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SOLAR-POWERED MOBILITY: CHARTING THE COURSE FOR A BRIGHTER FUTURE WITH SOLAR VEHICLES

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SOLAR-POWERED MOBILITY: CHARTING THE COURSE FOR A BRIGHTER FUTURE WITH SOLAR VEHICLES

A Project

Presented to the

Faculty of

California State University,

San Bernardino

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in

Information Systems and Technology

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by

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August 2023

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ABSTRACT

Solar-powered vehicles utilize photovoltaic panels to harness solar energy, offering a promising solution to reduce greenhouse gas emissions and promote sustainable transportation. This research project focused on the challenges and limitations of solar-powered vehicles and aims to provide solutions for their widespread adoption. The research questions explored in this study are: (Q1) How do different geographical locations and climate regions affect the feasibility and practicality of solar-powered vehicles due to variations in sunlight availability? (Q2) How has the adoption of solar-powered vehicles contributed to the reduction of greenhouse gas emissions? (Q3) What policies and incentives can promote the adoption of solar-powered vehicles? (Q4) What strategies and technologies promote effective recycling of retired electric vehicle batteries? Through a comparative analysis in Q1, Q2, and data analysis in Q3, and Q4, the research questions were analyzed, and provided the findings for each question as: (Q1) In comparing the two states, California and Washington, solar irradiance varies across regions, with California experiencing higher solar power generation (average just below 8.6MW) compared to Washington state (4.53). Northern US cities have an average annual solar irradiation of 4.0 to 4.6 kWh/m²/day, while southern cities receive 4.7 to 6.1 kWh/m²/day. (Q2) Comparing the categories of transportation with gases, light-duty vehicles contribute 45% of GHG emissions, with CO_2 accounting for 97% of vehicle emissions in the 2021 sample data that are released in the environment and the

composition of these gases that influence harmful emissions, there are significant differences to consider. However, (Q3) The Advanced Clean Cars Rule II (ACC-II) in California aims to achieve 100% zero-emission vehicles by 2035, with an intermediate target of 36% sales of zero-emission vehicles by 2026. In contrast, the California Public Utilities Commission (CPUC) Plan focuses on installing 250,000 zero-emission vehicle chargers, including 10,000 fast chargers, by 2025. (Q4) Battery demand is projected to increase by approximately 3818.42% from 0.01856 TWh in 2020 to 0.7087 TWh in 2030 due to the rise in electric vehicle sales. The conclusion for each question is (Q1) The areas with high solar irradiance (like California (average just below 8.6MW) have the potential to harvest more effective energy. However, in areas (For e.g., Washington with 4.53MW) with low solar irradiance, it is challenging for these vehicles. (Q2) CO2 has the highest contribution (97%) among the gases released with highest the proportion of internal combustion vehicles (Light Duty vehicles {45%}), to reduce greenhouse gas emissions, the shift to zero-emission vehicles and the adoption of solar-powered vehicles presents a perfect opportunity to reduce greenhouse gas emissions. With carbon-neutral operation, enhanced energy efficiency, and seamless integration with renewable energy grids, solar vehicles hold tremendous promise for a cleaner and sustainable future. (Q3) By Implementing effective policies and providing financial incentives, governments can attract investments and accelerate the transition towards solar vehicles for e.g. California plans to install 10,000 direct current fast chargers that demonstrates a progressive strategy for adopting these vehicles. (Q4) The growing demand for electric vehicles has increased the demand for lithium-ion batteries, projected to soar by an astounding 3818.42% by the year 2030, resulting in a strain on critical material supplies. Promoting battery recycling is essential to meet the demand, reduce reliance on new materials, and support a sustainable energy transition. Areas for further study include: Developing vehicles that can harness solar irradiation and combine it with electricity generated from various sources, including roof solar panels, nuclear power plants, and wind, to optimize solar energy utilization. Additionally, exploring energy management systems (EMS) can intelligently regulate energy flow, storage, and consumption in these solar-powered vehicles, ensuring efficient use of the available energy. Also, integrating hybrid systems into solar vehicles will allow them to benefit from multiple power sources, enhancing efficiency and adaptability, regardless of varying sunlight availability. By adopting this approach, the transportation sector can progress towards a greener and more sustainable future.

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to both Dr. Conrad Shayo and Dr. Benjamin Becerra for their exceptional support and guidance during the course of this research project. Dr. Shayo's expertise and unwavering commitment to excellence, as well as his passion for the subject matter, were truly inspiring. Their feedback and guidance were invaluable and played a critical role in the successful completion of this project. I extend my sincere appreciation and gratitude to both professors and for their unwavering support, which was a source of hope and strength throughout this journey.

DEDICATION

I would like to dedicate this project to my loving parents, Mahendra and Rekha Nayak, whose unwavering dedication and sacrifices have paved the way for my brighter future. Their constant support and belief in me have been the driving force behind my journey. Additionally, I would also like to thank my mentors, whose guidance and encouragement have inspired me to pursue my dreams and attain my Master's degree in the USA. In the end, I am immensely grateful to my cherished friends, who have stood by my side, offering their encouragement and companionship throughout this remarkable journey. This project is a testament to the collective influence and support of these exceptional individuals

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CHAPTER ONE

INTRODUCTION

Solar-powered vehicles utilize photovoltaic panels to harness the sun's energy and convert it into the electricity that power the vehicles (Dasolar, (n.d.)). This type of transportation is considered pollution eco-friendly, as it reduces our reliance on fossil fuels and can help address pressing environmental concerns of global warming (Shukla et al., 2019). With the advancements in technology, solar panels are becoming more efficient and cost-effective, which is making solar-powered electric vehicles increasingly accessible to the general public (Hayat et al., 2019).

Solar-powered vehicles rely on solar energy harnessed through photovoltaic panels for direct electric motor power (An, 2021; Dasolar, n.d.). Non-solar powered vehicles, such as battery electric vehicles (BEVs), depend on grid-charged electricity with lower greenhouse gas emissions compared to conventional internal combustion engine (ICE) vehicles (Athanasopoulou et al., 2018; Ma et al., 2012; Hayat et al., 2019). Hybrid electric vehicles (HEVs) integrate an internal combustion engine with an electric motor, offering combined benefits and adaptability (Hannan et al., 2014; Bhadra et al., 2020). Further research is needed to explore the environmental impact and potential of these vehicle types in sustainable transportation practices (Varatharaju et al., 2022).

Recent scholarly research on solar-powered vehicles has identified several key areas for further study. These include facing challenges in the development of solar vehicles because of their high initial cost, limited speed range, and low efficiency of 17% (Hayat et al., 2019). The implementation of charging stations at a large scale for these vehicles faces challenges due to the irregular availability of solar energy, weight, cost and volume as well as factors like manufacturability, uniformity and safety. Not only that but also it is difficult to build power electronic components that are linked with direct DC interconnection of solar PV and EV systems. Economic and performance criteria, as well as range issues restrict battery storage (Shariff et al., 2019).

Current Challenges and Problems

Although hybrid electric vehicles (HEVs) promises the future as a mode of transportation, several challenges must be considered before widely adoption can occur. One major challenge that aligns with this, is the dependability on intelligent systems that are used in HEVs, which are not yet equal to the needs of modern transportation (Hannan et al., 2014). Another major issue is range of these vehicles, which rely on energy that can be harvested through solar cells, which can only create electricity when they are exposed to sunshine (Shukla et al., 2019). These challenges limit the distance that can be traveled with solar vehicles, specifically in areas with limited sunlight or severe weather.

Moreover, increased demand for electrical power to support the growing number of vehicles on the road can also lead to a strain on the existing electrical infrastructure. In many regions, the grid may not be equipped to handle the increased demand for electricity, leading to blackouts or brownouts (reduced voltage) (Pareek et al., 2020). Electronic vehicles make up a small fraction approximately 0.9% in the USA this is due to consumer concerns about the availability of fast charging stations and the time taken by them to charge an electric car and safety issues (Bryden et al., 2018). In view of the current challenges that prevent solar vehicles to fully adopt on the roads, the solutions that can be implemented is the main focus of this culminating project.

