Fuel Type	Generator Nameplate Capacity [MW]
Coal	336,040
Liquid and Coke Petroleum	62,394
Natural and Other Gas	452,052
Nuclear	105,764
Renewable/Other	131,541

Table 3.25. Net U.S. energy generating by fuel type [3.11].

Fuel Type	Net Generation By Fuel Source [GWh]
Coal	1,994,385
Liquid and Coke Petroleum	45,354
Natural and Other Gas	888,521
Nuclear	808,972
Renewable/Other	377,648

Table 3.26. Estimated EAP by each fuel type in 2007 for the entire U.S. [3.12].

Fuel Type	CO₂ [kg]	NO_x [kg]
Coal	16,018,807,896,000	22,956,252,000
Liquid and Coke Petroleum	536,895,358,000	1,258,970,000
Natural and Other Gas	3,458,905,616,000	3,402,814,000
Renewable/Other	118,031,404,000	1,582,196,000

Further, the RTS electric load demand distribution [3.8] is used, but changing the peak electric load demand to 764,476 [MW] [3.13]. The number of vehicles in the power system test area is set to 135.7 million [3.14].

3.2.2.2 U.S. Experiment Results

Four simulations are considered for varying the percentage of PHEV penetration. The penetration levels simulated are 5%, 10%, 20% and 40%. For each scenario the number of IC vehicles (N_{IC}) and PHEVs (N_{PHEV}) is shown in Table 3.27.

Table 3.27. Number of vehicles for each U.S. simulation.

Scenario	BC	5%	10%	20%	40%
N_{PHEV}	0	6,783,495	13,566,990	27,133,979	54,267,959
N_{IC}	135,669,897	128,886,402	122,102,907	108,535,918	81,401,938

In Table 3.27, for each PHEV penetration level the total number of vehicles remains 135.7 million.

Each PHEV penetration scenario is repeated 30 times each, with a sample population of 100 vehicles using the same vehicle assumptions as for the RTS experiment.

One result of the probabilistic model of the added electric load due to PHEV charging is an increase in system maximum and minimum power demand. The increase in the maximum and minimum power demand is shown in Figure 3.20 for each of the simulated PHEV penetration levels. The maximum and minimum power demand for the PHEV scenarios is the average maximum and minimum power demand for the 30 PHEV penetration simulations.

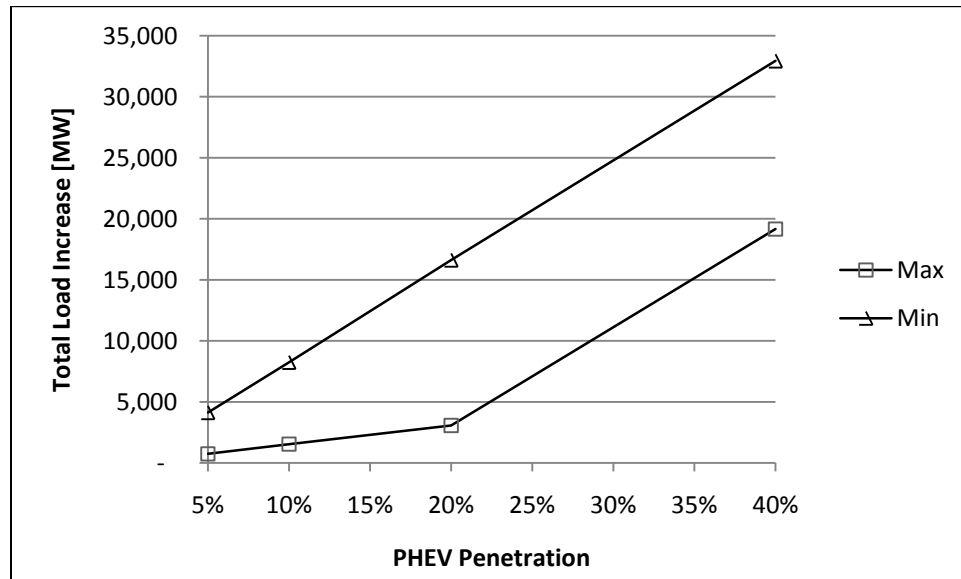


Figure 3.20. Increase in max and min power demand for each U.S. scenario.

As is the case for the RTS experiment the change in maximum and minimum power demand, the curves in Figure 3.20 show that the increase in system maximum load is smaller than the increase in system minimum load for each PHEV penetration scenario. This result indicates that the addition of PHEVs into a typical power system, with no control over when the vehicles are charged, will act to flatten the electric load demand curve. Specifically, for the U.S. experiment the base case result for maximum power demand is 764,810 MW and the minimum power demand is 229,200 MW.

Based on the projected electric load, the energy generated by each fuel type is shown in Figure 3.21. For the PHEV penetration scenarios the energy generated per fuel type is the average energy generated by each fuel type over the 30 simulations.

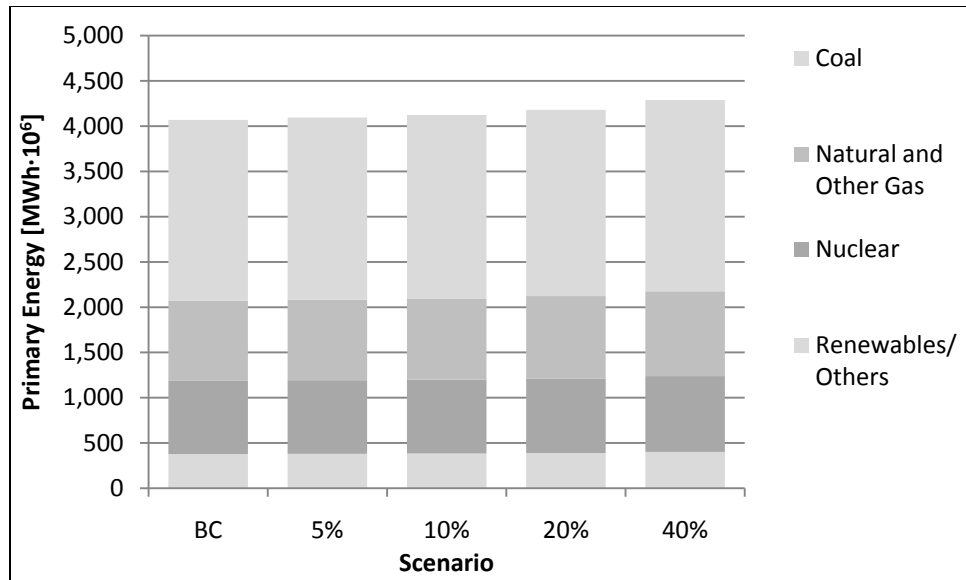


Figure 3.21. Primary energy generated for each U.S. scenario.

In Figure 3.21, as expected, the total generated energy increases as the level of PHEV penetration increases. In Figure 3.21, liquid and coke petroleum energy production is negligible (i.e. very small contribution to the total energy production) and is removed from the list of fuel types. The increase in fuel types energy production is shown in Figure 3.22 for each level of PHEV penetration.

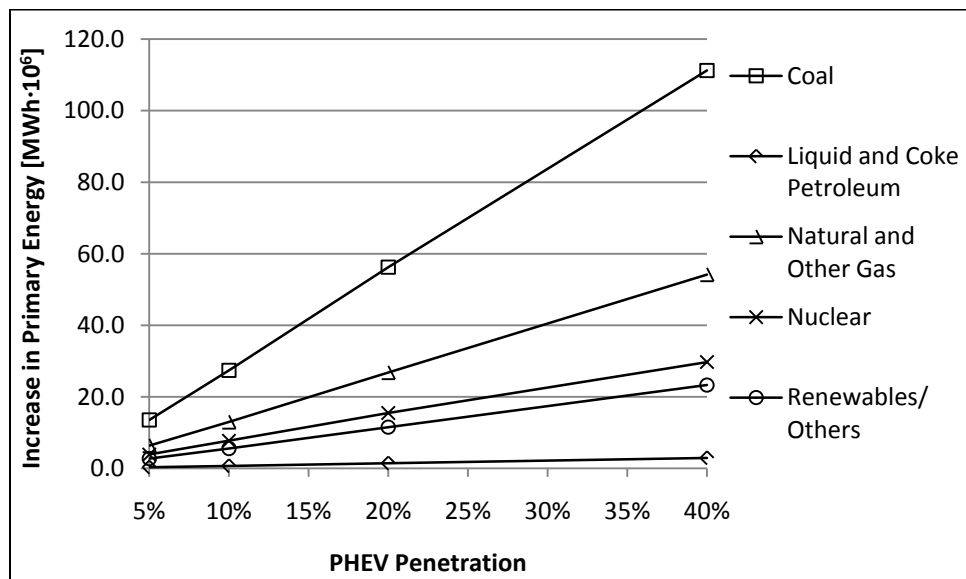


Figure 3.22. Increase in primary energy for each U.S. PHEV penetration scenario.

In Figure 3.22, the increase in energy produced by each fuel type is computed by subtracting the base case fuel type energy production from the average PHEV scenario fuel type energy production ($\Delta = \text{PHEV Scenario} - \text{Base Case}$). The significant increase in coal and natural gas energy production indicates that these two fuel types are utilized to charge PHEVs for the particular power system generating mix studied.

Due to a lack of generating unit reliability and fuel cost data the power system simulation procedure energy statistic results for the U.S. experiment simulations are not applicable.

The impact of displacing gasoline usage with increased utilization of electric energy, using the average U.S. power system, results in the percent change in NO_x and CO_2 shown is shown in Figure 3.23.

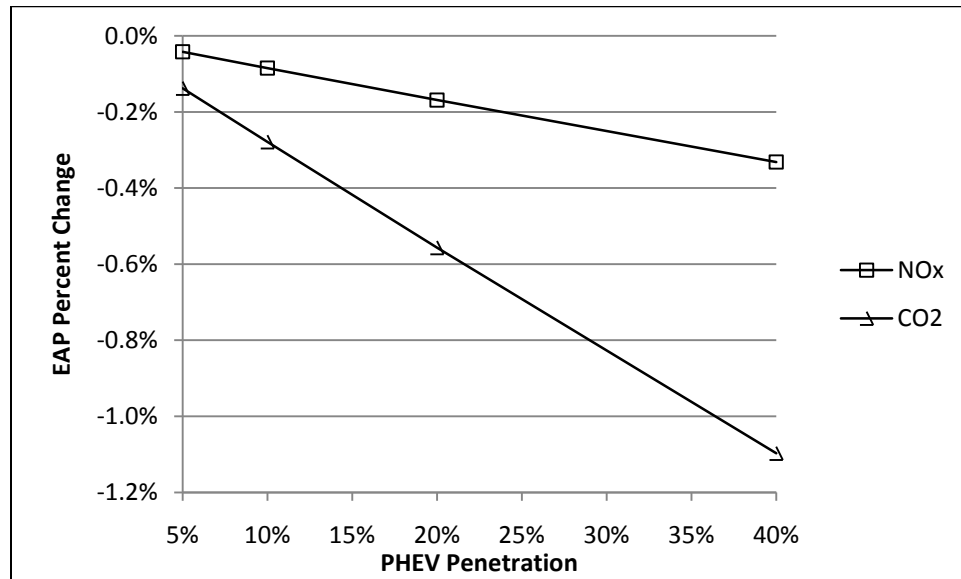


Figure 3.23. U.S. percent change of EAP as a function of PHEV penetration.

The percent change at 40% PHEV penetration is -0.33% of NO_x and -1.10% of CO_2 , which corresponded to annual decrease of 98 million kg of NO_x and an annual decrease of 230,133 million kg of CO_2 . This represents a significant reductions in both pollutants considered.

The gasoline utilization results reveal that the gasoline utilization decreases approximately linearly as PHEV penetration increases as shown in Figure 3.24.

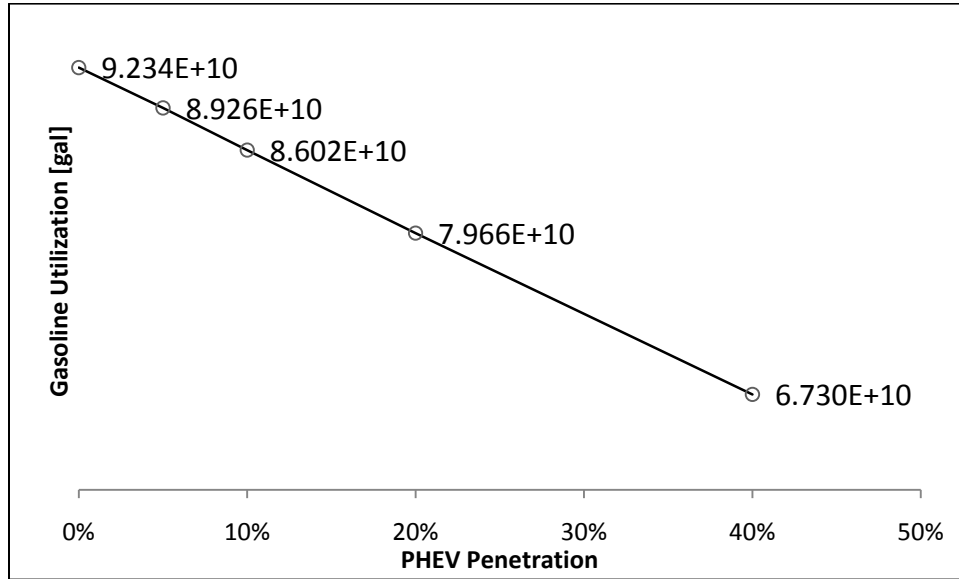


Figure 3.24. U.S. gasoline utilization as a function of PHEV penetration.

