Supplementary Information

Energy and climate effects of second-life use of electric vehicle batteries in California through 2050

Roger Sathre, Corinne D. Scown, Olga Kavvada, Thomas P. Hendrickson

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Table S1. PEV adoption groups used in the battery supply modeling.

Adoption group number	Qualifying characteristic	Adoption start year
1	Local PEV incentives (charging stations, high-occupancy vehicle lane access, financial incentives)	2015
2	Top 20% nationally by median income	2020
3	Top 30% nationally by median income	2022
4	Top 50% nationally by median income	2025
5	Remaining counties	2035

Table S2. County information and PEV adoption group categorization.

County name	FIPS	Early adopter MSA	Median income (national percentile)	Adoption group
Alameda County	6001	1	0.861	1
Alpine County	6003	0	0.315	5
Amador County	6005	0	0.480	5
Butte County	6007	0	0.203	5
Calaveras County	6009	0	0.540	4
Colusa County	6011	0	0.339	5
Contra Costa County	6013	1	0.920	1
Del Norte County	6015	0	0.058	5
El Dorado County	6017	0	0.837	2
Fresno County	6019	0	0.338	5
Glenn County	6021	0	0.193	5
Humboldt County	6023	0	0.114	5
Imperial County	6025	0	0.134	5
Inyo County	6027	0	0.326	5
Kern County	6029	0	0.344	5
Kings County	6031	0	0.306	5
Lake County	6033	0	0.065	5
Lassen County	6035	0	0.501	4
Los Angeles County	6037	1	0.662	1
Madera County	6039	0	0.292	5
Marin County	6041	1	0.969	1
Mariposa County	6043	0	0.252	5
Mendocino County	6045	0	0.175	5
Merced County	6047	0	0.223	5
Modoc County	6049	0	0.045	5
Mono County	6051	0	0.667	4
Monterey County	6053	1	0.686	1

Napa County	6055	0	0.818	2
Nevada County	6057	0	0.697	4
Orange County	6059	1	0.896	1
Placer County	6061	0	0.870	2
Plumas County	6063	0	0.215	5
Riverside County	6065	0	0.696	4
Sacramento County	6067	0	0.667	4
San Benito County	6069	0	0.757	3
San Bernardino County	6071	0	0.608	4
San Diego County	6073	1	0.784	1
San Francisco County	6075	1	0.899	1
San Joaquin County	6077	0	0.489	5
San Luis Obispo County	6079	0	0.685	4
San Mateo County	6081	1	0.971	1
Santa Barbara County	6083	1	0.724	1
Santa Clara County	6085	0	0.980	2
Santa Cruz County	6087	0	0.790	3
Shasta County	6089	0	0.201	5
Sierra County	6091	0	0.276	5
Siskiyou County	6093	0	0.066	5
Solano County	6095	0	0.819	2
Sonoma County	6097	0	0.759	3
Stanislaus County	6099	0	0.430	5
Sutter County	6101	0	0.385	5
Tehama County	6103	0	0.113	5
Trinity County	6105	0	0.056	5
Tulare County	6107	0	0.259	5
Tuolumne County	6109	0	0.333	5
Ventura County	6111	0	0.909	2

Table S3. Breakdown of plug-in hybrid electric vehicle sales by battery range, 1975-2050.

Model year	16 km range	64 km range	96 km range	160 km range
1975	1	0	0	0
1976	1	0	0	0
1977	1	0	0	0
1978	1	0	0	0
1979	1	0	0	0
1980	1	0	0	0
1981	1	0	0	0
1982	1	0	0	0
1983	1	0	0	0
1984	1	0	0	0
1985	1	0	0	0
1986	1	0	0	0
1987	1	0	0	0
1988	1	0	0	0
1989	1	0	0	0
1990	1	0	0	0
1991	1	0	0	0
1992	1	0	0	0
1993	1	0	0	0
1994	1	0	0	0

1995	1	0	0	0
1996	1	0	0	0
1997	1	0	0	0
1998	1	0	0	0
1999	1	0	0	0
2000	1	0	0	0
2001	1	0	0	0
2002	1	0	0	0
2003	1	0	0	0
2004	1	0	0	0
2005	1	0	0	0
2006	1	0	0	0
2007	1	0	0	0
2008	1	0	0	0
2009	1	0	0	0
2010	1	0	0	0
2011	1	0	0	0
2012	0.5	0.5	0	0
2013	0.4375	0.5625	0	0
2014	0.375	0.625	0	0
2015	0.3125	0.6875	0	0
2016	0.25	0.75	0	0
2017	0.1875	0.8125	0	0
2018	0.125	0.875	0	0
2019	0.0625	0.9375	0	0
2020	0	0.95	0.05	0
2021	0	0.9	0.1	0
2022	0	0.85	0.15	0
2023	0	0.8	0.2	0
2024	0	0.75	0.25	0
2025	0	0.7	0.3	0
2026	0	0.65	0.35	0
2027	0	0.6	0.4	0
2028	0	0.55	0.45	0
2029	0	0.5	0.5	0
2030	0	0.45	0.55	0
2031	0	0.4	0.6	0
2032	0	0.35	0.65	0
2033	0	0.3	0.7	0
2034	0	0.25	0.75	0
2035	0	0.2	0.8	0
2036	0	0.15	0.85	0
2037	0	0.1	0.9	0
2038	0	0.05	0.95	0
2039	0	0	1	0
2040	0	0	0.954545455	0.045454545
2041	0	0	0.909090909	0.090909091
2042	0	0	0.863636364	0.136363636
2043	0	0	0.818181818	0.181818182
2044	0	0	0.772727273	0.227272727
2045	0	0	0.727272727	0.272727273
2046	0	0	0.681818182	0.318181818
2047	0	0	0.636363636	0.363636364
2048	0	0	0.590909091	0.409090909
2049	0	0	0.545454545	0.454545455
2050	0	0	0.5	0.5