Research Background

On giving a prompt to ChatGPT (Artificial intelligence chatbot) for the purpose of findings and further study in solar-powered vehicles, it generated the areas covering Solar Panel Efficiency, Energy Storage and Battery technology, Vehicle Design and Aerodynamics, Solar Integration and Charging Infrastructure, Hybrid system and Energy Management, and Environmental Impact and Life Cycle Assessment (OpenAI, 2023). According to Fachrizal et al. (2020), smart charging of electric vehicles can be optimized by considering both photovoltaic power production and electricity consumption. However, further investigation is needed to understand the impact of different geographical locations, climate regions, and mobility behavior on PV smart charging. In conclusion, the authors emphasize the importance of efficient charging strategies to mitigate grid strain and promote the use of renewable energy sources.

Geng et al. (2022), presented a study on the potential of utilizing electric vehicle batteries for a second use in energy storage systems that can reduce the demand for new batteries. However, the author states that due to limited data and modeling, their study has limitations that they suggested for future study including the various energy storage system and the competition among them. Additionally, influences that contribute towards the supply of retired EV batteries for second use were not taken into account. In conclusion, their study highlights that recycling EV batteries for secondary usage in energy storage systems can provide considerable advantages. From a technical perspective, retired EV batteries can still have a considerable capacity for energy storage, making them suitable for stationary applications.

According to Diahovchenko, Petrichenko, Borzenkov, and Kolcun (2022), PV panels mounted on the roofs of electric vehicle can optimize the power management and storage of energy. They emphasized the need of considering factors such as panel curvature, driving patterns, duration of parking and driving stages, and the impact of shadows on energy conversion efficiency. For the future research, they recommended there is a plan to integrate modeling and analysis of vehicle-integrated photovoltaic systems, taking into account various factors that impact their performance. These factors include the curvature of PV panels, driving patterns, duration of parking and driving stages, as well as the effect of shadows on energy conversion efficiency. The authors concluded that the deployment of PV panels on EVs has the potential to increase driving range, reduce reliance on the grid, and contribute to overall transportation sustainability. More research and development are required to improve the efficiency and integration of PV panels with EVs in order to maximize their range of extension possibilities.

Problem Statement

Several challenges and problems, including high initial cost, limited speed range, low efficiency (Hayat et al., 2019), unreliable intelligent systems (Hannan et al., 2014), and reliance on sun for energy generation (Shukla et al., 2019), hold back the widespread use of solar-powered cars. Furthermore, the adoption of solar-powered EV charging stations confronts difficulties due to intermittent electricity, cost, weight, and manufacturability (Shariff et al., 2019). The existing electrical infrastructure may also struggle to satisfy the increasing demand for electricity from electric cars, perhaps resulting in blackouts or low voltage (Pareek et al., 2020). According to Bryden et al. (2018), customer reluctance to embrace electric vehicles is fueled by worries about the availability of fast charging stations, charging time, and safety concerns.

The transportation sector is a significant source of greenhouse gas (GHG) emissions, with California producing about 166 million metric tons of CO2 equivalent in 2019. However, California has set ambitious goals to reduce emissions, achieving the target of reaching 1990 emission levels by 2020 and aiming for a 40% reduction by 2030. The state has strengthened the Low Carbon Fuel Standard (LCFS) and is embracing trends such as vehicle electrification, shared mobility, and autonomous vehicles to transform the transportation sector (Li, Li, & Jenn, 2022). In addition to greenhouse gas emissions, conventional vehicles release a range of pollutants, including nitrogen oxides (NOx), particulate matter (PM), and carbon monoxide (CO), which are harmful to human health (Bhandarkar, 2013). The largest share of greenhouse gas emissions is generated by the transportation sector, primarily from burning fossil fuel for cars, trucks, ships, trains, and planes which are mostly petroleum-based (California Air Resources Board,2020).

Table 1: CO_2 Emissions by Category

Scoping Plan Category	**2020 Emissions (MMT CO_2e)**	**Percentage***
Transportation	135.8	36.8%
Industrial	73.3	19.9%
Electric Power	59.5	16.1%
Commercial & Residential	38.7	10.5%
Agriculture	31.6	8.6%

High GWP	21.3	5.8%
Recycling & Waste	8.9	2.4%

According to Sailaja et al . (2022), California is making significant progress in expanding the charging infrastructure for electric vehicles (EVs) to support their widespread adoption. In line with Governor Jerry Brown's objective of having one million EVs on California roads by 2023, Southern California Edison plans to deploy 1,500 charging stations initially and an additional 28,500 stations in the future. San Diego Gas & Electric also has plans for 3,500 new charging stations. Several companies, including Walgreens, Google, Coca-Cola, and automakers such as Nissan, BMW, and VW. Furthermore, BMW and VW have plans to install up to 100 charging stations in "express charging corridors" that span from San Diego to Portland, Oregon, and from Boston to Washington, DC. The auto industry as a whole is embracing EVs, with Ford aiming to electrify over 40% of its lineup by 2020 through a substantial $4.5 billion investment in EVs. Honda also has ambitious goals, with 66% of its lineup set to be electrified by 2020. Recognizing the momentum, Germany's auto industry is striving to catch up with EV leaders like Tesla, GM, Nissan, and BMW. These developments signify the growing commitment to EVs and the infrastructure required to support their mass adoption (Sailaja et al., 2022).

The automotive industry is making continuous efforts to minimize the environmental impact throughout the entire lifecycle of a vehicle, from raw material processing to production, usage, and recovery. To achieve this, eco-friendly strategies are being developed at both production and process levels during the manufacturing stage (Anthanasopoulou, 2018). Additionally, the challenges that are faced by these vehicles and those are related to the reliability of intelligent systems, limited range that can be traveled due to the reliance on sunlight and that depends on the location, current availability of infrastructure of electric charging stations and safety (Hannan et al., 2014; Bryden et al., 2018).

It is difficult to address these challenges and find effective solutions in order to fully realize the potential of these vehicles that can be widely adopted. This requires development in energy storage and battery technology, solar panel efficiency, solar integration, design and aerodynamics, hybrid systems and energy management, and charging infrastructure as well as environmental impact and life cycle assessment (Fachrizal et al., 2020; Geng at al., 2022; Diahovchenko et al., 2020).

Therefore, the purpose of this project is to investigate and present the solutions to the challenges and limitations that are proposed by the previous authors. This project aims to address issues such as energy storage, charging infrastructure, intelligent system reliability, range limitation with different climate conditions, and environmental impacts. By doing so, this study seeks to contribute to the wider adoption and acceptance of solar-powered vehicles that can mitigate the environmental concerns that are incurred with conventional vehicles.

This culminating experience project will contribute to a few of the areas recommended for further study by collecting, analyzing, and presenting solutions in the following areas: (a) energy management, (b) recycling of batteries, (c) range that can be covered with difference weather condition, and (d) mobility behavior, in California throughout the year, (e) incentives/policies to promote these vehicles, and (f) hybrid system and energy management.

Research Questions

Q1:- How do different geographical locations and climate regions affect the feasibility and practicality of solar-powered vehicles due to variations in sunlight availability?

Q2:- How has the adoption of solar-powered vehicles contribute to the reduction of greenhouse gas emissions ?

Q3:- What policies and incentives can promote the adoption of solar-powered vehicles?

Q4:-What strategies and technologies promote effective recycling of retired electric vehicle batteries?

Q5:- How can energy management systems optimize solar energy utilization in solar-powered vehicles?

Q6:- How can hybrid systems be integrated into solar-powered vehicles, and what are the benefits of such integration?

This project will focus on answering questions #1, #2, #3 and #4.