Specifically, with a fleet of 135.7 million IC vehicles the average yearly gasoline utilization is 92,340 million gallons whereas with 40% of the vehicle fleet replaced with PHEV this utilization reduces to 67,300 million gallons a reduction of 37.2%.

3.2.3 Modified Reliability Test System

Next, the third experiment, the modified RTS experiment, is described. In the third experiment the penetration level of PHEVs is constant and the RTS electric power generation capacity mix varies. The generating mix varies such that the total generating capacity is constant but the ratio of clean generating capacity increases. All other PPC power system simulation procedure input data is identical to the first experiment.

3.2.3.1 Modified RTS Experiment Data

Five simulation scenarios are considered (called RTS, C1, C2, C3, and C4) each with 5% penetration of PHEV in the RTS power system area, representing 76,950 PHEVs (1,462,050 IC vehicles, thus 1.539 million vehicles in total). The total generating capacity of each set of generators, where a set is comprised of all available generator using the same fuel type, is shown in Figure 3.25.

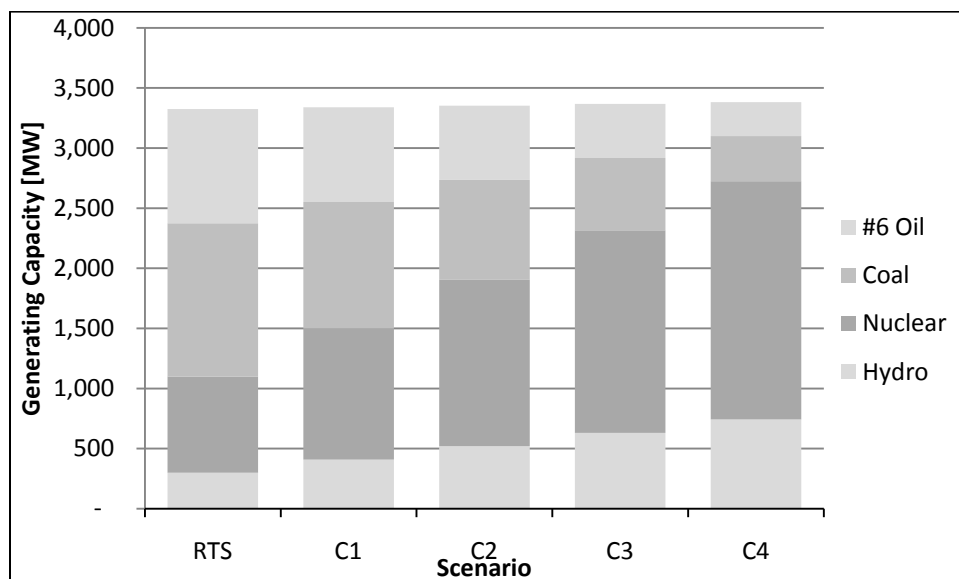


Figure 3.25. Clean energy experiment scenario generation capacities.

In Figure 3.25, the first column is the original RTS power generating capacity mix, and each subsequent column indicates the modified power generating mix capacity for each fuel type. In Figure 3.25, the #2 oil generating capacity is negligible and is removed from the list of fuel types. The generating capacity available from all nuclear and hydro (non-EAP producing) generators increases and the capacity available from #2 oil, #6 oil, and coal (all others fuel types) generators decreases; thus, the total generating capacity for each scenario is constant 3,405 MW.

3.2.3.2 Modified RTS Experiment Data

The percentage of non-EAP producing capacity and energy production is shown in Table 3.28 for each modified RTS scenario.

Table 3.28. Clean energy capacity and generated energy summary.

Percentage of Non-EAP Producing	RTS	C1	C2	C3	C4
Capacity	32.31%	44.00%	56.00%	68.00%	80.00%
Energy Generated	40.79%	55.40%	69.42%	80.71%	89.41%

Clearly, as the level of non-EAP producing capacity increases the energy generated by the non-EAP producing energy sources also increases. The amount of energy generated by each power system fuel type is shown in Figure 3.26.

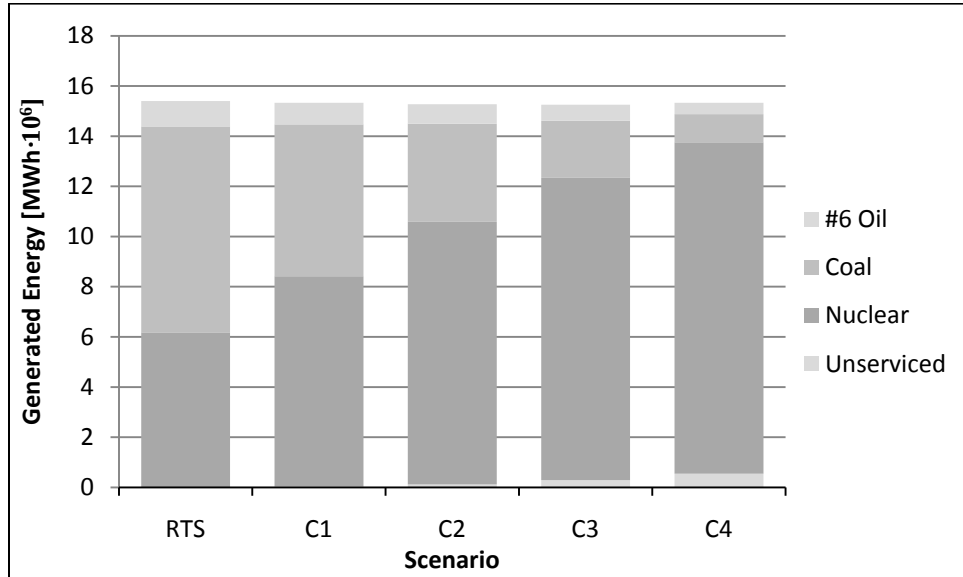


Figure 3.26. Clean energy experiment scenario generated energy.

In Figure 3.26, #2 oil and hydro energy production are negligible (i.e. very small contribution to the total energy production) and are removed from the list of fuel types. In Figure 3.26, as the level of nuclear energy reaches significant levels, scenarios C3 and C4 (78% and 85% respectively), the amount of unserved energy becomes noticeable (2% and 4% respectively). This result is due to the relatively high forced outage rate (FOR) for the nuclear generators (Table 3.11). The specific percentage increase for each fuel type is shown in Figure 3.27.

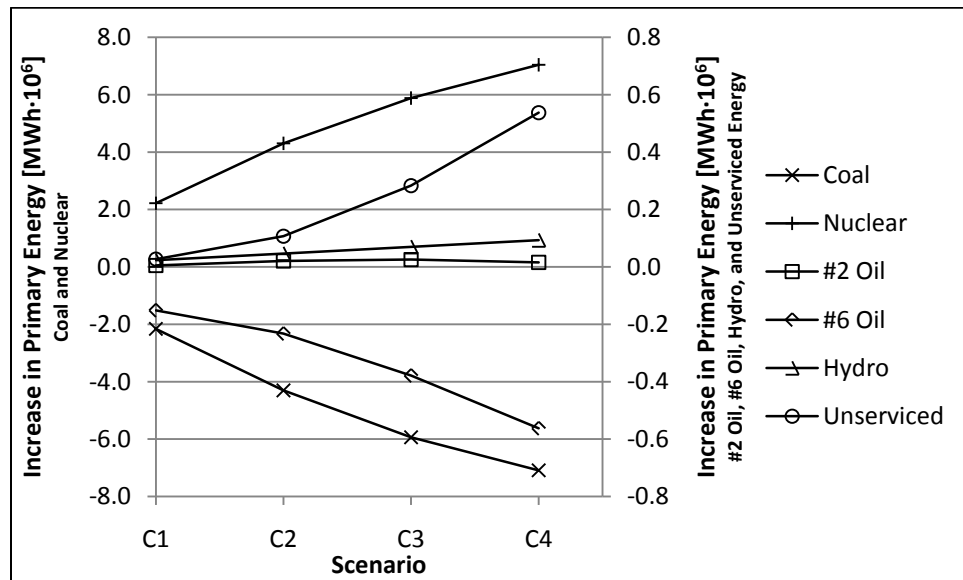


Figure 3.27. Clean energy experiment scenario increase in primary energy.

In Figure 3.27, the percentage increase for #2 oil, #6 oil, hydro, and unserved energy are an order of magnitude smaller than that of the percent increase of coal and nuclear energy, for this reason the percentage in #2 oil, #6 oil, hydro and unserved energy are plotted on a secondary (right-hand side) vertical axis, with a different scale than the primary (left-hand side) vertical axis..

This experiment indicates that nuclear energy is used to replace the energy originally derived by coal energy. The other three fuel types, #2 oil, #6 oil and hydro energy combined only produce less than 8% of the total generated energy for each scenario. The resulting change in EAP is shown in Figure 3.28.

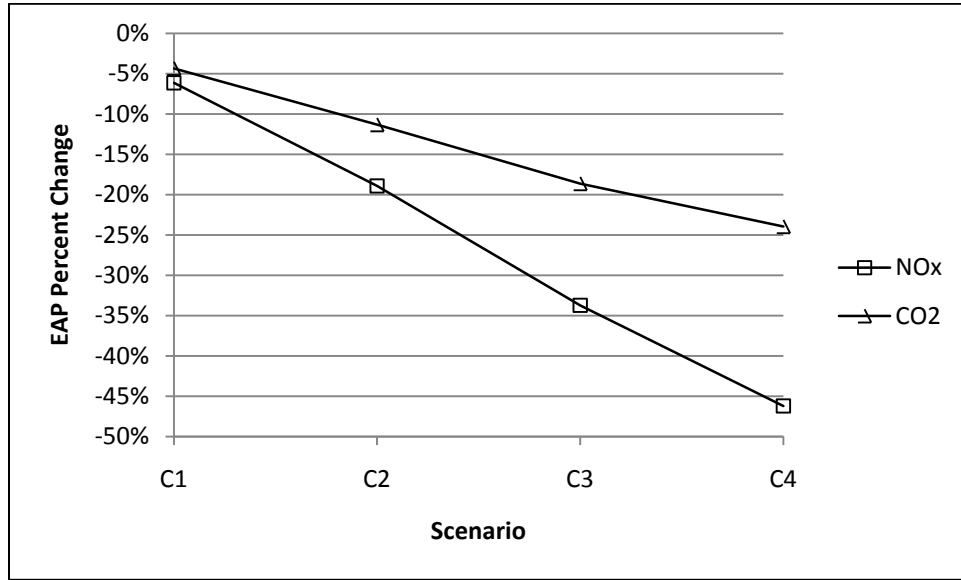


Figure 3.28. Clean energy experiment change in EAP for each simulated scenario.

Not surprisingly as the amount of energy produced from non-EAP producing sources increases, the total amount of EAP decreases significantly.

3.3 Conclusion

The use of PHEVs represents a feasible near term solution to the correlated global crisis of increased use of petroleum and increased generation of EAP. The impact of PHEV use in the context of these two issues is addressed in this chapter.

The change in primary energy source utilization due to PHEV charging is evaluated using the PPC power system simulation procedure [3.1]. For this research the PPC power system simulation procedure is augmented with a PHEV model. The PHEV model allows the amount of added electric energy demand to charge a fleet of PHEVs to be calculated. The results of this methodology include expected energy generated with and without the added electric load demand required to charge PHEVs, the expected EAP produced by the vehicle fleet and power system with and without PHEV charging, and fuel costs for IC vehicles and PHEVs.

Three experiments are presented. The first uses the 1979 RTS [3.8] to charge varying levels of PHEV penetration. The second uses the U.S. average generation mix to charge varying levels of PHEV penetration. The third varies the relative capacity of EAP producing and non-EAP producing generation in the RTS power system and simulated the primary energy utilized to charge 5% penetration of PHEVs.

The probabilistic simulation of an integrated power system with distributed PHEVs results depend on the integrated power system generation mix. The percent of the total generating capacity for each fuel type utilized in the original RTS system [3.8] is shown in Figure 3.29, the U.S. average generation [3.10] mix is shown in Figure 3.30, and the generating capacity of each fuel type for the five clean energy scenarios are shown in Figure 3.25.