Table S4. Breakdown of pure electric vehicle sales by battery range, 1975-2050.

Model year	112 km range	160 km range	240 km range	320 km range	400 km range	480 km range
1975	1	0	0	0	0	0
1976	1	0	0	0	0	0
1977	1	0	0	0	0	0
1978	1	0	0	0	0	0
1979	1	0	0	0	0	0
1980	1	0	0	0	0	0
1981	1	0	0	0	0	0
1982	1	0	0	0	0	0
1983	1	0	0	0	0	0
1984	1	0	0	0	0	0
1985	1	0	0	0	0	0
1986	1	0	0	0	0	0
1987	1	0	0	0	0	0
1988	1	0	0	0	0	0
1989	1	0	0	0	0	0
1990	1	0	0	0	0	0
1991	1	0	0	0	0	0
1992	1	0	0	0	0	0
1993	1	0	0	0	0	0
1994	1	0	0	0	0	0
1995	1	0	0	0	0	0
1996	1	0	0	0	0	0
1997	1	0	0	0	0	0
1998	1	0	0	0	0	0
1999	1	0	0	0	0	0
2000	1	0	0	0	0	0
2001	1	0	0	0	0	0
2002	1	0	0	0	0	0
2003	1	0	0	0	0	0
2004	1	0	0	0	0	0
2005	1	0	0	0	0	0
2006	1	0	0	0	0	0
2007	1	0	0	0	0	0
2008	1	0	0	0	0	0
2009	1	0	0	0	0	0
2010	1	0	0	0	0	0
2011	1	0	0	0	0	0
2012	1	0	0	0	0	0
2013	0.9	0	0	0.05	0.05	0
2014	0.9	0	0	0.05	0.05	0
2015	0.8	0.1	0	0.05	0.05	0
2016	0.77	0.13	0	0.05	0.05	0
2017	0.74	0.16	0	0.05	0.05	0
2018	0.71	0.19	0	0.05	0.05	0
2019	0.68	0.22	0	0.05	0.05	0
2020	0.65	0.24	0	0.05	0.05	0.01
2021	0.62	0.27	0	0.05	0.05	0.01
2022	0.59	0.3	0	0.05	0.05	0.01
2023	0.56	0.33	0	0.05	0.05	0.01
2024	0.53	0.36	0	0.05	0.05	0.01

2025	0.5	0.39	0	0.05	0.05	0.01
2026	0.45	0.41	0.03	0.05	0.05	0.01
2027	0.4	0.43	0.06	0.05	0.05	0.01
2028	0.35	0.45	0.09	0.05	0.05	0.01
2029	0.3	0.47	0.12	0.05	0.05	0.01
2030	0.25	0.5	0.14	0.05	0.05	0.01
2031	0.225	0.5	0.165	0.05	0.05	0.01
2032	0.2	0.5	0.19	0.05	0.05	0.01
2033	0.175	0.5	0.215	0.05	0.05	0.01
2034	0.15	0.5	0.24	0.05	0.05	0.01
2035	0.125	0.5	0.265	0.05	0.05	0.01
2036	0.1	0.5	0.29	0.05	0.05	0.01
2037	0.075	0.5	0.315	0.05	0.05	0.01
2038	0.05	0.5	0.34	0.05	0.05	0.01
2039	0.025	0.5	0.365	0.05	0.05	0.01
2040	0	0.5	0.39	0.05	0.05	0.01
2041	0	0.45	0.4	0.086	0.05	0.014
2042	0	0.4	0.41	0.122	0.05	0.018
2043	0	0.35	0.42	0.158	0.05	0.022
2044	0	0.3	0.43	0.194	0.05	0.026
2045	0	0.25	0.44	0.23	0.05	0.03
2046	0	0.2	0.45	0.266	0.05	0.034
2047	0	0.15	0.46	0.302	0.05	0.038
2048	0	0.1	0.47	0.338	0.05	0.042
2049	0	0.05	0.48	0.374	0.05	0.046
2050	0	0	0.49	0.41	0.05	0.05

Table S5. Energy and GHG intensities of transporting batteries in three second-life logistics scenarios. Energy use units are MJ of diesel fuel per ton of batteries.

