Well-to-wheels efficiency analysis for plug-in hybrid electricvehicles

*Abstract*—Global warming and its impacts on the environment has become one of the topics gaining a lot of attention in past few decades. As a result, different countries across the world began undertaking key measures to reduce the emission of greenhouse gases and committing to the goal of keeping the global temperature rise below 1.5 degrees Celsius from pre-industrial levels. Transportation is one of the key contributors to global warming owing to the significant use of fossil fuels. As a result, automotive sector has been under thorough scrutiny and has been facing increased pressure to cut down on greenhouse gas emissions. Following this demand to reduce carbon emissions, the automotive sector has seen a rise in more efficient cars being developed. This effort included the development of hybrid vehicles as well as electric vehicles that use battery power exclusively. Although electric vehicles have gained a lot of popularity over the last few years, there is still a significant share of market which is owned by hybrid vehicles. And owing to the recent plateau in the growth of EV sales, we can expect very slight chances of decrease in the sales of hybrid vehicles anytime in the next few years. Thus, it makes sense to explore different avenues to make hybrid cars more environmentally friendly. Understanding the operational energy consumption and efficiency is always the first step in making critical decisions on how to improve the efficiency and make transportation more environmentally friendly. However, when looking at the environmental impact, it is also important to consider all the processes including the manufacturing of vehicle, sourcing of fuel and end of lifecycle processes along with the operational efficiency of the vehicle. This methodology of including all energy sources in the life cycle of the vehicle leads to the computation of a term known as well-to-wheels efficiency.

This study focuses on comprehensive estimation of different energy consuming processes that form a part of the lifecycle of a typical plug-in hybrid vehicle and finally computes the resulting well-to-wheels efficiency. Furthermore, an analysis of the computed well-to-wheels efficiency is made for different operating conditions of plug-in hybrids based on the data gathered from real time usage patterns.

Keywords—Hybrid electric vehicles (HEVs), Plug in Hybrid electric vehicles (PHEVs), efficiency, well-to-wheels efficiency (WTW), global warming, sustainable transport.

# Introduction

On a mission to keep global warming levels under 1.5°C [1], several industrial sectors have started cutting down on their greenhouse gas emissions. Automotive sector being one of the major contributors of greenhouse gases (around 19.2% [2]) is no exception to these efforts. Even a small improvement in the efficiency of one vehicle SKU by one OEM, goes a long way to reduce the overall greenhouse gas emissions from this sector. Owing to these challenges, a number of new vehicle architectures have been developed to reduce greenhouse gas emissions. The list of innovations goes from hybrid vehicles, electric vehicles (EVs), hydrogen powered vehicles all the way to advanced transportation concepts like electric vertical takeoff and landing aircrafts (eVTOLs [3], [4] & [5]) and nuclear powered transport (especially for water based transportation).

Among all these innovations, the development of hybrid electric vehicles and electric vehicles has been one of the most predominant event in automotive sector over the last two decades. The development of hybrid vehicles started in the 90s with several OEMs developing their own architecture of hybrid vehicles (for e.g. series hybrids, parallel hybrids etc.). A significant number of hybrid SKUs still form a large part of automobiles sold even today. Electric vehicles on the other hand have been gaining a lot of attention in the past decade. Several key OEMs like Toyota, Honda, Hyundai and Kia Motors have a more than a few SKUs of pure electric vehicles. Besides these OEMs, a few automotive OEMs like Tesla and Rivian exclusively sell electric vehicles. Although electric vehicles are the future, there are a few issues that plague the wide adoption of electric vehicles in the market today. Electric vehicles are limited in terms of range and availability of electric charging stations is not adequate for large scale adoptions of electric vehicles. From the sales figures in the past few years, it can be inferred that growth curve of EVs is reaching a plateau. Thus, several automotive companies have already backtracked to also focus on development other vehicle product lines (especially hybrids). Thus, we can expect a robust growth in sales of hybrids over the next decade, at least until something changes in the electric vehicle scene.

