

# HYBRID 2.0

RENEWING THE HYBRID-ELECTRIC VEHICLE

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## 1. Introduction

As the automobile industry advances, releasing more energy-efficient vehicles, consumers turn increasingly towards the benefits associated with plug-in hybrid-electric vehicles (PHEVs). Calef and Goble discuss the negative externalities of fossil fuel-based vehicles, whose effects are often incentives or counted as benefits for switching to plug-in hybrid-electric vehicles.<sup>1</sup> These vehicles, including the fourth generation of the Toyota Prius, the Prius Plug-In, get their energy from the power grid in addition to generating their own electricity from gasoline conversion, familiar to conventional hybrid-electric vehicles.

By 2015, market forecasts expect hybrid-electric vehicle market penetration to lie around 4-6% market share.<sup>2</sup> These estimates vary considerably because of notable uncertainty in consumer acceptance and valuation. A. Lovins notes that one such factor to increase the consumer acceptance and therefore market penetration of plug-in hybrid-electric vehicles is to apply a government subsidy.<sup>3</sup> From this theory, it seems wise to consider stimulating the demand for PHEVs through policy that subsidizes the difference in cost between a plug-in hybrid electric vehicle and a standard hybrid electric vehicle. For our purposes, we will consider the case of estimating future demand by replacing the Toyota Prius hybrid-electric vehicle with the Toyota Prius PHEV. Simpson warns us, however, the shift towards PHEVs can have some unforeseen negative externalities. The demand of energy for switching from a HEV to a PHEV is transferred from refined petroleum to the electric grid, which often sources fossil-fuels, like coal energy or natural gas.<sup>4</sup>

A leading criticism of PHEV technology is that using power from the grid to charge PHEVs may produce additional emissions, depending on the energy source. If our goal is to reduce carbon emissions, we must drive less, greatly increase the efficiency of internal combustion engines, or switch to non-carbon-based fuels.<sup>5</sup> According to Litman, American drivers face an inelastic price elasticity of demand of -0.10 for driving, meaning individuals are not very willing to drive less to reduce carbon emissions.<sup>6</sup> For a policy to begin in 2010, we cannot expect significant internal combustion engine efficiency increases in such a short period. Thus we are left with the final option, to source energy for PHEVs from renewable resources.

In this design, we install a renewable energy source—a photovoltaic (PV) cell on the PHEV Prius' roof—to generate additional electricity. A second increase in the efficiency of a PHEV system is the effect of deploying the required upgrades to the electric grid infrastructure, called a “smart grid,” so that the PHEV driver can make informed decisions about when to charge the vehicle. The smart grid notifies the driver when an increase in grid-wide energy demand occurs, and the user can then react to changes in price

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<sup>1</sup> Calef, David, and Robert Goble. “The Allure of Technology: How France and California Promoted Electric Vehicles to Reduce Urban Air Pollution.” *Fondazione Eni Enrico Mattei, Working Papers: 2005.7*, 2005.

<sup>2</sup> Sperling, Daniel. “Energy 2050 Future of Transportation Fuels.” *Resources For the Future* (2005).

<sup>3</sup> Lovins, Amory B. “Smart Garage Charrette Report.” edited by Laura Schewel, 65: Rocky Mountain Institute, 2008.

<sup>4</sup> Simpson, A., and National Renewable Energy Laboratory (U.S.). “Cost-Benefit Analysis of Plug-in Hybrid Electric Vehicle Technology.” In Nrel/Cp 540-40485. Golden, Colo.: National Renewable Energy Laboratory, 2006.

<sup>5</sup> Thomas Turrentine, Mark Delucchi. “Quantifying the Benefits of Hybrid Vehicles.” 19. Davis, CA: University of California, Davis, 2006.

<sup>6</sup> Litman, Todd. “Transportation Elasticities.” 69: Victoria Transport Policy Institute, 2009.

of energy during peak and non-peak hours, refueling when prices are minimized. The smart grid will also enable the user to sell excess energy from the either the PHEV’s battery or photovoltaic cell to the electric grid, which may prove during peak hours to contribute to an overall reduction in the price of peak electricity.

In determining the length of the policy, we choose five years, from 2010-2015. Estimates for costs of batteries and PV cells become increasingly uncertain after 2015. Benefits will be considered based on the length of the PHEV’s lifetime. From the average Prius lifespan, we are able to approximate for our policy that the vehicles are taken off the road after nine years.<sup>7</sup>

This paper investigates the benefits and costs of enacting policy to subsidize the difference in cost between a PV-enabled PHEV Prius and the existing HEV Prius configurations.

