International Journal of New Innovations in Engineering and Technology

Comparative Analysis of Greenhouse Gas Emissions and Energy Consumption in Advanced Lithium-ion Battery Technologies using the GREET Model

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Abstract: Lithium-ion batteries have gained enormous attention due to their high charging capacity with incorporation of newly developed materials. These materials have a long cycle life and can handle high temperature generation. The selection of the material is based on the maximum binding energy of these materials which includes cathode ($LiMnO_2$), anode ($Li_{0.167}$ C) and electrolyte ($LiPF_6$). In this research paper using the GREET Model various energy input parameters are analyzed for the cathode, anode, and electrolyte materials. Through the GREET model analysis it has been found for manufacturing of cathode material approximate 3.10 Kg/ton of the GHG emissions are generated, the value for the anode material is 18.49 Kg/ton and 10.49 Kg/ton for the electrolyte.

***Keywords*: Lithium-ion Batteries, Carbon Footprint, GREET Model.**

I. ABBREVIATIONS

$LiMnO_2$	Lithium Manganese Oxide	$Li_{0.167}$ C	Lithium Carbide	$LiPF_6$	Lithium hexafluorophosphate
EV	Electrical Vehicles	Kg/mi	Kilogram per mile	BTU	British Thermal Unit
CO_2	Carbon Dioxide	CO	Carbon Monoxide	mAh/g	(mill ampere-hour per gram).

I. INTRODUCTION

The evolution of lithium-ion battery materials has yielded remarkable strides in terms of sustainability, enhanced charging capacity, elevated electrical conductivity, and significantly extended lifecycle. These advancements underscore a pivotal shift towards more ecologically sound and efficient energy storage solutions. The novel materials have demonstrated an exceptional propensity to align with sustainable practices while concurrently exhibiting a remarkable boost in charging capabilities. Their heightened electrical conductivity is a testament to their optimized energy transfer efficiency, contributing to enhanced overall battery performance. Additionally, the pronounced extension of the lifecycle speaks to their durability and resilience, effectively minimizing the need for frequent replacements. In essence, these material innovations mark a transformative leap in lithium-ion battery technology, propelling us closer to an era of superior energy storage solutions that align harmoniously with both environmental stewardship and technical prowess. In terms of novel materials, the authors have concentrated on the metal (Nickel) as a cathode material. The authors also concentrated on the long-term viability of incorporating novel materials for better optimizing performance in Battery Management Systems [1]. It has been discovered that among novel materials such as Si, Sn, and Ti, Si is the best material for anode owing to its greater capacity ratio, stability, non-reactivity, and availability in nature, as well as being cost efficient [2]. Enhancements in battery safety have been achieved through advancements in cathode and anode materials coupled with the utilization of non-flammable electrolytes. Flame-retardant additives and novel materials, along with these protective additives against overcharging, contribute to lowering the temperature rise during thermal events and ensuring stability in the electrochemical reactions within the battery system [3]. A new designation, expanded graphite, refers to graphite with a high degree of carbon separation obtained by different chemical, mechanical, and thermal abrasion methods. It has been established that this expanded graphite material has high electrical conductivity, facilitating the movement of electrons across the electrode to increase charging and discharging, improving the overall performance of the batteries [4]. Gel/polymer electrolyte and polymer coating have demonstrated that the disadvantage brought on by polysulfides dissolution in lithium-ion batteries may be removed with the use of composites with carbon materials [5]. The capacity loss at a temperature of 0^{o}C Celsius has been observed to be reduced by 19% when plate free charging is used. The author has also discovered a 21% reduction in charging time. Therefore, using fast charging during the week extends the life of electric cars and reduces the amount of time they need to charge over the winter [6]. The innovative anode materials for lithium-ion batteries include graphene and its derivatives, silicon-carbon composites, nanostructured carbons, and materials with doped carbon [7].

II. GREET MODEL

The Greet model has been developed by Argonne Laboratories, provides data on materials used in the automobile and manufacturing industries. The model also predicts energy consumption for various fuels and Electric Vehicle technologies. Emissions generated by different engine technologies including electric vehicles (Lithium-ion batteries) are presented in tabulated form, and the cradle-to-grave pathways are described. The model has been used by numerous scientists and engineers to validate their results and compare them with existing models, generating valuable insights for society.

Table 1 clear and concise summary of the carbon footprints of different vehicle types and fuel sources, allowing foreasy comparison and analysis.

Sr.No.	Technology	Carbon Footprint (kg/mi)
1.	EV 300 Electricity (Type I Li-ion/NMC 111Light weight Material)	0.1393
2.	Spark Ignition E25 vehicle	0.1139
3.	CIDI HEV LS Diesel	0.057
4.	CNG Spark Ignition vehicles	0.0531
5.	Spark Ignition E40 vehicles	0.1308
6.	Renewable Technology vehicles	0.113
7.	Spark Ignition E85 vehicles	0.1497
8.	Spark Ignition M85 vehicles	0.119

According to the data provided through the GREET model as shown in the table 1, the carbon footprint of various vehicle types ranges from 0.053 kg/mile to 0.1497 kg/mile. These numbers are important because they illustrate the differences in greenhouse gas emissions associated with different vehicle types and fuel sources.