In the mid-2000s, the development of electric propulsion architectures for hybrid vehicles made it possible to conceptualize cars that have a slightly bigger battery which can be charged via a wall outlet to achieve a useable electric only propulsion range. Thus, the idea of plug-in hybrid vehicles was born. Since their inception, plug in hybrids have also become popular along with the regular hybrids. Although their sales numbers did not reach the level of regular hybrids, they did present an opportunity of experiencing a purely EV range that gave customers an idea of driving experience of an electric vehicle.

There are many advantages to owning a plug-in hybrid over regular hybrids or electric vehicles. The usual miles per gallon estimate for plug in hybrid includes two numbers, namely MPGe for electric only driving and MPG for gas powered (but still a hybrid energy flow) driving. MPGe here refers to miles per gallon equivalent. MPGe compares the energy in a gallon of gas to the energy in a specific amount of electricity. For example, if an electric vehicle can travel 100 miles on 33.7 kilowatt hours of electricity, it has an MPGe of 100. In terms of MPGe, plug in hybrids usually have a rating of ~110eMPG [6]. On the other hand, when the battery is completely drained, plug in hybrids switch to charge sustain/hold mode where the operations emulate a regular hybrid vehicle. In this mode, the effective mileage of plug-in hybrids is about 40-45 MPG [7].

A typical usage pattern for plug in hybrids entails about 60% of driving on electric range only while the remaining is driven on gas power [8]. This means that for about 60% of the time, plug in hybrids behave like an EV and the remaining amount of driving is similar to a regular hybrid. Since plug in hybrids exhibit a higher MPG while driving in EV mode it is easy to infer that plug in hybrids are more efficient that regular hybrids.

On comparing directly with pure EVs, which drive on battery power 100% of the time, plug in hybrids fall short of EVs in terms of overall MPG. However, one of the main disadvantages of EVs which is the range anxiety is completely eliminated in a plug-in hybrid. A plug-in hybrid owner is offered with the option to use gas power for long range drives, which is not an option for EVs. Thus, driving long range on EVs is not preferred or requires meticulous planning [9]. This is however a short-term advantage that plug in hybrids possess until there are adequate number of charging stations to support EVs.

Although the MPG numbers matter in terms of estimating the energy consumption of all kinds of vehicles, it does not paint a comprehensive picture of the overall energy consumption required and energy losses endured to generate a certain energy output from the vehicle. well-to-wheels efficiency is a novel efficiency metric that captures the energy flow across different energy consuming process that occur over the entire lifecycle. It encompasses the entire lifecycle of fuel production, distribution, and vehicle operation, providing a holistic view of energy consumption and emissions [10]. In this study, a detailed computation of well-to-wheels efficiency of plug-in hybrids is presented along with an analysis of variation of well-to-wheels efficiency of plug-in hybrids with respect to the change in utilization pattern. Finally, the well-to-wheels efficiency for a typical usage pattern is estimated and compared with the equivalent well-to-wheels efficiency of regular hybrids.

# Prior literature

There is a plethora of research work on the topic of efficiency of automotive vehicles. This is a consequence of a lot of interest in understanding and attempting to reduce the global warming contributions due to automotive sector. Although, most of the body of literature focuses only on the efficiency of vehicle level energy conversion. This efficiency metric only considers the energy conversion between the calorific value of the fuel or the total electric energy of the battery to the energy being generated as useful work (propulsion at the wheels). On the other hand, the amount of literature related to well-to-wheels efficiency is minimal. However, a few studies related to well-to-wheels analysis are detailed below.

Chinthoju et. al. [11], demonstrate detailed computation of well-to-wheels efficiency of mild hybrid electric vehicles. The study that is about to be presented in few next sections also takes a similar approach to the approach followed in this article. This article details all the individual stages of energy consumption, transmission and conversion process that make up the lifecycle of a hybrid electric vehicle. Although the approach that will be presented in this study will be different to the one used in this article in terms of the individual stages that make up the lifecycle of plug-in hybrid. This is owing to the fact that plug in hybrids is more akin to electric vehicles rather than mild hybrids because the utilization trends of plug-in hybrids is biased towards using it as an EV most of the time.