	Transportation energy use (MJ ton^{-1})	**GHG emissions** ($kgCO_2e$ ton^{-1})
Decentralized solar		
Collection	151	11.2
Distribution	454	33.8
Recycling	639	47.6
Total	*1,243*	*92.6*
Decentralized wind		-
Collection	151	11.2
Distribution	423	31.5
Recycling	485	36.1
Total	*1,058*	*78.8*
Centralized renewable		
Collection	151	11.2
Distribution	469	34.9
Recycling	260	19.4
Total	*880*	*65.5*

Table S6. Base-case results of second-life battery use, showing cumulative (2015-2050) and annual (2050 only) components of energy and GHG balances.

	Cumulative	**2050**
	TWh	TWh per year
Energy balance	***-31.76***	***-4.43***
Battery transport	-0.06	-0.01
Battery cooling	-5.28	-0.74
Battery charging	-132.10	-18.43
Electricity delivered	105.68	14.75
	Mt CO_2e	Mt CO_2e per year
GHG balance	***-50.11***	***-6.99***
Battery transport	0.05	0.01
Battery cooling	0.14	0.02
Battery charging	3.59	0.50
Substituted electricity generation	-53.90	-7.52

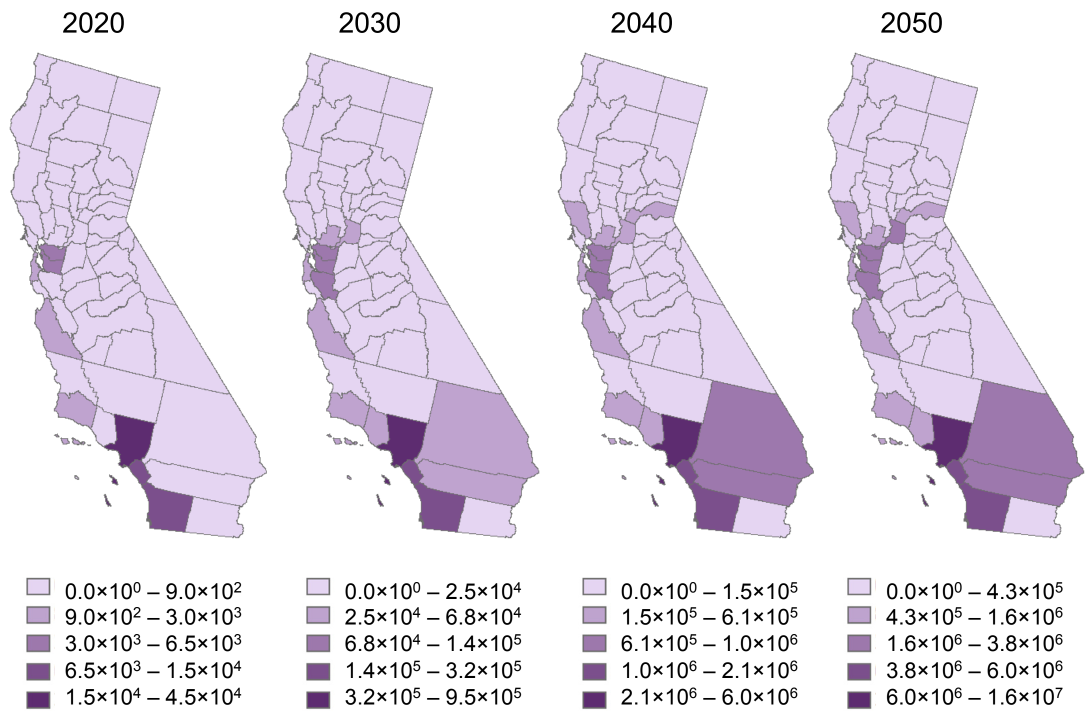

Figure S1. Distribution of PEVs by number in the fleet per year in California

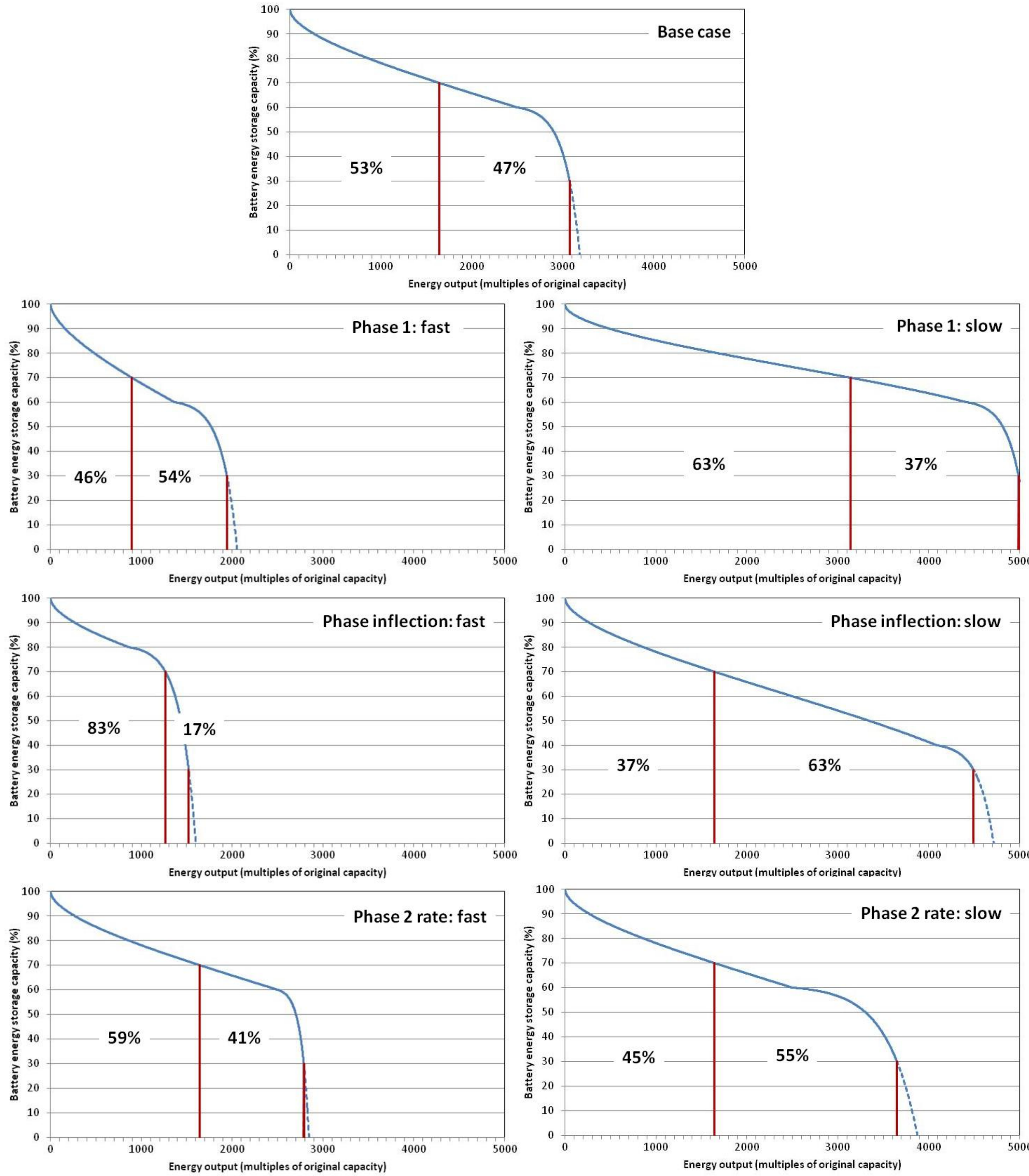

Figure S2. Battery degradation profiles under base-case conditions (top), and with fast and slow values of Phase 1 degradation rate, Phase inflection point, and Phase 2 degradation rate. Percentages indicate the percent of total life-cycle electricity output that is delivered during the first-life and second-life.

