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ASSESSMENT OF ENVIRONMENTAL IMPLICATIONS OF ELECTRIC VEHICLES: A REVIEW

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Abstract

The emergence of hybrid electric vehicles (HEVs) has paved a way for the automobile industry to tap into the vast potential of renewable sources of energy and to look for eco friendly alternatives to fossil fuels. Not only can the depletion of non renewable resources be countered effectively but the harmful detrimental effects of using these fossil fuels can also be reduced. Even though it has been established that HEVs tend to have more eco friendly benefits than their internal combustion engine vehicles (ICEV) counterparts, they too are not immune to adverse environmental implications. The production, operation and end of life phases of HEVs contribute to major adverse environmental effects related to greenhouse gases (GHG) emissions, human toxic by-products etc. Hence an assessment of their environmental implications is being discussed in this paper and light has been shed on different assessment categories such as acidification potential, eutrophication, human toxicity potential, global warming potential etc. Furthermore the phases and parts of a HEV which contribute majorly to these implications are also discussed briefly. The environmental implications of the energy generation sources used in these HEVs are also taken into account.

Keywords: Global warming; Greenhouse gases; Hybrid vehicles; Lifecycle assessment, Well to Wheel, Renewable energy, Automotive Engineering

1. Introduction

The current sources of energy are depleting at an alarming rate and the environmental hazards that the current sources produce has been a serious issue since decades and their adverse effects have been extremely evident in today's world. Sustainable development of resources has been a major field of research and development since the past decade and much prominent advancement has already been made. Introduction of hybrid vehicles and the study of alternate sources of energy to replace the current ones is one such advancement. Different resources are being studied regarding these hybrid electrical vehicles. Although most of them are incapable of being as efficient or economic as the current ones, they do provide a good eco-friendly approach and as for the cost; mass production might help deal with that too. Most modern smart cities have emphasized the importance of hybrid vehicles in their sustainable development projects to have a control on the accepted levels of harmful gases produced by the IC (internal combustion) engines. Reduction of these harmful gases has acted as a motivation and paved a way for sustainable advancement in the automotive industry. It is of utmost importance to get insights into the environmental effects of these hybrid electric vehicles. But prior to that one must have the pre-requisite knowledge of what these hybrid electric vehicles actually are; and their working principle. Based on their energy states we can classify them into multiple types. Few of them are as follows-

- Battery based
- Fuel cell based model

- Solar cell based

The battery based model involves the usage of battery which is evident from its name. Lead acid batteries have always been prominent in this regard. Nowadays the polymer lithium ion battery is predominantly used. The fuel cell based model comprises of a fuel cell which is built using an anode, anode catalyst layer, electrolyte cathode and cathode catalyst layer. DC electrical energy is produced via chemical reactions occurring at the cathode and anode. The solar cell based model as the name suggests works on the principle of energy conversion from solar energy to electrical energy via semiconductors.

Furthermore plug-in hybrid cars enable the usage of an all electric or an IC engine combination for optimum sustainable performance [1-2].

2. Literature Review

2.1 Environmental impacts of electric hybrid vehicles

To counter the depletion of natural resources and to aim for a more holistic approach in terms of sustainable development; tapping into the vast potential of hybrid electric vehicles is eminent and imminent. The electric vehicles cause less adverse effects on the environment in comparison with their traditional counterparts. One backdrop is that a part of the renewable or sustainable source of energy being used by these electric vehicles are in turn directly or indirectly dependant on the traditional resources for their generation. Comparisons based on global warming potential (GWP) and acidification potentials (AP) could help draw out the shortcomings and strengths. EVs, as expected, exhibit lesser adverse effects

on the environment as compared to IC engines. The production phase of EVs tends to be more expensive than their IC counterparts; the battery production being the primary reason. These production phases also contribute to the increase in GWP and AP considerably. Another adverse effect is the maintenance and production of the battery whose lifetime is actually lesser than the vehicle lifetime. Now due to the advanced technology and materials used for the fabrication of the parts of an EV, a huge pressure is put on the extraction of the raw materials such as steel, cobalt etc.