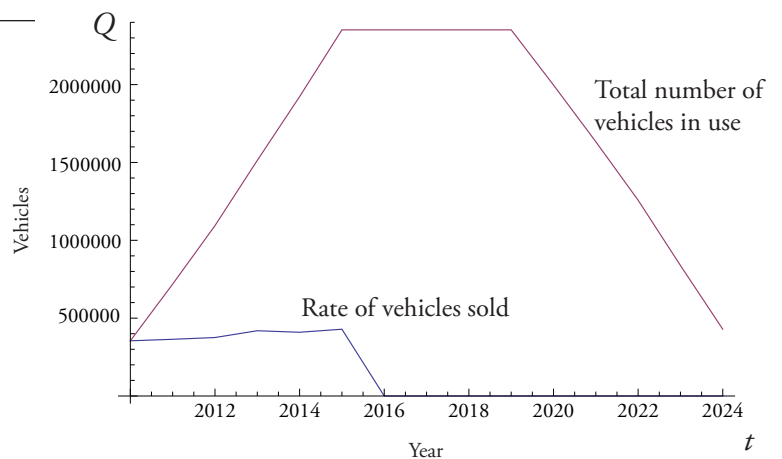
## 2. Effect on Consumers

In determining demand for PHEV Priuses, we consider the projected climate of factors which influence HEV demand. As we consider the long-term costs of oil, the question of oil security—that is what the remaining supply of oil is and the level of price certainty—becomes an increasingly consequential one. The Energy Information Administration (EIA) projects that world energy demand will grow by “nearly 45% between 2006 and 2030,” estimating roughly 20% of the new supply demands to be fulfilled with oil.<sup>8</sup> Additionally, a debate is intensifying over peak oil, namely, the time at which we achieve the maximum rate of extraction, with many believing that that moment has already passed. One prominent organization,

**Table 2.1.**  
Estimated number of cars sold annually

Year	Quantity PHEVs Sold	Total Vehicles in Use
2010	354439	354439
2011	364206	718645
2012	375600	1094245
2013	419142	1513387
2014	409376	1922763
2015	428908	2351671
2016	0	2351671
2017	0	2351671
2018	0	2351671
2019	0	2351671
2020	0	1997232
2021	0	1633026
2022	0	1257426
2023	0	838284
2024	0	428908
Total	2351671	

**Figure 2.1.**  
Plot of rate of sales and total quantity of vehicles



<sup>7</sup> “Toyota Warranty and Coverage.” Toyota Motor Sales, U.S.A., Inc., <http://www.toyota.com/prius-hybrid/warranty.html>.

<sup>8</sup> “Annual Energy Outlook 2009.” edited by Paul D. Holtberg, 230. Washington, DC: U.S. Department of Energy, 2009.

the Cambridge Energy Research Associates (CERA), has stated that demand for gasoline in the United States has already peaked, as early as Summer 2007, and the resulting magnified gasoline prices and increased fuel efficiency encouraging consumers to consider alternatives.<sup>9</sup>

When prices tripled from early 2007 to mid 2008,<sup>10</sup> the price of oil had two largely positive impacts: Americans began to drive less, and businesses began to develop more energy-efficient technologies, focused on minimizing oil expenditures.<sup>11</sup> Hybrid vehicles are estimated to account for at least 5% of all consumer vehicles in the U. S. in the year 2015.<sup>12</sup> From this estimate, we calculate the breadth of the intended policy for subsidizing PHEV Priuses from 2010-2015, as shown in Table 2.1. and Figure 2.1.

### 2.1. Health/environmental benefits and social costs

In considering the benefits of this policy, it is critical to measure the environmental effects of the PHEV-PVs compared to the HEVs replaced, since we can treat these differences as cost savings under the

**Table 2.2.**

Emissions reduction by component switching from HEV to PHEV-PV

Year	Hydrocarbons (tons)	Carbon Monoxide (tons)	NOx (tons)	CO <sub>2</sub> (tons)
2010	10820.69178	80004.77745	5328.044394	1606569.364
2011	21939.54269	162214.0493	10802.90057	3257407
2012	33406.24592	246995.2314	16449.03717	4959890.954
2013	46202.24193	341604.7846	22749.70965	6859737.619
2014	58700.07882	434009.8433	28903.57034	8715316.012
2015	71794.23397	530823.8908	35351.0546	10659430.95
2016	71794.23397	530823.8908	35351.0546	10659430.95
2017	71794.23397	530823.8908	35351.0546	10659430.95
2018	71794.23397	530823.8908	35351.0546	10659430.95
2019	71794.23397	530823.8908	35351.0546	10659430.95
2020	60973.54219	450819.1134	30023.01021	9052861.585
2021	49854.69128	368609.8415	24548.15403	7402023.949
2022	38387.98806	283828.6594	18902.01743	5699539.995
2023	25591.99204	189219.1063	12601.34495	3799693.33
2024	13094.15515	96814.04758	6447.484262	1944114.937
Totals	717942	5308239	353511	106594309

**Table 2.3.**

Social Costs for different vehicle types

	Internal Combustion	Prius	PHEV Prius	PHEV-PV Prius
Greenhouse warming	\$3750.00	\$1559.41	\$910.69	\$760.97
Local pollution	\$25,000.00	\$10,396.04	\$6071.29	\$5073.14
Total	\$28,750.00	\$11,955.45	\$6981.98	\$5834.11

<sup>9</sup> Jackson, Peter M. "The Future of Global Oil Supply." 16. Cambridge, MA: CERA, 2009.

