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Article

Ownership Cost Comparison of Battery Electric and Non-Plugin Hybrid Vehicles: A Consumer Perspective

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Abstract: This study evaluates eight-year ownership costs for battery electric vehicles (BEV) versus non-plugin hybrid vehicles using forecasting to estimate future electricity and conventional gasoline prices and incorporating these in a multiple design of experiments simulation. Results suggest that while electric vehicles are statistically dominant in terms of variable costs over an 8-year life-span, high-performance hybrid non-plugins achieve variable fuel costs nearly as good as low-performing electric vehicles (those attaining only 3 miles per kilowatt hour) and that these hybrid acquisition costs are (on average) lower yet the vehicles retain higher residual values. In general, the six smallest ownership costs are split evenly between hybrid and electric vehicles; however, inflation for conventional regular gasoline is estimated to outstrip inflation per kilowatt hour. Thus, non-plugin hybrid cars are likely to require considerably more advanced engineering to keep pace.

Keywords: BEV, ownership cost analysis, design of experiments, forecasting, Monte Carlo simulation

1. Introduction

With more constraints on energy resources coupled with stringent regulations due to fossil fuel pollution, the growth of energy efficient technologies and clean, renewable energy sources is essential for ensuring sustainable practices. When assessing the potential gains from energy efficient technologies, engineering efficiency analysis must consider both the scale of energy flow and the technical component for improvement. As part of this analysis, the industry must thoroughly evaluate and compare the costs and demand trade-offs from a consumer perspective to ensure that the engineering of sustainable products provides optimal consumer satisfaction [1].

With volatility of gasoline prices, the purchase of electric cars has become an attractive option to some, but understanding the actual ownership costs associated with such a purchase requires analysis. Acquisition costs must take into consideration tax credits, while variable fuel costs associated with electric vehicles should be based on the cost per kilowatt hour, usage, and other factors. Further, maintenance and residual value must be investigated to paint a complete picture of life-cycle costs from the consumers' perspectives.

Some work has been done in the area of ownership and life-cycle costs for vehicles, but the area is relatively new [2]. Delucchi & Lipman addressed the issue of lifecycle costs by developing a detailed model of the performance, energy use, manufacturing cost, retail cost, and lifecycle cost of battery-powered vehicles and comparable gasoline-powered vehicles [3]. They found in their 2001 study that for electric vehicles to be cost-competitive with gasoline-powered vehicles, batteries must have a lower manufacturing cost as well as a longer battery life. The work provides a reasonable framework for an updated study. In another dated (2006) study, Lipman & Delucchi developed a

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vehicle simulation cost model to analyze the manufacturing costs, retail prices, and lifecycle costs of hybrid gasoline-electric vehicles, conventional vehicles, electric-drive vehicles, and other alternative-fuel vehicles [4]. Due to its date, it lacks relevance based on the speed of technological change. Silva, Ross & Farias contributed to the worldwide methodology for calculation of fuel consumption and emission factors when regarding emission standards, with distinct driving styles [5]. Using this methodology, they simulated the energy consumption, emissions and cost of plug-in hybrid vehicles. Their work provides a good framework for cost estimation but focuses only on plug-in hybrids. Werber, Fischer & Schwartz compared the lifecycle costs of electric cars to similar gasoline-powered vehicles under different scenarios of required driving range and cost of gasoline [6]. They found that the electric cars with approximately 150 kilometers range are a technology viable, cost competitive, high performance, high efficiency alternative that can presently suit the vast majority of consumers' needs. This study uses similar methods. Weiller developed a simulation algorithm to explore the effects of different charging behaviors of plug-in hybrid electric vehicles (PHEVs) on electricity demand profiles and energy use, in terms of time of day and location (at home, the workplace, or public areas) [7]. The study focused on electrical demand of PHEVs but did demonstrate consumption of 1.5-2.0 kWh per day when electric chargers were available in the home. Ernst et al. introduce a total cost of ownership model for the average car user in Germany to compare the energy consumption of a conventional vehicle versus a plug-in hybrid electric vehicle [8]. This dated study found a break-even time frame of six years with 4kWH batteries. Many studies have found that electric vehicles might be cheaper or more expensive than combustion engine vehicles depending on assumptions [9], [10]. No studies compared solely BEV vs. PHEV vehicles.

Lieven et al. conducted a study forecasting the market potential of electric vehicles by analyzing both individual priorities and barriers due to social preferences [11]. Using a mixed multiple discrete-continuous extreme value model approach, Shin et al. investigated how the introduction of electric vehicles may influence the usage of existing cars. Additionally, they used a survey of 250 households to analyze a future automobile market that includes electric vehicles taking into account the heterogeneity of consumer preferences and usage patterns [12]. He, Chen & Conzelmann analyzed the vehicle usage and consumer profile attributes extracted from both National Household Travel Survey and Vehicle Quality Survey data to understand the impact of vehicle usage upon consumers' choices of hybrid vehicles in the United States [13]. Kelly, MacDonald & Keoleian studied the impacts that plug-in hybrid electric vehicles can have on energy consumption and related emissions, as they are dependent on vehicle technology, driving patterns, and charging behavior. Moreover, they developed a methodology to simulate charging and gasoline consumption based on driving pattern data in the National Household Travel Survey, examining the effects of charging location, charging rate, time of charging, and battery size [14]. Ozdemir & Hartmann calculate the energy consumption shares of plug-in hybrid vehicles for electricity from the grid and conventional fuel by determining the optimal electric driving range for different oil price levels [15]. In an interesting paper, Ahmadi, Cai & Khanna used optimization models to suggest that hybrid vehicles were generally better when considering total life-cycle costs under the assumption that miles traveled per day were high [16]. This detailed paper generalized overall vehicle classifications but did not use lifecycle forecasts for energy costs or use residual costs (a consumer perspective). In another good study, Palmer et al. used panel regression to compare life-cycle costs for four separate sites but did not calculate forecasts for energy costs, did not consider the effects of seasonal differences, and used vehicle data from 2016. Their study also focused on four specific locations rather than the U.S en toto [17].