Even motors such as the Permanent Magnet Synchronous Motors, are fabricated via the usage of rare earths like neodymium and dysprosium. However due to them being only a small portion of the part production, the share to the EV production phase is lower. As compared to the battery vehicle the plug-in version

contributed less to the acidification potential due to the size. Acidification potential is basically a measure of the reduction in the pH levels of rainwater and fog. Another important factor to take in to consideration while drawing comparisons is that the traditional automotive industry is more than a century old and had its fair share of development and advancements whilst the current automotive industry regarding the EVs is comparatively a much more of an early development phase and needs more investments and tests to be carried out in order to deliver an optimum result compatible with the needs of sustainable development. Lifetimes of the parts of the EVs such as batteries, e motors, power electronics etc play an important role in their environmental effects. Even for the charging of batteries we would require renewable resources and not only be dependent on the current ones.

Impact category	Unit	Li-ion 75 kW h	LMP 75 kW h	Li-ion 6 MW h	LMP 6 MW h
Carcinogens	kg C2H3Cl eq	1.30E+00	1.22E+00	8.02E-01	7.27E-01
Non-carcinogens	kg C2H3Cl eq	1.43E+00	1.28E+00	1.20E+00	1.05E+00
Respiratory inorganics	kg PM2.5 eq	5.09E-02	4.32E-02	3.96E-02	3.19E-02
Ionizing radiation	Bq C-14 eq	2.86E+02	4.02E+02	1.94E+02	3.10E+02
Ozone layer depletion	kg CFC-11 eq	4.06E-04	2.49E-06	4.05E-04	2.07E-06
Respiratory organics	kg C2H4 eq	9.65E-03	1.13E-02	7.52E-03	9.17E-03
Aquatic ecotoxicity	kg TEG water	6.73E+03	9.59E+03	5.33E+03	8.19E+03
Terrestrial ecotoxicity	kg TEG soil	1.58E+03	1.58E+03	1.23E+03	1.24E+03
Terrestrial acid/nutri	kg SO2 eq	7.59E-01	6.98E-01	6.24E-01	5.64E-01
Land occupation	m2org.arable	6.91E-01	8.78E-01	5.97E-01	7.84E-01
Aquatic acidification	kg SO2 eq	2.78E-01	2.27E-01	2.25E-01	1.75E-01
Aquatic eutrophication	kg PO4 P-lim	8.53E-02	1.29E-01	7.14E-02	1.15E-01
Global warming	kg CO2 eq	3.40E+01	2.56E+01	2.89E+01	2.05E+01
Non-renewable energy	MJ primary	3.70E+02	3.78E+02	3.01E+02	3.09E+02
Mineral extraction	MJ surplus	1.57E+01	1.18E+01	1.18E+01	8.02E+00

Fig. 1 is the impact scores

Because the extension of the lifetime of batteries would help control the AP levels along-with the energy densities of the batteries. Even if the EV itself might not have adverse environmental effects, one must also keep a strict check on the extraction of raw materials required for the part production of these EVs as an uncontrolled raw material extraction would only further deplete our resources [3-4]. The capacity and fabrication of the batteries is bound to play a major role in the impacts that EVs will have on the environment. The rise in the demand of stationary batteries could also have environmental implications. These batteries are modular,

exhibit high response rate and have reduced costs. Life cycle assessment is a good methodology that takes into account the entire lifecycle of production of the battery from the extraction of raw materials to the fabrication of the battery; i.e. a cradle to grave approach. The environmental implications that a battery can impose is primarily dependent on its lifetime, its exhibited efficient performance and its characteristic maximum depth of discharge. The efficiency is highly affected at each discharge and charge cycle. A comparative study carried out among different batteries yielded the following results as shown in Figure 1 and Figure 2 [5].

Damage category	Unit	Li-ion 75 kW h	Li-ion 6 MW h	LMP 75 kW h	LMP 6MW h
Human health	DALY	4.38E-05	3.38E-05	3.73E-05	2.74E-05
Ecosystem quality	PDF*m2*yr	1.43E+01	1.13E+01	1.47E+01	1.16E+01
Climate change	kg CO2 eq	3.40E+01	2.89E+01	2.56E+01	2.05E+01
Resources	MJ primary	3.86E+02	3.13E+02	3.90E+02	3.17E+02

Fig. 2 is the damage scores

The growing demand of transportation has to be countered with the emergence of eco friendly modes. The

construction involved in the transportation and its very own operation; are the primary reasons behind its adverse

impact on the environment as well our repository of energy resources[6].