<sup>10</sup> Graefe, Laurel. "The Peak Oil Debate." *Federal Reserve Bank of Atlanta: Economic Review* 94, no. 2 (2009): 1-14.

<sup>11</sup> Graefe, Laurel.

<sup>12</sup> Baum, Alan. "Market Penetration of Hybrid and Diesel Vehicles in the U.S. Market, 2004-2015." The Planning Edge, 2007.

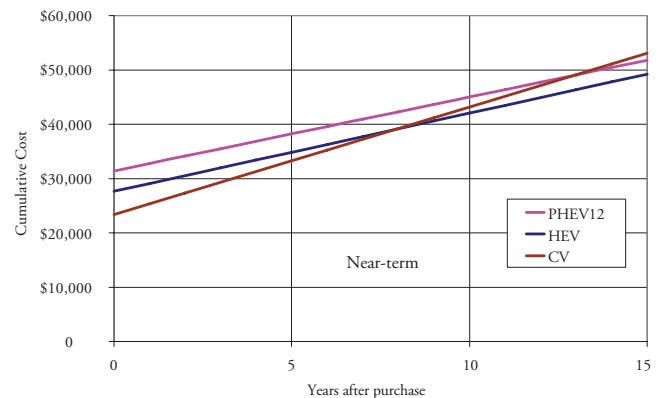
proposed policy. In burning gasoline, cars emit nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>) and hydrocarbons (VOCs). When VOCs and NO<sub>x</sub> combine, they create ground-level ozone. According to the EPA, ground-level ozone has significant health effects, including coughing, wheezing, inflammation of the lungs, aggravation of asthma and even permanent lung damage. In terms of the environment, ground-level ozone has detrimental effects on plants and ecosystems including leaf damage and reducing forest growth and crop yields.<sup>13</sup> We conclude that the PV-enabled PHEV (PHEV-PV) Prius has sizable reductions in emissions, as shown in Table 2.2. and the annual costs of these reductions are shown in Table 2.3., as estimated by Parry and Walls per mile driven,<sup>14</sup> and these values are verified by the \$0.22 per gas-powered mile that Axsen approximates.<sup>15</sup>

## 2.2 Maintenance Costs

Included in the costs of the vehicle throughout the PHEV's life are maintenance costs per mile driven. Delucchi exposes the life cycle of batteries used in a hybrid-electric vehicle. For a complete analysis of the cost of a battery-powered vehicle, we must consider the lifecycle cost. According to the National Renewable Energy Laboratory, whose findings are illustrated in Figure 2.2, the maintenance costs of HEVs are roughly equivalent to PHEVs, and we consider the maintenance costs of a PHEV be very similar to the PHEV equipped with a PV cell (PHEV-PV).<sup>16</sup> We cannot verify this hypothesis since there is no data on maintenance costs for PHEV-PVs, and it will be disregarded in net benefit calculations, since it is expected to be very close to the maintenance costs of HEVs.

**Figure 2.2.**

Cumulative maintenance costs of PHEV and HEV



## 3. Effect on Producers

Since the policy relies on the differences in costs and benefits from replacing the 2010-2015 demand for HEVs Priuses with PHEV-PV Priuses to determine subsidy size, we treat the MSRP of a 2010 Toyota Prius as a transfer. Further, we determine the costs and benefits faced by producers for deploying a smart grid infrastructure, the estimated enhancing the Prius HEV's batteries and installing PV cells that fit the roof of the vehicle.

### 3.1 Cost of Implementing Smart Grid Infrastructure

To launch a national PHEV system, foundational improvements must be made to the electric grid

<sup>13</sup> "Health and Environment | Ground-Level Ozone." US EPA, <http://www.epa.gov/air/ozonepollution/health.html>.

<sup>14</sup> Parry, Ian and Margaret Walls. "Automobile Externalities and Policies." *Journal of Economic Literature* XLV (2007): 384.

<sup>15</sup> Axsen, Jonn, Dean C. Mountain, and Mark Jaccard. "Combining Stated and Revealed Choice Research to Simulate the Neighbor Effect: The Case of Hybrid-Electric Vehicles." *Resource and Energy Economics* 31, no. 3 (2009): 221-38.