The problem of interest is a comparison of the life-cycle costs of electric vs. hybrid vehicles form the consumer perspective. This study examines the engineering trade-off considerations of average miles gallon (mpg) versus average miles per kilowatt hour (mpkWh) when considering cost for both gasoline and retail grid power. The research question for this study is then straightforward: what

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are the estimated life-cycle costs associated with the purchase of either an electric or hybrid vehicle in 2018? This research question addresses engineering efficiency trade-off considerations that might be reasonably assessable given fuel and electricity forecasting models. This may be the first study to compare specifically electric and hybrid vehicles based on known *2018* engineering capabilities as well as time series forecasts of energy costs.

2. Materials and Methods

Study Design, Setting, & Data

This study leverages 23 years of data from the U.S. Department of Energy on average price per kilowatt hour [18], average dollars per gallon for regular conventional gasoline [19], the distribution of vehicle miles driven per year [20], base manufacturer suggested retail prices (MSRP) [21], maintenance factors, insurance estimates, and simulation with design of experiments parameters to investigate life-cycle costs for electric and non-plugin hybrid vehicles. The study also includes time series forecasts for cents per kilowatt hour (cpkWh) and dollars per gallon to use in simulating an 8-year vehicle lifespan. While vehicles may last longer, the average length of ownership is approximately 6.5 years [22]. Further, electric battery warranties are often only 8 years [23].

The study includes base MSRP data as acquisition costs and forecasting of both cpkWh and cents per gallon of regular gasoline to estimate ownership costs. Maintenance is accounted for by applying 3.5 cents per mile for electric vehicles and 6 cents per mile for hybrids, although this is imprecise [24]. Insurance costs may be higher or lower depending on car value and insurance company, so a fixed value of 5% based on initial cost of the car is assigned. Electric vehicles depreciate at a more rapid rate than hybrid vehicles [25]. Over four years, gasoline cars retained on average 45% of their value, while electric vehicles just above 25% after adjustment for any Federal tax credit. It is unknown what the depreciation on new cars will be after an 8-year lifespan will be; however, it is assumed that the decay over the next four years will match the previous four, .45 remaining x .65 decay rate = .29 residual for gasoline cars and .25 remaining x .75 decay rate = .19 for electric cars.

The setting for this study is the entirety of the United States, although the analysis is readily parsed to any individual state for which data are gathered. For generalization, all coding is provided. Data sources for costs derive primarily from the U.S. Department of Energy.

Simulation Sets, Parameters, Stochastic Variables, Deterministic Variables, Formulae, and Flowcharts

Sets. Three index sets are used in the simulation. The first index i counts the number of simulation iterations, $i=\{1,2,..25\}$ (see *Simulation Iterations* under results). The second index t counts the day of the year, $t=\{1, 2,..365\}$. The third index y counts the number of years in the simulation, $y=\{1, 2,..8\}$.

Design of Experiments Parameters. The simulation leverages design of experiments (DOE) parameters that include miles per kilowatt hour (mpKh) design factor and miles per gallon (mpg) for gasoline powered cars. Daily miles driven is included as a probability distribution. Cost in cents per kilowatt hour (cpkWh) and in cents per gallon of fuel are forecasted as explicated in the results section for each month in the simulation, and those monthly estimates are applied to each day within the month. All DOE parameters are investigated within reasonable ranges as demonstrated through analysis of datasets.

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The parameter range of mpkWh for new electric cars derived from an analysis of EVadoption [26]. The distribution of interest was the daily mpkWh because it provides a mechanism for assessing comparative efficiency of vehicles when coupled with a time series analysis of cost per kWh. The minimum efficiency for 2018 electric cars based on distance and battery size is 2.89 mpKh (Tesla Model X P1000), and the maximum is 4.43 mpKh for the Hyundai Ioniq Electric. Thus, the DOE parameter is fixed simplistically within the range of 3 to 5 to represent a feasible engineering range.

The hybrid vehicle mpg parameter was evaluated using top 10, highest MPG hybrid vehicles provided by Fueleconomy.gov [27]. Due to mpg ties, there are actually 11 vehicles on this list. Gas mileage for these hybrid vehicles ranges from 46 mpg (Toyota Prius) to 58 mpg (Hyundai Ioniq). Given this range, the DOE parameter for mpg was set within the range of 40 to 60.

Stochastic Variable. Miles driven annually depends on many factors; however, Department of Transportation (DoT) provides average data on its website [28]. On average, drivers drove 13,476 miles annually in 2017 or approximately 37 miles per day. The variability is high among income groups and age groups [20]. Due to the high variability associated with driving vehicles, the study assumes a right-skewed exponential distribution centered at 37 miles.

Deterministic Estimates. Estimates of the daily cost per kilowatt hour ($ / kWh) and cost per gallon ($ / gl) are the primary deterministic components. These are estimated using forecasting techniques explicated in the Results section.

Formulae. The primary equations calculate variable costs for both the electric and the hybrid automobile options. For each iteration, day, year, and DOE parameter, the following equations are calculated.

$$C_e = \frac{\$}{kWh} \times \frac{kWh}{mile} \times D_t$$

$$C_h = \frac{\$}{gallon} \times \frac{gallons}{mile} \times D_t$$

The simulation flowchart is shown in Figure 1. For each of the iterations, the DOE parameters are set, driving distance is sampled, and costs for each vehicle are estimated for an 8-year vehicle lifespan.