Raykin et al. [12] demonstrates the implications of driving patterns on well-to-wheels efficiency of plug-in hybrid electric vehicles. This article argues for the use of plug-in hybrids as a means of short distance commutes while always recharging between commutes. This approach is the most ideal usage of plug-in hybrids but using it exclusively in this pattern should also be avoided. The main objective of plug-in hybrid is to fill the void between electric vehicles and conventional gas-powered cars, providing the best of both worlds in a sense. Thus, plug in hybrids should also be used for long range drives as that is the sole advantage of plug-in hybrids over electric vehicles.

Katrašnik et al. [13] demonstrate the detailed energy conversion phenomenon in plug in hybrid vehicles. This article includes a detailed model development for propulsion systems used in plug in hybrid vehicles. This analysis shows that energy conversion efficiencies significantly influence the optimal operating mode of plug-in hybrids. This is expected as internal combustion engines and electric motors have different operating rpm vs efficiency curves. In a regular hybrid, the main objective is to ensure that the engine runs at the highest efficiency most of the time. On the other hand, the key role of the internal combustion engine is to provide additional range when required. Thus, the engines are usually smaller than the equivalent mild hybrids. The internal combustion engine in a plug-in hybrid also is designed to run in the most efficient manner but the presence of additional battery capacity in plug in hybrids eases the requirement of engines to be bigger (thereby being less efficient) to generate short bursts of high power for acceleration in urban driving.

Elgowainy et. al.[14] focuses on the computation of well-to-wheels efficiency of plug-in hybrids. The main contribution of this article is that it argues for driving plug in hybrid vehicles on electric range majority of the time and charging it during the off-peak hours of energy demand on the grid. This helps with reducing the variability of load on the electrical grid while also reducing the overall cost of the electricity being used for charging during these off-peak hours.

He et al. [15], demonstrate a design of hybrid ethanol electric vehicle propulsion system. This is similar to plug in hybrid electric vehicle but instead of regular gasoline fuel powering the internal combustion engine, it is replaced with ethanol as the fuel. Over the past few years, gasoline that is made available to consumers was replaced from being pure gasoline to a mixture of gasoline and ethanol (typically less than 10%). Using ethanol is beneficial because its easier to produce and can be sustainable (albeit being also contributing to global warming) as it can produced as a biproduct of processing agricultural produce. This effectively makes it a cheaper alternative to gasoline but with a comparable calorific content. This article details out that E25-fuelled PHEVs reduce energy consumption by 5.9% and GHG emissions by 12.3%.

# Methodology

 The prior literature on the topic of well-to-wheels efficiency is diverse and inconsistent on different approaches taken to compute well-to-wheels efficiency. When referring these different approaches, the only consideration that works in the favor of a better approach is the level of comprehensiveness of that approach. Although there are many points of contention like whether to include maintenance and end of life energy consumption in the computation of well-to-wheels efficiency, this study takes the more comprehensive approach of including all energy consumption stages. This also proves useful in understanding the overall impact on environment with the use of a particular product as sometimes unobvious energy consuming stages can make or break the eco-friendly aspect of that product. For example, although solar panels are considered to be eco friendly as they tap renewable energy using photovoltaic cells, the ecological cost of manufacturing solar panels can be very high as compared to other energy production methods [16]. There are many studies following [16] which confirm that solar panels are still beneficial to use in the long run [17], however the fact that solar panels require a lot of energy is something that might not have been discovered if a comprehensive lifecycle analysis (like well-to-wheels efficiency in case of automotive vehicles) is computed.

Specifically for a plug-in hybrid, there are a lot of stages of energy consumption given the flexibility to consume different energy sources for propulsion (namely electricity and gasoline). To simplify the estimations for all these stages of energy consumption, various stages are grouped together based on which stages are common among both fuel sources and which are not common for both but fall in the bucket for being relevant with respect to one specific fuel source. Therefore, the classification for different energy consumption stages is as follows.