<sup>16</sup> Simpson, A., and National Renewable Energy Laboratory (U.S.). "Cost-Benefit Analysis of Plug-in Hybrid Electric Vehicle Technology." In Nrel/Cp 540-40485. Golden, Colo.: National Renewable Energy Laboratory, 2006.

infrastructure. These strength of these improvements, called “Smart Grids,” lie in their ability to adjust to different strains on the energy infrastructure during peak hours by sending signals to end users or possibly even devices themselves to reduce or delay consumption until peak hours are over.<sup>17</sup> From a utilities perspective this is a major breakthrough in the market of energy, facilitating people with elastic electricity demands, in other words, those who are flexible with when they consume electricity, to use it when demand is lowest. With smart grids in place, utility companies can flatten demand across hours of the day and perhaps avoid turning on expensive power plants entirely.

A second benefit to bidirectional, or specifically Vehicle-to-grid (V2G), smart grids is that they can take advantage of PHEV onboard batteries to off-load energy when demand is highest. This is impossible with the current electric grid infrastructure, but with smart grids, one would be able to take a fully charged vehicle to a docking station and unload part of the battery’s capacity during peak hours and charge later when demand decreases. Of course, there are some major limitations to this feature, if one wants to use a car after the smart grid has off-loaded most of the PHEV’s battery, there may be insufficient energy.<sup>18</sup> However, using the policy’s conceptual PHEV-PV, the solar panel allows the vehicle to autonomously generate electricity when the car is not in use. Under government subsidized PHEV-PVs, we create a mobile fleet of photovoltaic that may significantly impact the supply of energy during hours when these vehicles are not in use.

Importantly, for evaluating the net benefits of the smart grid in the policy, there is great uncertainty with respect to the total costs of the smart grid infrastructure. Most estimated costs are preliminary estimates before many smart grid systems have been deployed. For a 10% market penetration of the entire US electric grid by 2020, the Electric Power Research Institute estimates a \$30 billion cost, while other estimates are as high as \$65 B.<sup>19</sup> From these two estimates, we take an average cost of \$47.5 billion for our policy. According to the Galvin Electricity Initiative, benefits from smart metering can lead to consumer reductions of power consumption that “could add \$5 billion to \$7 billion per year back into the U.S. economy by 2015, and \$15 billion to \$20 billion per year by 2020.”<sup>20</sup> Two side-improvements over the current grid infrastructure are the reductions of disturbance costs and maintenance costs that are expected to occur with less frequency than with the current grid. Disturbance costs include power outages and cost the U.S. economy approximately \$49 billion annually. Similarly, forgone maintenance costs of the existing electric grid due to the replacement of smart grids may save between \$46 and \$117 billion over the next 20 years.<sup>21</sup> We have adjusted these figures assuming 10% of the current grid is converted to a smart grid system, as demanded by PHEVs.

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<sup>17</sup> Schweppe, Fred. “Frequency Adaptive, Power-Energy Re-Scheduler.” edited by US Patent Office. US: Massachusetts Institute of Technology, 1979.

<sup>18</sup> Lovins, Amory B. “Smart Garage Charrette Report.” edited by Laura Schewel, 65: Rocky Mountain Institute, 2008.

<sup>19</sup> Siddiqui, O. “The Green Grid: Energy Savings and Carbon Emissions Reductions Enabled by a Smart Grid.” Palo Alto, CA: Electric Power Research Institute, 2008.

<sup>20</sup> “What a Smart Grid Means to Our Nation’s Future.” edited by U.S. Department of Energy. Washington DC: Litos Strategic Communication 2009.

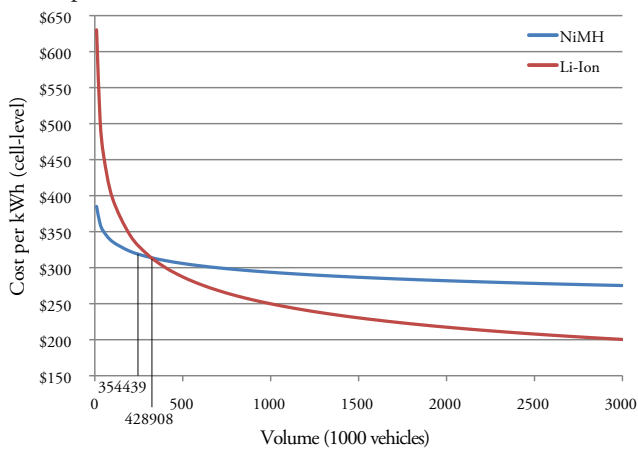
<sup>21</sup> Kurt Yeager, Clark W. Gellings. “Transforming Electricity Service Reliability and Value for the 21st Century.” 6-16. Palo Alto, CA: Galvin Electricity Initiative, 2005.