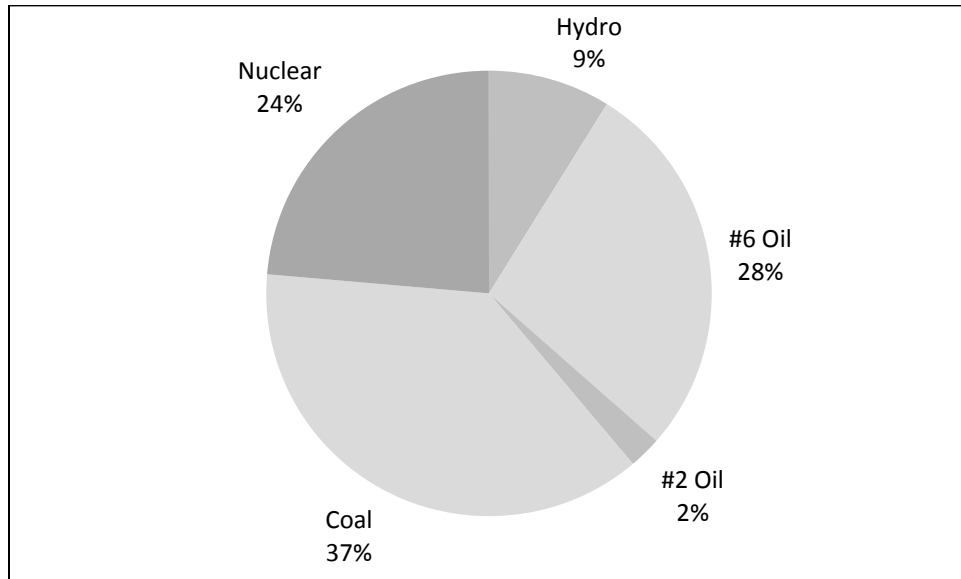


Figure 3.29. RTS generating capacity [3.8].

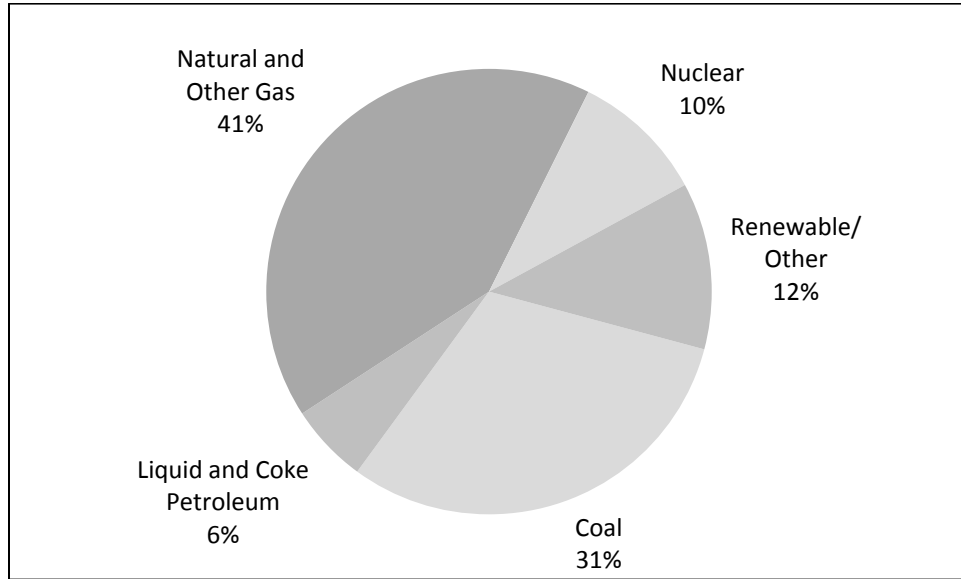


Figure 3.30. U.S. total generating capacity [3.10].

The expected energy production from each fuel type for the base case, no PHEVs included in the light duty vehicle fleet, and a scenario where 5% of the light duty vehicle fleet in the power system area is replaced with PHEVs, are shown in Table 3.29. In Table 3.29 the percentage change is given by

$$\text{Percent Change} = [(5\% \text{ PHEV} - \text{Base Case}) / \text{Base Case Total}] \cdot 100\% \quad (3.48)$$

where the base case total amount of generated energy is used to normalize the change in energy production so that the relative size of each fuel types contribution to the total energy generated is accounted for. Without this normalization the RTS simulation results percent increase in #2 oil energy production would be 17.71% and the percent increase in #6 oil energy production would be 9.67%, thereby incorrectly indicating a higher increase in #2 oil over #6 oil because the contribution of #2 oil is so small compared to all other fuel types. The modified RTS simulation results in Table 3.29 are the C1 scenario results. In the C1 scenario results the non-EAP producing capacity (nuclear and hydro) is increased to provide 44% of the total system capacity up from 32.31% in the original RTS generating capacity [3.8]. This scenario represents the smallest increase in clean production capacity simulated in the modified RTS experiment.

Table 3.29. Change in primary energy source utilization.

		Base Case [GWh]	5% PHEV Penetration [GWh]	Percent Change
RTS Simulations	#6 Oil	924	1,014	0.59%
	#2 Oil	5	6	0.01%
	Coal	7,988	8,212	1.47%
	Nuclear	6,167	6,167	0%
	Hydro	194	194	0%
U.S. Power System Simulations	Coal	2,000,000	2,014,000	0.33%
	Liquid and Coke Petroleum	45,530	45,880	0.01%
	Natural and Other Gas	882,800	889,200	0.16%
	Nuclear	808,600	812,500	0.09%
	Renewables/Others	377,900	380,700	0.07%
Modified RTS Simulations	#6 Oil	1,014	862	-0.97%
	#2 Oil	6	11	0.03%
	Coal	8,212	6,052	-13.85%
	Nuclear	6,167	8,384	14.22%
	Hydro	194	217	0.15%

In the RTS simulations the #6 oil and coal are utilized to meet the additional load created by PHEV charging, and the nuclear and hydro energy are fully utilized thus no increase in energy utilization of these fuel types is possible. In the U.S. power system simulations coal is utilized to meet the additional load created by PHEV charging. The modified RTS simulations introduce additional nuclear and hydro generation capacity compared to the RTS simulations. The modified RTS simulations result in a significant increase in nuclear energy generation and a slight increase in hydro energy generation.

In addition to the expected energy production, expected NO_x and CO₂ EAP production are also calculated. The total system EAP is the EAP produced by both the electric power system and the light duty vehicle fleet in the power system area. Table 3.30 shows EAP results for each experiments base case and 5% PHEV penetration simulations and the modified RTS experiment C1 scenario. Here the percent decrease is normalized by the base case results, as is the standard percent reduction calculation.

Table 3.30. Total system EAP.

		Base Case [kg]	5% PHEV Penetration [kg]	Percent Decrease
RTS Simulations	NO _x	4.432E+07	4.472E+07	-0.92%
	CO ₂	1.736E+10	1.720E+10	0.93%
U.S. Power System Simulations	NO _x	2.959E+10	2.958E+10	0.04%
	CO ₂	2.097E+13	2.095E+13	0.14%
Modified RTS Simulations	NO _x	4.472E+07	4.198E+07	6.13%
	CO ₂	1.720E+10	1.645E+10	4.34%

In the RTS simulations, an increase of 0.92% of NO_x represents an annual increase of 0.4986 million kg of NO_x; whereas, a decrease of 0.93% of CO₂ represents a decrease of 160.6 million kg of CO₂. Similarly in the U.S. simulations, a decrease of 0.04% of NO_x represents an annual decrease of 12.40 million kg of NO_x; further, a decrease of 0.14% of CO₂ represents a decrease of 28,900 million kg of CO₂. In the modified RTS simulations significant EAP reduction are simulated, a decrease of 6.13% of NO_x represents an annual decrease of 2.742 million kg of NO_x; further, a decrease of 4.34% of CO₂ represents a decrease of 745.9 million kg of CO₂.

The fuel cost of a PHEV includes gasoline and electricity purchasing. The average annual fuel cost is compared for PHEV versus IC vehicles in the RTS experiment. Assuming a constant gasoline price of \$3.00 per gallon and electricity rate of 8 cents per kWh all year long, it is found that PHEV fuel costs are 65% less expensive than IC vehicle fuel costs.

The results from Chapter 3 indicate that PHEVs offer cleaner transportation (depending on the generation mix used to charge the vehicles) with decreased gasoline utilization at a lower cost to consumers. The cost to pay for these three advantages in terms of impact on distribution transformers is discussed in Chapter 4.

4. Impact of PHEV charging on Distribution Transformers

This chapter examines the impact that charging plug-in hybrid electric vehicles (PHEVs) will have on distribution transformers. Distribution systems, and specifically the distribution transformer, are designed for specific load carrying capability based on typical load consumption patterns. When PHEVs are deployed the pattern of electric power demand will change. The power system may or may not be capable of handling the new pattern and level of demand.

To examine the impact that PHEV charging will have on distribution transformers, simulations of daily load flows are performed using random electric loads. Two scenarios are examined, the first provides a baseline comparison of the transformer percent loss of life (LOL) with no electric load due to PHEV, the second scenario provides the transformer LOL including PHEV charging in addition to the normal household electrical demand.

A center-tapped single phase transformer model is used to compute the expected transformer currents and an electro-thermal transformer model of the distribution transformer is used to compute the expected distribution transformer hourly hot-spot temperature.

Random distributions for both the normal house hold electric load demand and additional electric load demand for PHEV charging are utilized. Repeated simulations in both scenarios provide a distribution of the expected LOL results.

The remainder of this chapter is organized as follows:

1. The random transformer electrical load distribution is described.
2. The PHEV electrical load distribution is described.
3. The center-tapped single phase transformer model is described.
4. The electro-thermal transformer model is described.
5. The method of computing the transformer LOL is described.
6. The simulation methodology is described.
7. The transformer LOL results are compared.

4.1 Random Feeder Electrical Load

Two assumptions used to compute the random electric load representing the average electric demand for a three house distribution circuit are (1) the hourly peak real power demand, $P^{(h)}$ [W], is a normally distributed random variable (RV) with mean and variance as a function of the daily hour and (2) the hourly power factor ($p.f.^{(h)}$) for each hour is a discrete RV with probability mass function

$$P\{p.f.^{(h)} = x\} = \begin{cases} 0.3 & \text{if } x = 0.9 \\ 0.4 & \text{if } x = 0.95 \\ 0.3 & \text{if } x = 1 \end{cases} \quad (4.1)$$

The assumed time distribution for the average hourly peak load is shown in Figure 4.1.

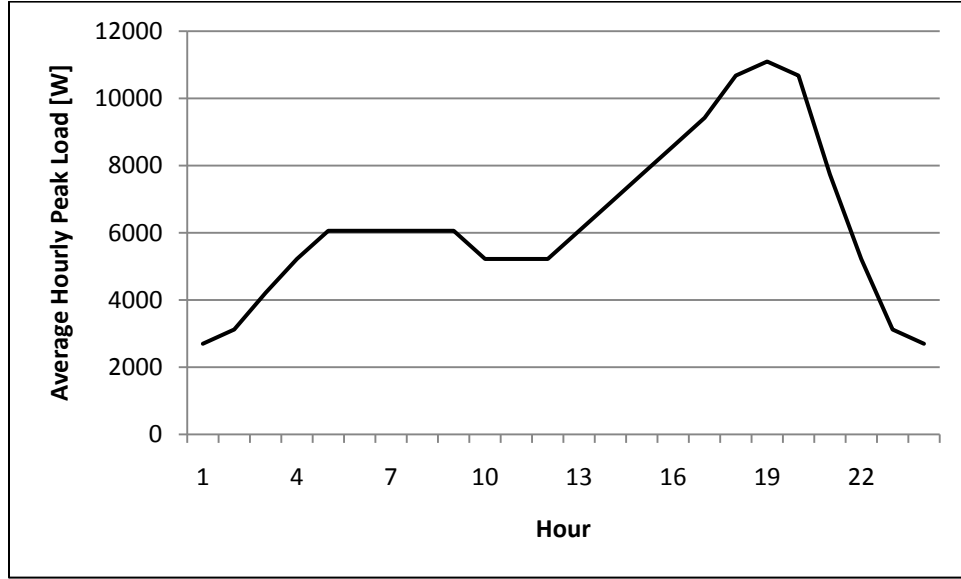


Figure 4.1. Hourly mean peak real power.

In Figure 4.1, this curve represents the mean value for the hourly real power demand at the distribution transformer over a typical day. The real power generated using this mean value is the real power electric load demand for three houses. The validity of this curve is checked by computing the average total daily electric energy demand represented by this curve. The resulting average daily electric energy computed is 151.2 kWh which is consistent with an assumed average household monthly electric load demand of 1,500 kWh.

From the hourly mean peak real power, $\mu_p^{(h)}$ [W] the real power variance is computed as

$$\sigma_p^{(h)} = \mu_p^{(h)} / 4 \quad (4.2)$$

From the generated real power quantity ($P^{(h)}$) and power factor ($p.f.^{(h)}$) the reactive power demand, $Q^{(h)}$ [VAR] is computed as

$$Q^{(h)} = \sin[\cos^{-1}(p.f.^{(h)})] \cdot (P^{(h)} / p.f.^{(h)}) \quad (4.3)$$

4.2 PHEV Electrical Load

The added electric load due to PHEV charging is assumed to 90% of the estimated PHEV-40 battery capacity, where PHEV-X indicates a PHEV which is capable of driving X miles using the battery alone. This electric load represents the useful capacity of the total PHEV battery capacity. This scenario models the situation where a PHEV returns home with a completely discharged battery. A fully discharged battery represents the largest possible demand from the PHEV, representing a worst case scenario in terms of added electric load demand to the distribution transformer. Further, it is assumed that the vehicle begins charging as soon as it is plugged in.