Organization of the Project

This culminating experience project is organized into five chapters as follows: Chapter 1 provided an introduction to the project, the motivation for the study, the problem statement, and the research questions. Chapter 2 will cover the literature review, examining existing research related to the project's topic. This chapter will provide a thorough understanding of the current state of knowledge and highlight gaps in the research that the project aims to fill. Chapter 3 will cover the research methods to answer the questions. This chapter will describe the research design, data collection, and data analysis procedures. Chapter 4 will present the findings of the research, including tables, graphs, and other visual aids to help the reader understand the results. Chapter 5 will discuss the implications of the research findings and provide the conclusion and areas for further research.

CHAPTER TWO

LITERATURE REVIEW

Several studies have been conducted on solar-powered vehicles. This literature review will focus on the extended studies that was found on Google scholar, IEEE, OneSearch, Science Direct and are recommended by the authors for further study in their studies. The areas that will be focused are energy storage and management, impact of PV energy storage in different climate conditions, government policies to promote these vehicles, and recycling of the need of batteries to overcome the problem of the supply chain.

Question: Q1: - *How do Different Geographical Locations and Climate Regions Affect the Feasibility and Practicality of Solar-powered Vehicles due to Variations in Sunlight Availability?*

The performance of solar these vehicles heavily depends on sunlight availability, which can be limited to regions with low levels of solar radiation. Thiel et al., (2022) addressed the implications of energy of photovoltaic integrated on light-duty vehicles and light delivery vans. The authors looked at how several environmental conditions, such as temperature, solar irradiance, and air quality, affect the performance and efficiency of integrated PV systems in electric cars. Thiel et al., (2022) implemented models like simulation model to measure the performance of PV-integrated EVs under various climatic circumstances using a combination of field measurement, laboratory studies, and computer models.

According to Thiel et al. (2022), it is critical to include climatic conditions in the certification or performance labeling of photovoltaic-integrated electric vehicles (PVEVs). This approach is consistent with the planned inclusion of climatic factors in PV module certification in the European Union. Furthermore, the authors note that, unlike internal combustion engine cars, even battery electric vehicles (BEVs) without vehicle-integrated photovoltaics (VIPV) can be severely influenced by climatic circumstances. As a result, taking climatic factors into account in the certification or performance evaluation of both PVEVs and BEVs is critical. For future research, the authors suggested to conduct a test comparing the performance of battery electric vehicles (BEVs) with and without vehicle-integrated photovoltaics (VIPV) to further validate and benchmark the models used in the analysis. Additionally, exploring an extended range of factors and their variability could be considered, and employing global sensitivity analysis methods, as presented in the study, to design a comprehensive assessment of the impacts on PVEV performance.

Salameh et al. 2021, proposed the solution as to incorporate energy storage systems, such as batteries or ultracapacitors, to store excess energy generated during periods of high solar radiation. Another strategy is to integrate other renewable energy sources, such as wind or hydroelectric power, to complement solar energy in powering the vehicle (P. Nunes et al., 2015).

Additionally, with the help of solar tracking systems, that have been proposed to maximize the collection of solar energy by changing the direction of solar panels to follow the sun's movement (Kelly and Gibson, 2009). Furthermore, the use of efficient power management technologies, such as regenerative braking and efficient motor controllers, can increase the energy efficiency of solar-powered cars.

Sailaja et al. (2022), presented a study where they developed flexible solar panel specifically designed for electric vehicles and showed why California state is the bright future to adopt eco-friendly vehicles. Factors contributing to the rise of electric vehicle (EV) sales include falling battery prices, the introduction of more affordable EV models with longer ranges, and the development of improved charging infrastructure. Sailaja et al. (2022), projected that EVs will displace a significant amount of crude oil consumption, with estimates of 2 million barrels by 2023 and 13 million barrels by 2040. According to Sailaja et al. (2022), California is actively working towards promoting EV adoption by deploying thousands of charging stations, with utilities like Southern California Edison and San Diego Gas & Electric leading the effort. Major corporations such as Walgreens, Google, and Coca-Cola are also setting up charging stations.

Question: Q2:- *How has the Adoption Of Solar-Powered Vehicles Contributed to the Reduction of Greenhouse Gas Emissions?*

The environmental effect of conventional automobiles has been the topic of extensive research in recent years. One of the challenging issues is the role greenhouse gas emissions in climate change. According to Environmental Protection Agency (EPA), among all the sectors, transportation sector is the biggest source of greenhouse gas emissions in the United States (EPA, 2021). Not only that, According to International Energy Agency (IEA) research, the transportation sector accounts for around 24% of globally CO2 emissions (IEA, 2019).

According to Massar et al. (2021), the effects related to autonomous vehicles (AVs) are complicated on greenhouse gas emissions, and it rely on various factors, that include vehicle economy, demand of traveling, sources of energy, and behavior of driving. Massar et al. (2021) did a thorough analysis of the existing literature on AVs and their influence on greenhouse gas emissions. The authors concluded that policymakers and stakeholders must examine the issues and support renewable energy sources, implementing AVs into sustainable transportation networks that can make an impact. Future research, according to Massar et al. (2021), should focus on developing tools and techniques that can better understand the impacts of greenhouse gas emissions and building methodologies that can linked with the deployment of autonomous vehicles at various levels. Also, they highlight the need of using a proper approach to acquire a better understanding of this issue.

Ma et al. (2012) conducted an analysis that investigated the numerous factors that contributed to GHG emissions in both BEVs and internal combustion vehicles (ICVs). Vehicles manufacturing procedures, energy sources that are used for generating electricity, vehicle operating, fuel production and end-of-life disposal are among these aspects. The study discovered that BEVs has lower life cycle GHG emissions as compared to ICVs, this is due to the reduced emissions that were associated with BEV operation. The authors analyzed that BEV manufacturing emissions are greater than those of ICVs, owing mostly to the production of lithium-ion batteries. However, the reduced emissions during the operational phase of BEVs, specifically when driven by low-carbon energy, balance the higher manufacturing emissions contribution during the vehicle’s lifetime. Ma et al. (2012) concludes that overall, BEVs have the potential to reduce life cycle GHG emissions compared to ICVs, particularly when powered by electricity from low-carbon sources. The authors emphasize that for the future study, it is up-to-date, primary, and detailed vehicle life cycle inventory analysis would be beneficial in studying a vehicle's actual potential to contribute to reductions in greenhouse gas (GHG) emissions.

Question: Q3: - *What Policies and Incentives can Promote the Adoption Of Solar-Powered Vehicles?*

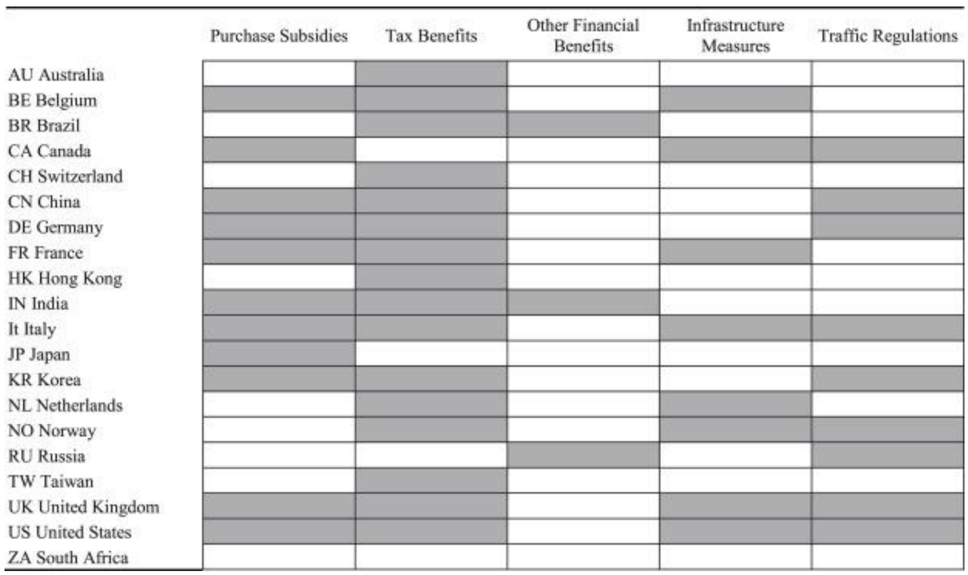

Figure 2.1 National Policy Measures Promoting EVs in 20 Countries

Note: by (Rietmann & Lieven, 2019)