### 3.1. Cost of Batteries

Valuing the cost of batteries is exacerbated by recent technological developments, the industry diverging between Nickel-metal hydride (NiMH), and Lithium-Ion (Li-Ion) sorts. NiMH batteries are currently used in HEVs since they have been historically less expensive than Li-Ion batteries. Still, Li-Ions are preferred to NiMHs because they do not suffer from the “memory effect,” which is the reduction in total capacity of the battery each time the battery is recharged.<sup>22</sup> Other advantages of Li-Ions include higher energy density than NiMHs, which means car manufacturers can replace NiMH batteries with an equally sized Li-Ion battery and achieve increased kWh capacity for the PHEV.

The Plug-in Prius is estimated to cost roughly \$2,000-4,000 more than the current Prius, valued at \$22,750, though Toyota has not yet officially released details on the price.<sup>23</sup> The cost differential is expected to be relatively small because Toyota is attempting to keep the PHEV model competitive to current Prius offerings, which implies that most of the cost difference will be resulting from the battery. From this minimal amount of money towards a battery capacity increase, we have a better understanding of why the PHEV Prius attains a mere 12 miles on electricity alone. For comparison, the 2010 Chevrolet Volt is expected to be PHEV-40, or reach approximately 40 miles per charge, but the Volt uses an \$8000 Li-Ion battery, as

**Figure 3.1.** Experience curve for NiMH & Li-Ion batteries.<sup>25</sup>



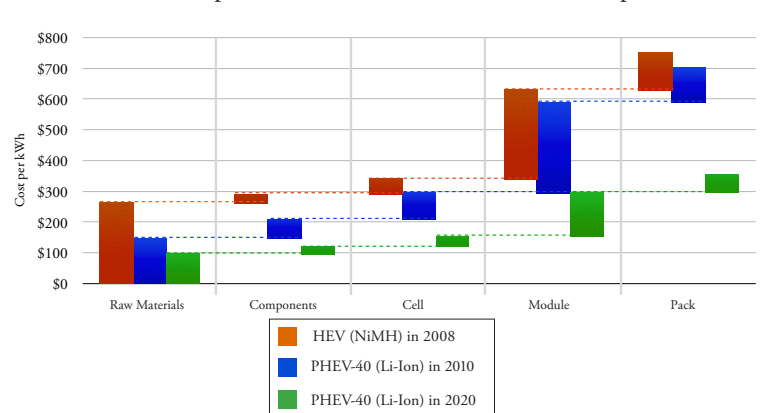
**Table 3.1.** Cost of batteries per year for HEVs and PHEVs

Year	Cost per kWh	Number of vehicles sold	Discounted cost of battery		
			PHEV	HEV	Total difference in total cost
2010	720.2	354439	\$1,887.50	\$1,080.30	\$286,103,218
2011	714.8428571	364206	\$1,784.25	\$1,021.20	\$277,905,090
2012	709.4857143	375600	\$1,686.55	\$965.29	\$270,906,087
2013	704.1285714	419142	\$1,594.11	\$912.38	\$285,741,535
2014	698.7714286	409376	\$1,506.65	\$862.32	\$263,771,849
2015	693.4142857	428908	\$1,423.90	\$814.96	\$261,179,183

<sup>22</sup> Delucchi, Mark A., and Timothy E. Lipman. “An Analysis of the Retail and Lifecycle Cost of Battery-Powered Electric Vehicles.” *Transportation Research: Part D: Transport and Environment* 6, no. 6 (2001): 371-404.

<sup>23</sup> Squatriglia, Chuck. “Plug-in Prius Coming This Year.” In *Autotopia*. San Francisco, CA: Condé Nast Digital., 2009.

**Figure 3.3.** Converted cost per kWh from raw materials to NiMH pack.<sup>25</sup>



opposed to the Prius’ NiMH battery, the battery cost factors heavily in the Volt’s \$40,000 MSRP.<sup>24, 25</sup>

In determining the value of the PHEV’s battery over time for the purposes of this policy, we look towards The Rocky Mountain Institute’s findings for trends in costs for each battery, reproduced in Figures 1.1., and 1.2. For our policy we are estimating demands for batteries, one per vehicle ranging from 354,439 in 2010 to 428,908 in 2015. According to The Rocky Mountain Institute, the costs of Li-Ion batteries will exceed the costs of NiMH batteries until demands for batteries approach approximately 430,000 vehicles, just beyond the expected demand limit for our policy.<sup>26</sup> Other factors include the demand other car manufacturers place on Li-Ion batteries, since that will influence the industry-wide price, but for the simplicity of the policy, we will assume the PHEV Prius uses the same parts throughout the policy, and doesn’t switch battery technologies midway.