The method to compute the required power and time when the vehicle is connected to the power system is computed by the following three steps:

1. The vehicles arrival, A_T [h], and departure times, D_T [h], are randomly generated.
2. The vehicles added electric energy load, BC [Wh], is randomly generated.
3. The additional real, P [W], and reactive, Q [VAR], power demand power demand is computed.

The arrival (A_T) and departure (D_T) times are assumed to be normally distributed RVs. The distribution parameters (Table 4.1) are the weekday distribution parameter values previously defined (Table 3.9). In Table 4.1, the parameter p in the distribution parameters mean, $\mu_T^{(p)}$ [h], and variance, $(\sigma_T^{(p)})^2$ [h], indicates one of the two possible daily timing distributions: weekday departure or weekday arrival.

Table 4.1. PHEV timing distribution parameters.

Parameter	Departure	Arrival
$\mu_T^{(p)}$	7	18
$(\sigma_T^{(p)})^2$	3	3

The vehicles added electric energy load (BC) is assumed to be a normally distributed RV with a mean (μ_{BC}) of 16,000 Wh and a standard deviation (σ_{BC}) of 4,000 Wh. These parameters are selected to include all four vehicle classes previously defined. Finally, the vehicle charger is assumed to have a power factor of 0.99. All RVs are assumed to be independent.

From these distributions the added charging power (4.4) and reactive power, (4.5) can be computed.

$$P = BC / [(24 - A_T) + D_T] \quad (4.4)$$

$$Q = (P/0.99) \sin[\cos^{-1}(0.99)] \quad (4.5)$$

In (4.4) $(24 - A_T) + D_T$ is the total time, in hours, that the vehicle will be charging.

4.3 Center-Taped Single-Phase Distribution Transformer Model

The typical residential distribution system distribution transformer model is used to compute the expected transformer currents for a specified electric load demand. The model, shown in Figure 4.2, is fully described in [4.1]. The specific scenario modeled here is a single phase distribution transformer feeding three typical houses. The transformer is a 7.960 kV to 120/240 V transformer rated at 15 kVA. The transformer has a series resistance (R_A) and reactance (X_A) of 0.007 p.u. and 0.035 p.u. respectively.

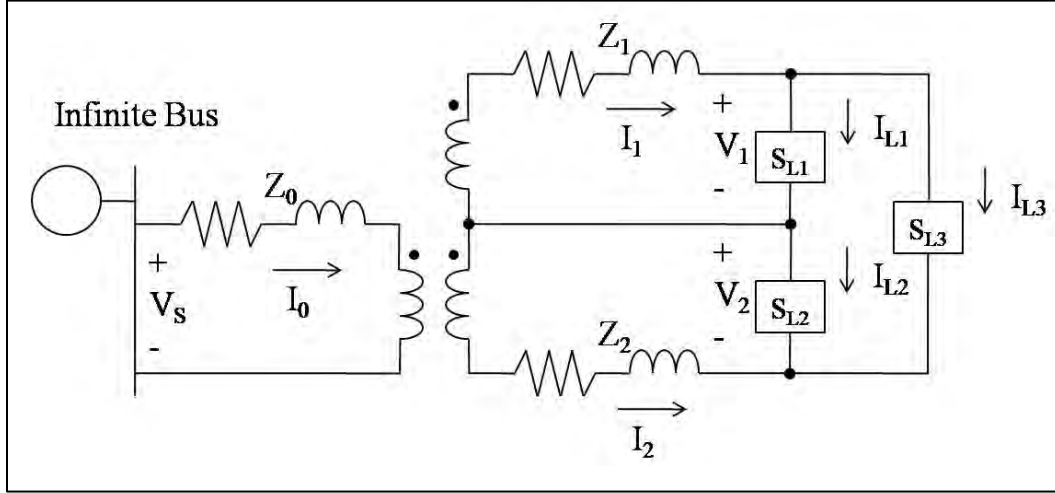


Figure 4.2. Center-tapped single phase transformer model [4.1].

To compute the winding impedances Z_0 , Z_1 , and Z_2 the interlaced transformer design equations are used [4.1]

$$Z_{p.u.0} = 0.5 \cdot R_A + j \cdot 0.8 \cdot X_A \quad (4.6)$$

$$Z_{p.u.1} = Z_{p.u.2} = R_A + j \cdot 0.4 \cdot X_A \quad (4.7)$$

The per-unit impedance values are converted to actual units by multiplying them by the per-unit base impedances

$$Z_{\text{base high voltage}} = (V_s^2 / S_{\text{transformer rated}}) \quad (4.8)$$

$$= 7,960^2 / 15,000 = 4224 \, \Omega$$

$$Z_{\text{base low voltage}} = 240^2 / 15,000 = 3.84 \, \Omega \quad (4.9)$$

Thus,

$$Z_0 = Z_{\text{base high voltage}} \cdot Z_{p.u.0} \quad (4.10)$$

$$= 4,224 \cdot (0.5 \cdot 0.007 + j \cdot 0.8 \cdot 0.035)$$

$$= 14.78 + j \cdot 118.3 \, \Omega$$

$$Z_1 = Z_2 = Z_{\text{base low voltage}} \cdot Z_{p.u.1} \quad (4.11)$$

$$= 3.84 \cdot (0.007 + j \cdot 0.4 \cdot 0.035)$$

$$= 0.0269 + j \cdot 0.0538 \, \Omega$$

The turns ratio (n_t) is the ratio of the primary and secondary voltages

$$n_t = 7960 / 120 = 66.33 \quad (4.12)$$

Finally, the total complex power is distributed between the two 120 V circuits (S_{L1} and S_{L2} [VA]) and the 240 V circuit (S_{L3} [VA]) assuming that 60% of the power demand in a

typical household is 120 V (split evenly between the two 120 V lines) and the remaining 40% is 240 V. Thus,

$$S_{L1} = S_{L2} = 0.3 \cdot (P^{(h)} + j \cdot Q^{(h)}) \quad (4.13)$$

$$S_{L3} = 0.4 \cdot (P^{(h)} + j \cdot Q^{(h)}) \quad (4.14)$$

To compute the winding currents I_0 , I_1 , and I_2 in Figure 4.2 an iterative process from [4.1] is utilized. These currents form the input to the electro-thermal transformer model, which is in turn used to compute the expected distribution transformer temperature, and thus the distribution transformer LOL. The method outlined in [4.1] to compute the transformer currents is an iterative process consisting of a forward sweep and a backward sweep. As an example of this method the transformer currents are computed in detail below for the average assumed electric load including average real power $\bar{P}$ [W], average power factor $\overline{p.f.}$, and average reactive power $\bar{Q}$ [VAR]

$$\bar{P} = E\{P^{(h)}\} = 1/24 \cdot \sum_{h=1}^{24} P^{(h)} = 6,298 \text{ W} \quad (4.15)$$

$$\overline{p.f.} = E\{p.f.^{(h)}\} = 1 \cdot 0.3 + 0.95 \cdot 0.4 + 0.9 \cdot 0.3 = 0.95 \quad (4.16)$$

$$\bar{Q} = \sin(\cos^{-1}(0.95)) \cdot 6298/0.95 = 2,070 \text{ VAR} \quad (4.17)$$

Thus, the average electric load demand at the transformer, representing the total demand for three average houses, is $\bar{S}_{L1}$ (120 V load number 1), $\bar{S}_{L2}$ (120 V load number 2), and $\bar{S}_{L3}$ (240 V load)

$$\bar{S}_{L1} = \bar{S}_{L2} = 0.3 \cdot (6,298 + j \cdot 2,558) = 1,889 + j \cdot 621.0 \text{ VA}$$

$$\bar{S}_{L3} = 0.4 \cdot (6,298 + j \cdot 2,558) = 2,519 + j \cdot 828.0 \text{ VA}$$

The first step to compute the transformer currents is to assume no average low voltage line currents

$$\begin{bmatrix} \bar{I}_1 \\ \bar{I}_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \text{ A} \quad (4.18)$$

Next, the average load voltages are computed

$$\begin{aligned} \begin{bmatrix} \bar{V}_1 \\ \bar{V}_2 \end{bmatrix} &= (n_t \cdot \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix})^{-1} \cdot \left(\begin{bmatrix} V_s \\ V_s \end{bmatrix} - \begin{bmatrix} Z_1 + \frac{1}{n_t^2} Z_0 & -\frac{1}{n_t^2} Z_0 \\ \frac{1}{n_t^2} Z_0 & -Z_2 - \frac{1}{n_t^2} Z_0 \end{bmatrix} \cdot \begin{bmatrix} \bar{I}_1 \\ \bar{I}_2 \end{bmatrix} \right) \\ &= \begin{bmatrix} 0.0151 & 0 \\ 0 & 0.0151 \end{bmatrix} \cdot \left(\begin{bmatrix} 7960 \\ 7960 \end{bmatrix} - \begin{bmatrix} 0.0303 + j \cdot 0.0807 & -0.0034 - j \cdot 0.0269 \\ 0.0034 + j \cdot 0.0269 & -0.0303 - j \cdot 5.3518 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \end{bmatrix} \right) \\ &= \begin{bmatrix} 120 \\ 120 \end{bmatrix} \text{ V} \end{aligned} \quad (4.19)$$

Then, the average load currents are computed

$$\begin{bmatrix} \overline{I_{L1}} \\ \overline{I_{L2}} \\ \overline{I_{L3}} \end{bmatrix} = \begin{bmatrix} \left(\frac{\overline{S_{L1}}}{V_1} \right)^* \\ \left(\frac{\overline{S_{L2}}}{V_2} \right)^* \\ \left(\frac{\overline{S_{L3}}}{V_1+V_2} \right)^* \end{bmatrix} = \begin{bmatrix} 15.75 - j \cdot 5.175 \\ 15.75 - j \cdot 5.175 \\ 10.50 - j \cdot 3.450 \end{bmatrix} \text{ A} \quad (4.20)$$

Next, the average line currents are computed

$$\begin{bmatrix} \overline{I_1} \\ \overline{I_2} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ 0 & -1 & -1 \end{bmatrix} \cdot \begin{bmatrix} \overline{I_{L1}} \\ \overline{I_{L2}} \\ \overline{I_{L3}} \end{bmatrix} = \begin{bmatrix} 26.24 - j \cdot 8.625 \\ -26.24 + j \cdot 8.625 \end{bmatrix} \text{ A} \quad (4.21)$$

Finally, the average load voltages are computed. Now using the average load currents computed in the preceding step

$$\begin{bmatrix} \overline{V_1} \\ \overline{V_2} \end{bmatrix} = \begin{bmatrix} 120.0 - j \cdot 0.0382 \\ 120.0 - j \cdot 0.0382 \end{bmatrix} \text{ V} \quad (4.22)$$

This process is repeated until the error (e) falls below a specified tolerance ($e < 0.001$) [4.1]

$$\begin{aligned} & \begin{bmatrix} 7960 \cdot e \\ 7960 \cdot e \end{bmatrix} = \\ & \begin{bmatrix} \overline{V_s} \\ \overline{V_s} \end{bmatrix} - \left(n_t \cdot \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \overline{V_1} \\ \overline{V_2} \end{bmatrix} + \begin{bmatrix} n_t \cdot Z_1 + \frac{1}{n_t^2} Z_0 & -\frac{1}{n_t^2} Z_0 \\ \frac{1}{n_t^2} Z_0 & -n_t \cdot Z_2 - \frac{1}{n_t^2} Z_0 \end{bmatrix} \cdot \begin{bmatrix} \overline{I_1} \\ \overline{I_2} \end{bmatrix} \right) \\ & = \begin{bmatrix} 0.0 \\ 0.0 \end{bmatrix} \text{ V} \end{aligned}$$

Once the iterative process converges the average high voltage winding current can be computed

$$\begin{aligned} \begin{bmatrix} \overline{I_0} \\ \overline{I_0} \end{bmatrix} &= \frac{1}{n_t} \begin{bmatrix} 1 & -1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \overline{I_1} \\ \overline{I_2} \end{bmatrix} \\ &= \begin{bmatrix} 0.0151 & -0.0151 \\ 0.0151 & -0.0151 \end{bmatrix} \cdot \begin{bmatrix} 26.24 - j \cdot 8.625 \\ -26.24 + j \cdot 8.625 \end{bmatrix} \\ &= \begin{bmatrix} 0.7912 - j \cdot 0.2601 \\ 0.7912 - j \cdot 0.2601 \end{bmatrix} \text{ A} \end{aligned} \quad (4.23)$$

The electro-thermal transformer model, described next, computes the expected transformer winding temperature based on real valued currents, and thus the following magnitudes of the complex current values are used

$$\begin{bmatrix} |\overline{I_0}| \\ |\overline{I_1}| \\ |\overline{I_2}| \end{bmatrix} = \begin{bmatrix} 0.8328 \\ 27.62 \\ 27.62 \end{bmatrix} \text{ A}$$

4.4 Electro-Thermal Transformer Model

Different electro-thermal transformer models of transformers have been experimentally developed in [4.2] and [4.3], and a similar model is used here to calculate the hot-spot temperature of a distribution transformer for random daily load patterns. Variations of the model used in this thesis, shown in Figure 4.3, have also been used by others in [4.4] and [4.5] and is a simplified electro-thermal transformer model of a center-tapped single phase convection cooled distribution transformer.

