Well-to-wheel efficiency analysis for mild hybrid vehicles

Abstract—**Over the last few decades, there has been an increased focus on reducing greenhouse gas emissions among all sectors to keep the global temperature increase below 1.5°C above pre-industrial levels. Automotive sector has been at the fore front of this transition as necessitated by the impact that gas powered vehicles play on overall greenhouse gas emissions. Consequently, the past few decades saw rapid increase in the efficiency of gas-powered vehicles as well as introduction of alternative technologies to power ground transportation such as hybrid electric vehicles and battery powered electric vehicles. Hybrid electric vehicles have been prominent in increasing vehicle efficiency owing to the unique architecture of power generation and transmission. Today, most automotive OEMs have a significant hybrid electric vehicle portfolio along with battery electric vehicles and traditional combustion engine portfolio. Although battery electric vehicles have been gaining in popularity, hybrid electric vehicles have been in the market for more than two decades and there are still a considerable number of vehicles being developed and operated as compared the battery electric vehicles running today. Thus, understanding the chain of energy conversions and transmissions in operating a hybrid electric vehicle is crucial to formulate strategies to improve the overall efficiency and reduce greenhouse gas emissions. Although, efficiency is a universally used term that signifies the energy consumed to energy generated, the scope of application is different. Most generally, efficiency of a vehicle refers to the amount of energy consumed (via the fuel) vs amount of useful energy generated at the wheels. This scope is limiting in that it does not consider the efficiency of the sourcing the fuel. This work presents a detailed quantification of efficiency from sourcing the fuel to the energy delivered at the wheels in the context of a hybrid electric vehicle.**

Keywords—Hybrid electric vehicles (HEVs), efficiency, well-to-wheel efficiency (WTW), global warming, sustainable transport

I. INTRODUCTION

With global warming posing a significant threat to biodiversity of planet, there has been an intensive effort to keep the global temperature increase (as compared to pre-industrial levels) under 1.5°C [1]. This effort is exacerbated in transportation sector owing to the significant contribution (around 19.2%) of greenhouse gases released by transportation sector alone [2]. Even a slight improvement in the reducing the greenhouse gas emissions from the transportation sector will go a long way in our effort to stay within the target of being under 1.5°C of global warming with respect to pre industrial levels.

Within the transportation sector, one of the primary contributors to greenhouse effect is the operation of internal combustion engines. This is because of both the low efficiency of these engines as well as the predominant usage of these kind of propulsion systems for personal transportation. As a result of this, many alternate sources of fuel and alternate engine designs have been devised over the past few decades with the hybrid electric engine being the most successful among them. Hybrid electric engines were introduced in the late 1990's and have gained significant traction in the personal transportation sector owing to the massive efficiency boost over traditional internal combustion engines while being comparable in affordability. The other alternative energy sources for transportation include electricity (as in battery electric vehicles and eVTOLs [3], [4]), hydrogen fuel cell vehicles, nuclear propulsion based vehicles (specifically for oceanic transportation) to name a few.

Since their introduction, the hybrid electric engines have become highly popular with almost every OEM having a significant number of SKUs occupied by these models. In recent years, some OEMs have opted to completely get rid of the traditional internal combustion engine SKU's for their vehicles all together, while others have plans to do so in the future with the development work on design of traditional internal combustion engine based SKUs already being ceased. As a result, the number of hybrid electric vehicles in operation today is significantly high. Although traditional internal combustion engine models still account for a large percentage of vehicle models, the volume of hybrid electric vehicles in operation today is still significant and any effort made in reducing the greenhouse gases emissions generated by these vehicles will go a long way to keep us within the 1.5°C target.

Most academic and industrial narration about the term efficiency broadly refers to efficiency of the vehicle system alone which covers the energy conversion from the fuel's calorific value to the energy applied at the wheels of the vehicle. This definition is has a narrow scope as it does not consider the effects of energy transition and transfer from the source of the fuel to the energy applied at the wheels. This approach is most comprehensive and will give a better understanding on the overall impact of operation of these vehicles over their lifetime. To differentiate this overall efficiency term from the most broadly used term of just the vehicle level efficiency, the overall efficiency term is named as well-to-wheel (WTW) efficiency. This signifies the efficiency associated with energy spent right from the sourcing of the fuel all the way till its being applied to propel the vehicle via its wheels.

