Environmental Effects of Electric Vehicles - An Overview: Present & Future

Gaurav Patil

INFO-601 | Foundations of Information

Pratt Institute | School of Information

May 6, 2022

Environmental Effects of Electric Vehicles - An Overview: Present & Future

Gaurav Patil

Abstract

Global warming has become a prominent concern in the present day. Lead causes of this problem are carbon & greenhouse emissions. Transportation sector has a significant share in these emissions. EVs have emerged as an alternative means of transportation and are promoted as eco-friendly alternatives for fossil fuel based vehicles. This paper attempts to examine whether EVs are truly eco-friendly. This paper begins with introducing the problem of global warming & its effects and attempts to explain the need for an environmentally sustainable means of transportation. Further, this paper describes the measurement metrics for environmental effects in the context of EVs. Further, this paper attempts to create a lifecycle framework to conduct a case study of EVs to assess their effects on the environment. Within the framework this paper looks at four stages - production, in-use, after-use & recycling, and waste & disposal. Along with the environmental effects this paper also attempts to look at the cultural differences & value systems of people in the context of EVs. Additionally, this paper also tries to discuss the infrastructure and design questions for EVs. Furthermore, this paper explores the Li-ion battery from its origin to its present day version with a look at possible future developments in this technology. This paper then attempts to map the composition of the world energy grid and how it affects the efficacy of EVs to be environmentally friendly. Finally, this paper looks at alternative technologies that are being developed to achieve the goal of environmentally sustainable transportation.

Keywords

Lithium-ion Batteries, Electric Vehicles, Battery Electric Vehicles, Rare Earth Elements, Cobalt, Lithium, Energy Generation, Alternative Fuels, Environmentally Sustainable Transportation.

Introduction

For the past few decades the problem of global warming has become prevailing and needs to be addressed in the near future. The world has already started to feel its effects in the form of several abnormal events. Some noteworthy changes in the environment include erratic monsoons in South Asia, extreme heat waves in Americas, record breaking low temperatures in Europe and droughts in rain-prone regions of Asia. These changes in weather patterns along with the melting ice caps, which inturn translates to the rising sea levels, are some of the prominent effects of global warming. Greenhouse Gasses (GHGs) are attributed as one of the major causes of global warming.

The Intergovernmental Panel for Climate Change (IPCC) recommends reducing the emissions of GHGs to limit global warming to < 1.5 ºC by the year 2050.[1] The main contributor to these emissions is electricity and heat generation with transportation contributing up to 25% of these emissions depending on the geographical location.[2] Hence there is a clear motivation to reduce emissions from transportation and electricity generation for environmental sustainability.

These GHGs have been conventionally emitted by burning fossil fuels. Consequently, Internal Combustion Engine Vehicles(ICEVs) are one of the major causes of emission in the transportation sector. As a result of this many countries have already started to look into several technologies to reduce emissions from these two (transportation & electricity generation) sectors. Several countries have started to transition their power grids towards renewable sources of energy. Further, in order to reduce the emissions in the transportation sector, Electric Vehicles (EVs) are being promoted as a promising solution. In this paper I intend to explore whether that is truly the case and EVs are as eco-friendly and emissions free as they are projected to be.

I have attempted to develop a framework for assessing the environmental effects caused due to EVs. Although I am using this framework for looking at EVs, the same framework or part of it can be applied in some manner for looking at other products as well. This framework takes a look at a complete lifecycle of EVs starting from the production stages including the effects on environment due to mining and processing of mineral resources, operation or in-use stage, after-use & recycling stage, and finally waste & disposal stage. Additionally, I have also discussed other key topics like Li-ion batteries and Energy generation as a part of this framework.