1. Energy consumed common to both fuel sources.
2. Energy consumption specific to using gasoline as fuel.
3. Energy consumption specific to using electricity as fuel.

Each of these categories has multiple stages of energy consumption processes and the aim is to combine the efficiency of all these stages into one quantity per category. This will simplify the final computation of energy consumption and efficiency while it still leaves behind the flexibility to run different scenarios to determine the efficiency of plug-in hybrids for different usage patterns.

### Energy consumed common to both fuel sources:

This category includes processes that form a part of the vehicle life cycle that are required to be conducted irrespective of the fuel source being used. The various stages that form a part of this are manufacturing of vehicle, maintenance of vehicle and end of life processes.

To analyze the energy consumption involved with the manufacturing of the vehicle, lets consider the manufacturing process of a mid-size sedan plug in hybrid. In the world of hybrids and plug in hybrid manufacturing OEMs, different OEMs implement different hybrid architectures. However, the details of the specific hybrid architecture implementation used in this study are not important as all the OEMs promise a similar hybrid efficiency and the cost to manufacture each of these vehicle architectures is more or less similar owing to the fact that all these different vehicle SKUs have a similar pricing [18]. A typical hybrid architecture typically involves two motors along with a medium sized battery and an internal combustion engine. Again, although most hybrid architectures are different, the following energy flow can be assumed for a typical plug-in hybrid. Effectively, the internal combustion engine drives the wheels when the host is moving at high speeds (making use of the fact that engines have their best efficiency at high RPMs). At low speeds, the engine continues to run at high RPM while charging the battery which in turn powers the wheels. This makes use of the fact that engines have low efficiency at low RPMs while electric motors have constant high efficiency throughout the entire range of RPMs. This also means that in a plug-in hybrid, preference would always be given to utilize the battery power at low speeds and high speeds, when the battery has some useable charge.

Manufacturing of plug-in hybrid vehicles involves different processes such as material transformation, machining, assembly, and testing, painting etc. All these processes consume different forms and different amounts of energy. For example, metal forming can involve furnaces that operate on coal power while machining typical runs of electric power. An estimate of energy consumption in MJ for all these different processes is as shown in Table 1.

Table 1: Energy consumption and CO2 emissions for different processes that form a part of vehicle manufacturing [19]

|  |  |  |
| --- | --- | --- |
| Manufacturing Process | Energy (MJ) | CO2 (kg) |
| Material transformation | 19,340 | 1,065 |
| Machining | 982 | 56 |
| Vehicle Painting | 4,167 | 268 |
| HVAC & lighting | 3,335 | 225 |
| Heating | 3,110 | 195 |
| Material handling | 690 | 46 |
| Welding | 920 | 62 |
| Compressed air | 1,380 | 93 |
|  |  |  |
| Total | 33,924 | 2,013 |

The above table refers to all the processes involved in the manufacture of an internal combustion vehicle. However, a few necessary additions will be needed to account for all the processes that make up the manufacturing of a plug-in hybrid electric vehicle. These include energy consumed in the manufacture of a plug-in hybrid battery (around 16kWh capacity [20]) and cost of manufacturing two motors. While the manufacture of additional motors has very minimal energy cost requirement, the energy consumed to manufacture the battery required for plug in hybrids is quite significant. The energy cost of manufacturing these components comes out to 7,452 MJ as per Burnham et al. [21]. This adds up to a total energy consumption figure of 44,218MJ.

Maintenance is another key contributor to the overall energy consumed in the life cycle of a plug-in hybrid vehicle. This stems from the fact that typically plug in hybrids will need their battery to be replaced before reaching 200,000 miles on the odometer (ideally one replacement every 150,000 miles [23]). However, other components of maintenance are like maintenance of hybrid electric vehicles. Just like mild hybrids, plug in hybrids also need regular oil changes and regular air filter replacements. Typical oil changes are needed every 300 miles [22]. Assuming a lifetime mileage of 200,000 miles, 67 oil changes would need to be performed. A similar analysis for this energy consumption figure is performed in [11] and the conclusion is that 67 oil changes will need 5,737MJ of energy.