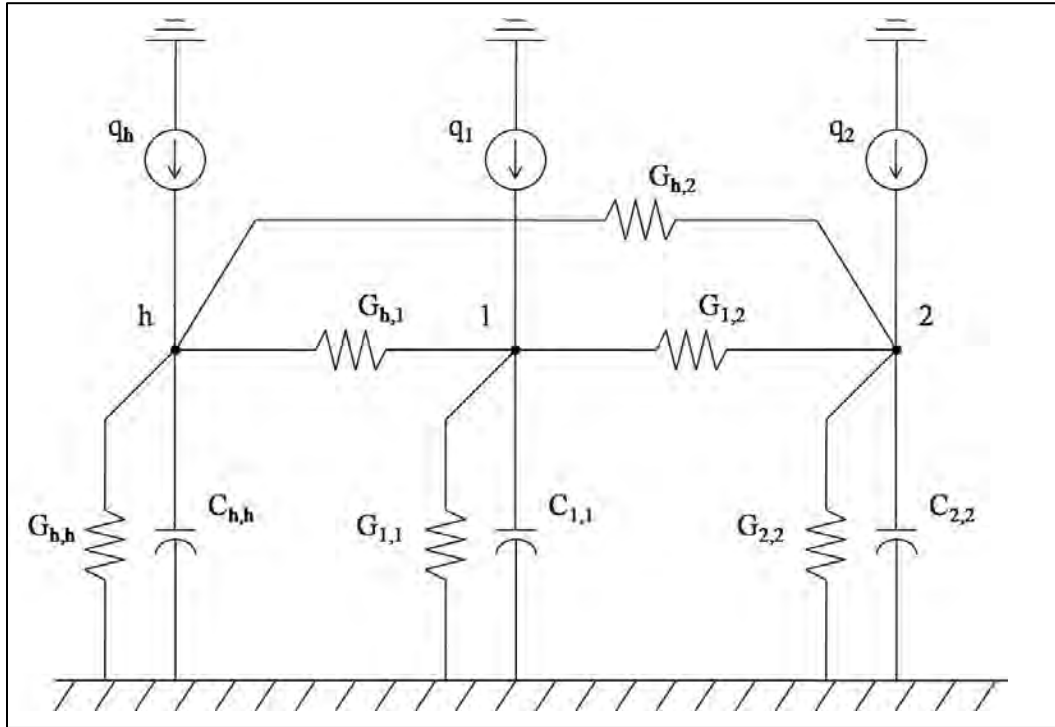


Figure 4.3. Electro-thermal transformer model.

The nodes in Figure 4.3 represent:

- The high voltage winding (node h).
- The low voltage winding center tap 1 (node 1).
- The low voltage winding center tap 2 (node 2).

Each circuit element represents a thermal phenomenon: the conductance components represent heat transfer within and between the transformer windings (estimated from temperature gradients between transformer windings [4.6]); the capacitive components represent transformer winding thermal inertia (computed from the winding mass and winding specific heat constant [4.6]); and the current sources represent heat sources in the form of ohmic losses in each of the transformer windings.

The dynamics of the transformer winding temperatures [4.6] are described by the following differential equation

$$\mathbf{C} \cdot d\vec{T}/dt = -\mathbf{G} \cdot \vec{T} + \vec{Q} \quad (4.24)$$

where $\mathbf{C}$ [joules/°C] is the thermal capacitance matrix

$$\mathbf{C} = \begin{bmatrix} C_{h,h} & 0 & 0 \\ 0 & C_{1,1} & 0 \\ 0 & 0 & C_{2,2} \end{bmatrix} \quad (4.25)$$

$\vec{T}$ [°C] is the components temperature vector

$$\vec{T} = [T_h \quad T_1 \quad T_2]^T \quad (4.26)$$

$\vec{Q}$ [W] is the heat input vector

$$\vec{Q} = [Q_h \quad Q_1 \quad Q_2]^T \quad (4.27)$$

which represent ohmic losses in the transformer windings and as such can be modeled as the following function of the winding currents and resistances

$$\vec{Q} = [14.78 \cdot I_h^2 \quad 0.0269 \cdot I_1^2 \quad 0.0269 \cdot I_2^2]^T \quad (4.28)$$

and $\mathbf{G}$ [W/°C] is the thermal conductance matrix, which represents the thermal conductance among the three windings

$$\mathbf{G} = \begin{bmatrix} G_{h,h} + G_{h,1} + G_{h,2} & -G_{h,1} & -G_{h,2} \\ -G_{h,1} & G_{1,1} + G_{h,1} + G_{1,2} & -G_{1,2} \\ -G_{h,2} & -G_{1,2} & G_{2,2} + G_{h,2} + G_{1,2} \end{bmatrix} \quad (4.29)$$

The numeric values of the circuit parameters chosen were analytical computed and experimentally verified [4.7]

$$\mathbf{C} = \begin{bmatrix} 468 & 0 & 0 \\ 0 & 375 & 0 \\ 0 & 0 & 365 \end{bmatrix} \frac{\text{joules}}{^\circ\text{C}}$$

$$\mathbf{G} = \begin{bmatrix} 0.78 + 2.1 + 2.0 & -2.1 & -2.0 \\ -2.1 & 0.44 + 2.1 + 3.5 & -3.5 \\ -2.0 & -3.5 & 0.46 + 2.0 + 3.5 \end{bmatrix} \frac{\text{W}}{^\circ\text{C}}$$

A trapezoidal integration method is used to calculate the solution of (4.24). In particular, the integration within the time interval $[t - u, t]$ is

$$\begin{aligned} \vec{T}(t) = & (\mathbf{C} + \mathbf{G} \cdot u/2)^{-1} \cdot (\mathbf{C} - \mathbf{G} \cdot u/2) \cdot \vec{T}(t - u) \\ & + (\mathbf{C} + \mathbf{G} \cdot u/2)^{-1} \cdot \vec{Q} \cdot u \end{aligned} \quad (4.30)$$

where u is the time step of the integration.

The input to the above model is the transformer currents I_h , I_1 , and I_2 over a specific time period, typically one day. The result from the trapezoidal integration is the estimated transformer temperature with respect to ambient temperature over the simulated time span. An assumed flat daily temperature profile is used for simplicity (20°C).

4.5 Transformer Loss-of-Life (LOL) Calculation

The process of insulation degradation, for oil filled transformer, is a function of three phenomenon (1) temperature, (2) moisture, and (3) oxygen content [4.8]. The second two consist of water and oxygen contamination of the transformer oil and can be controlled through “oil preservation systems” [4.8] and thus are not considered in this analysis. The following method outlined in [4.8] is used to compute the LOL.

The LOL, P_L [%], is a function of the equivalent life, E_L [h], and the normal insulation life, N_L [h], [4.8]

$$P_L = (E_L \cdot 100)/N_L \quad (4.31)$$

where E_L is computed as a function of the aging acceleration factor, θ_u ,

$$E_L = \sum_{u=1}^U (\theta_u \cdot \Delta t_u) \quad (4.32)$$

and θ_u is computed as a function of the aging rate constant, B [K], and the transformer hot-spot temperature, $\tilde{T}_u$ [°C], at time u

$$\theta_u = \exp\{B/383 - B/(\tilde{T}_u + 273)\} \quad (4.33)$$

The LOL calculations are computed for a typical day based on hourly increments, thus U [h] is 24 and Δt_u is 1 hour. The LOL calculation variables E_L and θ_u are computed for each hour of the simulated day based on the simulated hot-spot temperature $\tilde{T}_u$ in that hour (the maximum simulated transformer winding temperature for a given hour).

The LOL constants N_L and B are selected based on historically accepted values. The historical perspective on the insulation life values and LOL calculations is quite interesting, and the values in Table 4.2 for normal insulation life and in Table 4.3 for aging rate constant are surrounded in ambiguity; however, in [4.8] a conclusion is drawn that the “chemical test measurement of degree of polymerization is a much better indication of cellulosic insulation mechanical characteristics than loss of tensile strength,” therefore the normal insulation life used is 150,000 hours (17.1 years) and the aging rate constant used is 14,580 K.

Table 4.2. Normal insulation life times [4.8].

Basis	Normal Insulation Life [h]
50% retained tensile strength of insulation (former IEEE Std. C57.92-1981)	65,000
25% retained tensile strength of insulation	135,000
200 retained degree of polymerization in insulation	150,000
Interpretation of distribution transformer functional life test (former IEEE std. C57.91-1981 criterion)	180,000

Table 4.3. Aging rate constant [4.8].

Basis	Aging rate constant [K]
50% retained tensile strength of insulation (former IEEE Std. C57.92-1948)	14,830
50% retained tensile strength of insulation (former IEEE Std. C57.92-1981)	16,054
DT life tests (former IEEE Std. C57.92-1981)	14,594
250 retained degree of polymerization in insulation	14,580

Normal LOL, using the normal insulation life and aging rate constant selected, for operation of a constant 110 °C for 24 hours is 0.016%. Intuitively, this indicates that a transformer which withstood a 24 hour period with hot-spot temperature of 110 °C aged the equivalent of 0.016% of its useful life. Note that 24 hours is 0.016% of 150,000 hours.

4.6 Transformer Impact Simulation Procedure

A block diagram of the simulation procedure is shown in Figure 4.4.

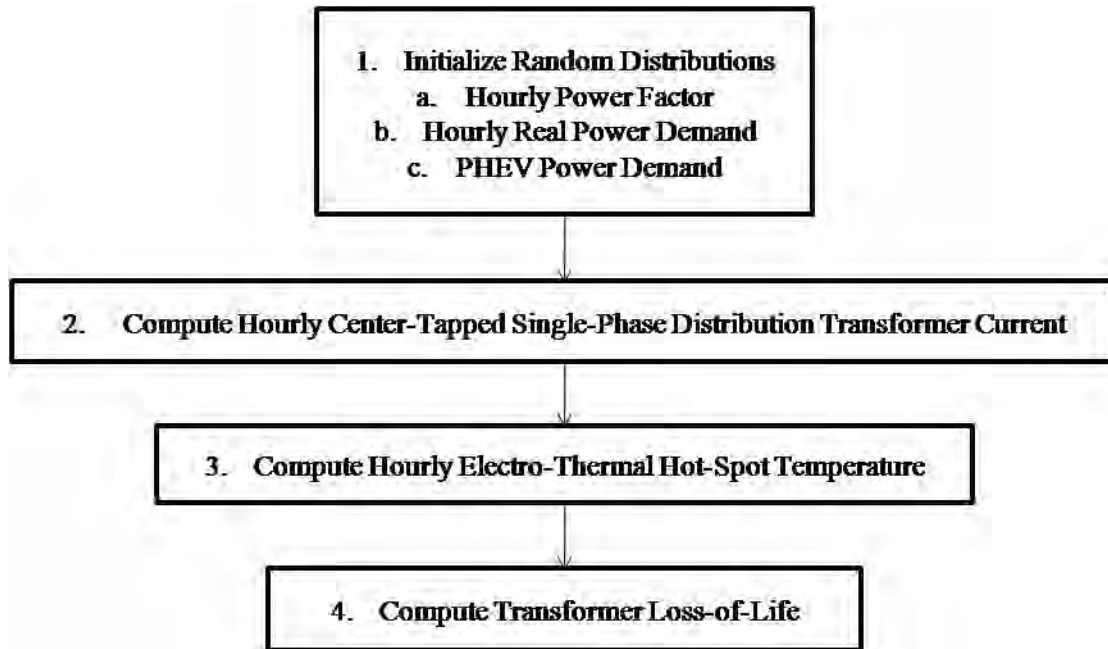


Figure 4.4. Transformer impact simulation block diagram.

The first step in Figure 4.4 is to generate all RVs used in the simulation procedure. The first RV generated is the hourly household power factor, this is a discrete value, and to generate this RV an inverse transform method is used [3.5]. The cumulative distribution

function of the RV is inverted and evaluated using uniform (0, 1) values to generate the random power factor values.

$$F^{-1}(U) = \begin{cases} 0.9 & 0 \leq U < 0.3 \\ 0.95 & 0.3 \leq U < 0.7 \\ 1 & 0.7 \leq U \leq 1 \end{cases} \quad (4.34)$$

where U is a RV distributed uniform (0, 1) and is generated using the C function *rand()*.