Since there are many stages associated with the energy flow in a comprehensive well-to-wheel efficiency analysis, it becomes critical to detail each of these energy flow stages and compute the energy lost or generated at each stage. This approach of detailing efficiency at each stage of conversion also has an added benefit of computing the carbon foot print and the levelized cost of operation simultaneously. However, this study mostly focuses on the efficiency computation to simplify the scope of this study.

When computing the well-to-wheel efficiency of any transportation vehicle, there two different kinds of energy transfer stages that need to be considered. The first one is the energy spent during the manufacturing of the vehicle and the consequent maintenance which are both onet-ime costs. The second one being the energy spent in procuring the fuel and the total calorific value of the fuel. Again, to simplify things, this study takes the approach of computing the efficiency over the entire lifecycle of the vehicle, so that one-time costs relating to the acquisition and maintenance of the vehicle can be amortized over the lifecycle.

II. Prior Literature

There is plenty of research work contributing to the prior literature on the topic of efficiency of hybrid electric vehicles. However, the literature focusing specifically on well-to-wheel efficiency is not as abundant. This is primarily a result of well-to-wheel efficiency not being as popular to begin with. Some of the prominent literature on the topic of well-to-wheel efficiency is detailed below.

Williamson et. al. [5] demonstrate the computation of well-to-wheel efficiency of hybrid electric and fuel cell vehicles as a product of well-to-tank and tank-to-wheel efficiencies. This approach argues that the overall well-to-wheel efficiency can split into the stages up until the refinement of the fuel (which includes the mining, transportation and refinement of the fuel) and the stages from refinement to the energy being applied at the wheels of the vehicle (which includes the distribution of the refined fuel and the conversion efficiency of the vehicle). This work however only talks about the operating efficiency of hybrid electric and fuel cell vehicles and does not consider the energy expenditure during the manufacturing and the maintenance of the vehicle.

Moghbelli et. al. [6] demonstrate a comprehensive approach of computing the well-to-wheel efficiency along with the performance characteristics and the fuel economy of hybrid electric battery electric and conventional gas powered vehicles. Although comprehensive in terms of number of performance metrics and the type of vehicles analyzed, this work does not include the cost of energy expended during the manufacturing and the maintenance of these vehicles. This is particularly important for both hybrid electric and battery electric vehicles as manufacturing and replacement of batteries for both of these vehicle topologies takes up significant energy resources and thus cannot be ignored.

Shoki et. al. [7] does a great job in detailing out the efficiency of hybrid electric vehicles including the manufacturing energy expenditure. This work focuses mostly on the material acquisition and manufacturing cost for building hybrid electric vehicles and it also computes the efficiency improvements that can be realized by switching from using steel to aluminum to construct the frame of the vehicle. In addition, there is also a computation of the projected improvements to the efficiency considering the improvements to material choice and improvements to battery manufacturing processes.

Elgowainy et. al.[8] details out the well-to-wheel analysis for plug in hybrid architecture which is similar to hybrid electric vehicles with the addition of a larger battery. The case for plug in hybrid architecture is that its bigger battery enables commuting small distances completely on battery power and thus eliminates the greenhouse gas emissions for shorter rides. This also comes at the expense of poor efficiency in longer drives that rely more on the combustion engine since the extra weight of the heavier battery will require the vehicle to pull a heavier mass as compared to a regular hybrid electric vehicle. In addition, plug in hybrids are also more expensive owing to the bigger battery and bigger electric motor required to operate these vehicles on battery power alone for a longer duration Elgowainy et. al.[8] also argues a case for using plug in hybrid vehicles with charging done during the off peak powers which also 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.