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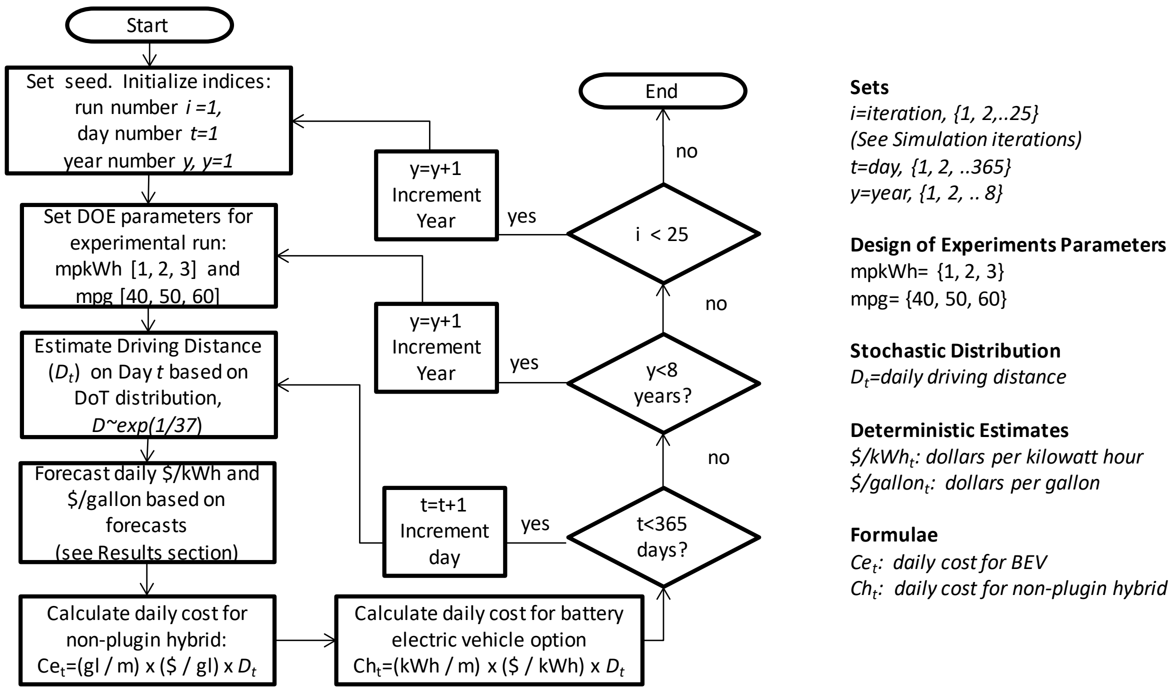

Figure 1. Simulation Flowchart

After the simulation is run over the nine possible DOE combinations, the results are then coupled with fixed cost estimates of maintenance (per type of vehicle), estimates for insurance, and estimated residual values to generate a total cost of ownership picture for specific vehicles in the study.

3. Results

Descriptive Statistics

The analysis of results begins with variable costs. Table 1 provides the pure electric car range in miles per kWh for available U.S. battery electric vehicles [26]. Smart ForTwo was eliminated from this list due to its limited range (58 miles). The average mpkWh is 3.56, and the median is 3.50. The standard deviation is quite small at .38. The median base manufacturer suggested retail price (MSRP) for new electric vehicles is $35,000. Tesla models largely effect the mean ($56,920.71) [21].

Table 1. This table provides the range per kWh of currently available fully electric vehicles used in the study along with the base MSRP.

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Make	Model	Range in Miles	kWh Battery Pack	Miles / kWh	MSRP Base
BMW	i3	114	33	3.45	$ 44,450.00
Fiat	500e	87	24	3.63	$ 32,995.00
Ford	Focus Electric	115	33	3.48	$ 29,120.00
Chevrolet	Bolt EV	238	60	3.97	$ 36,620.00
Honda	Clarity Electric	89	25.5	3.49	$ 33,400.00
Hyundai	Ioniq Electric	124	28	4.43	$ 29,500.00
Kia	Soul EV	111	30	3.70	$ 32,250.00
Nissan	Leaf	107	30	3.57	$ 29,990.00
Tesla	Model 3	310	78	3.97	$ 35,000.00
Tesla	Model S 75D	275	75	3.67	$ 74,500.00
Tesla	Model S 100D	351	100	3.51	$ 94,000.00
Tesla	Model S P100D	337	100	3.37	$ 135,000.00
Tesla	Model X 75	237	75	3.16	$ 70,532.00
Tesla	Model X 100D	295	100	2.95	$ 96,000.00
Tesla	Model X P100D	289	100	2.89	$ 140,000.00
VW	e-Golf	125	35.8	3.49	$ 30,495.00

Table 2 illustrates the comparison group, hybrid electric vehicles (non-plugin). This group consists of Fueleconomy.gov's top 10 vehicles (11 listed due to mpg ties), all of which are 4 cylinder automatics [27]. The average mpg for hybrid vehicles in the study is 50.64 mpg with a median of 50.00 mpg and a standard deviation of 4.31 mpg. The median MSRP is $23,475 with a mean of $24,865 [21].

Table 2. This table illustrates the non-plugin hybrid vehicles included in the study and their associated estimated miles per gallon.