Even though electric vehicles can help reduce the heavy reliance of the transport industry on fossil fuels, these vehicles do require additional sources for the production of electricity which could further have other adverse implications. Life cycle assessment (LCA) is an efficient methodology for analyzing the environmental implications of different goods or services. As mentioned earlier, its efficiency lies in its cradle to grave approach. All processes

form an intricate web of links and these are further assessed for their impacts on the natural system with each category having its own set of implications. Well-to-wheel study is a type of LCA of vehicles wherein the primary focus is on the lifetime and lifecycle of the propulsion unit. It has further sub-categories [7].

Fig. 3 is the WTW and equipment flow- simplified view

The following data in Figure 4 shows the WTW GHG emissions.

Fig. 4 is the Well to Wheel Greenhouse Gases emissions involving degrees of electrification related with multiple electricity productions.

The traffic conditions play a major role as well in the environmental implications of these hybrid vehicles.

Fig. 5 is the Well to Wheel Greenhouse Gases emissions for multiple conditions of traffic, the degree of electrification and different family vehicles.

The impact of the supplied source of electricity for charging purposes along with the degree of electrification

and the mode of operation play vital roles in the assessment of the well-to-wheel reports.

One of the most crucial categories is the airborne pollutants generation and its impact on the global warming potential values. These may be generation of harmful gases responsible for smog etc. Acidification and eutrophication are the primary categories discussed [8].

The mode of operation would also be impacted by the battery efficiency and other battery parameters. The following compilation is a summary of the recycling score of different types of batteries with similar dimensional metrics.

Fig. 6 is the data of environmental scores of different types of batteries.

The well to wheel statistics suggest that the emissions of harmful gases show a reducing trend as the power-train exhibits characteristics of an increasing trend with respect to electrification. Also dependence on fossil fuels is an important factor and Battery electric vehicles and Plug in variants can help tapping into the vast potential of counter measures against global warming. Different factors need to be taken into consideration from the fabrication and extraction of raw materials to mode of operation and to different driving traits along with the traffic traits. All these are crucial for any proper assessment.

2.2 Life Cycle Assessment

Comparisons drawn with respect to usage of energy are quite helpful in getting an insight into the generation of electricity along with its transmission and distribution. Furthermore other factors too contribute to environmental implications, namely, the disposal of the batteries and whether or not the parts of the HEV can be recycled or reused. Considering the total life cycle, one

would observe that the green house gases emission and their impacts are the primary characteristics of phase energy consumption and the electricity mix involved during the process of charging. Both BEVs and PHEVs however exhibit better characteristics as compared to ICEVs in this regard. The electricity generation also plays a crucial role. Electricity generated by coals tends to have low green house gases (GHG) impacts. The source of electricity generation also has a pivotal role in determining the efficiency of the EV. Lower carbon electricity powered EVs tend to exhibit improved efficient characteristics [9-10].

HEVs definitely have an edge over the conventional ICs in an urban environment but the production costs due to lower rates of mass production hampers its vast potential [11].

Apart from the well to wheels cycle, the vehicle life cycle as cited above also is an important factor. To decrease the adverse impacts of a HEVs lifecycle on the environment, cleaner production scenarios are required with enhanced manufacturing efficiency. The use phase and energy consumption impacts should be taken into consideration during the vehicle production phase. The use phase is also related to the battery's cycles of charge and discharge which in turn is a function of the vehicles operation duration and travelled distance along with the energy dissipated during the processes of heating and cooling. For the data regarding the energy source lifecycle; if we consider the production of gasoline, the stages requiring assessment would be the extraction of oil and its transport; the refining processes and finally the usage. Similarly for ethanol, the indirect usage of energy required for the seeds, agrochemicals etc and the direct energy requirement as well. All these data is required for appropriate approximation of the emissions produced during their lifecycle. Now taking into account the processes involved in the energy generation procedure. The technological processes that involve the fossil fuel will undoubtedly contribute to higher GHG levels directly- mostly during the installation and initial generation stages. But on the contrary, the GHG emissions from the technologies involving energy generation from renewable resources generally occur more at the supporting industrial processes and infrastructures. GHG levels vary from one electricity generation station to another depending on the process, be it hydro-electric power-plant, or from natural gases or sugarcane bagasse or thermal power-plants [12-13].