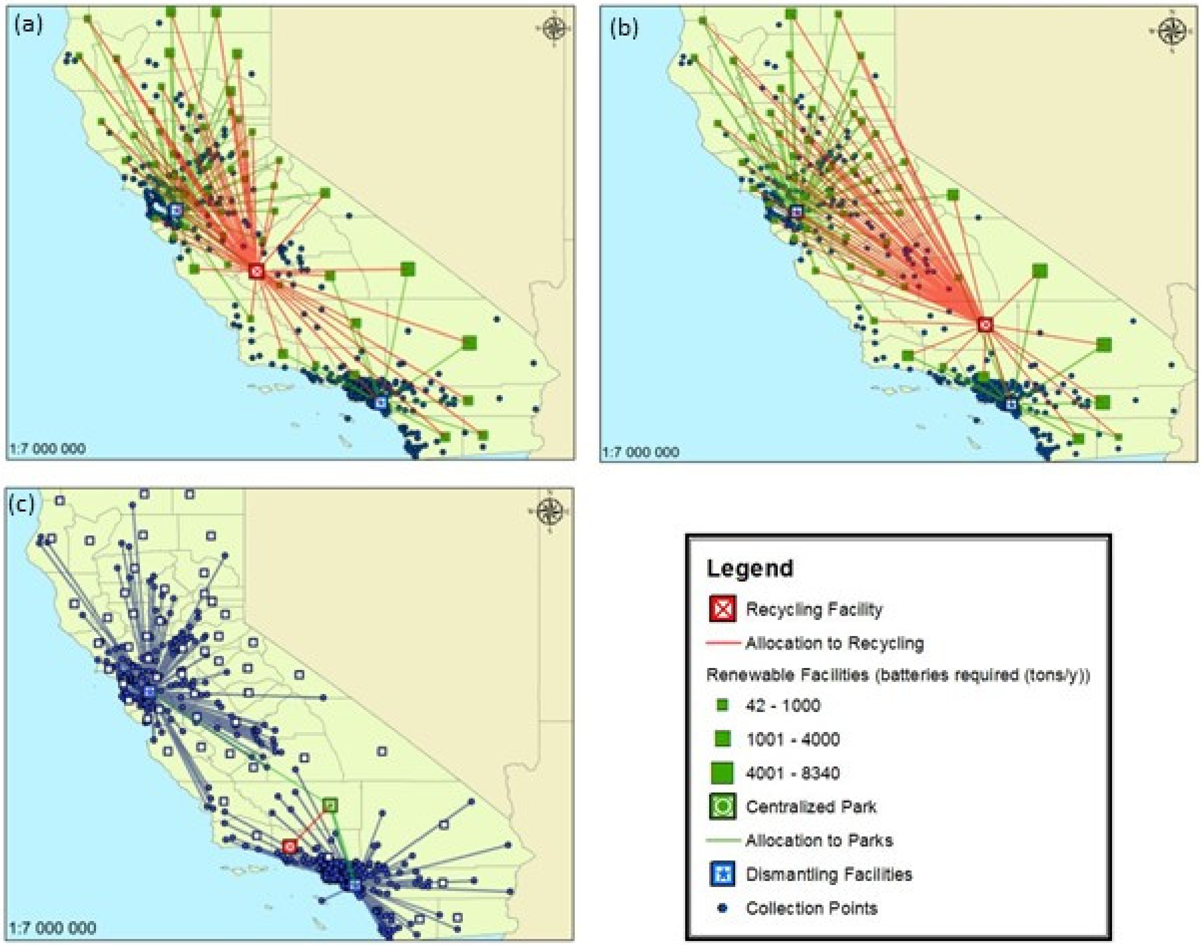

Figure S3. GIS modeling results for 3 different logistics scenarios for second-life battery use in California: (a) decentralized solar, (b) decentralized wind, (c) centralized renewable.