Make	Model	Engine Size (all 4 Cylinder Automatics)	Estimated mpg	MSRP
Hyundai	Ioniq Blue	1.6 Liter	58	$22,200.00
Toyoto	Prius Eco	1.8 Liter	56	$25,165.00
Hundai	Ioniq	1.6 Liter	55	$22,000.00
Toyota	Camry Hybrid LE	2.5 Liter	52	$27,950.00
Toyota	Prius	1.8 Liter	52	$23,475.00
Kia	Niro FE	1.6 Liter	50	$23,340.00
Kia	Niro	1.6 Liter	49	$23,340.00
Honda	Accord Hybrid	2.0 Liter	47	$25,100.00
Chevrolet	Malibu Hybrid	1.8 Liter	46	$27,920.00
Toyota	Camry Hybrid LXE	2.5 Liter	46	$32,400.00
Toyota	Prius c	1.5 Liter	46	$20,630.00

The nation-wide average price per gallon of regular conventional gasoline for the United States rose from $1.11 in January of 1995 to $2.77 as of April 2018 [19]. During the same span of time, the mean cost per kWh for electricity increased from .0785 cents to .1289 cents.

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As depicted in Figure 2, retail regular gasoline prices rose fairly consistently through 2008 and then experienced a precipitous drop, perhaps due to the economic slowdown [29]. They then rose again until 2014 prior to another major downward adjustment, perhaps due to OPEC ineffectiveness as a cartel as well as the laws of supply and demand [30]. The mean gas price over this time is $2.21 / gallon, while the median is $2.22 / gallon. The standard deviation of $.88 / gallon matches the variability seen in the graph.

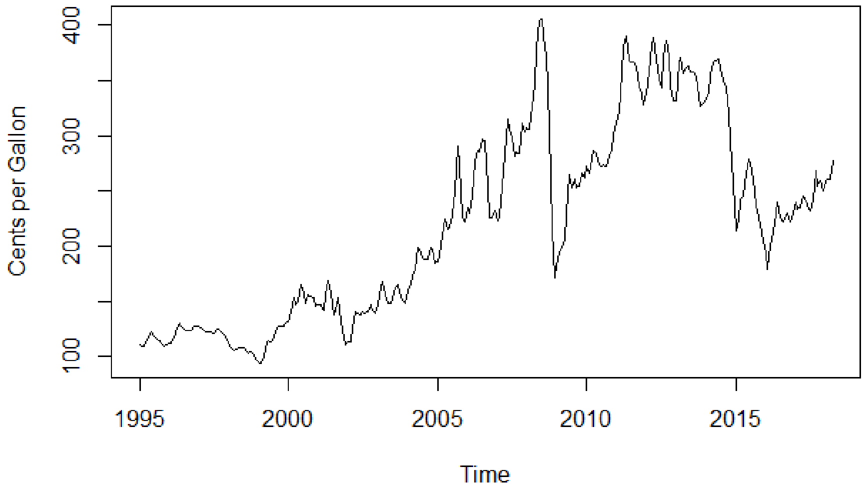

Figure 2. Average retail regular gasoline prices over time illustrate a constant trend with two major corrections (2008 and 2014).

Similarly, cents per kWh has increased. Figure 3 demonstrates the highly seasonal and trend-driven nature of kWh consumption and the steady trend using an additive decomposition diagram. The upper portion of the graph is the observed data, while the trend, seasonal, and error components are (in order) the other graph components. The mean, median, and standard deviation of the cents per kWh are 10.28 cents, 10.17 cents, and 1.8 cents respectively.

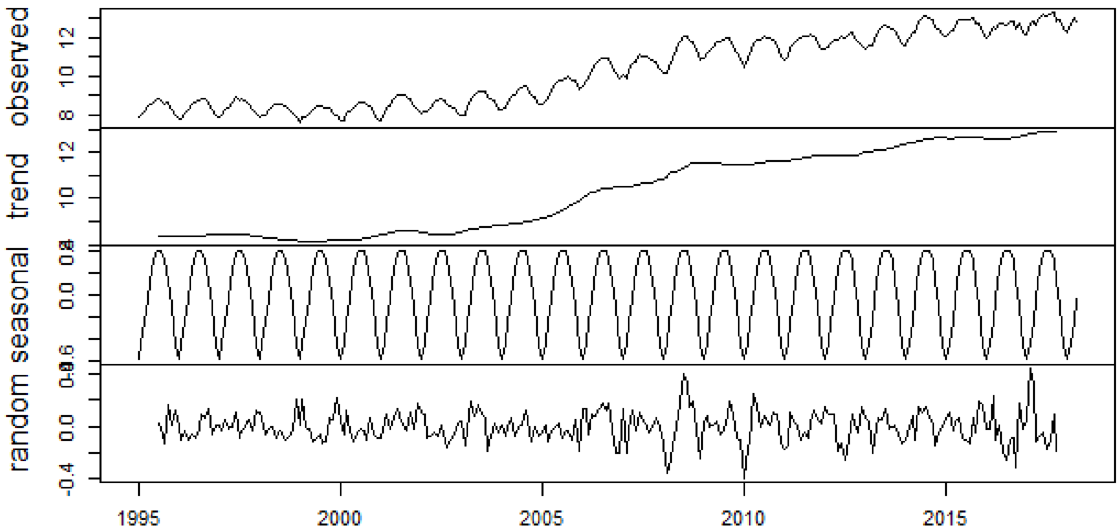

Figure 3. The additive decomposition of cents / kWh illustrates the significant seasonality and trend components of the time series.

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Spearman's correlation between the cost per gallon (cents) and the cents / kWh is positive and strong (ρ=.787, p<.001). Fitting a linear model suggest that the price per kWh increases at 81% of the rate that price per retail conventional gasoline increases.