Government policies and incentives have been identified as key factors in promoting the development and adoption of solar-powered vehicles. In the study of Adoption of Environment-Friendly Cars, Consumers' environmental concerns have been shown to influence the likelihood of adopting eco-friendly products accordingly. Moreover, governmental initiatives such as incentives are intended to impact the rate of adoption of environmentally friendly products (Wujin Chu, Baumann, Hamin & Hoadley, 2018). In their study, they have deployed convergence, divergence, and crossvergence (CDC) framework to examine the international perspective of the adoption of Environmentally friendly Cars. The researchers concluded that four out of five markets show concerns and significant efforts to adopt these vehicles. On the contrary, according to researchers' government incentives seem ineffective in encouraging these cars in the same four markets. According to Wujin Chu, Baumann, Hamin, and Hoadley (2018), further research could be extended using a more extensive set of survey items to gain a comprehensive understanding of the adoption of Eco-friendly cars. To deploy solar panels and charging piles in public infrastructure projects, government financial incentives or subsidies may be required. Alternatively, private companies can invest in these projects through the public-private partnership (PPP) mode, as explored by Fang et al., 2019. According to Gorjian et al. (2021), government incentives are crucial in encouraging the widespread use of solar-powered vehicles. Tax credits or rebates for the acquisition and usage of solar-powered vehicles, along with financing research and development initiatives in this field, are among the potential incentives.

Question : *Q4:-What Strategies and Technologies Promote Effective Recycling of Retired Electric Vehicle Batteries?*

Battery recycling is an important part of achieving sustainable growth and lowering the environmental effect of the burgeoning electric vehicle (EV) sector.

Due to the country's increasing demand for EVs and limited indigenous stocks of essential elements like as lithium and cobalt, the potential for battery recycling in India is enormous (Kala & Mishra, 2021).

The study by Mayyas, Steward, and Mann (2019) provides an overview of the case for recycling and discusses the challenges in the material supply chain for automotive lithium-ion batteries. The authors examine the importance of recycling in the context of sustainable materials and technologies. They focus specifically on the recycling process and associated challenges related to automotive lithium-ion batteries. Their study likely delves into the environmental impact of battery materials and the potential benefits of recycling, such as resource conservation and reduction of waste. According to Mayyas, Steward, Mann (2019) While supply chain challenges provide a strong rationale for recycling, the authors state that further research into the reverse supply chain and recycling economics is required to properly understand the potential influence of recycling on future LIB manufacture.

Another study by Li, Dababneh, and Zhao (2018) focuses on the development of a cost-effective supply chain for electric vehicle (EV) battery remanufacturing. They used CLSC model to examine the EV Li-Ion Batteries (LIB) and to extend their lifespan and reduce environmental impact. The authors propose strategies and models for optimizing the cost-effectiveness of the battery remanufacturing supply chain. The future work recommendations from the study by Li, Dababneh, and Zhao (2018) include the following:

1. Consideration of Heterogeneous Batteries: Instead of assuming all batteries entering the supply chain network are homogeneous, it would be valuable to assess the profitability and capability of the network to handle different designs and models of spent batteries concurrently. This would involve considering various types of batteries, their specific processing and material requirements, and developing a multi-product supply chain network model.
2. Development of an Agent-Based Model: An agent-based model could be developed to study the impact of consumer behavior, the quality levels of spent batteries, and capacity ratings on the supply chain. This would provide insights into how these factors influence the dynamics and performance of the supply chain network.
3. Study of Remanufacturing Processing Requirements: Analytically studying and modeling the remanufacturing processing requirements as a function of the quality level of the spent batteries would enhance understanding. This analysis could help optimize the remanufacturing process and identify efficient approaches based on the quality level of the batteries.

CHAPTER THREE

RESEARCH METHODOLOGY

For this project, resources like Google scholar, CSUSB OneSearch, and Government datasets for analysis that have been collected and used. This project will focus on answering the questions that are listed in Chapter 1.

Dataset

For each question posited in chapter 1, there are different datasets that has been gathered from different sources. The datasets collected will be analyzed to answer the questions.

To answer the question #1: *How do different geographical locations and climate regions affect the feasibility and practicality of solar-powered vehicles due to variations in sunlight availability?* This project will use quantitative data for Solar power irradiation that has been gathered and that target California and Washington state Solar in the year of 2006 by NREL Transforming Energy. The study will provide a comparative analysis between the two states. And using that data the solar radiation throughout the year 2006 between day 1 and 365 will be visualized with graphs to show the trends.

For Q#1, the dataset has been collected from NREL Transforming Energy which consists of the data as shown in figure 2.

1	LocalTime	Power(MW)
122	1/1/2006 10:00	2.7
123	1/1/2006 10:05	3.1
124	1/1/2006 10:10	2.8
125	1/1/2006 10:15	3.2
126	1/1/2006 10:20	4
127	1/1/2006 10:25	4.3
128	1/1/2006 10:30	4.7
129	1/1/2006 10:35	4.7
130	1/1/2006 10:40	4.8
131	1/1/2006 10:45	3.4
132	1/1/2006 10:50	3.9
133	1/1/2006 10:55	4.4
134	1/1/2006 11:00	4.1
135	1/1/2006 11:05	3.8
136	1/1/2006 11:10	3.3
137	1/1/2006 11:15	3.1
138	1/1/2006 11:20	3
139	1/1/2006 11:25	2.8
140	1/1/2006 11:30	2.6
141	1/1/2006 11:35	2.7
142	1/1/2006 11:40	2.8
143	1/1/2006 11:45	3

Figure 3.1: California State Solar Radiation Power in 2006 (Source: - https://www.nrel.gov/grid/solar-power-data.html)

To answer the question #2: *How has the adoption of solar-powered vehicles contribute to the reduction of greenhouse gas emissions?* Massar et al. (2021) used systematic review followed by the guidelines established by Kitchenham and Charters (2007), which involved tasks such as establishing a review protocol, selecting primary studies, extracting and synthesizing data, and reporting the findings. This project will provide the visualization of the data by Sampling the data from the United States Environmental Protection Agency (EPA) website that has been achieved to explore the category of vehicles that contribute towards the carbon footprint. EPA provides analysis and findings of greenhouse gas emissions by each category of transportation.

For Q#2, two datasets will be used to examine the results Table 2 and Table 3. shows the sample of data the will be used to answer this question.

Table 2. Vehicle Type Breakdown and Growth Trends from 1990 to 2021 (Source:- epa.gov https://www.epa.gov/system/files/documents/2023-05/420f23015.pdf)

Source	**1990**	**2005**	**2017**	**2018**	**2019**	**2020**	**2021**	**Absolute**	**Percent**
On-Road Vehicles	1202	1637.9	1535.1	1557.9	1549.1	1374.1	1496.4	294.4	24.5
Passenger Cars	648.4	564.4	392.7	398.7	395.5	341.7	374.2	-274.2	-42.3
Light-Duty Trucks	302.5	659.5	716.2	720.6	711.8	615.4	671.8	369.4	122.1
Motorcycles	3.4	5	7.2	7.4	7.5	6.7	7.5	4.1	120.9
Buses	13.4	17.7	23.4	24.4	24.8	23.6	25.7	12.3	91.5
Medium- and Heavy-Duty Trucks	234.3	391.3	395.6	406.7	409.5	386.7	417.1	182.9	78

Table 3. Greenhouse Gas Emissions by Vehicle Type in Metric Tons (MT) (Source:- epa.gov https://www.epa.gov/system/files/documents/2023-05/420f23015.pdf)

Source	**CO_2**	**CH_4**	**N_20**	**HFCs**	**Total**	**Percent**
On-Road Vehicles	1459.4	1	9.4	26.6	1496.4	74.3
Passenger Cars	365	0.3	1.9	7	374.2	18.6
Light-Duty Trucks	654	0.5	4.2	13	671.8	33.3
Motorcycles	7.4	0	0.1	0	7.5	0.4
Buses	25.1	0	0.2	0.4	25.7	1.3
Medium and Heavy-Duty Trucks	407.8	0.1	3	6.3	417.1	20.7

To answer the question #3: *How can government policies and incentives promote the development and adoption of solar-powered vehicles?* This project will looked into the data of policies and Incentives that government currently promote for the widespread adoption of these vehicles.