The energy usage for manufacturing lithium-ion battery cells varies, but recent estimates suggest that it ranges from 50 to 65 kWh of electricity per kWh of battery capacity. This implies that for a 16-kWh battery pack, approximately 640kWh (or 2304MJ) of energy is required for the manufacturing process. This brings the total cost of maintenance to 7,755MJ. Combining the maintenance and manufacturing energy cost, we get

$$\begin{array}{c}E\_{fixed}= 7,755MJ+44,218MJ=51,973MJ\#\left(1\right)\end{array}$$

### Energy consumption specific to using gasoline as fuel

The approach taken in this study to compute the recurring energy expenditure is to separate the number of miles powered by gasoline as fuel and number of miles powered by electric propulsion and compute the energy consumed in both the pathways.

The energy consumption specific to using gasoline as fuel involves the following stages.

1. Mining of the fuel
2. Transportation of the raw fuel
3. Refining of crude oil
4. Distribution of the refined fuel
5. Fuel conversion to power the vehicle.

It is estimated that mining one gallon of crude oil consumes 3.4% of calorific value of the crude oil [25], [26]. Considering that a typical lifecycle mileage of 200,00 miles for a plug in hybrid and assuming that the ratio of number of miles driven on gasoline power to the number of miles driven on electric power is $x :1$, the following computation gives us the total energy consumption for the mining of fuel consumed during the lifecycle of a plug in hybrid.

$$\begin{array}{c}G=\frac{200,000x}{mpg (x+1)}\#\left(2\right)\end{array}$$

Where G is the total number of gallons consumed in the entire lifecycle of the plug-in hybrid and $mpg$ is the average MPG of the plug-in hybrid (which is about 40miles/gallon). Furthermore,

$$E\_{mining}=G×Cal\_{gasoline}×\frac{3.4}{100}$$

$$=\frac{200,000x}{40\_{mpg} (x+1)} × 38.6\_{\frac{MJ}{gal}}×\frac{3.4}{100}$$

$$\begin{array}{c}E\_{mining}=\left(193,000×\frac{3.4}{100}\left(\frac{x}{x+1}\right) \right) MJ\#\left(3\right)\end{array}$$

Where $E\_{mining}$ is the total energy cost of mining G gallons of fuel.

高有山, et al. [27], computes the typical cost of transporting crude oil (assuming a 1:1 mix of domestic and international imports) as 0.345MJ/gallon. This is approximately 0.9% of the calorific value of gasoline. Thus using a similar computation as above leads us to the following total energy consumption for the transportation of raw fuel

$$\begin{array}{c}E\_{transport}=\left(193,000X\frac{0.9}{100}x\right) MJ\#\left(4\right)\end{array}$$

Compared to the mining and transportation (even including distribution of refined fuel), the refining of the raw fuel (crude oil) is very energy intensive. Crude oil refining involves fractional distillation which is evaporation of the raw fuel and cooling down to obtain different petroleum products. The energy required to boil the crude oil takes up most of the energy consumption. Gaines et al. [28], estimates that the refining processes take up about 10% of the calorific value of the raw fuel. Therefore, a similar computation as above gives,

$$\begin{array}{c}E\_{refining}= \left(193,000×\frac{10}{100}\left(\frac{x}{x+1}\right)\right) MJ\#\left(5\right)\end{array}$$

Once the crude oil is refined to obtain gasoline, this refined fuel must be distributed to end consumer. The distribution of refined fuel involves transporting the fuel, through a network of different pipelines and freight by roadways and waterways. The US has approximately 95,000 miles of pipelines that transport refined fuel to around 150,000 filling stations in addition to roadways and waterways [29]. Yet majority of the distribution network is dependent on road-based transport, owing to the requirement to have last mile connectivity. This means that although the distance covered for the transportation of raw fuel from extraction point to the refineries is like the distance travelled by the refined fuel from the refineries to gas stations, the energy consumed in distribution is higher because of this dependency on road transportation. Chinthoju et al. [11] estimates this energy consumed to be about 5% of the calorific value of the fuel. Thus, following similar calculations like before, the energy consumed by the distribution network for the whole lifecycle of the vehicle is given by.