Forecasts

While the *Annual Energy Outlook* from the Energy Information Administration provides forecasts for gasoline and electrical consumption, the data are provided annually for dollars per one million British Thermal Units ($/MBtu) through 2050, which ignores the seasonality and is less useful for consumers [31]. Figure 4 is a graph for 2018-2026 from the *Annual Energy Outlook.*

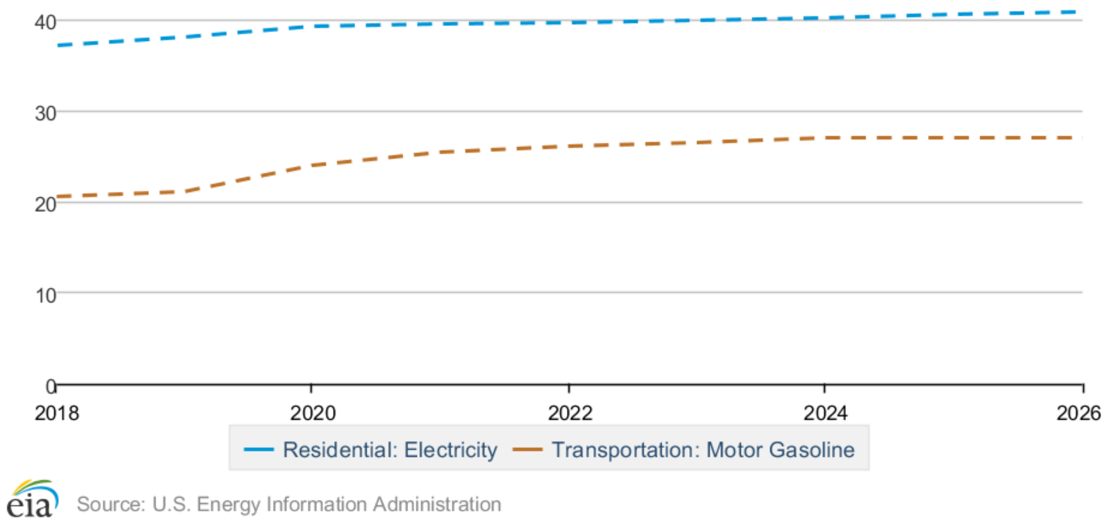

Figure 4. Energy price forecasts from the U.S. Energy Information Administration in $/MMBtu

To facilitate decision-making over the life-span of a vehicle, an 8-year horizon for gasoline and kWh costs was estimated using error / trend seasonality (ETS) and auto-regressive integrated moving average (ARIMA) models. The best performing models for both kWh and gasoline prices based on the mean absolute scaled error, MASE, (a ratio of the model's mean absolute error divide by the mean absolute error of a seasonal naïve model) were used for forecasting. The MASE provides a comparative metric of forecasting performance by leveraging a model's performance versus a seasonal naïve model. Values of MASE less than 1 indicate model performance better than the seasonal naïve [32].

The "ets" and "auto.arima" functions [33] in R [34] were used on both the price per kWh and the price per gallon of gas. For both variables, ETS models proved to have the best accuracy based on MASE scores when predicting a 20% validation set. When using the entirety of the data, the model selected for price per kWH was a Holt-Winter's ETS (smoothed error, trend, and seasonality components) with multiplicative error, additive trend, and additive seasonality components. The resulting MASE was .36, indicating a far superior performance to the seasonal naïve model. The model selected for the price per gallon of gasoline was another Holt-Winter's ETS with multiplicative error, additive trend, and multiplicative error. The MASE was .23, far superior to a seasonal naïve model. Table 3 depicts the metrics for both variables and the optimized ETS and ARIMA models.

Table 3. The accuracy metrics for the forecast models are shown below. ME is the mean error (a measure of bias), RMSE is the root mean squared error (a measure of variability), MAE is the mean

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absolute error (a measure of variability), MPE is the mean percent error (a measure of bias), MAPE is the mean absolute percent error (a measure of variability), and MASE is the mean absolute scaled error (a comparative measure of performance versus the seasonal naïve with lower values meaning better performance.

	ME	RMSE	MAE	MPE	MAPE	MASE
ETS Gasoline	0.450	13.096	8.538	0.082	3.835	0.235
ARIMA Gasoline	0.666	12.689	8.802	0.220	3.881	0.242
ETS kWh	0.004	0.133	0.102	0.043	0.990	0.355
ARIMA kWH	0.003	0.134	0.103	0.043	0.995	0.358

Forecasts using these models were generated for eight-years, which is quite a long forecast generating large error bands. Figure 5 illustrates both forecasts. Each of the 8 year x 12 month = 96 forecasts for each variable are used to feed the simulation model.

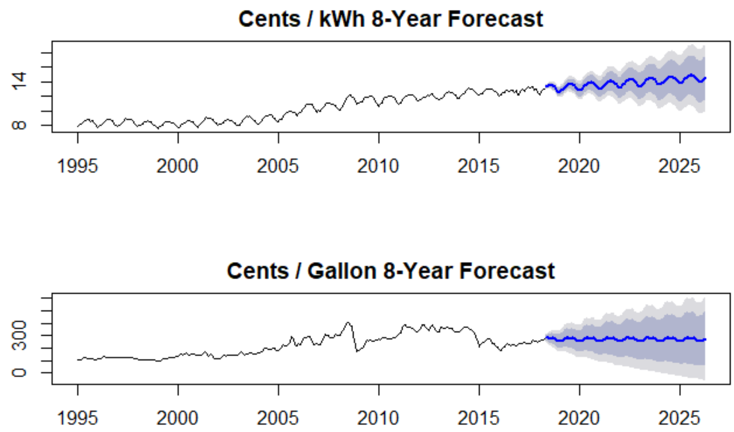

Figure 5. Forecasts for cents / kWh and cents / gallon of gasoline for the best ETS models are shown. The large forecast period results in error bands being wide.