III. Methodology:

As described earlier, a comprehensive well-to-wheel analysis should consist of all stages where there is energy being spent or retrieved. It is still a point of contention whether any energy expenditure related to manufacturing and maintenance of the vehicle can be included in this analysis or not. The argument of considering manufacturing and maintenance stages in this analysis is more related the context of the analysis. If the well-to-wheel efficiency arrived upon is used in the context of comparing cost of operating the vehicle, its best to ignore the energy expenditure for manufacturing and maintenance of the vehicle and just rely on efficiency computation based on running costs. If the well-to-wheel efficiency is computed in the context of using this metric to understand the impact on global warming, its more beneficial to use the energy expenditure during the manufacturing and maintenance stages of the vehicle. In this study, the well-to-wheel analysis also includes the computation or estimation of energy expenditure during manufacturing and the maintenance of the vehicle to ensure that the well-to-wheel efficiency being computed is more comprehensive and so that its impact of global warming and greenhouse gas emissions can be understood.

To simplify the computation of well-to-wheel efficiency, an approach of evaluating the energy expended and the energy retrieved in the form of energy delivered to the wheels over the lifetime of the vehicle is assumed. Broadly, the following are the different stages of energy flow considered in this study

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

A. Manufacturing of the vehicle:

For the purpose of this study, let's consider a mid-size sedan with a hybrid electric architecture. There are several variations even within the hybrid electric architecture. There are approaches that use two motors (one acts as a motor, one acts as a generator), one motor, different engines sizes and even different kinds of transmissions of no transmission. Over approximately two decades of developing hybrid electric vehicles, one of the observations made is that the hybrid vehicle architecture is good at increasing the efficiency of the vehicle when going at slower speed [9]. This means that most of the architecture is designed around enabling use of motor assisted power delivery to the wheels when going at slower speeds and then switching to direct transfer of power from the engine to the wheels at higher speed. Thus many OEMs these days have taken the approach of using two motors in which one acts as a generator and the other acts as a motor (only powering the wheels for slow speeds). Additionally because of the direct energy flow from the engine to the wheels for higher speeds, the needs for a transmission can be eliminated. This is critical as transmissions can be one of the most challenging parts of the car to design reliably. By avoiding the need for including a transmission and effectively replacing its function (at lower speeds) with the use of generator and a motor, the overall reliability of the vehicle goes up. This is also because the motor and generator combination is much more efficient and less maintenance prone as compared to a traditional transmission.

With regard to the manufacture of a typical hybrid electric vehicle with this architecture, the different processes within the manufacturing such as material transformation, machining, painting, material handling, assembly etc. consume energy in the form of electricity or indirectly as fuel burnt to power these processes. Sullivan et. al. [10], demonstrates approximate amounts of energy consumed in theses processes which is shown in table

Table 1: Energy consumption and CO_2 results for major manufacturing processes

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

This table primarily shows the energy consumption for a generalized 1532 kg combustion engine car. When considering the energy required for the production of hybrid car, there are a few variations that need to be considered. One is the energy required to manufacture a bigger battery. Secondly, the material composition changes as compared to a conventional combustion engine car as result of elimination of majority of the transmission assembly. And finally, the additional motors being used also bring along additional energy consumption.

Considering all these factors, Sullivan et. al. [10] arrives at a number of 33,946MJ or 33.946 GJ of energy being consumed for manufacturing of a hybrid electric vehicle. The total mass of CO_2 emitted in the process is about 2,033kg.

B. Mining of fuel:

The main source of fuel for hybrid electric vehicles is gasoline. Plug in hybrids that usually include a bigger battery have the ability to change the vehicle to drive for short distances on electric power alone but hybrids (more specifically known as mild hybrids) do not have that advantage. This is an important distinction because the cost of fuel is usually the single most significant cost among all other factors of the ownership of a vehicle during its life time. Although mild hybrid do not have a large enough battery to make driving on battery power alone feasible, other advantages of a electric powered drive such as regenerative braking, more finer control on acceleration etc. still hold for mild hybrid electric vehicles.

Before jumping into the cost of mining fuel, it is important to understand the amount of fuel being used in the complete lifetime of hybrid electric vehicles. According to leading automotive OEMs, hybrid vehicles can last until 200,000 miles if taken care of adequately [11]. Assuming an average mpg rating of 40 miles/gallon which is typical of hybrid vehicles, we can arrive at a number of 12,500 gallons of gasoline being used during the lifetime of operation of the vehicle. This means that at least 12,500 gallons of gasoline must be mined, transported and refined in order to be used as fuel for one hybrid electric vehicle in its life time.