$$\begin{array}{c}E\_{distribution}= \left(193,000×\frac{5}{100}\left(\frac{x}{x+1}\right)\right) MJ\#\left(6\right)\end{array}$$

While plug in hybrids can be run on electric power with vastly better efficiency, they can also have good efficiency of conversion while being operated in hybrid mode (charge hold mode). Like mild hybrid electric vehicles, plug in hybrid electric vehicles can be ran at 40 mpg. Thus, a conversion efficiency of 30% from [11], can also be utilized in the computations here. However, since the input here is the refined fuel with which has exactly 100% of calorific value of the fuel, the energy consumed in this stage can be estimated as 100% of the calorific value of the fuel used in the lifetime.

$$\begin{array}{c}E\_{conversion}= \left(193,000×\frac{100}{100}\left(\frac{x}{x+1}\right)\right) MJ\#\left(7\right)\end{array}$$

The amount of useful work generated on the other hand would be 30% of calorific value of the fuel, which is.

$$\begin{array}{c}W\_{gasoline}= \left(193,000×\frac{30}{100}\left(\frac{x}{x+1}\right)\right) MJ\#\left(8\right)\end{array}$$

Finally, combining all the energy consumption stages in gas as fuel mode, we get a total energy consumption as

$$E\_{gas}=E\_{mining}+ E\_{transport}+E\_{ditribution}+E\_{conversion}$$

$$\begin{array}{c}E\_{gas}=\left(193,000×\frac{119.3}{100}\left(\frac{x}{x+1}\right)\right) MJ\#\left(9\right)\end{array}$$

Figure 1: Energy flow diagram depicting losses for gasoline specific energy consumption stages.

### Energy consumption specific to using electricity as fuel

Plug in hybrid electric vehicles have a minimal electric only range of about 30-40miles on a full charge. Although this seems miniscule compared to the overall range of the car which can be upwards of 300 miles, the amount of time spent driving on electric only mode can be much higher than time spent on driving on charge holding (gasoline powered) mode. This is because of the usage pattern of the plug-in hybrid electric vehicle. These vehicles are meant to be mostly a commute vehicle and thus the daily median distance travelled will be under 30miles (for a short commute). On the other hand, an occasional long trip of 400miles a month would be completely on charge holding mode. Thus, in this specific scenario, in a month the vehicle is run on electric charge for 900 miles and on charge hold mode for 400miles. This comparison obviously depends on each person’s usage patterns but the point to be made here is that the plug-in hybrid is meant to be used primarily for commute.

With regard to energy consumed in sourcing electricity, this number again depends on the specific geographic location of the place where the car is being changed and the energy source composition for that specific region’s electric grid. Today’s electric power is generated from a mix of different energy sources that include renewables such as solar, wind and non-renewable sources such as coal powered and natural gas-powered thermal power plants etc. The below figure shows the percentages of various sources of electricity generation in 2023.

 

Figure 2: Sources of US electricity generation in 2023[31]

In addition to being dependent on the specific geographic location, the mix of electricity sources also depends on the time of the day in which the power is being drawn from the outlet [30].

Although energy generation using renewables is definitely not efficient, in this study, we assume that renewables have no energy lost during production. One of the key differences between renewable and nonrenewable sources is that there is no recurring cost in extracting the fuel or tapping the energy required to produce electricity in renewable sources. For example, solar and wind energies are available worldwide and one does not need to spend an additional recurring cost to tap in the already available energy [32]. Thus, by this logic, there is no wastage or loss in unconverted energy when generating electricity using renewables. Non renewables on the other hand need some energy consumption to extract the fuel needed o generate electricity and in addition, these fuel sources are limited in supply. Thus, it can be safely assumed in this that renewable sources are completely efficient.