Daily Driving Distribution

Daily driving distance should logically be restricted within certain bounds based on an analysis of driving characteristics of US drivers. The US Department of Transportation statistics suggest that 37 miles per day per driver is likely a good center estimate (US Department of Transportation, 2018 #42). This value is largely confirmed by the 2016 American Survey of Drivers conducted by the Automobile Association of America [35]. The distribution is therefore skewed. To account for large variations and probable right skew (the distribution is truncated at zero), daily driving distance is modeled as an exponential distribution with λ=37.

Simulation Iterations

The number of simulation runs was set to 25. This number of runs resulted in maximum standard errors of less than one cent for both the electric car and hybrid car analyses. For electric cars, the associated standard errors for 25 runs were {.60, .45, .36} cents for {3, 4, 5} mpkWh runs. For hybrid cars, the standard errors for 25 runs were {.93, .74, .62} cents for {40, 50, 60} mpg runs.

Verification and Validation

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All parameters were recorded in a .csv file and checked for appropriateness. Descriptive statistics helped to ensure that values were appropriate. The simulation produced an average daily driving distance of 36.3 miles, which is to be expected given that the mean of the a priori exponential distribution was 37. Other components of the simulation were based on DOE parameters or forecasts, which are fixed.

To be valid for comparison, we needed to ensure that the random streams were identical across experimental conditions for the stochastic distribution of miles driven. To do so, we used a Mersenne-Twister and a common pseudo-random distance for each 8-year, 365-day run. Only one set of random exponentials was produced for all 8 years and 365 days runs to ensure that changes in DOE factors would use the identical pseudo-random stream.

Simulation Results

Rolling up the results of the simulation for each of the DOE parameters by day of the year reveals that, in general, high-performing hybrid cars (those near 60 mpg) have a mean variable fuel cost only slightly higher to that of low-performing electric cars ($1.64 per day versus $1.58 per day.) Over 8 years, one would expect (on average) total fuel variable costs to be {$4.63K, $3.47K, $2.78K, $7.18K, $5.74K, $4.79K) for {3 mpkWh, 4 mpkWh, 5 mpkWh, 40 mpg, 50 mpg, 60 mpg} respectively. Table 4 compares the daily cost by DOE parameters.

Table 4. Results of the simulation

n=365 days	*Mean for 3 mpkWh*	*Mean for 4 mpkWh*	*Mean for 5 mpkWh*	*Mean for 40 mpg*	*Mean for 50 mpg*	*Mean for 60 mpg*
Mean	$ 1.58	$ 1.19	$ 0.95	$ 2.46	$ 1.97	$ 1.64
Std. Error	$ 0.03	$ 0.02	$ 0.02	$ 0.05	$ 0.04	$ 0.03
Median	$ 1.46	$ 1.10	$ 0.88	$ 2.29	$ 1.83	$ 1.53
Std. Dev.	$ 0.58	$ 0.44	$ 0.35	$ 0.91	$ 0.72	$ 0.60
Range	$ 2.91	$ 2.18	$ 1.75	$ 4.45	$ 3.56	$ 2.97
Minimum	$ 0.44	$ 0.33	$ 0.26	$ 0.68	$ 0.54	$ 0.45
Maximum	$ 3.35	$ 2.51	$ 2.01	$ 5.13	$ 4.10	$ 3.42

The average cpkWh was 13.09 cents with a maximum of 13.46 cents, and the average cost per gallon of regular gasoline was $2.70 with a maximum of $2.82. Running time series across the average of all DOE parameters reveals that hybrid car variable costs, on average, are significantly larger than those of electric cars due to gasoline prices. Figure 6 illustrates this difference.

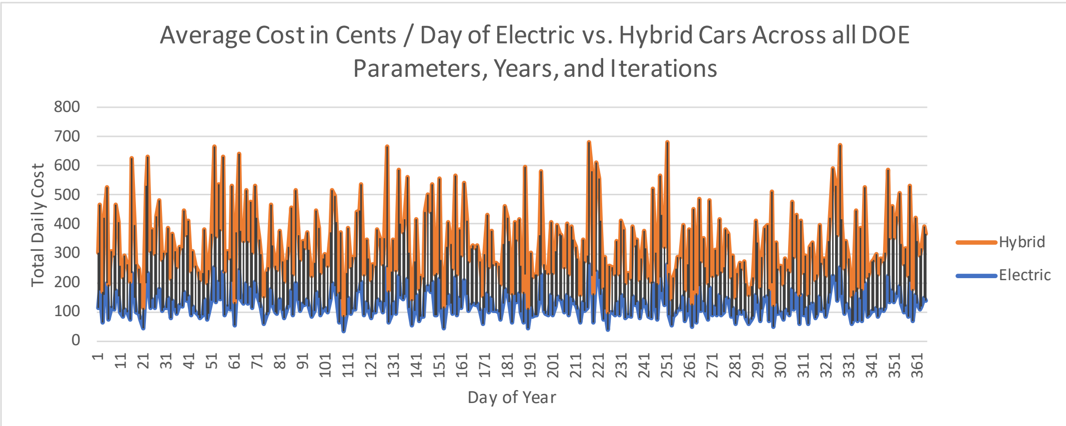

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Figure 6. Time series for electric vs. hybrid car costs averaged over all DOE parameters reveal that BEV variable costs are generally lower than PHEV costs. The black vertical lines represent the distance between the two cost structures.