Fleet turnover model script (written in R)

```
library(plyr)
library(udunits2)
library(reshape2)

#**********USER INPUTS************

#Scaling factor for adjusting EV/PHEV sales fraction up or down.  Default = 1
sigmoid.scaling.factor <- 1

#Battery degradation scenario:
#1: percent of batteries remaining if 75% of people have batteries that last
     10 years or longer (DEFAULT scenario) -- % remaining at year "age" = 1 /
     (1 + 2.3*exp(-0.28 *(16.9 - age)))
#2: if 60% of people have batteries lasting 10 years or longer
     (UNDERPERFORMING scenario) -- % remaining at year "age" = 1 / (1 +
     4.6*exp(-0.28 *(16.9 - age)))
#3: if 90% of people have batteries lasting 10 years or longer
     (OVERPERFORMING scenario) -- % remaining at year "age" = 1 / (1 +
     .8*exp(-0.28 *(16.9 - age)))
bat.deg.scen <- 1

#Capacity of batteries at time of retirement from vehicle use (fraction of
     orginal kWh storage capacity)
cap.at.disp <- 0.8

#Age cutoff for battery replacement - age (years) of vehicle at which point
     it makes more sense to just purchase a new car rather than replace a
     failing battery
age.cutoff <- 20

#*************************************
#EIA sales projections for the Pacific census region by vehicle and year
pacific.baseline.sales <-
     read.csv("~/scenario_model/PHEV_Pacific_Car_Sales.csv", header=T)

#County-level population projections for the United States. Source: Zarnoch,
     S. J.; Cordell, H. K.; Betz, C. J.; Langner, L. Projecting county-level
     populations under three future scenarios: a technical document supporting
     the Forest Service 2010 RPA Assessment; SRS-128; U.S. Department of
     Agriculture Forest Service: Asheville, NC, 2010.
pop.proj <- read.csv("~/scenario_model/Pop_proj.csv", header=T)

#County info from NHTS, census bureau.  Provided in Table S3
county.info <- read.csv("~/scenario_model/County_MSA_info.csv", header=T)

#Provided in Table S4
phev.range.ratios <- read.csv("~/scenario_model/range_ratios.csv", header=T)

rownames(phev.range.ratios) <- phev.range.ratios$model_year

#Provided in Table S5
ev.range.ratios <- read.csv("~/scenario_model/ev_range_ratios.csv", header=T)
rownames(ev.range.ratios) <- ev.range.ratios$model_year
```

```
phev.to.ev.sales.ratios <-
     read.csv("~/scenario_model/phev_to_ev_sales_ratios.csv", header=T)
rownames(phev.to.ev.sales.ratios) <- phev.to.ev.sales.ratios$model_year

#Battery energy density - NAS estimates that Li-ion batteries will max out at
     250-300 Wh/kg.  Nissan Leaf has density of 205 Wh/kg.  We start at 205
     and increase linearly to 300 by 2050.
battery.densities <-
     read.csv("~/scenario_model/battery_energy_densities.csv", header=T)
rownames(battery.densities) <- battery.densities$Model_year

#******ESTABLISHING MANUFACTURER'S MARKET SHARES FOR EV/PHEV SALES*********

mfg.mkt.shares <- read.csv(paste("~/scenario_model/market_shares_",
     mfg.mkt.share.scen, ".csv", sep=""), header=T)
#EV/PHEV auto sales for 2013 YTD provided by
     http://www.hybridcars.com/september-2013-dashboard/
rownames(mfg.mkt.shares) <- mfg.mkt.shares$Mfg
mfg.mkt.shares$Mfg <- NULL
colnames(mfg.mkt.shares) <- as.character(2013:2050)

#*****CALCULATING CA BASELINE SALES PROJECTIONS FROM EIA***************
pop.proj <- subset(pop.proj, as.numeric(substr(FIPS,1,2)) == 41 |
     as.numeric(substr(FIPS,1,2)) == 53 | as.numeric(substr(FIPS,1,1) == 6))
#OR fips = 41, WA fips = 53, CA fips = 6
for (x in 2:length(pop.proj[1,])) {
  pop.proj[,x] <- as.numeric(pop.proj[,x])
}
pacific.pop.2014 <- sum(pop.proj$Year_2014)
pop.proj <- subset(pop.proj, as.numeric(substr(FIPS,1,1)) == 6)
ca.pop.2014 <- sum(pop.proj$Year_2014)
ca.frac.pac <- ca.pop.2014/pacific.pop.2014
ca.baseline.sales <- subset(pacific.baseline.sales, Year >= 2012)
ca.baseline.sales$Year <- as.factor(ca.baseline.sales$Year)
ca.baseline.sales[, c(2:15)] <- ca.baseline.sales[, c(2:15)] * ca.frac.pac