To mine one gallon of crude oil, the estimates on the amount of energy expended vary from 1.4 kWh to 3.3kWh. [12]. To convert the energy from kilowatt-hours (kWh) to joules (J), following conversion factor can be used:

$$1\,kWh = 3.6 \times 10^{\wedge}6\,J$$

So, the estimate in joules is:

$$1.4\,kWh/gal \times 3.6 \times 10^{\wedge}6\,J/kWh = 5.04\,MJ/gal\,(lower\ bound)$$

$$3.3\,kWh/gal \times 3.6 \times 10^{\wedge}6\,J/kWh = 11.97\,MJ/gal\,(upper\ bound)$$

Considering an average of 8.5MJ/gal, the total energy expended in mining 12,500 gallons of gasoline is 106.250GJ. This is a cost to the lifecycle analysis and hence will be part of the energy put into the system.

C. Transportation of the raw fuel:

Although mining of fuel takes a lot of energy, it is also important to consider the transportation of fuel. There are two stages of fuel transportation in acquiring the fuel required to drive a gasoline powered car or hybrid electric car. The raw fuel, which is typically crude oil mined at offshore or onshore locations needs to be transported to refineries for its processing. The processing of the fuel involves different stages of refining and separating the specific fuel components to extract gasoline out of crude oil. Thus this processing also consumes energy. Once the crude oil is processed and gasoline is extracted from the fuel, the refined gasoline is further transported to the final end user through a chain of different stages of transport that make up a large distribution network. The energy consumed by this distribution also needs to be considered in the case of a comprehensive analysis of energy consumed in the entire lifecycle of operating hybrid electric vehicles

高有山, et al.[13] analyses the cost of transporting crude oil for domestic as well as foreign imports. For domestic crude oil, the energy consumption is significantly lower at 1.46kJ per MJ of crude oil transported. For international imports, the cost of transporting crude oil is 8.95kJ per MJ of crude oil transported. Averaging both these numbers (for a 1:1 mix of international and domestic crude oil), cost of transporting crude oil is about 5.75kJ per MJ of crude oil transported. The energy content of crude oil is about 38.6MJ per gallon. Using this conversion factor, the energy consumed for transporting a gallon of crude oil can be computed as 345.47kJ/gallon or 0.3MJ/gallon. This puts the estimate of energy consumed for transporting crude oil from oil fields at about 1% of the energy content of gasoline. This estimate of energy consumed at each stage in terms of the percentage of energy contained in 1 gallon of gasoline is crucial for computing the well-to-tank efficiency which will be detailed in later sections of this study.

D. Refining the crude oil:

Refining of crude oil is an energy intensive process. The average efficiency of gasoline production is about 88.6% in the US [15]. Gaines et al. [14] estimates that crude oil refining consumes about 10% of calorific value of crude oil itself. Considering that the energy content of crude oil is 38.6MJ per gallon, an estimate of 10% of calorific value for the energy consumed would estimate the energy consumed at 3.86MJ per gallon.

E. Distribution of refined crude oil (gasoline):

The average energy consumption for the distribution of gasoline from refineries to gas stations involves a complex infrastructure, primarily consisting of pipelines. In the United States, there are approximately 95,000 miles of pipelines dedicated to transporting refined products like gasoline and diesel from refineries to around 150,000 filling stations [16]. However, the specific energy consumption for this distribution process is not detailed in the provided data.

Here’s a breakdown of the factors that contribute to the energy consumption:

Pipeline: Pipelines are the most energy-efficient way to transport gasoline. It generally takes around 0.1 to 0.5 kWh (kilowatt-hours) of energy to transport one gallon of gasoline over 100 miles via pipeline.

Truck: Trucks are less efficient and consume more energy. The energy required for transportation by truck can be around 1 to 2 kWh per gallon over 100 miles, depending on factors like load and terrain.