A Friedman's test for data averaged by day across the six DOE parameters revealed statistically significant differences (H=1825, p<.001). Wilcoxon Signed Rank tests (paired on the day) are all statistically significant as well (p<.001 in all cases), indicating statistical differences among all combinations of parameters. The small effect size between hybrids at 60 mpg and electric cars at 3mpkWh may be practically irrelevant, particularly when considering acquisition costs.

Table 5 provides a detailed breakdown of the eight-year total costs of ownership per possible vehicle evaluated in this study. Fuel cost estimates were interpolated when falling between DOE parameters. The top six vehicles in terms of ownership costs include three hybrids and three electric vehicles, all within $800 of each other. To place this in context, a $100 error in the insurance estimate (which is based solely on initial price) would affect the order of these vehicles. The top 10 vehicles are within $3,014 of each other, which is not a large deviation in terms of and 8-year ownership life.

Table 5. Vehicle total costs of ownership (8-year lifespan) from least expensive to most expensive

Make	Model	Type	MSRP Base	Fuel $	Tax Credits	Maintenance	Insurance	Residual	Ownership Costs
Hyundai	Ioniq Electric	Electric	$ 29,500	$ 3,173	$ (7,500)	$ 3,781	$ 11,800	$ (5,605)	$ 35,148.90
Toyota	Prius c	Hybrid	$ 20,630	$ 5,859	$ -	$ 6,482	$ 8,252	$ (5,983)	$ 35,240.49
Ford	Focus Electric	Electric	$ 29,120	$ 4,073	$ (7,500)	$ 3,781	$ 11,648	$ (5,533)	$ 35,589.25
Hundai	Ioniq	Hybrid	$ 22,000	$ 4,866	$ -	$ 6,482	$ 8,800	$ (6,380)	$ 35,768.77
Hyundai	Ioniq Blue	Hybrid	$ 22,200	$ 4,819	$ -	$ 6,482	$ 8,880	$ (6,438)	$ 35,942.90
Nissan	Leaf	Electric	$ 29,990	$ 3,969	$ (7,500)	$ 3,781	$ 11,996	$ (5,698)	$ 36,537.82
VW	e-Golf	Electric	$ 30,495	$ 4,061	$ (7,500)	$ 3,781	$ 12,198	$ (5,794)	$ 37,241.43
Toyota	Prius	Hybrid	$ 23,475	$ 4,914	$ -	$ 6,482	$ 9,390	$ (6,808)	$ 37,453.88
Kia	Niro FE	Hybrid	$ 23,340	$ 5,744	$ -	$ 6,482	$ 9,336	$ (6,769)	$ 38,133.71
Kia	Niro	Hybrid	$ 23,340	$ 5,773	$ -	$ 6,482	$ 9,336	$ (6,769)	$ 38,162.43
Kia	Soul EV	Electric	$ 32,250	$ 3,818	$ (7,500)	$ 3,781	$ 12,900	$ (6,128)	$ 39,122.01
Toyoto	Prius Eco	Hybrid	$ 25,165	$ 4,850	$ -	$ 6,482	$ 10,066	$ (7,298)	$ 39,265.96
Fiat	500e	Electric	$ 32,995	$ 3,899	$ (7,500)	$ 3,781	$ 13,198	$ (6,269)	$ 40,104.45
Honda	Accord Hybrid	Hybrid	$ 25,100	$ 5,830	$ -	$ 6,482	$ 10,040	$ (7,279)	$ 40,173.47
Tesla	Model 3	Electric	$ 35,000	$ 3,506	$ (7,500)	$ 3,781	$ 14,000	$ (6,650)	$ 42,137.12
Toyota	Camry Hybrid LE	Hybrid	$ 27,950	$ 4,914	$ -	$ 6,482	$ 11,180	$ (8,106)	$ 42,421.13
Chevrolet	Malibu Hybrid	Hybrid	$ 27,920	$ 5,859	$ -	$ 6,482	$ 11,168	$ (8,097)	$ 43,332.39
Chevrolet	Bolt EV	Electric	$ 36,620	$ 3,506	$ (7,500)	$ 3,781	$ 14,648	$ (6,958)	$ 44,097.32
Honda	Clarity Electric	Electric	$ 33,400	$ 4,061	Lease Only	$ 3,781	$ 13,360	$ (6,346)	$ 48,256.48
Toyota	Camry Hybrid LXE	Hybrid	$ 32,400	$ 5,859	$ -	$ 6,482	$ 12,960	$ (9,396)	$ 48,305.19
BMW	i3	Electric	$ 44,450	$ 4,107	$ (7,500)	$ 3,781	$ 17,780	$ (8,446)	$ 54,173.26
Tesla	Model X 75	Electric	$ 70,532	$ 4,443	$ (7,500)	$ 3,781	$ 28,213	$ (13,401)	$ 86,068.01
Tesla	Model S 75D	Electric	$ 74,500	$ 3,853	$ (7,500)	$ 3,781	$ 29,800	$ (14,155)	$ 90,279.22
Tesla	Model S 100D	Electric	$ 94,000	$ 4,038	$ (7,500)	$ 3,781	$ 37,600	$ (17,860)	$ 114,059.34
Tesla	Model X 100D	Electric	$ 96,000	$ 4,859	$ (7,500)	$ 3,781	$ 38,400	$ (18,240)	$ 117,300.81
Tesla	Model S P100D	Electric	$ 135,000	$ 4,200	$ (7,500)	$ 3,781	$ 54,000	$ (25,650)	$ 163,831.32
Tesla	Model X P100D	Electric	$ 140,000	$ 5,137	$ (7,500)	$ 3,781	$ 56,000	$ (26,600)	$ 170,818.49

It is important to note that if insurance based on car value is removed from this equation, then the top five vehicles are indeed electric (see Table 6). Looking at the top 14 with insurance estimates removes shows that 7 are hybrids and 7 are electric cars, all within $5,851 of each other. Over 8 years, that is $731 per year.