ca.baseline.sales$Gas_or_EV <- ca.baseline.sales$Gas +
     ca.baseline.sales$Flex_Fuel + ca.baseline.sales$PHEV_10 +
     ca.baseline.sales$PHEV_40 + ca.baseline.sales$EV_100 +
     ca.baseline.sales$EV_200
ca.baseline.sales$Gas <- NULL
ca.baseline.sales$Flex_Fuel <- NULL
ca.baseline.sales$PHEV_10 <- NULL
ca.baseline.sales$PHEV_40 <- NULL
ca.baseline.sales$PHEV_100 <- NULL
ca.baseline.sales$PHEV_200 <- NULL
row.names(ca.baseline.sales) <- ca.baseline.sales$Year

#**************CALCULATING SALES FOR CA COUNTIES******************
county.info <- subset(county.info, State == "CA")
pop.proj <- subset(pop.proj, as.numeric(substr(FIPS,1,1)) == 6)
adop.grp.launch.yrs <- c(2013, 2020, 2022, 2025, 2035)

sales <- function(year) {
  sales <- sigmoid.scaling.factor * ca.baseline.sales[as.character(year),
    "Gas_or_EV"] * (1.0 / (1.42 * (1 + exp(-0.25 * (year - 2012) + 5))))
  return(sales)
}
```

```
sales.growth <- function(year) {
  sales <- sales(year)
  if(year < 2013) {
    prev.yr.sales <- 0
  } else {
    prev.yr.sales <- sales(year-1)
  }
  growth <- sales - prev.yr.sales
  return(growth)
}

#Baseline PHEV/EV/ICE sales estimates
m <- matrix(0, ncol = (2050-2012), nrow = nrow(pop.proj))
baseline.sales.by.yr <- data.frame(m)
colnames(baseline.sales.by.yr) <- paste("Year_", c(2013:2050), sep = "")
rownames(baseline.sales.by.yr) <- pop.proj$FIPS
ca.baseline.sales$Year <- NULL
for(x in 2013:2050) {
  column <- paste("Year_", x, sep = "")
  pop.sum <- sum(pop.proj[,column])
  baseline.sales.by.yr[,paste("Year_", x, sep = "")]  <-
     ca.baseline.sales[as.character(x), "Gas_or_EV"] * pop.proj[,column]/
     pop.sum
}

#EV/PHEV sales estimates
ev.phev.sales.by.yr <- data.frame(m)
colnames(ev.phev.sales.by.yr) <- paste("Year_", c(2013:2050), sep = "")
rownames(ev.phev.sales.by.yr) <- pop.proj$FIPS
adop.grp.mask <- function(year) {
  for(x in 1:5) {
    if(year >= adop.grp.launch.yrs[x]) {
      grp.num <- x
    }
  }
  mask <- county.info$New_adoption_groups <= grp.num
  mask <- mask + 0
}
for(x in 2013:2050) {
  baseline.sales.by.yr[,paste("Year_", x, sep = "")] <-
     baseline.sales.by.yr[,paste("Year_", x, sep = "")] * adop.grp.mask(x)
  if(x > 2013) {
    prev.yr <- ev.phev.sales.by.yr[,paste("Year_", x - 1, sep = "")]
  } else {
    prev.yr <- 0
  }
  ev.phev.sales.by.yr[,paste("Year_", x, sep = "")] <- prev.yr +
     sales.growth(x) * baseline.sales.by.yr[,paste("Year_", x, sep = "")] /
     sum(baseline.sales.by.yr[,paste("Year_", x, sep = "")])
}

#Begin calculating battery sales by setting them equal to vehicle sales.
     Later we need to add in replacement battery sales.
battery.sales.by.yr <- ev.phev.sales.by.yr

#Calculate batteries available by end-of-life year
```

```
frac.remaining <- function(age, bat.deg.scen) {
  if(bat.deg.scen == 1) {
    frac <- 1 / (1 + 2.3*exp(-0.28 *(16.9 - (age))))
  } else if(bat.deg.scen == 2) {
    frac <- 1 / (1 + 4.6*exp(-0.28 *(16.9 - (age))))
  } else if(bat.deg.scen == 3) {
    frac <- 1 / (1 + .8*exp(-0.28 *(16.9 - (age))))
  } else {
    print("You have chosen an invalid battery degradation scenario!")
  }
  if(age < 0) {
    frac <- 0
  }
  return(frac)
}

frac.disp <- function(model.year, current.year, bat.deg.scen) {
  if(model.year >= current.year) {
    frac <- 1 - frac.remaining(current.year - model.year, bat.deg.scen)
  } else {
    frac <- (1 - frac.remaining(current.year - model.year, bat.deg.scen)) -
     (1 - frac.remaining(current.year - 1 - model.year, bat.deg.scen))
  }
  return(frac)
}

frac.vehicles.retired <- function(model.year, current.year) {
  if(current.year == model.year) {
    frac <- 1 - 1 / (1 + exp(-0.28 * (16.9 - (current.year-model.year))))
  } else if(current.year > model.year) {
    frac <- (1 - 1 / (1 + exp(-0.28 * (16.9 - (current.year-model.year))))) -
     (1 - 1 / (1 + exp(-0.28 * (16.9 - ((current.year-1)-model.year)))))