For Q#3, sample of data of policies is shown in Table 4.

Table 4. Incentive/Policies Data in the USA (Source:- International Energy Agency (IEA) https://www.iea.org/data-and-statistics/data-tools/global-ev-policy-explorer)

Country/Economy	Level	Policy type	Key policy measures and targets	Year announced	Category	Source
United States	National	Legislation	Subsidies in the form of tax credits for commercial	2023	M/HDV	Government of the United States

			EVs (Commercial Clean Vehicle Credit).			
United States	Subnational	Legislation	250 000 electric vehicle charging stations by 2025 (as indicated in the Executive Order B-48-18).	2018	EVSE	California Public Utilities Commission
United States	National	Legislation	Eligible commercial projects can receive 30% of the project cost, with fixed grants available for residential projects, both in the form of tax credits (Alternative Fuel Infrastructure Tax Credit).	2023	EVSE	Government of the United States

To answer the question #4: *What strategies and technologies promote effective recycling of retired electric vehicle batteries?* Using the dataset the possible trends in the graphs can be predicted to study the market of Electric vehicles that uses the batteries and how these batteries demand is increasing in parallel with the demand and using of battery powered vehicles.

For Q4, a dataset will be used that shows the sales increased of battery powered electric vehicles throughtout years along with the data demand of batteries in the USA from 2020 through 2030 to answer the question.

USA	EV sales	Cars	BEV	2010	Vehicles	1200
USA	EV sales	Cars	BEV	2011	Vehicles	9800
USA	EV sales	Cars	BEV	2012	Vehicles	15000
USA	EV sales	Cars	BEV	2013	Vehicles	48000
USA	EV sales	Cars	BEV	2014	Vehicles	63000
USA	EV sales	Cars	BEV	2015	Vehicles	71000
USA	EV sales	Cars	BEV	2016	Vehicles	87000
USA	EV sales	Cars	BEV	2017	Vehicles	100000
USA	EV sales	Cars	BEV	2018	Vehicles	240000
USA	EV sales	Cars	BEV	2019	Vehicles	240000
USA	EV sales	Cars	BEV	2020	Vehicles	230000
USA	EV sales	Cars	BEV	2021	Vehicles	470000
USA	EV sales	Cars	BEV	2022	Vehicles	800000

Figure 3.2. EV Sales of BEV and PHEV Data (Source:- International Energy Agency https://www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer)

Analysis:

For the analysis, SQL and Power BI are used to read the database file. Moreover, I used Extract, Transform, and Load (ETL) tool to gather multiple sources of data in one place and perform operations. Since the collected data was 5-minute solar data with more than 100K rows in it. I performed SQL queries to make it average day-to-day solar power throughout the year. That resulted in 365 days of peak, average and low solar power data.

Steps Involved in Data Analysis

1. Collect the data for each questionnaire with specific detailing.
2. For Insert queries and perform analysis, SQL server Integrated with PowerBI are used.
3. Clean the data and make it more purposeful by implementing operations in SQL.
4. Queried data to filter out from 5 minutes data to a day of analysis.

CHAPTER FOUR

DATA ANALYSIS AND FINDINGS

This chapter presents the data analysis and findings from the datasets presented in Chapter 3.

Figure 4.1 through figure 4.3 will answer question #1.

How do different geographical locations and climate regions affect the feasibility and practicality of solar-powered vehicles due to variations in sunlight availability?