Rail: Rail transportation falls somewhere between pipelines and trucks in terms of energy efficiency. It might take around 0.2 to 0.7 kWh per gallon over 100 miles.

Therefore the energy consumption in transporting gasoline, depending on the method and distance, can range from 0.1 kWh to 2 kWh per gallon of gasoline over 100 miles. The most common method, pipelines, tends to be on the lower end of that spectrum. However, 0.5kWh would be representative of the average value of transporting a gallon of gasoline over 100 miles. This assumes that most of the distance is covered using transportation by the means of pipelines and only the final mile transportation is using rail or trucks for transport.

The energy required for transporting gasoline is a small fraction of the total energy content of the gasoline itself. Therefore, transport energy typically represents only a small percentage of the total energy involved in getting gasoline to the end users.

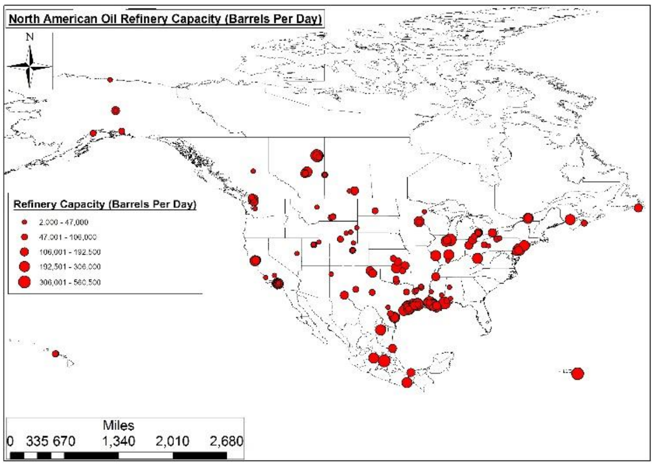

Figure 1: North American oil refineries [23]

Looking at the map of oil refineries in the US, one can estimate that the average distance between any two refineries is about 200 miles. This means that on average the distance between refineries and gas stations is about 100 miles. This estimates the energy consumed to transport one gallon of gasoline at 0.5kWh. In joules, this equates to about 1.8MJ of energy. Thus the energy consumed to distribute the gasoline to gas stations is about 5% of the total energy of the gasoline itself.

Before looking at the energy conversion efficiency of hybrid electric cars, its important to understand the significance of a metric known as Well to Tank efficiency. This term represents the ratio of energy content of the fuel to the total energy input (1).

$$well\ to\ tank\ efficiency = \frac{Energy\ content\ of\ Fuel}{total\ energy\ input} X\ 100 \quad (1)$$

The energy content of the fuel is just the calorific value of the fuel. This number is 38.6MJ for a gallon of gasoline. Total energy input is the sum of energy consumed during transportation, refining and distribution and energy content of the fuel.

$$total\ energy\ input = energy\ content\ of\ fuel + Energy\ consumed\ during\ transportation + energy\ consumed\ during\ refining + enrgy\ consumed\ during\ distribution \quad (2)$$

In terms of percentage of gasoline calorific value, the total energy input can be computed as shown below.

$$total\ energy\ input = 100\% + 1\% + 10\% + 5\% = 116\%$$

Computing the resulting well-to-tank efficiency,

$$well\ to\ tank\ efficiency = \frac{100}{116} X\ 100 = 86.2\% \quad (3)$$

Thus it can concluded that the well-to-tank efficiency of gasoline produced in the US is about 86.2%. This is a useful result even beyond the scope of this study. This result can be used to compare the efficiency of production of different energy sources for transportation. A similar analysis can be conducted for electricity production or compressed natural gas production or hydrogen production which are all possible energy source alternatives to gasoline.

F. Fuel conversion to power the vehicle

Conversion efficiency of hybrid car represents the ratio of useful work extracted from the vehicle to the total amount of energy input to the car in the form of fuel. This is also referred to as the tank-to-wheel efficiency in a lot of the existing literature. However, this would not be an accurate representation of the overall tank-to-wheel efficiency of hybrid cars as this would ignore the energy spent in maintenance of the car. This maintenance which has both a regular maintenance and an unscheduled maintenance component will still be useful energy that needs to be input into the vehicle system to accurately depict the amount of energy consumed by the vehicle over its life time. Thus in this study, this metric is only referred to as the conversion efficiency of hybrid electric car.