The second and third RVs are generated using the Box-Müller method, (3.8). The second RV, the hourly real power demand is computed by

$$P^{(h)} = \mu^{(h)} + \sigma^{(h)} \cdot N \quad (4.35)$$

The third RV, the PHEV power demand is computed using (4.4). This value represents the added grid electric energy required for one PHEV.

The second step in Figure 4.4 is to compute the transformer current based on the assumed distribution transformer electric load demand. The methodology assumes that the distribution transformer electric load demand is constant for each hour of the simulated day. The iterative process, to compute the transformer currents for the simulated day, is repeated twice for every hour of the simulated day, once for the base case scenario and again for the PHEV scenario. The final result of the iterative process is the transformer currents for the specified load.

The third step in Figure 4.4 is to compute the transformer hot-spot temperature for every hour of the simulated day. Here hot-spot temperature is defined as the maximum winding temperature in a given hour. A step length of 10 seconds is used in the trapezoidal integration method described above. Thus, the transformer currents, from the center-tapped single phase distribution transformer, are sampled every 10 seconds as input to the electro-thermal transformer model simulation. The final result of this simulation is the hot-spot temperature of the distribution transformer, which is the maximum temperature observed from each hour of the simulated day.

The fourth step in Figure 4.4 computes the transformer LOL. Using the described method the LOL is computed for each simulated day for both scenarios, without PHEV charging (base case) and with PHEV charging (PHEV scenario).

Sample results are described below to clarify the procedure. The sample results consist of one day with the base case feeder demand (feeder demand with no electric load due to PHEV charging), and one day with the added electric load demand of charging three PHEVs. The input to the sample results are the average hourly peak load shown in Figure 4.1, and the average PHEV required grid electric energy of three PHEVs charged over the average arrival and departure times. Figure 4.5 shows the base case feeder load (called “BC Feeder Demand”), required PHEV grid electric energy due to three PHEVs (called “PHEV Feeder Demand”), and total feeder load with added PHEV electric load (called “Total Load with PHEVs”).

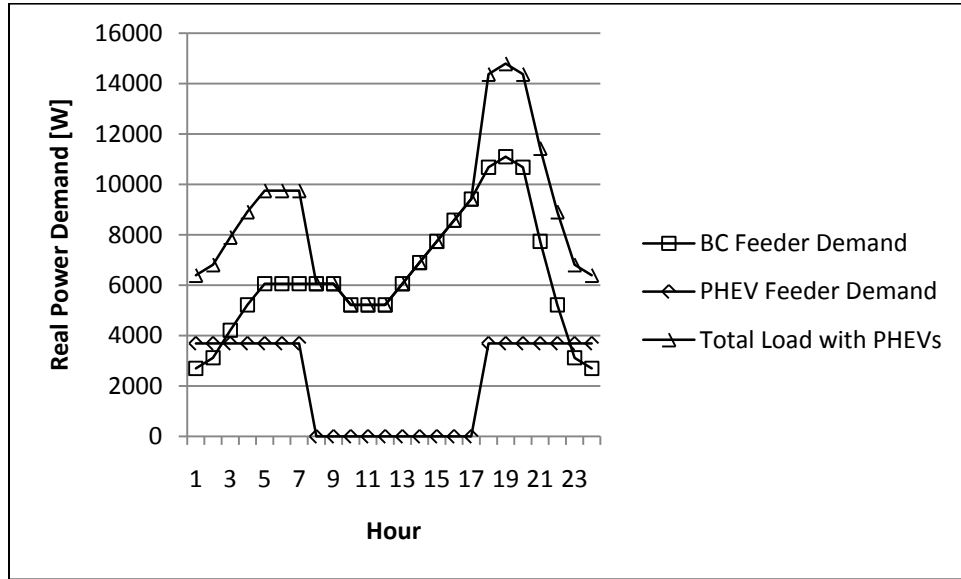


Figure 4.5. Sample scenario feeder load data.

In Figure 4.5 the total load with PHEVs is the hour by hour sum of the PHEV feeder demand and the base case feeder demand. The total load with PHEVs has a maximum real power demand of 14,792 W which is an increase of 33% over the base case feeder demand; moreover the total load with PHEVs has a minimum real power demand of 5,200 W, which is an increase of 93% over the base case feeder demand.

The next step in the transformer impact simulation is to compute the expected distribution transformer winding currents. This calculation includes two scenarios: one with no additional load due to PHEV charging (called “BC”) and a second with the added electric load due to PHEVs (called “PHEV”). Both scenarios winding current results include two low voltage winding currents and one high voltage winding current. Because the load on both the low voltage windings is balanced, the low voltage winding current results are the same; for this reason and for simplicity, only one low voltage winding current result (called “Low V”) and the high voltage winding current result (called “High V”) are shown for both scenarios in Figure 4.6.

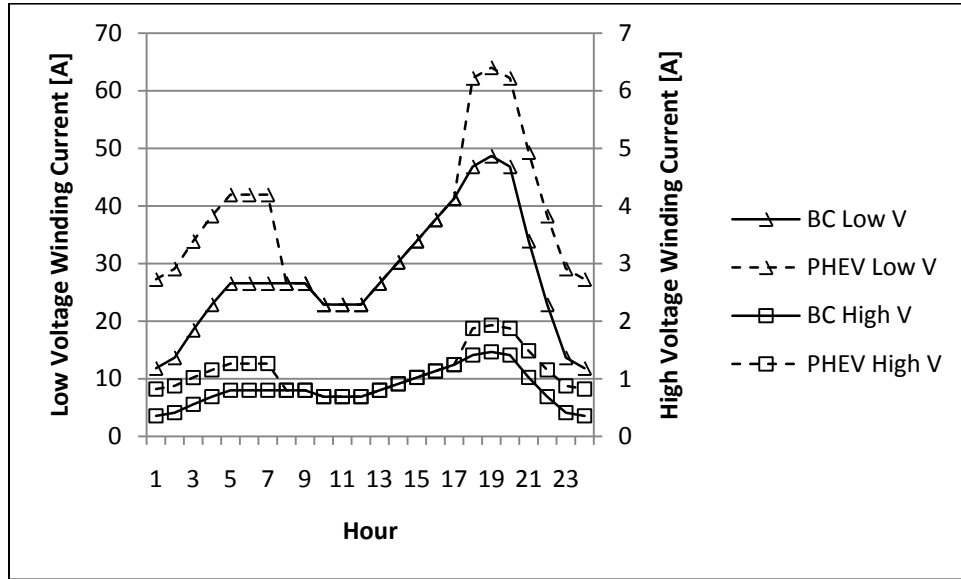


Figure 4.6. Sample scenario winding currents.

In both scenarios the high voltage winding currents are significantly smaller in amplitude than the low voltage winding currents; thus, in Figure 4.6 the high voltage winding currents are plotted for the secondary (right-hand side) vertical axis using a different scale than the primary (left-hand side) vertical axis.

The next step in the transformer impact simulation is to compute the expected distribution transformer winding temperature for both scenarios (“BC” and “PHEV”). The electro-thermal transformer model is utilized to compute these expected temperatures. The results of the electro-thermal transformer model using the winding currents in Figure 4.6 are shown in Figure 4.7. Again, because the load on the low voltage windings is balanced, the currents in the low voltage windings are the same and thus the low voltage winding temperatures are the same. For this reason and for simplicity only one low voltage winding temperature (called “Low V”) and the high voltage winding temperature (called “High V”) are shown in Figure 4.7.

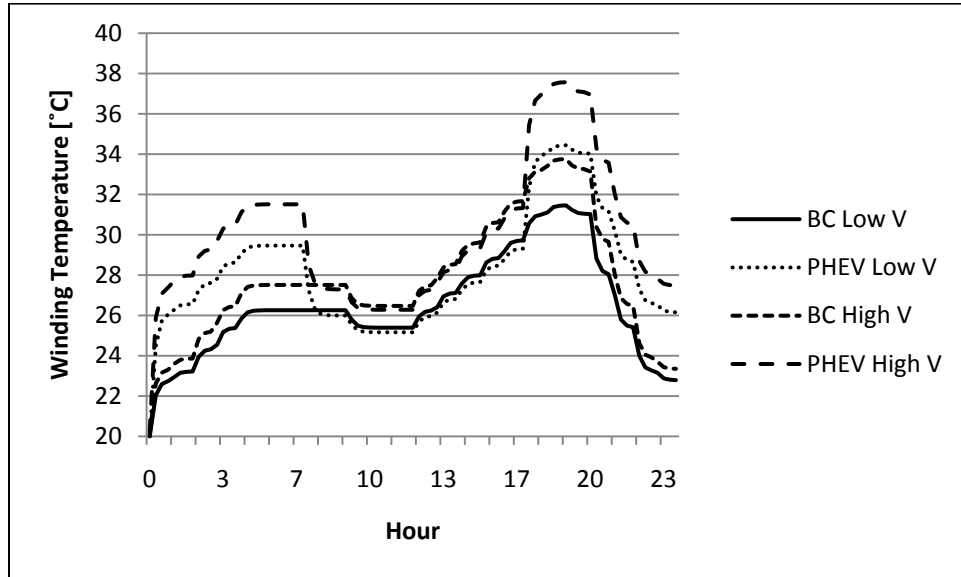


Figure 4.7. Sample scenarios winding temperatures.

Notice that, the significantly smaller high voltage winding current than the low voltage winding currents in Figure 4.6 result in similar amplitude temperature results for both high and low voltage winding temperatures. This change is due to the significantly larger high voltage winding resistance of 14.78Ω , see (4.10) than the low voltage winding resistance of 0.0269Ω , see (4.11).

The next step in the transformer impact simulation is to compute the hot-spot winding temperature for both scenarios (“BC” and “PHEV”). The hot spot temperature is the maximum winding temperature in a given hour. Based on the winding temperatures in Figure 4.7, the windings hot-spot temperatures is computed and shown in Figure 4.8.

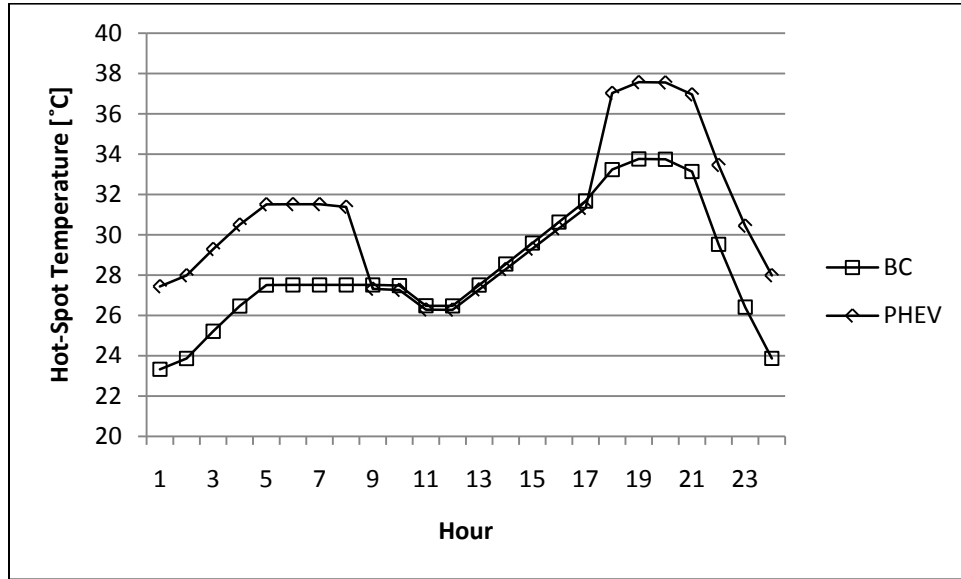


Figure 4.8. Sample scenarios hot-spot temperature.

The last step in the transformer impact simulation is to compute the distribution transformer LOL for both scenarios. Finally, from the hot-spot temperatures the aging acceleration values are computed shown in Table 4.4 and the resulting LOL are, $5.8891\text{E-}07\%$ and $9.0037\text{E-}07\%$, for the base case and PHEV feeder demand respectively shown in Figure 4.5.

Table 4.4. Hot-spot temperature results and LOL calculation.

Hour	BC $\tilde{T}_u$	BC θ_u	PHEV $\tilde{T}_u$	PHEV θ_u
1	23.33	1.460E-05	27.44	2.863E-05
2	23.87	1.596E-05	27.98	3.126E-05
3	25.22	1.994E-05	29.29	3.853E-05
4	26.47	2.445E-05	30.50	4.670E-05
5	27.51	2.895E-05	31.51	5.476E-05
6	27.52	2.898E-05	31.51	5.481E-05
7	27.52	2.898E-05	31.51	5.481E-05
8	27.52	2.898E-05	31.38	5.370E-05
9	27.52	2.898E-05	27.32	2.807E-05
10	27.48	2.884E-05	27.26	2.782E-05
11	26.48	2.451E-05	26.29	2.375E-05
12	26.47	2.448E-05	26.28	2.373E-05
13	27.51	2.895E-05	27.29	2.793E-05
14	28.55	3.424E-05	28.30	3.287E-05
15	29.59	4.044E-05	29.31	3.865E-05
16	30.63	4.771E-05	30.32	4.539E-05
17	31.68	5.622E-05	31.33	5.324E-05
18	33.24	7.173E-05	37.03	1.285E-04
19	33.76	7.785E-05	37.57	1.394E-04
20	33.75	7.766E-05	37.55	1.390E-04
21	33.14	7.066E-05	36.96	1.271E-04
22	29.53	4.002E-05	33.46	7.428E-05
23	26.41	2.425E-05	30.45	4.631E-05
24	23.87	1.597E-05	27.99	3.127E-05

The hot-spot temperatures estimated by the sample results indicate average results. The developed probabilistic model varies the electric load above and below the average with variance as a function of the average peak real power, see (4.2), thus the sample results provide validation of the developed probabilistic simulation.