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Table 6. Ownership costs excluding insurance based on vehicle value

Make	Model	Type	MSRP Base	Fuel $	Tax Credits	Maintenance	Residual	Ownership Costs
Hyundai	Ioniq Electric	Electric	$ 29,500	$ 3,173	$ (7,500)	$ 3,781	$ (5,605)	$ 23,348.90
Ford	Focus Electric	Electric	$ 29,120	$ 4,073	$ (7,500)	$ 3,781	$ (5,533)	$ 23,941.25
Nissan	Leaf	Electric	$ 29,990	$ 3,969	$ (7,500)	$ 3,781	$ (5,698)	$ 24,541.82
VW	e-Golf	Electric	$ 30,495	$ 4,061	$ (7,500)	$ 3,781	$ (5,794)	$ 25,043.43
Kia	Soul EV	Electric	$ 32,250	$ 3,818	$ (7,500)	$ 3,781	$ (6,128)	$ 26,222.01
Fiat	500e	Electric	$ 32,995	$ 3,899	$ (7,500)	$ 3,781	$ (6,269)	$ 26,906.45
Hundai	Ioniq	Hybrid	$ 22,000	$ 4,866	$ -	$ 6,482	$ (6,380)	$ 26,968.77
Toyota	Prius c	Hybrid	$ 20,630	$ 5,859	$ -	$ 6,482	$ (5,983)	$ 26,988.49
Hyundai	Ioniq Blue	Hybrid	$ 22,200	$ 4,819	$ -	$ 6,482	$ (6,438)	$ 27,062.90
Toyota	Prius	Hybrid	$ 23,475	$ 4,914	$ -	$ 6,482	$ (6,808)	$ 28,063.88
Tesla	Model 3	Electric	$ 35,000	$ 3,506	$ (7,500)	$ 3,781	$ (6,650)	$ 28,137.12
Kia	Niro FE	Hybrid	$ 23,340	$ 5,744	$ -	$ 6,482	$ (6,769)	$ 28,797.71
Kia	Niro	Hybrid	$ 23,340	$ 5,773	$ -	$ 6,482	$ (6,769)	$ 28,826.43
Toyoto	Prius Eco	Hybrid	$ 25,165	$ 4,850	$ -	$ 6,482	$ (7,298)	$ 29,199.96
Chevrolet	Bolt EV	Electric	$ 36,620	$ 3,506	$ (7,500)	$ 3,781	$ (6,958)	$ 29,449.32
Honda	Accord Hybrid	Hybrid	$ 25,100	$ 5,830	$ -	$ 6,482	$ (7,279)	$ 30,133.47
Toyota	Camry Hybrid LE	Hybrid	$ 27,950	$ 4,914	$ -	$ 6,482	$ (8,106)	$ 31,241.13
Chevrolet	Malibu Hybrid	Hybrid	$ 27,920	$ 5,859	$ -	$ 6,482	$ (8,097)	$ 32,164.39
Honda	Clarity Electric	Electric	$ 33,400	$ 4,061	Lease Only	$ 3,781	$ (6,346)	$ 34,896.48
Toyota	Camry Hybrid LXE	Hybrid	$ 32,400	$ 5,859	$ -	$ 6,482	$ (9,396)	$ 35,345.19
BMW	i3	Electric	$ 44,450	$ 4,107	$ (7,500)	$ 3,781	$ (8,446)	$ 36,393.26
Tesla	Model X 75	Electric	$ 70,532	$ 4,443	$ (7,500)	$ 3,781	$ (13,401)	$ 57,855.21
Tesla	Model S 75D	Electric	$ 74,500	$ 3,853	$ (7,500)	$ 3,781	$ (14,155)	$ 60,479.22
Tesla	Model S 100D	Electric	$ 94,000	$ 4,038	$ (7,500)	$ 3,781	$ (17,860)	$ 76,459.34
Tesla	Model X 100D	Electric	$ 96,000	$ 4,859	$ (7,500)	$ 3,781	$ (18,240)	$ 78,900.81
Tesla	Model S P100D	Electric	$ 135,000	$ 4,200	$ (7,500)	$ 3,781	$ (25,650)	$ 109,831.32
Tesla	Model X P100D	Electric	$ 140,000	$ 5,137	$ (7,500)	$ 3,781	$ (26,600)	$ 114,818.49

4. Discussion

This study suggests that electric vehicles will outperform hybrid vehicles in terms of variable fuel costs; however, total costs of ownership show that both electric and hybrid vehicles compete successfully with each other. The top six vehicles in terms of lifecycle costs are split between electric and hybrid options when insurance is based on car value. When insurance is excluded, electric vehicles take the first 6 positions; however, hybrids own 7 of the top 14. The ownership costs appear to be smoothly spread between vehicle types.

It is important to note that inflation for conventional gasoline costs should continue to outstrip inflation for electrical production costs based on time series forecasts, so hybrid mpg increases beyond 60 are likely required to keep hybrids competitive in terms of variable fuel costs. Further, this study made no attempt to assess the ecological impact of electric and hybrid cars or the possibility of using electric cars to support local loads when idle. These are areas for additional research.

This study may be the first of its type to apply energy cost forecasting coupled with simulation across multiple DOE factors. The results run contrary to previous studies that suggest either hybrid or electric cars are better in terms of owner costs. Given the estimates and distributions of the study, both electric and hybrid vehicles compete successfully in terms of total cost of ownership.

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