The following diagram on the next page is a simplified flowchart depicting the lifecycle of any HEV.

Fig.7 is the lifecycle of HEV

GHG emissions of the HEVs can be evaluated with the help of their consumption of electricity and also the indirect GHG emission during the production phase of electricity generation. The levels specified by most companies are unrealistically low as they do not take into account many crucial practical conditions and the mode and nature of HEV operation. There exists a strong variation in the operational lifetime carbon footprints whilst considering the varying nature of usage of different cars. The carbon impact related to the production phase of electricity generation influences the GHG emissions to a great extent during the HEV operation [14].

PHEVs and BEVs have similar usage of electricity in this regard. The difference arises on the manufacture and size of batteries.

The high GHG values as mentioned for HEVs are due to the implications emerging from the production phase along with the maintenance and end of life treatment phase of the batteries. All this accounts for around 30% of the entire HEVs carbon footprint. And out of the mentioned phases, the construction phase is the major contributing phase both for HEVs and ICEVs. For HEVs, manufacturing involving the cathode and anode raw materials generate a major part of these battery emissions. The end of life treatment is mostly negligible in terms of carbon footprint contributions. The scenario does show changes when we consider a fully electric vehicle and a hybrid one [15].

Multiple studies do suggest that the use phase of batteries contribute significantly in the environmental impacts throughout its lifetime. The charge/discharge cycle is a contributing factor in this. The amount of these cycles, battery degradation, depth of discharge, the rate of charging and the duration and temperature of operation;

all these are accountable. The calendric aging is a contributor to the operation temperature of the batteries which further aids in determining the calendric life of the battery. Furthermore, the efficiency of the battery and the energy losses during the charge/discharge cycles because of the chemical composition and the internal resistances of the batteries; are also potentially relevant. The energy density of these batteries is described with the aid of their active material and also the magnitude of the additional passive parts (responsible for other functionalities apart from storing energy). The overall lifecycle of these batteries, the energy densities and their internal efficiency form a major part of their environmental impacts [16-17].

As discussed earlier the transport stage must also be assessed for environmental impacts. The mode of transport and distribution is very crucial. The transportation of these bio-fuels from one point to another along with the electricity losses in the grid are to be taken into account as well. Then we have the end of life phase. Even though the impact of this phase is comparatively low, it still is an integral point of discussion. This phase includes the reuse or recycling of the HEV's parts along with the disposal of the non-reusable parts. The energy consumption of the recycling process must also be assessed along with the rate of recycling as well. Recycling of materials such as aluminum, iron etc does provide economic as well as environmental advantages. The most recycled EV part is the battery due to cost effective measures involving its manufacturing process and extraction of its raw materials. Moreover the recycling is more cost effective when compared to the elimination process of these batteries. Even though GHG emission reduction measures are of main concern, the GWP is the primary point of focus while developing new HEVs [18].

Fig. 8 is the contributing factors of GWP in PHEVs.

Another category of assessment is the Ozone Layer Depletion Potential (ODP). It describes the depletion of ozone gas in the stratosphere. Chlorofluorocarbons (CFCs) generating vehicles along with carbon tetrachloride etc tend to exhibit higher ODP values. A major percentage of these emissions occur at the manufacturing phase of the vehicles. The battery production phases also impact the ODP levels. Abiotic Depletion Potential (ADP) is a measure of the potential negative effects of the demand has on the availability of the raw materials which are mostly the natural resources. The consumption of abiotic compounds during the phase of manufacturing also contributes to ADP levels. Another factor influencing the ADP levels is the electricity production and the demand for lithium for the Li-ion batteries [19].