With the use of NiMH batteries for the PHEV Prius, we estimate a battery size of approximately 2.6208 kWh, compared to the current Prius’ 1.5 kWh battery. Using the Rocky Mountain Institute’s data on the prices of NiMH batteries relative to demand, we compare the costs of the PHEV Prius’ and the HEV Prius’ NiMH batteries throughout the policy, shown in Table 3.1.

**3.3. Cost of PV Cells**

PV cell costs have been falling precipitously in recent years, from \$4.88/watt in 2006 to current levels of \$4.31/watt, and are projected to decrease to a staggering \$1.98 by 2020.<sup>27</sup> From these trends, we construct Table 3.2 of projected PV prices over the next 10 years, assuming prices decrease at an increasing rate between -\$0.19/year (from 2006 to 2009 values) to -\$0.29/year to projected values in 2020. Based on the expected yield from a PV cell fitted to just below the dimensions of the Prius’ roof, 4532.89 in<sup>2</sup>, we expect approximately 525.24 kWh to be generated annually, multiplied by the number of PHEV under the policy. The results are shown in Table 3.3., and we will use the kWh produced by PV cells to offset the consumption of carbon-based electricity in our estimates for the benefits of installing PV cells on the roof of PHEV Priuses.

**Table 3.2.**

Projected costs of PHEV PV cell by year<sup>1</sup>

Year	\$/watt	Cost of PV Cell
2010	\$4.88	\$1,891.15
2011	\$4.47	\$1,730.97
2012	\$4.06	\$1,572.97
2013	\$3.66	\$1,417.72
2014	\$3.27	\$1,265.72
2015	\$2.88	\$1,117.39

<sup>1</sup>Estimating 387.53 w for PV cell size; discount rate of 5%.

**Table 3.3.**

kWh of coal power saved due to PV cells

Year	kWh of Coal Saved
2010	186165540.4
2011	377461099.8
2012	574741243.8
2013	794891387.9
2014	1009912038
2015	1235191676
2016	1235191676
2017	1235191676
2018	1235191676
2019	1235191676
2020	1049026136
2021	857730576.2
2022	660450432.2
2023	440300288.2
2024	225279637.9

<sup>24</sup> Connor, Mike. “Could the EPA Cripple the Chevy Volt?” 2009.

<sup>25</sup> “2011 Volt | Electric Car | Chevrolet.com.” Chevrolet, <http://www.chevrolet.com/pages/open/default/future/volt.do>.

<sup>26</sup> Anderson, David. “Status and Trends in the HEV/PHEV/EV Battery Industry.” Rocky Mountain Institute, 2008.

<sup>27</sup> “Solar Module Price Highlights — December 2009.” Solarbuzz.

## 4. Estimation of Benefits

**Table 4.1.**

Annual Estimated Benefits at 5% discount rate.

Year	Value of reduced coal <sup>a</sup>	Value of reduced CO <sub>2</sub> emissions <sup>b</sup>	Benefits of smart grid <sup>c</sup>	Value of social benefits <sup>d</sup>
2010	\$24,889,933	\$80,328,468	\$13,668,367,347	\$4,237,476,162
2011	\$48,062,609	\$155,114,619	\$13,017,492,711	\$8,182,591,581
2012	\$69,741,439	\$224,938,365	\$12,397,612,106	\$11,865,928,803
2013	\$91,862,240	\$296,284,964	\$11,807,249,625	\$15,629,600,137
2014	\$111,153,589	\$358,505,603	\$11,244,999,643	\$18,911,863,541
2015	\$129,230,907	\$417,597,153	\$10,709,523,469	\$22,029,053,301
2016	\$123,077,054	\$397,711,575	\$10,199,546,161	\$20,980,050,763
2017	\$117,142,526	\$378,772,928	\$9,713,853,487	\$19,981,000,727
2018	\$111,564,310	\$360,736,122	\$9,251,289,035	\$19,029,524,502
2019	\$106,184,860	\$343,558,212	\$8,810,751,462	\$18,123,356,668
2020	\$85,832,487	\$277,883,586	\$8,391,191,868	\$14,658,896,907
2021	\$66,838,544	\$216,390,505	\$7,991,611,303	\$11,415,017,327
2022	\$49,045,659	\$158,685,857	\$7,611,058,384	\$8,370,985,945
2023	\$31,159,710	\$100,752,925	\$7,248,627,032	\$5,314,911,711
2024	\$15,193,236	\$49,095,508	\$6,903,454,317	\$2,589,880,498
Total	\$1,180,979,102	\$3,816,356,389	\$148,966,627,950	\$201,320,138,574

### 4.1. Methods

a. **Reduction in Quantity of Coal Consumed:** First, we estimated the tons of coal abated by using PV cells to generate electricity. We took that figure, and used the projected price of coal to estimate the savings of coal due to PV cells annually. Lastly, we added the social cost of coal (not including CO<sub>2</sub> emissions) per ton to this figure to account for the net benefit of coal reduction.