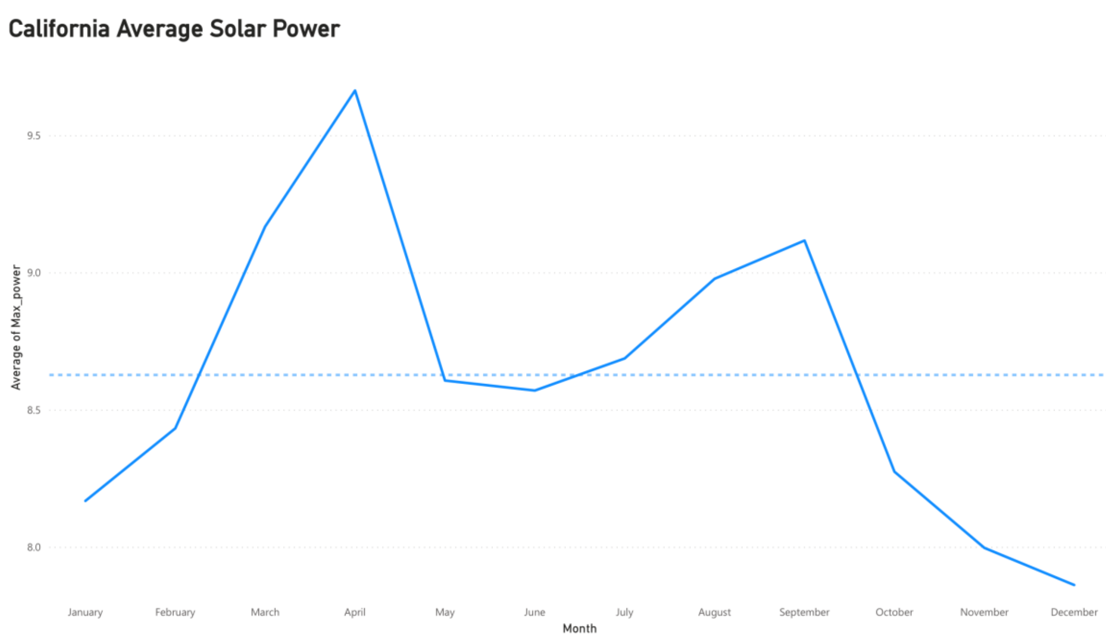

Figure 4.1: Solar Irradiation Throughout the year 2006 in California

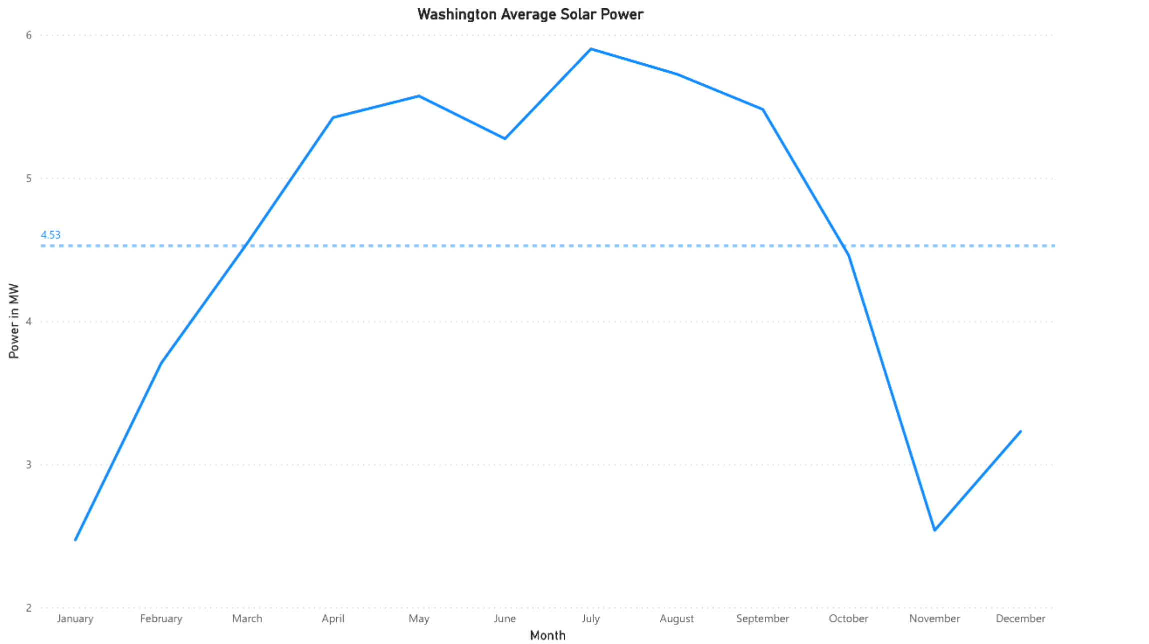

Figure 4.2: Solar Irradiation Throughout the year 2006 in Washington

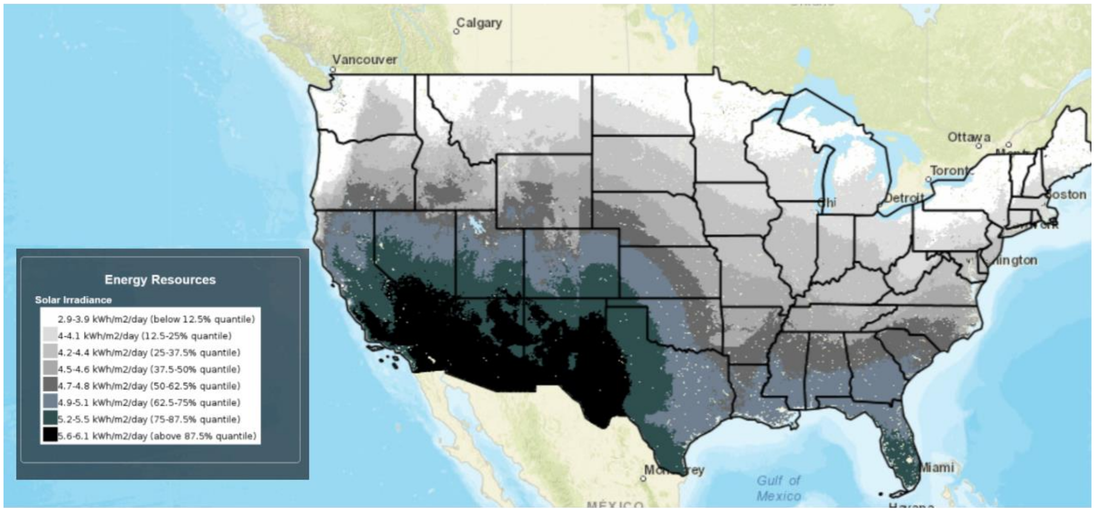

Figure 4.3: US Global Solar Radiation (Tool :- https://www.sciencebase.gov/catalog/item/5f63a09682ce38aaa23affcd?content-type=text/html)

Findings:

In figure 4.1, it was determined the rise of solar power from the month January to April is quite obvious due to the high intensity of sun beam on the earth surface. From April to September, the solar power is assumed as average because of the rainy season. The global annual average for solar power in California was just below 8.6MW. Comparing this with Washington state, then the average global solar irradiance in Washington is 4.53 as shown in figure 4.2. This is due to the climate which is generally cloudier and receives higher rainfall compared to California. According to Figure 4.3, the average annual solar irradiation in the northern part of the United States, including cities like New York, Chicago, and Boston, ranges from approximately 4.0 to 4.6 kilowatt-hours per square meter per day ($kWh/m^2/day$). In contrast, the southern part of the United States, encompassing cities such as Los Angeles, Houston, and Miami, experiences an average annual solar irradiation ranging from approximately 4.7 to 6.1 kilowatt-hours per square meter per day ($kWh/m^2/day$).

Figure 4.4 through 4.6 will answer question #2.

How has the adoption of solar-powered vehicles contributed to the reduction of greenhouse gas emissions?

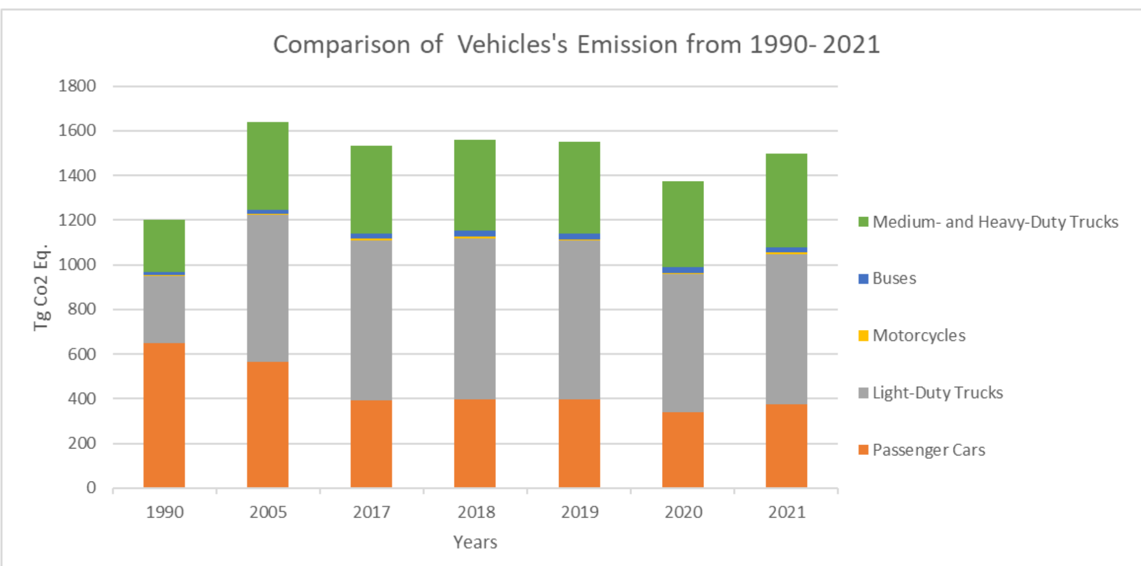

Figure 4.4: Comparison of Vehicles Emission Range 1990-2021 (Source: - epa.gov https://www.epa.gov/system/files/documents/2023-05/420f23015.pdf

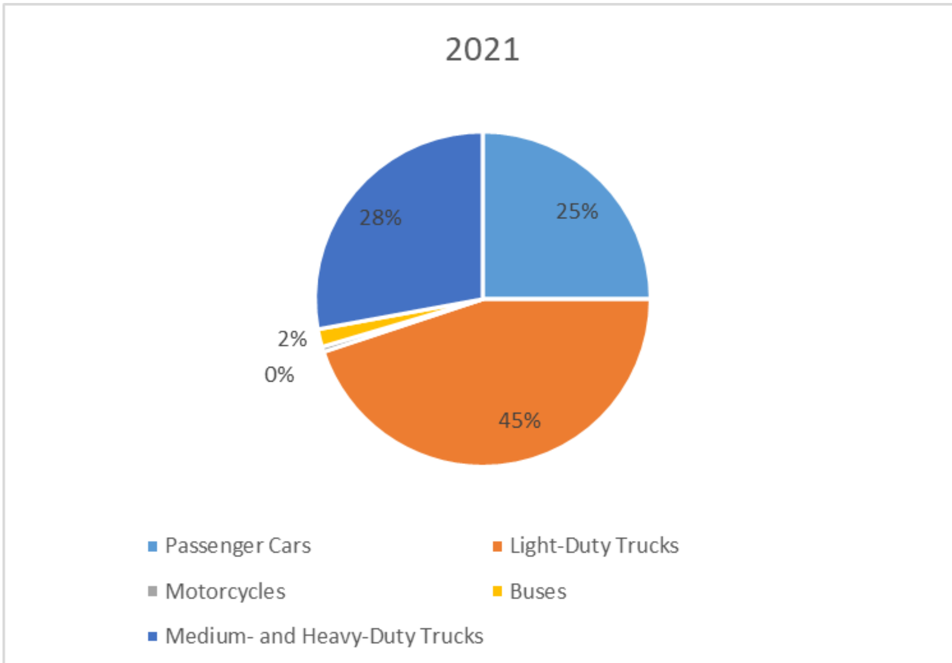

Figure 4.5: Percentage of Each Vehicle GHG Emission in 2021 (Source: - epa.gov https://www.epa.gov/system/files/documents/2023-05/420f23015.pdf)