Hybrid electric cars typically boast higher conversion efficiencies than regular gas powered cars. This is in essence due to the presence of a hybrid electric architecture that makes use of battery to store energy ensuring that the vehicle engine can operate at an RPM which corresponds to the highest efficiency. Thus regions of the torque – RPM – efficiency map that have lower efficiencies are avoided and battery energy is used in those scenarios to power the vehicle. The modulation between use of battery power and the engine power being sent to the wheels or to charge the battery is an implementation detail that varies between different automotive OEMs but most of the hybrid electric vehicles promise a similar efficiency metric. Hence, this study in particular does not go into details of different hybrid electric vehicle architectures and the details about modulation of power sources.

In the case of a hybrid electric vehicle, a lot of literature exists that estimates the efficiency of the vehicle. As described earlier, this study considers the entire lifetime of the hybrid electric vehicle with a total mileage of 200,000 miles. The reports presented in [17] and [18] show that the miles per gallon metric of different hybrid electric sedans varies from 57mpg to 42mpg. The mpg of different hybrid electric sedans is as tabulated below:

Table 2: MPG of different hybrid electric car models

Model year	Car model	MPG
2024	Toyota Prius	57
2024	Hyundai Elantra hybrid	50
2024	Toyota Corolla Hybrid	50
2024	Honda Accord Hybrid	44
2024	Lexus ES 300h	43
2024	Toyota Crown	42

From the tabulation above the average value of mpg for hybrid electric sedans can be considered as 48mpg. This means that over 200,000 miles, a typical hybrid electric vehicle will consume about 4200 gallons.

In terms of an power input to power output metric that only considers the instantaneous efficiency during operation of the vehicle, Lorenzo et al. [22] estimates it to be around 30%. Once again, considering an estimate of 30% efficiency, the amount of useful energy generated by the system can be obtained as follows.

$$total\ energy\ input = 4200\ gallons\ X \frac{38.6MJ}{gallon}$$

$$= 162{,}120MJ \tag{4}$$

$$total\ energy\ output = conversion\ efficiency\ X\ total\ energy\ input$$

$$= 30\%\ of\ 162{,}120MJ = 48{,}636\ MJ \tag{5}$$

G. Maintenance of the vehicle

Hybrid electric vehicles fall in between conventional internal combustion vehicles and battery electric vehicles in terms of the maintenance requirements. Some advantages of using a battery electric vehicle such as less degradation of brake pads (because of extensive use of regenerative braking) and lack of transmission (thereby requiring less maintenance) are also reciprocated in hybrid electric vehicles. Yet hybrid electric vehicles share some of the disadvantages of conventional internal combustion engines such as requiring regular oil changes, oil filter changes and requiring maintenance on engine. Additionally, one more maintenance responsibility is the replacement of hybrid battery. The battery used in hybrid electric vehicles is still of a smaller capacity as compared to a battery electric vehicle but it still would need replacement.

Schwartz et al. [19], recommends that the ideal interval of oil changes is every 3000 miles. This means that over a lifetime mileage of 200,000 miles, the vehicle would require 67 oil changes. Assuming 5 quarts of oil is required for each oil change, a total of 335 quarts of oil is needed for all the oil changes required by a hybrid electric vehicle in its lifetime. Additionally 67 oil filter and air filter replacements are needed over the lifetime of a hybrid electric vehicle. Since there is no actual data present on the energy consumption of these components, it is assumed that the man power will be the biggest energy consumer for regular maintenance activities. Assuming that two personnel can complete a regular maintenance activity in 30 minutes, a total of 1 man-hour is required for each gear change. Danilecki et al. [21] estimates the following electricity and gas consumption for repair related man-hours.

$$Electricity\ consumption: 2.09kWh/man - hour$$

$$Gas\ consumption: 12.25\ kWh/man - hour$$

$$Total\ consumption: 14.34kWh/man - hour\ or\ 51MJ/man - hour$$

$$Energy\ consumption\ for\ 67\ oil\ changes: 51MJ/man - hour\ X\ 67 = 3{,}147MJ$$

Marano et al. [20], estimates that a battery pack replacement is needed every 150,000 miles. Therefore for a hybrid electric vehicle with 200,000 miles of lifetime mileage, at least one battery pack replacement is needed.