b. **Reduction in Carbon Dioxide Emissions:** We estimated how many tons of CO<sub>2</sub> are abated using photovoltaic cells in the PHEV vehicle technology, and accounted for a \$50 CO<sub>2</sub> abatement cost.

c. **Benefits from Smart Grid Infrastructure:** The smart grid infrastructure is estimated to have discounted benefits of approximately \$13.7 billion annually.

d. **Social Benefits of PHEV with PV Cell:** Under the proposed policy, we consider the social costs of hybrid-electric vehicles being replaced by the plug-in hybrid-electric vehicles with solar cells. Because of this accounting, if we consider the social costs of PHEVs with PV cells in our policy's costs, we can treat as benefits the social costs of HEVs, including emissions from HEVs in the form of Hydrocarbons, Carbon Monoxide, Oxides of Nitrogen and Carbon Dioxide.

## 5. Costs

### 5.1. Methods

a. **Solar Panels:** Looking at the projected price of solar panels each year, from 2010-2015, we calculate the cost of solar panels for the fleet of PHEVs by multiplying the cost of each PV cell by the estimated number of vehicles per year. These are one-time costs per each vehicle.

b. **Cost of Smart Grid Infrastructure:** The estimate of an initial \$47.5 billion is a one-time cost at the beginning of the implementation of the policy. Every year, approximate maintenance costs of a discounted \$2.3 billion occur after the first year.

c. **Cost of Battery:** Battery costs are estimated in a similar manner to the cost of solar panels. Considering the projected cost of a 2.6208 kWh battery for each year, multiplied by the number of vehicles sold each year. These are one-time costs per each vehicle.

d. **Estimated Social Cost of PHEV with PV Cell:** To measure the social cost of each vehicle, we consider the social costs of emissions from HEVs in the form of hydrocarbons, CO, oxides of nitrogen and CO<sub>2</sub> per gas-powered mile. These social costs occur each year for the estimated nine-year lifespan of the PHEV.

**Table 5.1.**

Annual Estimated Costs at 5% discount rate.

Year	Solar Panels <sup>a</sup>	Smart Grid <sup>b</sup>	Battery <sup>c</sup>	Social Cost <sup>d</sup>
2010	\$670,296,039	\$47,500,000,000	\$286,103,218	\$2,067,836,213
2011	\$630,428,689	\$2,326,530,612	\$277,905,090	\$3,993,003,982
2012	\$590,806,621	\$2,215,743,440	\$270,906,087	\$5,790,427,212
2013	\$594,226,516	\$2,110,231,848	\$285,741,535	\$7,627,052,501
2014	\$518,156,579	\$2,009,744,617	\$263,771,849	\$9,228,756,644
2015	\$479,259,575	\$1,914,042,492	\$261,179,183	\$10,749,906,882
2016	\$0	\$1,822,897,612	\$0	\$10,238,006,554
2017	\$0	\$1,736,092,964	\$0	\$9,750,482,433
2018	\$0	\$1,653,421,870	\$0	\$9,286,173,745
2019	\$0	\$1,574,687,495	\$0	\$8,843,974,996
2020	\$0	\$1,499,702,376	\$0	\$7,153,361,272
2021	\$0	\$1,428,287,978	\$0	\$5,570,387,962
2022	\$0	\$1,360,274,264	\$0	\$4,084,938,112
2023	\$0	\$1,295,499,299	\$0	\$2,593,611,500
2024	\$0	\$1,233,808,857	\$0	\$1,263,829,807
Total	\$3,483,174,019	\$71,680,965,725	\$1,645,606,962	\$98,241,749,813

## 6. Summary of Cost-Benefit Analysis Results

**Table 6.1.**

Total Annual Costs and Benefits

Total Benefits	Year	Total Costs
\$18,011,061,910	2010	\$50,524,235,470
\$21,403,261,520	2011	\$7,227,868,373
\$24,558,220,713	2012	\$8,867,883,360
\$27,824,996,966	2013	\$10,617,252,399
\$30,626,522,375	2014	\$12,020,429,689
\$33,285,404,831	2015	\$13,404,388,132
\$31,700,385,553	2016	\$12,060,904,166
\$30,190,769,668	2017	\$11,486,575,396
\$28,753,113,969	2018	\$10,939,595,615
\$27,383,851,202	2019	\$10,418,662,491
\$23,413,804,848	2020	\$8,653,063,648
\$19,689,857,679	2021	\$6,998,675,939
\$16,189,775,845	2022	\$5,445,212,376
\$12,695,451,377	2023	\$3,889,110,799
\$9,557,623,558	2024	\$2,497,638,663
\$355,284,102,014	Total	\$175,051,496,518
	Net Benefits	\$180,232,605,496

As we see in Table 6.1, we ultimately achieve net benefits of approximately \$180,232,605,496 after 5 years, and the duration of the proposed policy's impact.