The LOL values computed indicate that in the simulated 24 hour period the transformer aged only 8.837E-4, and 1.350E-3 years for the base case and PHEV feeder demand respectively. This amount of aging is 5.889E-07% and 9.004E-07% (base case and PHEV feeder demand respectively) of the total expected life of 150,000 hours. There are two reasons for the smallness of these results. First, the transformer is oversized for the modeled electric load. Second, the ambient temperature used is very conservative. The nameplate rating of the modeled transformer is 15 kVA. The peak average electric load is 11.1 kW. This indicates that there is 26% = $(1 - 11.1/15) \cdot 100\%$ spare transformer capacity for the peak average load. The ambient temperature assumed is 20 °C (≈ 68 °F) and is very conservative for warm temperate climate summer temperatures.

The amplitude of the LOL is not the focus of this study. Rather the relative increase in LOL which is the increase in transformer degradation caused by the additional electrical load caused by PHEV charging. The percent increase for the sample results is 52.89%. This shows that the sample results indicate that the life time of an average transformer will be decreased by 53% because of the added stress of charging three PHEVs. Next, results are presented which show the LOL results using the developed probabilistic models. It is expected that the probabilistic model results will on average approximate the sample results.

4.7 Transformer Impact Results

Each simulated day results in slightly different LOL values and therefore the LOL results are presented in histograms. Two LOL histograms are provided as visual evidence that the LOL results are normally distributed. The expectation is that the LOL results should follow a normal distribution due to the law of large numbers. The base case LOL results from 100 simulated days are shown in Figure 4.9. The PHEV scenario with the added electric load due to one PHEV in the distribution system is shown in Figure 4.10. The results for the added electric load due to two and three PHEVs are quite similar and are not shown.

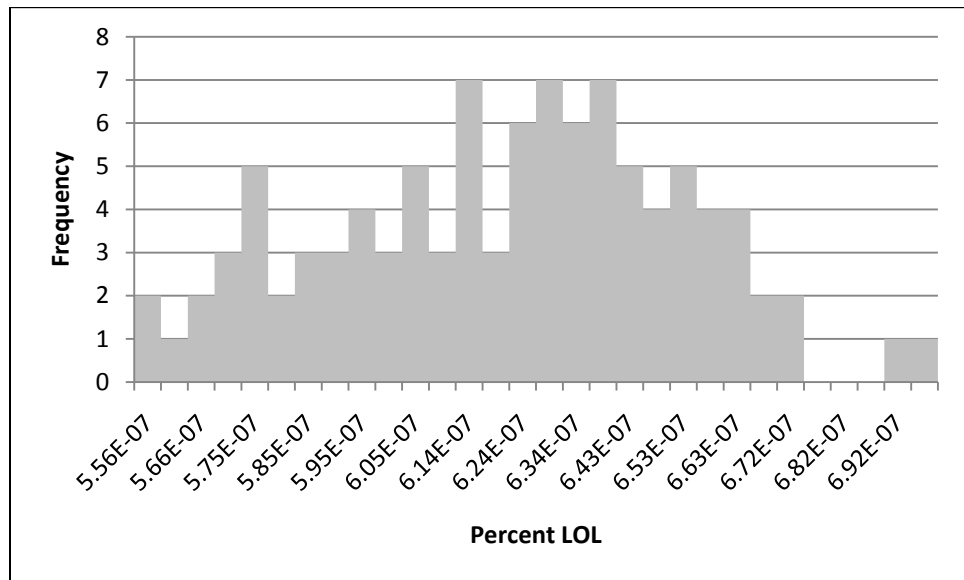


Figure 4.9. Base case LOL histogram.

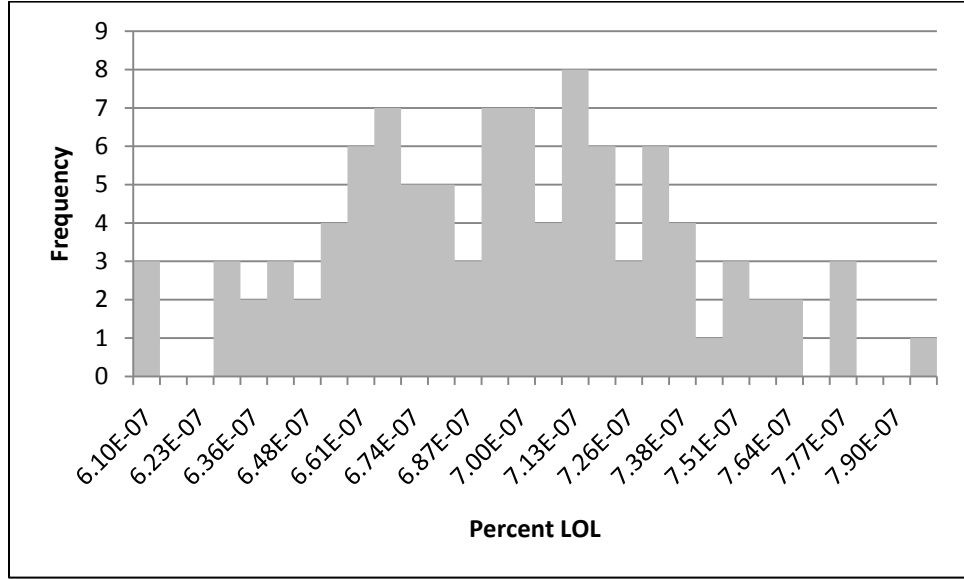


Figure 4.10. Single PHEV charging LOL histogram.

The simulation results are further characterized using a normal distribution maximum likelihood estimator (MLE)

$$\hat{\mu} = 1/N \cdot \sum_{i=1}^N x_i \quad (4.36)$$

where N is the number of repeated simulations (100) and x_i represent the LOL result from iteration- i . This equation is valid assuming that the LOL results will follow a normal distribution. From the mean MLE results for each of the four scenarios simulated, the percent change in average LOL is computed, indicating the impact PHEV charging will have on distribution transformers.

Table 4.5 compares all four scenarios mean MLE results. The calculated values for $\hat{\mu}$ show a percent change of 11.99% (from 6.212E-07% to 6.957E-7%) when adding one PHEV, 28.84% (from 6.212E-07% to 8.004E-7%) when adding two PHEVs, and 43.75% (from 6.212E-07% to 8.930E-7%) when adding three PHEVs.

Table 4.5. LOL MLE results.

	$\hat{\mu}$
Base Case	6.212E-07
One PHEV	6.957E-07
Two PHEVs	8.004E-07
Three PHEVs	8.930E-07

Also, the change in LOL comparing the probabilistic results versus the deterministic sample results from Section 4.6 show a 5.49% change in base case results (computed as $[1 - (6.212E-07/5.889E-07) \cdot 100\%]$ where 6.212E-07 is the base case $\hat{\mu}$ in Table 4.5

and the 5.8891E-07 is the deterministic sample base case LOL result), and a 0.82% change in the three PHEV scenario (computed as $[1 - (8.930\text{E-}07/9.004\text{E-}07) \cdot 100\%]$ where 8.930E-07 is the three PHEV scenario $\hat{\mu}$ in Table 4.5 and the 9.004E-07 is the deterministic sample three PHEV scenario.

4.8 Conclusion

To examine the impact that PHEV charging will have on distribution transformers, simulations of daily load flows are performed using random electric loads. Two scenarios are examined, the first provides a baseline comparison of the transformer LOL with no PHEV electric load, and the second scenario provides the transformer LOL including PHEV charging in addition to the normal household electrical demand.

A center-tapped single phase transformer model is used to compute the expected transformer currents and an electro-thermal transformer model of the distribution transformer is used to compute the expected distribution transformer hourly hot-spot temperature.

On average it is assumed that the average daily electric demand experienced by a distribution transformer for three typical houses is 150 kWh. The average added electric load due to PHEVs is on average 16 kWh. The percent increase in feeder load and percent increase in average LOL are shown in Table 4.6.

Table 4.6. Increase in average electric load and resulting average transformer LOL.

	Percent Increase	
	Average Electric Load	Transformer LOL
One PHEV	10.67%	11.99%
Two PHEVs	21.33%	28.84%
Three PHEVs	32.00%	43.74%

The results in Table 4.6 show that adding the additional electric load demand to distribution transformers will have a measurable effect on the expected life of the distribution transformer. Specifically, if it is assumed that an average distribution transformer would operate for 150,000 hours (17.1 years), then the added impact of one PHEV decreases this expected lifetime to 132,015 hours (15.1 years). Similarly, the added impact of two PHEVs decreases it to 106,740 hours (12.2 years) and the added impact of three PHEVs decreases this expected lifetime to 84,390 hours (9.6 years).

5. Conclusion

Plug-in hybrid electric vehicles (PHEVs) are a vehicle designed similar to a traditional hybrid electric vehicle (HEV) with more dependence on the electric drive system. PHEVs have the added ability, over HEVs, to recharge from the electric power system. The wide spread adoption of PHEVs has the potential benefit to (1) generate a lucrative new semi-dispatchable load for the electric utility industry and (2) diversify the transportation sector energy usage by displacing petroleum usage with electric energy.

Two power system level impacts of PHEV charging are investigated in this thesis. The first investigation quantifies the primary energy source utilization due to PHEV charging and the second quantifies the impact of PHEV charging on distribution transformers. In Chapter 3 the primary energy source utilization describes which power system fuel types are utilized to meet the added electric load demand created by PHEV charging. Additionally, the tradeoff between vehicle tailpipe environmental air pollution (EAP) and power system EAP is compared when PHEVs are used to replace varying levels of the light duty vehicle fleet in a given power system area. Finally, the annual fuel cost is computed for conventional internal combustion (IC) vehicles, which includes only gasoline purchasing, and that of PHEVs, which includes gasoline and electricity purchasing. The results from Chapter 3 indicate that PHEVs offer cleaner transportation (depending on the generation mix used to charge the vehicles) with decreased gasoline utilization at a lower cost (in terms of annual fuel costs) to consumers.

In Chapter 4 the impact of PHEV charging on distribution transformers is quantified using a transformer insulation percent loss-of-life (LOL) calculation. Two models are utilized to compute the data required for the LOL calculation, namely a center-tapped model and a simplified electro-thermal transformer model. The center-tapped single phase transformer model simulates the transformer winding currents for random daily load demand values. The electro-thermal model simulates the winding temperature as a function of the winding currents. The LOL calculation is based on the hourly transformer hot-spot temperature which is defined as the maximum winding temperature for each hour of the simulation period. The transformer LOL results indicate that adding the additional electric load demand to distribution transformers has a measurable effect on the expected life of the distribution transformer.

Future work which could follow this thesis includes:

- Model verification of the probabilistic consumer behavior including miles driven per day, arrival time and departure time random variables.
- Additional simulations of the effect that real time electric price signals could have on PHEV charging and primary energy source utilization.
- Power system data of existing power system could provide experimental results for existing power systems.
- Additional development of the transformer impact chapter could include investigations into the impact of ambient temperature profiles, the impact of vehicle charging time, and the impact of transformer sizing.