  } else {
    frac <- 0
  }
  return(frac)
}

for(x in 2013:2050) {
  temp <- data.frame(m)
  colnames(temp) <- paste("Year_", c(2013:2050), sep = "")
  rownames(temp) <- pop.proj$FIPS
  for (y in 2013:2050) {
    if (y >= x) {
      if(y - x < age.cutoff && y - x >= 0) {
        frac.replaced <- frac.disp(x, y, bat.deg.scen) -
     frac.vehicles.retired(x, y)
      } else {
        frac.replaced <- 0
      }
      battery.sales.by.yr[,paste("Year_", y, sep = "")] <-
     battery.sales.by.yr[,paste("Year_", y, sep = "")] +
     battery.sales.by.yr[,paste("Year_", x, sep = "")] * frac.replaced
      temp[paste("Year_", y, sep = "")] <-
     battery.sales.by.yr[,paste("Year_", x, sep = "")] * frac.disp(x, y,
     bat.deg.scen)
     }
```

```
  }
  assign(paste("model.", x, ".batteries.disposed", sep = ""), temp)
}

#Battery degradation scenario:
#1: percent of batteries remaining if 75% of people have batteries that last
     10 years or longer (DEFAULT scenario) -- % remaining at year "age" = 1 /
     (1 + 2.3*exp(-0.28 *(16.9 - age)))
#2: if 60% of people have batteries lasting 10 years or longer
     (UNDERPERFORMING scenario) -- % remaining at year "age" = 1 / (1 +
     4.6*exp(-0.28 *(16.9 - age)))
#3: if 90% of people have batteries lasting 10 years or longer
     (OVERPERFORMING scenario) -- % remaining at year "age" = 1 / (1 +
     .8*exp(-0.28 *(16.9 - age)))

#*************ESTIMATING BATTERY SIZE BY VEHICLE RANGE****************
epa.phev.range.mi <- c(11,38,21)
phev.battery.size.kWh <- c(4.4,16.5,7.6)
phev.battery.size.lm <- lm(formula = phev.battery.size.kWh ~
     epa.phev.range.mi)

#**WARNING: THIS EQUATION MUST BE MANUALLY ADJUSTED IF INPUT DATA CHANGES****
phev.battery.size.est <- function(range.mi) {
  bat.size.kWh <- 0.4562*range.mi - 1.1440
  return(bat.size.kWh)
}

epa.ev.range.mi <- c(73,208,265)
ev.battery.size.kWh <- c(24,60,85)
ev.battery.size.lm <- lm(formula = ev.battery.size.kWh ~ epa.ev.range.mi)

#**WARNING: THIS EQUATION MUST BE MANUALLY ADJUSTED IF INPUT DATA CHANGES***
ev.battery.size.est <- function(range.mi) {
  bat.size.kWh <- 0.3085*range.mi + 0.1872
  return(bat.size.kWh)
}

#Battery ranges (mi) of interest for scenarios
phev.battery.ranges <- c(10,30,40,60,100)
ev.battery.ranges <- c(70,100,150,200,250,300)

#Fraction of PHEV/EV sales made up by pure EVs
ev.sales.frac <- function(year) {
  frac <- 0.0174 * (year - 2014) + 0.1011
  #Linear equation from regression of EV share in AEO Pacific census region
     projections (2012)
  return(frac)
}

#NAS report data (mid case projections for BEV):
#2010: 130 mi range - 37.6 kWh
#2030: 130 mi range - 25.8 kWh
#2050: 130 mi range - 19.9 kWh
x <- c(2010,2030,2050)
y <- c(37.6,25.8,19.9)
size.lm <- lm(formula = y ~ x)
```

```
#**WARNING: THIS EQUATION MUST BE MANUALLY ADJUSTED IF INPUT DATA CHANGES****
#Relationship between year and battery size required for 130 mi range EV
size.kWh.130mi <- function(yr) {
  return(-0.4425*yr + 926.0417)
}
#This function adjusts the battery size for a given vehicle range based on
     time-dependent technological innovation.  The year adjustment is based on
     a linear regression of the NAS predictions for battery size reductions in
     130 mi range EV.
battery.size.est <- function(vehicle.type, year, range.mi) {
  if(vehicle.type == "phev") {
    size.kWh <-
     phev.battery.size.est(range.mi)*size.kWh.130mi(year)/size.kWh.130mi(2013)
  } else if(vehicle.type == "ev") {
    size.kWh <-
     ev.battery.size.est(range.mi)*size.kWh.130mi(year)/size.kWh.130mi(2013)
  } else {
    print("You have chosen an invalid vehicle type.  Please enter either phev
     or ev.")
  }
  return(size.kWh)
}

#Create two data frames containing the corresponding battery sizes (kWh) for
     each range of interst for each yr
m <- matrix(0, ncol = length(phev.battery.ranges), nrow = (2050-2012))