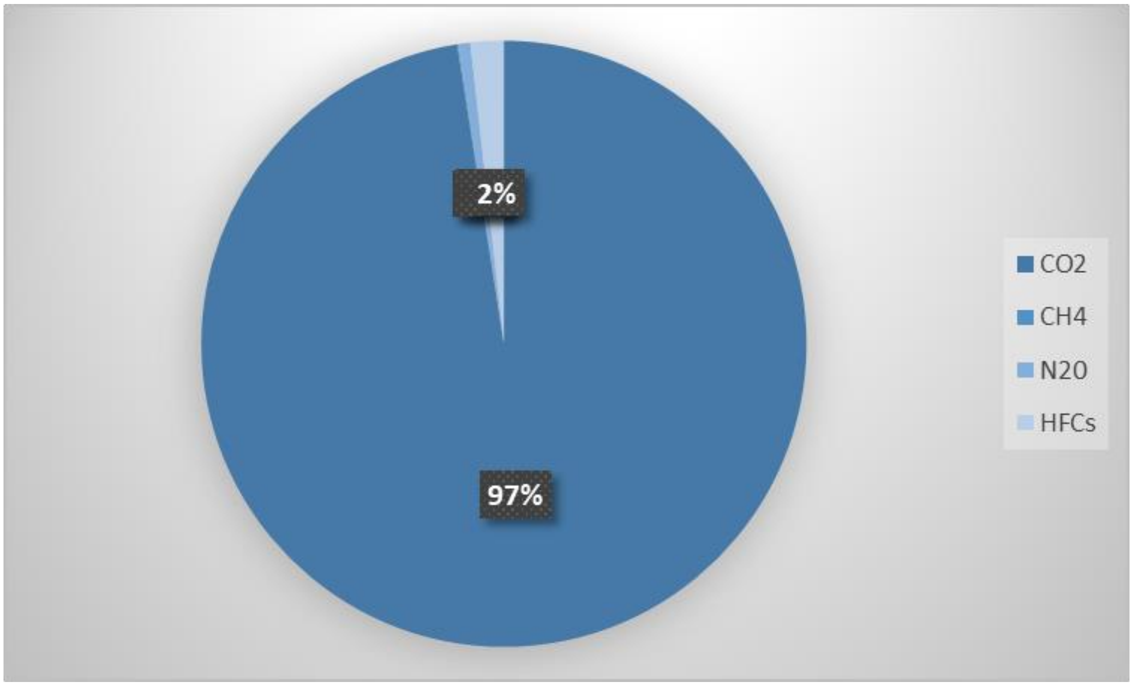

Figure 4.6: Different Emitted Gases in the year 2021 (Source: - epa.gov https://www.epa.gov/system/files/documents/2023-05/420f23015.pdf)

Findings:

In comparing the vehicles, light-Duty vehicles were among the highest contributed towards the GHG emissions. With the sample data of 2021, light-duty vehicles were 45% of GHG emissions followed by Medium and Heavy-duty vehicles that made up to 28% and then passenger cars that accounted for 25% (figure 4.4).

Of the vehicle's gas emissions, these gases can be categorized into Co2, CH4, N2O, and HFC (hydrofluorocarbons). Among these gases, CO2 has overall accounted for 97% according to the data sample of 2021 GHG emissions that are caused by the combustion of fuels (figure 4.5).

For Q#3, the policies have been reviewed

What policies and incentives can promote the adoption of solar-powered vehicles?

Upon conducting the study on government initiatives that have been taken on energy-efficient vehicles in north America, there are total 38 policies that were accounted from the dataset found in IEA.org.

The Policies and incentives for zero emissions vehicles that are published by the international Energy Agency (IEA), is an informative resource that sheds light on the necessary policies for supporting the widespread use of electric vehicles (EVs) worldwide.

These policies cover a wide range of topics and provide measurable outcomes. For example, fiscal incentives such as purchasing subsidies, tax rebates, and exemptions that can significantly increase the adoption of EV. Advanced Clean Cars Rule II (ACC-II) that was proposed by the California Air resources board that has set the target for 100% Zero-emission vehicles by 2035, starting with 36% sales requirement in 2026. The purpose of the regulation is to reduce air pollutants that cause health problems and climate change.

Another Legislation policies area that was highlighted by California Public utilities commission in December 2018 that, by 2025, 250,000 zero-emission vehicle chargers will be installed that will also include 10,000 direct current fast chargers.

For Q#4, figure 4.7 through 4.8 will answer the question.

What strategies and technologies promote effective recycling of retired electric vehicle batteries?

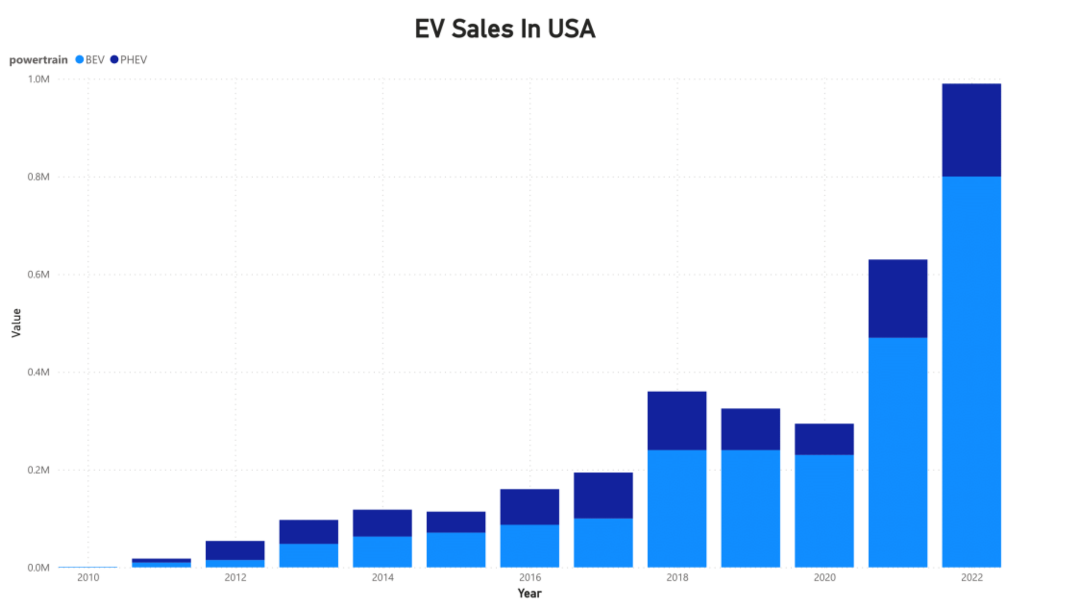

Figure 4.7, Sales of Battery Electric Vehicles and Plug-in Hybrid Vehicles from 2010 – 2022.