The EV 300 Electricity vehicle (Type I Li-ion/NMC 111 Light weight Material) has the highest carbon footprint of all the vehicles listed, at 0.1393 kg/mile. This may seem surprising, a electric vehicles are often touted as environmentally friendly. However, it's important to note that the carbon footprint of an electric vehicle is heavily dependent on the source of electricity used to charge it. If the electricity comes from coal-fired power plants, for example, the carbon footprint of the EV would be much higher than if the electricity comes from renewable sources such as windor solar. On the other end of the spectrum, the CIDI HEV LS Diesel and CNG Spark Ignition Vehicles have the lowest carbon footprints, at 0.057 kg/mile and 0.0531 kg/mile, respectively. These vehicles are powered by diesel and compressed natural gas, which are considered relativelyclean fuels compared to gasoline.

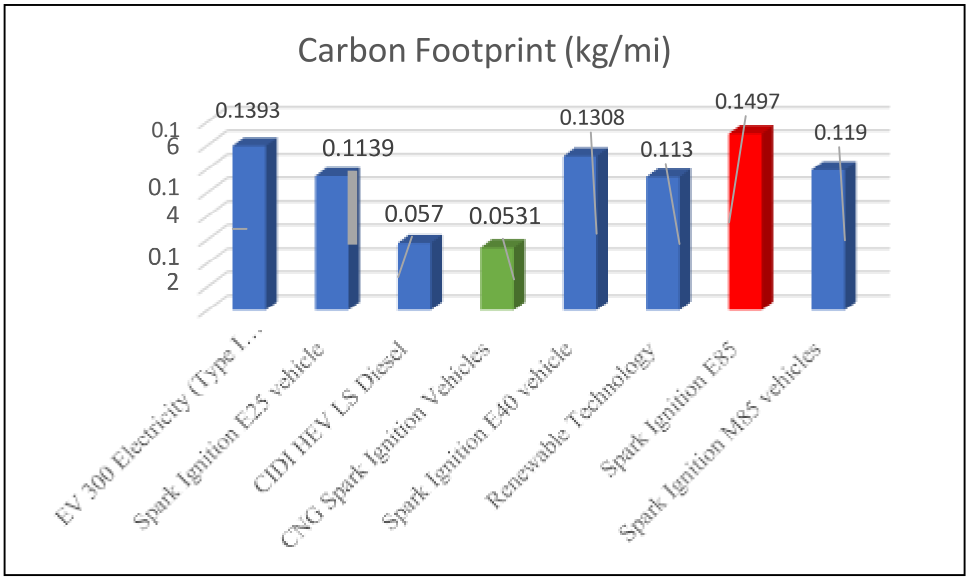

Fig.1. Various Technologies carbon footprint (kg/mil)

The present Figure 1 illustrates a comparative analysis of carbon footprints among various technologies, including Electric Vehicles (EVs) equipped with Lithium-ion batteries. The data within the figure reveals a range of carbon footprint values spanning from 0.0531 kg/mi to 0.1393 kg/mi. Strikingly, the highest carbon footprint value is attributed to Electric Vehicles. This observation might initially appear paradoxical, given the popular perception of EVs as environmentally conscious alternatives. Renewable technologies have a carbon footprint of 0.113 kg/mile, which is in the middle of the range of the vehicles listed. It's unclear what specific technologies are included in this category,but it's likely that they include renewable energy sources such as wind and solar.

III. RESULTS AND DISCUSSION

Table 2 Types of Lithium-ion Materials

Cathode Materials	Anode Materials	Separate Electrolyte Materials
$LiNiCoO_2$	**$Li_{0.167}C$ (372 mAh/g)**	PET (Polyethylene-terephathatate)
$LiMnCoO_2$	$Li_{3.75}Si$	PVDF (Polyvinlyle fluoride)
$LiNiMnCoO_2$	$Li_{4.4}Sn$	PVDF - HFP(Hexafluoropropolyene
$LiNiMnO_2$	Lithium Containing SiC nanocomposite	PI (Polyamide)

$LiMnO_2$ (Maximum Binding Energy – 4.5 (eV) 148 mAh/g		**$LiPF_6$**

Presented in table 2 are diverse configurations of Lithium-ion battery materials. The choice of a specific material configuration hinges on the maximum binding energy characteristic to each cathode, anode, and electrolyte separator. The GREET model, a comprehensive tool for analyzing energy and technology aspects, provides insights into material selection, technological intricacies, and energy considerations throughout the manufacturing process.

In this context, table 2 underscores the pivotal role of binding energy in determining the suitability of various materials for specific battery components. The interplay between cathode, anode, and electrolyte separator materials directly influences the battery's performance, efficiency, and overall lifecycle. By prioritizing binding energy as a selection criterion, this approach ensures the optimization of energy storage and transfer mechanisms within the battery.