## 7. Conclusion

### 7.1 Uncertainty

In determining the costs and benefits of enacting the proposed policy, we find two areas of uncertainty, first the costs of the smart grid, and second, the maintenance costs of a PHEV-PV.

Costs for a smart metering grid infrastructure remain relatively unclear because they rely so heavily on the market penetration of PHEVs and sample size. In our calculations, we used a small testing zone in San Diego, however we are unsure if the costs and benefits of these grids scale linearly, as we assumed in our calculations, or at an increasing or decreasing rate. Further, it is unclear whether the smart grid technology is ready for wide-scale deployment.<sup>28</sup> Our policy cost estimates could be much lower than actual enacted costs if the smart grid is undervalued or if the technology has high maintenance costs because of insufficient testing. Finally, if we were to ultimately exclude the comparatively uncertain smart grid costs, we continue to see significant net benefits from the policy, of approximately \$102.9 billion.

The second area of uncertainty is the valuation of maintenance costs for a PHEV-PV per year. This could easily be determined once a few vehicles are built and tested, but since this vehicle is a hypothetical product, we are unable to determine more reasonable figures.

### 7.2 Discussion

Most of the calculations from the proposed policy involve accurately predicting demand estimates of HEVs, and by extension the PHEV-PVs, which in the proposed policy replace the HEVs. Only looking five years into the future, our policy is still well poised to have near accurate estimates for the demand of HEVs. One assumption the policy makes is that HEVs, PHEVs, and PHEV-PVs are all at least substitute goods, or more rigorously:

$$\text{PHEV-PV} \geq \text{PHEV} \geq \text{HEV}$$

We assume that given the choice to consume a PHEV-PV or a PHEV, the consumer would choose the PHEV-PV, and given the choice to consume a PHEV or an HEV, the consumer would choose the PHEV. Since this policy aims to subsidize the difference in cost between PHEV-PV and HEVs, the consumer's demand for Priuses should transition directly to an equal demand for PHEV-PV Priuses. In fact, demand should increase due to increased utility from the PHEV-PV at the same cost as the equivalent HEV, however it is difficult to predict to what extent the demand would increase relative to current HEV projections.

The policy could be enhanced in two ways: first, we can consider the policy for subsidizing other cars than the Toyota Prius. Secondly, because the lifespan of the car is shorter than the lifespan of the PV cell, we should seek whether the policy has greater net benefits if we installed the PV cells elsewhere.

The choice of the Toyota Prius in this policy was due to understanding historic demand for the Prius,

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<sup>27</sup> Motavalli, Jim. "Power to the People: Run Your House on a Prius." *The New York Times*, September 2, 2007.

so we have a relatively clear expectation of future demand for the vehicle. Yet, the plug-in Prius as a PHEV-12 uses a NiMH battery and achieves 28 fewer miles on a single charge compared to the Chevrolet Volt. This is a weighty difference considering the average American drives approximately 34.24 miles a day.<sup>29</sup> Therefore the difference between the Chevrolet Volt and the Toyota Prius when PVs are installed on each vehicle's roof is essentially the difference between generating energy for the electric grid during peak hours or refueling with electricity when not in use. Unfortunately, it is difficult to predict the demand for the Chevrolet Volt considering that it has yet to be sold in the United States, and has a difference in MSRP of at least \$12,000 when compared to the PHEV Prius. The intended policy also used the same model Prius for five years, ignoring any possible increases in efficiency, price changes, or design changes that would change consumer preferences, shifting demand in an unforeseen way. We would expect Toyota to continue releasing a new model each year, but it is impossible to determine their plans from available data.

Another possible enhancement to the proposed policy would be to install PV cells on the smart meters instead of the vehicles themselves. Consider that the lifespan of a PV cell is 25 years whereas the lifespan of a Prius is nine years, if the roof PV cells are not recyclable, 16 years of the PV cell's life would be wasted. One caveat is that the surface area of a vehicle is larger than most designs for smart meters, but designs for smart meters allow links to local PV cells, perhaps on the roof of an adjacent building.

While it is very evident that the costs of the policy are outweighed by its benefits, the policy is unequivocally quite expensive to enact. It would be worthwhile to determine how costs could be spread more evenly throughout several years, and how to optimally phase-in PHEVs while simultaneously launching a V2G infrastructure. As indicated by the diminishing costs of PV cells and batteries, with future promise in increased capacity by volume Li-Ion batteries, there is evidence to suggest that the timing of the policy alone can reduce costs.

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<sup>29</sup> "Emission Facts: Average Annual Emissions and Fuel Consumption for Passenger Cars and Light Trucks." Washington, DC: Environmental Protection Agency, 2000.

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