 Starting with nuclear power, there are various kinds of nuclear power stations that use different fuel and different kind of reactors. Boiling water reactors have an efficiency of about 32%, pressurized water reactors have an efficiency of 33% and small modular reactors have an efficiency of 33.4% [33]. Thus, on average, the efficiency of power generation using nuclear fuel is 33%.

Coal power plant efficiency varies widely and is again influenced by technology, plant size, and operational practices. While conventional plants achieve around 45% efficiency, advanced technologies and optimizations can push this higher [34].

Natural gas power plants, especially those using combined cycle technology, are among the most efficient fossil fuel-based power generation systems, with efficiencies typically exceeding 60% [35].

The combined efficiency of power generation using all these sources can be computed as the percentage weighted average of various sources of energy generation.

$$η\_{elec gen}= \frac{21.4}{100}×100+\frac{18.6}{100}×33+\frac{16.2}{100}×45+\frac{43.1}{100}×60$$

$$\begin{array}{c}η\_{elec gen}=60.68\%\#\left(10\right)\end{array}$$

In addition to the losses due to inefficiency in electricity generation, the distribution of electricity to end users also has some losses. The U.S. Energy Information Administration (EIA) estimates that annual electricity transmission and distribution (T&D) losses averaged about 5% of the electricity distributed and transmitted in the US between 2018 to 2022 [36]. Thus, the efficiency of the distribution stage is about 95%.

$$\begin{array}{c}η\_{dist}=95\%\#\left(11\right)\end{array}$$

Finally, the efficiency of propulsion using electric power varies between 80-90% [37]. This is significantly higher than the thermal efficiency of conversion of gasoline into propulsion because in the case of electric power, the energy is converted from chemical energy of the batteries into mechanical power. This means that electric propulsion does not have a fundamental limitation such as the maximum limit for a heat engine (Carnot efficiency). Thus, an average estimate of 85% propulsion efficiency is considered for this study.

$$\begin{array}{c}η\_{prop}=85\%\#\left(12\right)\end{array}$$

Thus, the overall efficiency of all the stages involving electric propulsion is given by.

$$η\_{electric}= η\_{elec gen}× η\_{dist}×η\_{prop} $$

$$\begin{array}{c}η\_{electric}=\frac{60.68×95×85}{10000}=49\%\#\left(13\right)\end{array}$$

To convert the above calculations into gallons equivalent, MPGe estimates of plugin hybrids can be used. Typically plug in hybrids have an MPGe rating of about 110 mpg. This means that for driving $\frac{200,000}{x+1}$ miles on electric power alone (based on gasoline to electric driving ratio of $x$:1), the vehicle would have consumed an energy of

$$E\_{electric}= \frac{200,000}{110}×\frac{38.6}{x+1}×\frac{100}{60.68}×\frac{100}{95} MJ$$

$$\begin{array}{c}=\frac{121,746.20}{x+1} MJ \#\left(14\right)\end{array}$$

Total amount of work generated would just be the propulsion efficiency times the energy input to the vehicle.

$$\begin{array}{c}W\_{electric}= \frac{200,000}{110}×\frac{38.6}{x+1}×\frac{85}{100}=\frac{59,654}{x+1} MJ\#\left(15\right)\end{array}$$

# Results

Using the results from the previous section, an estimate for the overall well-to-wheels efficiency of plug-in hybrid electric vehicles can be computed. To compute the well-to-wheels efficiency using all the metrics computed earlier, we can follow the generic formula of ratio of total work done to the total energy consumed.