References

- [1.1] Energy Information Administration, “U.S. crude oil supply and disposition,” September 2008, http://tonto.eia.doe.gov/dnav/pet/pet_sum_crdsnd_adc_mbbbl_m.htm.
- [1.2] Energy Information Administration, “Weekly inputs, utilization & production,” September 2008, http://tonto.eia.doe.gov/dnav/pet/pet_pnp_wiup_dcu_nus_w.htm.
- [1.3] J. Voelcker, “Plugging away in a Prius,” *IEEE Spectrum*, vol. 45, issue 5, pp. 30-48, May 2008.
- [1.4] Energy Information Administration, “U.S. weekly product supplied,” August 2008, http://tonto.eia.doe.gov/dnav/pet/pet_cons_wpsup_k_w.htm.
- [1.5] Energy Information Administration, Annual Energy Review 2007, tables 1.3 and 2.1b-2.1f, and 10.3.
- [2.1] C. H. Stephan and J. Sullivan, “Environmental and energy implications of plug-in hybrid-electric vehicles,” *Environ. Sci. Technol.*, vol. 42, no. 4, pp. 1185–1190, January 2008.
- [2.2] M. Kintner-Meyer, K. Schneider, and R. Pratt, “Impacts assessment of plug-in hybrid vehicles on electric utilities and regional U.S. power grids; part 1: Technical analysis”, September 2008, <http://www.ferc.gov/>.
- [2.3] P. Denholm and W. Short, “An evaluation of utility system impacts and benefits of optimally dispatched plug-in hybrid electric vehicles,” National Renewable Energy Laboratory, Golden, Colorado, USA, Tech. Rep. NREL/TP-620-40293, 2006.
- [2.4] K. Parks, P. Denholm, and T. Markel, “Costs and emissions associated with plug-in hybrid electric vehicle charging in the Xcel Energy Colorado service territory,” National Renewable Energy Laboratory, Golden, Colorado, USA, Tech. Rep. NREL/TP-640-41410, 2007.
- [2.5] S. Hadley and A. Tsvetkova, “Potential impacts of plug-in hybrid electric vehicles on regional power generation,” Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA, ORNL/TM-2007/150, 2008.
- [2.6] T. Markel, A. Brooker, T. Hendricks, V. Johnson, K. Kelly, B. Kramer, M. O’Keefe, S. Sprik, and K. Wipke, “ADVISOR: a systems analysis tool for advanced vehicle modeling,” *Journal of Power Sources*, vol. 110, iss. 2, pp. 255-266 August 2002.
- [2.7] Electric Power Research Institute, “Environmental assessment of plug-in hybrid electric vehicles; volume 1: Nationwide greenhouse gas emissions,” EPRI, Palo Alto, Calif., 1015325, 2007.
- [2.8] Energy Information Administration, “The National Energy Modeling System: An Overview 2003,” Washington D.C., DOE/EIA-0581, March 2003.
- [2.9] R. Sioshansi and P. Denholm, “Emissions impacts and benefits of plug-in hybrid electric vehicles and vehicle-to-grid services,” *Environ. Sci. Technol.*, vol. 43, no. 4, pp. 1199–1204, January 2009.

- [2.10] Electric Power Research Institute, “Environmental assessment of plug-in hybrid electric vehicles; volume 2: United States air quality analysis based on AEO-2006 assumptions for 2030,” EPRI, Palo Alto, Calif., 1015326, 2007.
- [2.11] C. Samaras and K. Meisterling, “Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy,” *Environ. Sci. Technol.*, vol. 42, no. 9, pp. 3170–3176, April 2008.
- [2.12] S. Blumsack, S. Constantine, and P. Hines, “Long-term electric system investments to support plug-in hybrid electric vehicles” in *Power and Energy Society General Meeting – Conversion and Delivery of Electrical Energy in the 21st Century*, pp. 1-6, 2008.
- [3.1] A. P. Meliopoulos, "Computer aided instruction of energy source utilization problems," *IEEE Transactions on Education*, vol. E-24, no. 3, pp. 204-9, August 1981.
- [3.2] Argonne National Lab, “Powertrains system analysis toolbox (PSAT),” July 2008, <http://www.anl.gov/techtransfer/pdf/PSAT.pdf>.
- [3.3] MathWorks, “Technical Solutions”, March 2009, <http://www.mathworks.com/support/solutions/data/1-18DGY.html?solution=1-18DGY>.
- [3.4] L. Sanna, “Driving the solution the plug-in hybrid electric vehicle”, *EPRI Journal*, pp. 8-17, Fall 2005.
- [3.5] “Random variate generation” class notes for ISYE 6644 Simulation, H. Milton Stewart School of Industrial and Systems Engineering at the Georgia Institute of Technology, Summer 2008.
- [3.6] J.E. Gentle, *Numerical Linear Algebra for Applications in Statistics*. Berlin: Springer-Verlag, 1998.
- [3.7] A. M. Law, *Simulation Modeling & Analysis*, The McGraw-Hill Companies, Inc. 2007.
- [3.8] Reliability Test System Task Force of the Application of Probability Methods Subcommittee, “IEEE reliability test system,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-98, no. 6, pp. 2047-54, November 1979.
- [3.9] Tennessee Valley Authority, “TVA reservoirs and power plants,” July 2008, July 2008, http://www.tva.gov/sites/sites_ie2.htm.
- [3.10] Energy Information Administration, “Existing Capacity by Energy Source,” May 2009, <http://www.eia.doe.gov/cneaf/electricity/epa/epat2p2.html>.
- [3.11] Energy Information Administration, “Net Generation by Energy Source: Total (All Sectors),” May 2009, http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html.
- [3.12] Energy Information Administration, “U.S. Electric Power Industry Estimated Emissions by State (EIA-767 and EIA-906),” May 2009, <http://www.eia.doe.gov/cneaf/electricity/epa/epat5p1.html>.
- [3.13] Energy Information Administration, “Net Internal Demand, Capacity Resources, and Capacity Margins by North American Electric Reliability Council Region,” May 2009, <http://www.eia.doe.gov/cneaf/electricity/epa/epat3p2.html>.

- [3.14] U.S. Department of Transportation Federal Highway Administration, "State Motor-Vehicle Registration," May 2009,
<http://www.fhwa.dot.gov/policy/ohim/hs03/mv.htm>.
- [4.1] W. H. Kersting, *Distribution System Modeling and Analysis*. CRC Press: Taylor & Francis Group, 2007.
- [4.2] J. F. Lindsay, "Temperature rise of an oil-filled transformer with varying load," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-103, no. 9, pp. 2530-36, September 1984.
- [4.3] D. K. Whirlow and A. M. Lockie, "Thermal performance of distribution transformers in underground vaults: II-Mathematical model," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS 87, no.9, pp. 1745-54, September 1968.
- [4.4] A. P. Meliopoulos, "State estimation methods applied to transformer monitoring," in *Proceedings of the 2001 Power Engineering Society Summer Meeting*, vol. 1, pp. 419-23, Vancouver, BC, July 2001.
- [4.5] A. P. Meliopoulos, G. J. Cokkinides, and T. J. Overbye, "Component monitoring and dynamic loading visualization from real time power flow model data," in *Proceedings of the 37th Annual Hawaii International Conf. System Sciences (HICSS)*, Waikoloa, Big Island, HI, USA, January, 2004.
- [4.6] "Electric Power Quality" class notes for ECE 4833 Electric Power Quality, School of Electrical and Computer Engineering at the Georgia Institute of Technology, Fall 2007.
- [4.7] A. P. Meliopoulos, (private communication), 2009.
- [4.8] ANSI/IEEE C57.91-1995, Guide for Loading Mineral-Oil-Immersed Transformers.

Appendix A: PSAT Simulation Results

The PSAT simulation results in this appendix are used to compute performance metrics for both internal combustion (IC) and plug-in hybrid electric (PHEV) vehicles. The IC vehicle performance metrics include fuel efficiency, NO_x generated per mile driven, and CO₂ generated per mile driven. The PHEV performance metrics include energy required per mile, gasoline efficiency, NO_x generated per mile driven, and CO₂ generated per mile driven. The methodology used to compute the performance metrics is described in Chapter 3.

PHEV simulations were performed using the Powertrain System Analysis Toolkit (PSAT). PSATs Matlab/Simulink/State-Flow models, of conventional vehicle and hybrid powertrain components, of various architectures, were assembled and simulated to generate operational data for PHEVs.

Once the complete vehicle models had been selected, PSAT allowed for the simulated operation of the developed vehicles over specified driving schedules with a variable amount of driving energy supplied from the vehicles battery.

PHEV PSAT results for each vehicle class are shown in Tables A.1 - A.4. IC PSAT results are shown in Table A.5.

Table A.1. Vehicle class 1 PHEV PSAT results.

Driving Schedule	k _{PHEV}	Electric Energy Per Mile [kWh/mi.]	GPM [gal./mi.]	NO _x Per Mile [kg/mi.]	CO ₂ Per Mile [kg/mi.]
HWFET	0.1156	0.0807	0.0146	7.720E-05	0.1316
	0.2183	0.1471	0.0125	5.100E-05	0.1123
	0.7196	0.2508	0.0023	6.700E-06	0.0208
	1.000	0.2626	0.0001	0.00	0.00
UDDS	0.1461	0.1167	0.0162	7.080E-05	0.1457
	0.2757	0.1973	0.0123	4.790E-05	0.1109
	0.5193	0.2666	0.0059	2.040E-05	0.0528
	1.000	0.2235	0.0001	0.00	0.00
US06	0.1141	0.1281	0.0235	1.273E-04	0.2115
	0.1803	0.1820	0.0196	1.016E-04	0.1760
	0.4114	0.3162	0.0107	4.920E-05	0.0963
	0.9463	0.4341	0.0006	2.300E-06	0.0052

Table A.2. Vehicle class 2 PHEV PSAT results.

Driving Schedule	k _{PHEV}	Electric Energy Per Mile [kWh/mi.]	GPM [gal./mi.]	NO _x Per Mile [kg/mi.]	CO ₂ Per Mile [kg/mi.]
HWFET	0.1131	0.0987	0.0183	1.025E-04	0.1651
	0.1210	0.1070	0.0184	1.022E-04	0.1659
	0.1340	0.1117	0.0171	9.500E-05	0.1538
	0.4617	0.2698	0.0074	3.250E-05	0.0671
	0.6035	0.2808	0.0044	2.230E-05	0.0393
	0.7829	0.2952	0.0022	9.300E-06	0.0197
UDDS	0.1898	0.1818	0.0186	8.860E-05	0.1680
	0.4534	0.3168	0.0091	3.100E-05	0.0820
	0.7613	0.3016	0.0023	7.800E-06	0.0203
	0.9664	0.2950	0.0002	1.000E-06	0.0022
	1.0000	0.2866	0.0001	0.00	0.00
US06	0.0992	0.1374	0.0300	1.370E-04	0.2692
	0.1215	0.1609	0.0278	1.367E-04	0.2492
	0.3608	0.3539	0.0149	6.960E-05	0.1336
	0.5108	0.4232	0.0097	3.990E-05	0.0864
	0.9199	0.4672	0.0010	3.600E-06	0.0087

Table A.3. Vehicle class 3 PHEV PSAT results.

Driving Schedule	k _{PHEV}	Electric Energy Per Mile [kWh/mi.]	GPM [gal./mi.]	NO _x Per Mile [kg/mi.]	CO ₂ Per Mile [kg/mi.]
HWFET	0.0482	0.0780	0.0364	1.307E-04	0.3287
	0.2976	0.2950	0.0165	5.250E-05	0.1484
	0.4217	0.3790	0.0123	3.800E-05	0.1108
	0.7746	0.4143	0.0029	9.400E-06	0.0257
	1.000	0.4247	0.0001	0.00	0.00
UDDS	0.0596	0.1145	0.0427	1.612E-04	0.3850
	0.3006	0.3927	0.0216	7.370E-05	0.1949
	0.6990	0.3889	0.0039	1.240E-05	0.0357
	1.000	0.3872	0.0001	0.00	0.00
US06	0.0530	0.1165	0.0492	2.436E-04	0.4436
	0.1872	0.3362	0.0344	1.549E-04	0.3108
	0.3516	0.5259	0.0228	8.750E-05	0.2064
	0.4718	0.6694	0.0176	6.400E-05	0.1595
	0.7168	0.7204	0.0066	2.260E-05	0.0605

Table A.4. Vehicle class 4 PHEV PSAT results.

Driving Schedule	k _{PHEV}	Electric Energy Per Mile [kWh/mi.]	GPM [gal./mi.]	NO _x Per Mile [kg/mi.]	CO ₂ Per Mile [kg/mi.]
HWFET	0.0630	0.1024	0.0361	1.746E-04	0.3254
	0.2503	0.2985	0.0212	9.000E-05	0.1909
	0.5925	0.4820	0.0078	3.240E-05	0.0706
	0.9096	0.5155	0.0012	4.600E-06	0.0109
UDDS	0.0719	0.1494	0.0461	1.892E-04	0.4158
	0.3406	0.4816	0.0221	7.720E-05	0.1987
	0.7526	0.4819	0.0037	1.320E-05	0.0338
	1.000	0.5189	0.0001	0.00	0.00
US06	0.0577	0.1360	0.0532	2.642E-04	0.4770
	0.3484	0.5736	0.0253	1.342E-04	0.2280
	0.4982	0.6986	0.0165	8.500E-05	0.1497
	0.6900	0.7606	0.0080	3.860E-05	0.0726
	0.8776	0.8530	0.0028	1.270E-05	0.0253

Table A.5. IC PSAT results.

Class	Drive Schedule	MPG [mi./gal.]	NO _x Per Mile[kg/mi.]	CO ₂ Per Mile [kg/mi.]
1	HWFET	33.21	9.190E-05	0.2715
	UDDS	26.17	1.508E-04	0.3446
	US06	25.82	2.042E-04	0.3483
2	HWFET	18.54	1.593E-04	0.4866
	UDDS	14.17	2.530E-04	0.6366
	US06	14.21	3.448E-04	0.6341
3	HWFET	19.31	1.453E-04	0.4674
	UDDS	12.17	2.651E-04	0.7411
	US06	14.20	3.090E-04	0.6351
4	HWFET	14.07	1.946E-04	0.6411
	UDDS	11.42	2.904E-04	0.7902
	US06	11.16	4.032E-04	0.8081