Using the energy requirement metrics from Sullivan et al. [10], we can estimate that one battery pack replacement for hybrid vehicle would cost 1,060MJ.

Additionally another 30 repairs with each costing 1 man hour are factored in for unforeseen repair works. This would add another 1,530 MJ of energy consumed for unforeseen repairs.

Overall, the sum of all these maintenance activities consumes about 5,737 MJ of energy. This in itself can account for 1-2% of the total energy input as will be computed in the next section. Thus involving the energy consumed by maintenance activities is crucial for accurate well-to-wheel efficiency computation.

IV. Results

With the estimates of the total energy consumed and the total useful energy obtained in the form of energy converted to propulsion, an estimate for the overall well-to-wheel efficiency of hybrid vehicles can be computed.

To compute the total energy consumed, firstly the total energy input from fuel procured is computed as shown in (6)

$$Energy\ input\ from\ fuel\ procured\ = total\ calorific\ energy\ of\ the \frac{fuel}{well-to-tank\ efficiency} = \frac{162{,}120MJ}{86.2\%} = 188{,}074\ MJ \tag{6}$$

This total energy input from fuel procured is then added to the maintenance and the manufacturing cost of the vehicle itself, which gives the total energy input into the system over the lifetime of a hybrid electric vehicle. This is computed as shown in (7)

$$Total\ energy\ input\ = 188{,}074\ MJ + 5{,}737\ MJ + 33{,}946\ MJ = 227{,}757\ MJ \tag{7}$$

The total useful energy generated by the hybrid electric vehicle over its lifetime is 48,636 MJ.

Thus well-to-wheel efficiency of a hybrid electric vehicle can be calculated as shown in (8).

$$Well-to-wheel\ efficiency\ = \frac{total\ energy\ output}{total\ energy\ input}\ X\ 100 = \frac{48{,}636MJ}{227{,}737MJ}\ X\ 100 = 21.35\ \% \tag{8}$$

A preemptive disclaimer here is that the computed value represents the approximate well-to-wheel efficiency for a typical hybrid electric sedan alone and the actual value of well-to-wheel efficiency can vary depending on the vehicle form factor and the actual hybrid architecture.

V. Conclusion

As detailed in the previous section, a rigorous method to compute well-to-wheel efficiency is demonstrated in this study. The inference of well-to-wheel efficiency being 21.35% for hybrid electric vehicle means that although hybrid vehicles are considered to be environmentally friendly, they still are significantly inefficient (predominantly in the form of energy lost during conversion from calorific value of the fuel to the energy applied at the wheels). This finding also leaves us with a lot of scope for improvement and more importantly also provides a deeper understanding of efficiency of each individual stages from source to the actuator. Future work involves extending this study to determine the well-to-wheel efficiency of other vehicle types such as battery electric vehicles, plug in hybrid electric vehicle, conventional internal combustion engine vehicles and even for other modes of transportation.

References

[1] Masson-Delmotte, Valérie, et al. "Global warming of 1.5 C." An IPCC Special Report on the impacts of global warming of 1 (2019): 93-174.

[2] Abraham, Sarin, et al. "Impact on climate change due to transportation sector–research prospective." Procedia engineering 38 (2012): 3869-3879.

[3] Chinthoju, Prajwal, et al. "Optimal Design of eVTOLs for Urban Mobility using Analytical Target Cascading (ATC)." AIAA SCITECH 2024 Forum. 2024.

[4] Chinthoju, Prajwal Kumar. "Cost Per Flight Analysis Of Tilt-Wing Evtols For Urban Mobility."

[5] Williamson, Sheldon S., and Ali Emadi. "Comparative assessment of hybrid electric and fuel cell vehicles based on comprehensive well-to-wheels efficiency analysis." IEEE transactions on vehicular technology 54.3 (2005): 856-862.