$$\begin{array}{c}η\_{well-to-wheel}=\frac{W\_{output}}{E\_{consumed}}\#\left(16\right)\end{array} $$

$$=\frac{W\_{electric}+W\_{gasoline}}{E\_{electric}+E\_{gas}+E\_{fixed} }$$

$$=\frac{\frac{59,654}{x+1}+193,000×\frac{30}{100}\left(\frac{x}{x+1}\right)}{\frac{121,746.20}{x+1}+193,000×\frac{119.3}{100}\left(\frac{x}{x+1}\right)+51,973} $$

$$=\frac{\frac{59,654+57,900x}{x+1}}{\frac{121,746.2+230,249x}{x+1}+51,973}$$

$$=\frac{59,654+57,900x}{121,746.2+230,249x+51,973\left(x+1\right)} $$

$$\frac{59,654+57,900x}{121,746.2+230,249x+51,973\left(x+1\right)}$$

$$\begin{array}{c}η\_{well-to-wheel}= \frac{59,654+57,900x}{173,719+282,222x}\#\left(17\right)\end{array}$$

Using the above relation, we can analyze the variation of well-to-wheels efficiency of plug-in hybrid electric vehicles over different gasoline only to electric power only usage ratios ($x)$. Since ratios are difficult to visualize over chart, the ratio is converted to a percent of gasoline miles and the resulting plot is showing below.



Figure 3: well-to-wheels efficiency vs percentage gasoline mileage.

This relationship is approximately linear with 100% gasoline miles resulting in 20.51% of well-to-wheels efficiency and 100% electric miles resulting in 34.11% of well-to-wheels efficiency.

To understand the percentage of utilization on gasoline vs utilization on electric power, a term known as utility factor has been traditionally used in previous literature. The utility factor (UF) represents the ratio of miles traveled in electric mode to the total miles traveled by a plug-in hybrid electric vehicle. The real-world electric utility factor of plug-in hybrid varies a lot between different vehicle models and variants. In [38], Goebel et al. combine several references to estimate a 30% UF for Prius, 45–55% for the Volvo V60 and Mitsubishi Outlander as well as 78% for the Chevrolet Volt/Opel Ampera. One of the key indicators of the electric utility factor is the all-electric range (AER). In [39], Elgowainy et al. estimate that for an AER of 20, 30, 40, and 60 miles, they achieve an electric utility factor of 41%, 53%, 63%, and 75%, respectively. Therefore, the results in [38] are obvious once the AER of each of these vehicle models is considered. The variants launched these days typically come with an AER that is greater than 40 miles and thus assuming an average of 63% AER would be a conservative estimate. This 63% AER would correspond to 57% of gasoline miles which would in turn correspond to 27.58% of well-to-wheels efficiency.

# Conclusion

As mentioned in the abstract, the scope of this study is to perform a detailed analysis of energy consumption at each stage of energy conversion or transport in the life cycle of plug in hybrid electric vehicles and to estimate an average estimate for the overall well-to-wheels efficiency based on typical usage patterns. The detailed estimates of energy consumption yielded a relationship for the overall well-to-wheels efficiency which is approximately linearly varying with percentage of gasoline mileage. A quick glance at the variation in the well-to-wheels efficiency from one extreme of 100% gasoline miles to the other extreme of 100% electric miles shows us that there can be an increase in well-to-wheels efficiency of over 14%, which is significant considering the well-to-wheels efficiency of 100% gasoline miles (proxy for regular hybrid) is 20.51%. Similarly, the estimate for a typical electric utility factor of modern plug-in hybrids shows an improvement of 7.5% which is again a 30% increase over regular hybrids.

In addition to computation of these estimates for well-to-wheels efficiency, key policy or consumer purchasing decisions can also be made considering the relationship between well-to-wheels efficiency and percentage gasoline miles (which is a proxy for AER of different plug-in hybrid variants). For e.g. a consumer could consider that sacrificing 10% of the benefits of pure electric cars is acceptable to get gasoline powered range (to overcome range anxiety) for occasional long range trips and using this assumption and the relationship in [17], that consumer can easily estimate the AER of the plug in hybrid which he/she should opt for.

Future work to this research involves estimating the well-to-wheels efficiency for electric vehicles and arguing a case for the benefits of plug-in hybrids as a compromise over electric vehicles and mild hybrids.

**COMPETING INTERESTS DISCLAIMER:**

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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