The Fossil Fuel Abiotic Depletion Potential (FDP) as the name suggests is related to the usage of the non renewable fossil fuels. The vehicles which predominantly use fossil fuels as sources of energy generation have higher impacts on the FDP levels. The human Toxicity Potential (HTP) describes the relation between the harmful emissions and their adverse impacts on human health. EVs tend to exhibit higher values of HTP during production and use phase. The

battery production involving lithium is one of the primary reasons for this as a lot of toxic substances are released during the battery manufacturing process. Even copper and aluminium is required in comparatively higher amounts during the production of these batteries thus contributing to the HTP levels as well. Even during the electricity generation using different processes; involving ethanol, etc; a significant impact on the HTP levels is observed. Although with respect to LCA database, production of Li-ion batteries are on the right path of sustainability. This would be further enhanced once a complete shift occurs from fossil fuels to bio-fuels and other renewable alternatives

The Photochemical Oxidant Formation Potential (POP) is related to the emissions of NO_x, unburned hydrocarbons etc which are the toxic substances behind summer smog. Furthermore, the Acidification Potential (ACP), as discussed earlier relates the emissions of acidifying pollutants responsible for the acidification of rainwater such as NH₃, NO_x, etc. BEVs show a more worrying trend due to the usage of the agrochemicals and fertilizers during the sugarcane bagsse production stages along with the other production stages related to the electricity generation processes. Combustion of fossil fuels also impacts the ACP levels [20-21].

Fig. 9 is the contributing factors of HTP for HEVs.

Fig. 10 is the contributing factors of ACP for hydrogen vehicles

Eutrophication Potential (ETP) describes the implications of higher levels of macronutrients on the environment mostly due to the processes involving disposal. ETP levels are influenced by vehicle production stages, gasoline and ethanol production etc. One of the primary reasons is the disposal of soil that occurs during the mining of lignite which further occurs from surface landfill.

The CO₂ life cycle impact is also very crucial. CO₂ emissions are dominant for both HEVs and ICEVs. Power generation infrastructures of most of the power-plants work on fossil fuels which also lead to a considerable amount of CO₂ emissions. It is difficult to eradicate the processes involved in these stages thus making it a serious issue for preventing environmental implications of manufacturing HEVs. An energy economic assessment is also necessary for the charging stations of PHEVs. A proper analysis helps in preventing excessive charging loads on power grid. Installing multiple parking infrastructures with adequate charging facilities would also encourage more and more people to purchase PHEVs [22-23].

2.3 Implications of Alternate Renewable Resources

Alternative sources of renewable energies for potential energy production in these HEVs will also have their own environmental impacts. For nuclear energy considerations, the power plant would require water as raw material along with fuel element chemicals, fossil fuels and the necessary transportation facilities and infrastructures. The toxic and contaminated water by-products will cause adverse environmental implications on aquatic life and on the water bodies. Furthermore, the by-products would also contain radioactive water which is detrimental for humans and other species alike. For biomass energy considerations, the extraction of fuel, the production of biomass, the power-plant itself and the related transportation facilities and infrastructures will have their own environmental implications. For hydropower

considerations similarly, reservoirs will too have few implications if not as adverse as the nuclear power-plant considerations. Same goes for other renewable resources like wind energy, solar energy and a mix of multiple renewable resources. The pros and cons must be taken into account with proper elimination of the cons before considering mass production [24-25].

3. Conclusions

Despite the eco friendly advantages of HEVs, they too have many environmental impacts. Theoretically the HEVs provide an efficient and cleaner alternative to ICEVs, but practically the scenario is a bit more complex. Life cycle assessment of these HEVs has revealed many crucial facts. The extraction of the raw materials for the production of these HEVs contributes to CO₂ emissions. This further affects the GWP levels. The by-products of the production and use phase of these HEVs lead to higher values of HTP levels. Similarly the manufacturing and battery production phase lead to higher levels of ODP levels. Acidification and eutrophication are other environmental implications of either the emission of GHG or lignite mining. Apart from the production phase, the operation phase also contributed to the emission of GHG depending on the mode of operation or other traits like traffic etc. Similarly it has also been found that the energy sources of the renewable resources like nuclear energy, biomass etc and their associated infrastructures also have adverse implications. Hence, it is of utmost importance to take into account all pros and cons of HEVs and attempts to eliminate as many as of these cons is quite crucial.

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