TABLE 3 (GREET MODEL - CATHODE MATERIAL ($LiMnO_2$) RESPONSE)

Overall Energy					
Input Response				Output Response	
Lithium Carbonate	0.2043 ton	Natural Gas	13.1842mm BTU	Lithium Manganese oxide	1 ton
Manganese Oxide	0.8731 ton	Electricity	15840 BTU	CO_2	110.40 Kg
				Lithium Manganese oxide	1Kg – 3.4012 Kg (GHG Emission)

Table 3 provides a comprehensive overview of the input and output dynamics associated with the cathode material in the context of Lithium-ion batteries. The focal point of this analysis is the cathode material's production process, revealing a significant environmental consideration: the generation of 1 kg of $LiMnO_2$ is accompanied by the release of 3.4 kg of greenhouse gas (GHG) emissions. Within the realm of Lithium-ion batteries, the cathode serves as a critical component that facilitates the movement of lithium ions during charge and discharge cycles. The cathode material's synthesis involves intricate processes that demand various inputs, encompassing raw materials, energy, and manufacturing procedures. These inputs collectively contribute to the overall environmental footprint associated with cathode production.

TABLE 4 (GREET MODEL - ANODE MATERIAL ($Li_{0.167}C$) RESPONSE)

Overall Energy					
Input Response				Output Response	
Water Process	9586.1142 gal	Coal Average	116.8450 mmBTU	Lithium Carbonate	1 ton
Electricity	5.5718 mmBTU	Sodium Carbonate	2.0749 ton	CO_2	0 gm
Sodium Hydroxide	0.0521	Spondumene Concentrate	7.300 ton	Lithium Carbonate	1Kg – 18.49 Kg(GHG Emission)

Sulphuric Acid	1.7449 ton	Calcium Carbonate	0.7143 ton		

The provided data in table 4 offers a comprehensive glimpse into the intricate energy dynamics associated with a specific process, encompassing both input and output responses. Within this context, various inputs and their corresponding quantities are highlighted, revealing the multifaceted nature of energy consumption. Key input resources include water, electricity, sodium hydroxide, and sulphuric acid, each with their respective consumption values. These inputs play a critical role in facilitating the process, which involves the production of materials like lithium carbonate, sodium carbonate, and calcium carbonate. It has been found out through the GREET Model analysis that for 1Kg of the anode material there is 18.49 Kg of GHG emitted in the environment.

Table 5 (GREET MODEL – Electrolyte Material (LiPF6 Lithium hexafluorophosphate) Response)

Overall Energy					
Input Response				Output Response	
Natural Gas	0 BTU	Electricity	73 mmBTU	***LiPF6***	907.18 Kg
Residual oil	0.3650 mmBTU	Sulfuric Acid	5262 Kg	Lithium Hexa fluoro phosphate (100 mA for standard battery size)	1Kg – 10.49 Kg (GHG Emission)

The data presented in the provided table offers a comprehensive perspective on the overall energy dynamics of a particular process, shedding light on both input and output responses. Within this context, distinct energy sources are examined in terms of their input quantities, and the resulting output responses provide insights into material production and environmental implications. Among the energy sources, natural gas plays a significant role in the process, contributing 0 BTU as an input. In contrast, electricity assumes a more prominent role, accounting for 73 mm BTU in the process. These inputs collectively fuel the intricate mechanisms and stages of the process, underlining the diverse energy mix required for its successful execution. On the input side, residual oil also features, contributing 0.3650 mm BTU. This input source, though relatively smaller, adds to the overall energy matrix driving the process. It has been found out through the GREET Model analysis that for 1Kg of the electrolyte material there is 18.49 Kg of GHG emitted in the environment.

IV. Conclusions

- In conclusion, this research article offers a comprehensive exploration into the comparative analysis of greenhouse gas emissions and energy consumption in advanced lithium-ion battery technologies, utilizing the GREET Model. The study highlights the significant advancements made in lithium-ion battery materials, showcasing their successes in terms of sustainability, enhanced charging capacity, elevated electrical conductivity, and extended lifecycle. The incorporation of newly developed materials has paved the way for more ecologically sound and efficient energy storage solutions, aligning harmoniously with both environmental stewardship and technical prowess.
- The research emphasizes the critical role of material selection in optimizing battery performance and environmental impact. The study delves into the specific binding energy considerations for cathode (LiMnO2), anode (Li0.167 C), and electrolyte (LiPF6) materials, shedding light on their contributions to energy consumption and greenhouse gas emissions. Through rigorous analysis using the GREET Model, the authors provide valuable insights into the energy input parameters associated with these battery components.
- The outcomes of the study, as presented in the GREET Model analysis, reveal the environmental

implications of manufacturing these materials. It is discovered that for the cathode material, approximately 3.10 kg/ton of greenhouse gas emissions are generated, while the anode material results in 18.49 kg/ton emissions and the electrolyte material contributes 10.49 kg/ton emissions.

- This research advances our understanding of the intricate interplay between material selection, energy consumption, and environmental impact in lithium-ion battery technologies. The study's findings provide valuable guidance for the industry to make informed decisions aimed at improving the sustainability and efficiency of energy storage systems. As the demand for advanced energy storage solutions continues to grow, the insights presented in this research hold significance in steering the direction of future battery technology development and deployment.

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