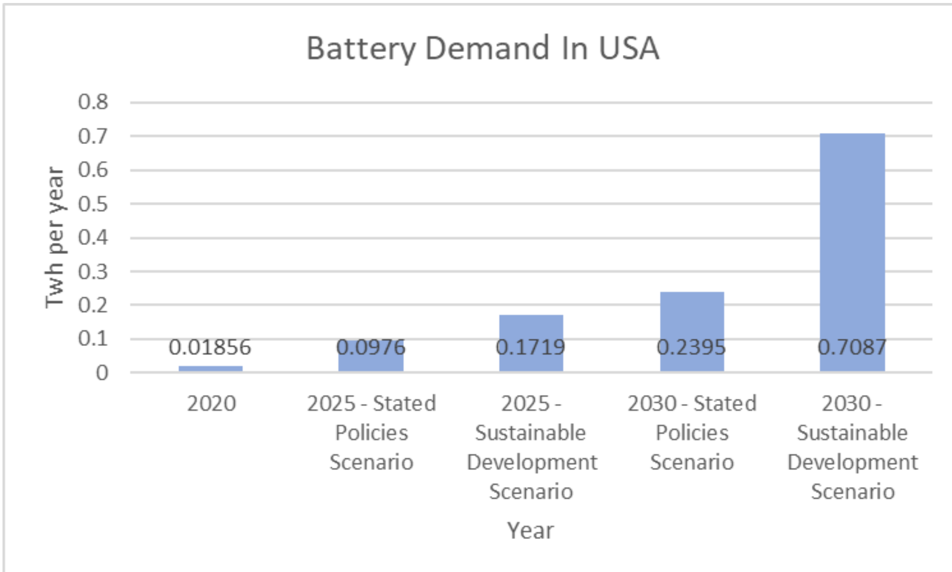

Figure 4.8 Demand of Batteries in the USA (Source: - IEA (2023), Global EV Outlook 2023)

Findings:

Throughout 2010 and 2022, there has been a significant increase in electric vehicle sales in the USA. With the increment in the sales of battery electric vehicles and plug-in hybrids electric vehicles the manufacturing of batteries and the demand for batteries also increased. According to fig. 4.8, the demand for batteries in TWh was 0.01856 in 2020 in the USA, and by 2030 it is expected to be 0.7087 which is approx. 3818.42% increment of demand.

CHAPTER FIVE

DISCUSSION, CONCLUSION AND AREAS FOR FURTHER STUDY

Chapter 5 discusses the research findings, conclusions and areas for future study.

Discussion

The questions that are discussed in the project:

Q1: - How do different geographical locations and climate regions affect the feasibility and practicality of solar-powered vehicles due to variations in sunlight availability?

Q2: - How has the adoption of solar-powered vehicles contributed to the reduction of greenhouse gas emissions?

Q3: - How can government policies and incentives promote the development and adoption of solar-powered vehicles?

Q4: - What strategies and technologies promote effective recycling of retired electric vehicle batteries?

The findings and conclusions for each question are:

Q1. The data presented in Figures 4.1, 4.2, and 4.3 highlight the differences in solar irradiance in various regions of the United States. California experiences higher solar power generation, with an annual average of just below 8.6MW, while Washington state has a lower average global solar irradiance of 4.53. The northern part of the United States, including cities like New York, Chicago, and Boston, shows an average annual solar irradiation ranging from approximately 4.0 to 4.6 kWh/m²/day. In contrast, the southern part of the United States, encompassing cities like Los Angeles, Houston, and Miami, experiences higher solar irradiation, ranging from approximately 4.7 to 6.1 kWh/m²/day. Although the study by Barrit and Salih-Alj (2012) doesn't directly discuss the influence of climatic conditions, it emphasizes the importance of utilizing hybrid backup systems in solar-powered vehicles. This perspective aligns with the idea that hybrid solutions can help overcome challenges associated with seasonal variations and reduced sunlight availability. Thiel et al. (2022), on the other hand, specifically examined the influence of climate conditions on photovoltaics that are mounted over electric vehicles. According to their findings, factors that play a significant role in these vehicles are solar radiation, temperature, and shading. The impact of these factors can affect the efficiency and effectiveness of these vehicles. In conclusion, solar power generation on solar-powered cars is highly influenced by location and weather conditions, which affect efficiency. Seasonal changes and hybrid backup systems are critical for optimal functioning in various regions. Evaluating local climate is crucial for integrating photovoltaics into electric vehicles, leading to successful solar-powered transportation solutions.

Q2. The analysis shows that light-duty vehicles contribute 45% of GHG emissions, followed by Medium and Heavy-duty vehicles at 28%, and passenger cars at 25% (Figure 4.5). CO2 accounts for 97% of vehicle emissions in the sample data for 2021, mainly from fuel combustion (Figure 4.6). Varma et al. (2020) provide support for the for migration from conventional electricity generation method to Solar that contribute to a significant reduction in greenhouse gas emissions compared to conventional vehicles. However, Athanasopoulou et al. (2018) present a contrasting view by emphasizing the need to consider the emissions associated with battery production and charging infrastructure when assessing the overall emissions reduction potential of electric vehicles, including solar-powered ones. In conclusion, the analysis highlights the substantial impact of light-duty vehicles on GHG emissions and the dominance of CO2 in the vehicle sector. Solar vehicles show promise in reducing emissions, especially for light-duty vehicles, but a comprehensive lifecycle analysis is required to fully assess their environmental benefits.

Q3. The Advanced Clean Cars Rule II (ACC-II), outlines long-term objectives, aiming to achieve a complete transition to 100% zero-emission vehicles by 2035 in California. As part of its incremental approach, the policy sets an intermediate target of requiring 36% of vehicle sales to be zero-emission vehicles by 2026. In contrast, the California Public Utilities Commission (CPUC) Plan for Zero-Emission Vehicle Chargers, operates on a shorter timeframe. The plan focuses on the immediate goal of installing 250,000 zero-emission vehicle chargers, including 10,000 fast chargers, by 2025. Most Countries like China becoming the largest market for adopting solar powered vehicles and they provide financial incentives, such as purchase subsidies, public procurement programs, and R&D funding. Fang et al. (2019) agrees with the idea that policies and financial incentives, such as subsidies and tax benefits, are crucial for promoting vehicles. However, Chu et al. (2018) present a contrasting view, highlighting the need to consider consumers' environmental concern and other factors in addition to financial incentives. This suggests that a comprehensive approach, considering various aspects such as infrastructure availability and consumer attitudes, is necessary to drive the adoption of eco-friendly vehicles, including solar-powered ones.

Q4. The analysis shows a remarkable rise in electric vehicle sales in the USA from 2010 to 2022, resulting in a surge in demand for batteries. According to Figure 4.8, battery demand in terawatt-hours (TWh) was 0.01856 in 2020 and is projected to increase to 0.7087 by 2030, a substantial increment of around 3818.42%. The Increase in sales of battery powered vehicles raised the demand for manufacturing of more batteries than ever that are required to run the electric vehicle. Designing EV batteries with recyclability in mind can facilitate the recycling process. Improper disposal or ineffective recycling of EV batteries can result in environmental pollution. The release of hazardous materials during the recycling process, such as heavy metals and volatile organic compounds, poses risks to ecosystems and human health. Mayyas et al. (2019) support the notion that effective recycling processes are crucial to minimize the environmental impact of EV battery manufacturing and disposal. However, Li et al. (2018) presents a contrasting view by proposing a cost-effective supply chain approach that focuses on battery remanufacturing as a means to reduce environmental impacts. These differing perspectives highlight the need for further research and exploration of different strategies to manage EV battery waste and mitigate environmental pollution. Concluding, that the rapid growth in electric vehicle sales and the resulting increase in battery demand. To ensure environmental sustainability, effective recycling and battery remanufacturing should be explored. Striking a balance between rising demand and sustainable practices is crucial for the success of electric vehicles in reducing emissions and advancing cleaner transportation solutions.

Areas for Future Research

Future research should focus on innovative approaches to address the challenges posed by geographical and climatic variations in integrating solar energy into vehicles. By developing cars that can harness solar irradiation and utilize multiple energy sources, such as existing electricity generation, roof solar panels, nuclear power plants, and wind, we can make substantial strides in adopting solar energy in the transportation sector. Additionally, exploring energy management systems (EMS) can optimize solar energy utilization in solar-powered vehicles, intelligently regulating energy flow, storage, and consumption based on varying solar availability. Moreover, integrating hybrid systems into solar-powered vehicles presents an exciting avenue for further investigation, combining solar energy with other power sources to enhance efficiency and tackle limitations associated with varying sunlight availability. By studying and implementing these advancements in solar vehicle technology, researchers and policymakers can create a more sustainable and reliable transportation ecosystem, significantly contributing to reducing carbon emissions, mitigating climate change, and paving the way for a greener future.

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