n <- matrix(0, ncol = length(ev.battery.ranges), nrow = (2050-2012))
battery.sizes.phev.kWh <- data.frame(m)
battery.sizes.ev.kWh <- data.frame(n)
colnames(battery.sizes.phev.kWh) <- phev.battery.ranges
colnames(battery.sizes.ev.kWh) <- ev.battery.ranges
rownames(battery.sizes.phev.kWh) <- 2013:2050
rownames(battery.sizes.ev.kWh) <- 2013:2050
for(x in 2013:2050) {
  for(y in phev.battery.ranges) {
    battery.sizes.phev.kWh[as.character(x),as.character(y)] <-
     battery.size.est("phev", x, y)
  }
  for(y in ev.battery.ranges) {
    battery.sizes.ev.kWh[as.character(x),as.character(y)] <-
     battery.size.est("ev", x, y)
  }
}

#Creates list of all possible battery sizes sold between 2013 and 2050
sizes <- c()
for(sales.yr in 2013:2050) {
  sizes <- c(sizes,
     as.matrix(battery.sizes.phev.kWh[as.character(sales.yr),]),
     as.matrix(battery.sizes.ev.kWh[as.character(sales.yr),]))
}

batteries.disposed <- array(0, dim = c(2050-2012, nrow(pop.proj), 2050-2012,
     length(sizes)), dimnames = list(as.character(2013:2050), pop.proj$FIPS,
     as.character(2013:2050), sizes))
#Dimensions are as follows: model year, fips, disposal year, battery sizes
```

```
for (disp.yr in 2013:2050) {
  for(sales.yr in 2013:disp.yr) {
    for (range in phev.battery.ranges) {
      battery.size <- battery.sizes.phev.kWh[as.character(sales.yr),
     as.character(range)]
      batteries.disposed[as.character(sales.yr), , as.character(disp.yr),
     as.character(battery.size)] <- batteries.disposed[as.character(sales.yr),
     , as.character(disp.yr), as.character(battery.size)] +
        get(paste("model.", sales.yr, ".batteries.disposed", sep =
     ""))[,paste("Year_", disp.yr, sep = "")] *
     phev.range.ratios[as.character(sales.yr), paste("X", range, sep = "")] *
     phev.to.ev.sales.ratios[as.character(sales.yr), "phev"]
     }
    for (range in ev.battery.ranges) {
      battery.size <- battery.sizes.ev.kWh[as.character(sales.yr),
     as.character(range)]
      batteries.disposed[as.character(sales.yr), , as.character(disp.yr),
     as.character(battery.size)] <- batteries.disposed[as.character(sales.yr),
     , as.character(disp.yr), as.character(battery.size)] +
        get(paste("model.", sales.yr, ".batteries.disposed", sep =
     ""))[,paste("Year_", disp.yr, sep = "")] *
     ev.range.ratios[as.character(sales.yr), paste("X", range, sep = "")] *
     phev.to.ev.sales.ratios[as.character(sales.yr), "ev"]
     }
  }
}
#This rounds batteries to nearest integer so we don't have fractions of
     batteries floating around
batteries.disposed <- round(batteries.disposed, 0)

#mass.disposed <- matrix(0, ncol = (2050-2012), nrow = nrow(pop.proj))
#mass.disposed <- data.frame(mass.disposed)
#rownames(mass.disposed) <- pop.proj$FIPS
#colnames(mass.disposed) <- as.character(2013:2050)

#Mass will be calculated in kg
mass.disposed <- batteries.disposed
kWh.disposed <- batteries.disposed
for(disp.yr in 2013:2050) {
  for(fips in pop.proj$FIPS) {
    for(sales.yr in 2013:2050) {
      kWh.disposed[as.character(sales.yr), as.character(fips),
     as.character(disp.yr), ] <- kWh.disposed[as.character(sales.yr),
     as.character(fips), as.character(disp.yr), ] * as.array(sizes)
     }
    for(size in sizes) {
      mass.disposed[ , as.character(fips), as.character(disp.yr),
     as.character(size)] <- kWh.disposed[ , as.character(fips),
     as.character(disp.yr), as.character(size)] *
     as.array(battery.densities$kg_per_kWh)
     }
  }
}

mass.disposed.expanded <- apply(mass.disposed, c(1, 2, 3), sum)

mass.disposed <- apply(mass.disposed, c(2, 3), sum)
```

```
kWh.disposed <- apply(kWh.disposed, c(2, 3), sum)
kWh.disposed <- kWh.disposed * cap.at.disp
write.csv(mass.disposed, file = "~/scenario_model/mass_disposed.csv",
     row.names = TRUE)
write.csv(kWh.disposed, file = "~/scenario_model/kWh_disposed.csv", row.names
     = TRUE)
```