[6] Moghbelli, Hassan, et al. "A comparative review of fuel cell vehicles (FCVs) and hybrid electric vehicles (HEVs) part I: performance and parameter characteristics, emissions, well-to-wheels efficiency and fuel economy, alternative fuels, hybridization of FCV, and batteries for hybrid vehicles." SAE transactions (2003): 1860-1870.

[7] Kosai, Shoki, Masaki Nakanishi, and Eiji Yamasue. "Vehicle energy efficiency evaluation from well-to-wheel lifecycle perspective." Transportation Research Part D: Transport and Environment 65 (2018): 355-367.

[8] Elgowainy, Amgad, et al. Well-to-wheels analysis of energy use and greenhouse gas emissions of plug-in hybrid electric vehicles. No. ANL/ESD/10-1. Argonne National Lab.(ANL), Argonne, IL (United States), 2010.

[9] Shinnaka, Shinji, and Takayuki Sagawa. "New optimal current control methods for energy-efficient and wide speed-range operation of hybrid-field synchronous motor." IEEE transactions on industrial electronics 54.5 (2007): 2443-2450.

[10] Sullivan, John Lorenzo, Andrew Burnham, and Michael Wang. Energy-consumption and carbon-emission analysis of vehicle and component manufacturing. No. ANL/ESD/10-6. Argonne National Lab.(ANL), Argonne, IL (United States), 2010.

[11] "How Long Do Hybrid Cars Last?: Hybrid Car Durability." *Preston Chrysler Dodge Jeep Ram of Dover Dover, DE*, www.dovercdjr.com/blogs/4531/index.php/2024/08/26/how-long-do-hybrid-cars-last/. Accessed 15 Jan. 2025.

[12] Guilford, Megan C., et al. "A new long term assessment of energy return on investment (EROI) for US oil and gas discovery and production." Sustainability 3.10 (2011): 1866-1887.

[13] 高有山, et al. "Analyses of the energy consumption and emissions of crude oil transportation." Journal of Mechanical Engineering 48.20 (2012): 147-152.

[14] Gaines, L. L., and A. M. Wolsky. Energy and materials flows in petroleum refining. No. ANL/CNSV-10. Argonne National Lab., IL (USA), 1981.

[15] Elgowainy, Amgad, et al. "Energy efficiency and greenhouse gas emission intensity of petroleum products at US refineries." Environmental science & technology 48.13 (2014): 7612-7624.

[16] P. Meier et al. "Petroleum Crude Oil." (2020): 19-50. https://doi.org/10.1093/OSO/9780190098391.003.0002.

[17] "20 Hybrids with Best Gas Mileage for 2022 - TrueCar." *Www.truecar.com*, www.truecar.com/best-cars-trucks/fuel-hybrid/by-gas-mileage/.

[18] "The Hybrids with the Best Gas Mileage You Can Buy in 2022." MotorTrend, www.motortrend.com/features/best-gas-mileage-hybrids/.

[19] Schwartz, Shirley E., and Donald J. Smolenski. "Development of an automatic engine oil-change indicator system." SAE transactions (1987): 62-78.

[20] Marano, Vincenzo, et al. "Lithium-ion batteries life estimation for plug-in hybrid electric vehicles." 2009 IEEE vehicle power and propulsion conference. IEEE, 2009.

[21] K. Danilecki et al. "Modeling inventory and environmental impacts of car maintenance and repair: A case study of Ford Focus passenger car." Journal of Cleaner Production, 315 (2021): 128085. https://doi.org/10.1016/J.JCLEPRO.2021.128085.

[22] Lorenzo Rambaldi et al. "Preliminary experimental evaluation of a four wheel motors, batteries plus ultracapacitors and series hybrid powertrain." Applied Energy, 88 (2011): 442-448. https://doi.org/10.1016/J.APENERGY.2010.08.008.

[23] PhD, Ted Auch. "US Oil Refineries and Economic Justice - by FracTracker Alliance." *FracTracker Alliance*, 24 Aug. 2016, www.fractracker.org/2016/08/us-oil-refineries-economic-justice