There are several studies done on the life cycle assessment (LCA) of EVs. Some of them are comprehensive and broad in scope while some of them focus on specific aspects of the topic.[3] In this paper I have also talked about value & cultural differences from

[1] Vitta, "Electric Cars – Assessment of 'Green' Nature Vis-à-Vis Conventional Fuel Driven Cars," December 1, 2021.
[2] Vitta.
[3] Lattanzio and Clark, "Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles"; Prantik Dutta, "Assessment of Environmental Implications of Electric Vehicles"; Efstathios E. Michaelides, "Primary Energy Use and Environmental Effects of Electric Vehicles"; Burchart-Korol and Folęga, "Environmental Footprints of Current and Future Electric Battery Charging and Electric Vehicles in Poland"; Vitta, "Electric Cars – Assessment of 'Green' Nature Vis-à-Vis Conventional Fuel Driven Cars," December 1, 2021; Lifang Wu and Wei Yang, "Tackling Supply Chain Challenges of Tesla Model 3"; Smith, "Can EV (Electric Vehicles) Address Ireland's CO.Sub.2 Emissions from Transport?"

several perspectives in the context of EVs, infrastructure questions, and few design aspects, along with the environmental effects. Most of the literature on this topic does not address the differences in culture and value systems around the globe. I have attempted to give my insight on these themes wherever they arise throughout this paper.

Background

In assessing the environmental effects, life cycle assessment practitioners and researchers may focus on several metrics including air quality, water quality and resource availability.[4] When looking at the environmental effects in this paper, the following factors are considered - global warming potential, air pollution potential, human health & ecosystem effects, and resource consumption. The global warming potential is measured through CO_2 emissions, GreenHouse Gasses (GHGs) emissions and carbon formation. Generally, GHG emissions are measured in terms of equivalent carbon dioxide (CO_2) emissions.[5] While measuring the air pollution potential several factors are considered including ozone (O_3) formation, volatile organic compound (VOC) emissions, carbon monoxide (CO) emissions, nitrogen and sulfur oxides (NO_x & SO_x) emissions, particulate matter emissions (PM), and sulfur dioxide (SO_2) emissions.[6] Factors considered when looking at human health & ecosystems include human toxicity, terrestrial acidification, eutrophication, and terrestrial, freshwater and marine toxicity.[7] Whereas resource consumption includes consumption of water, minerals and fossil resources.[8]

Lifecycle

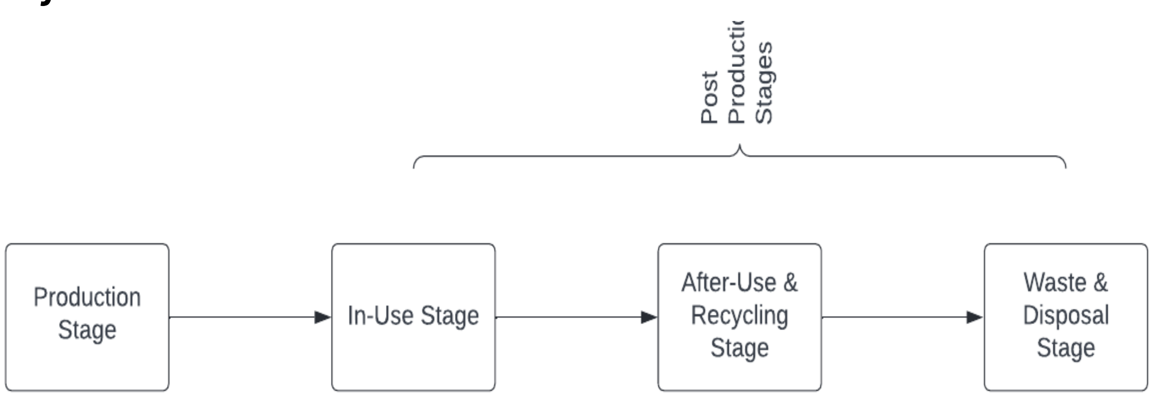

Fig #1: Life Cycle Stages of EVs

[4] Lattanzio and Clark, "Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles."
[5] Lattanzio and Clark.
[6] Lattanzio and Clark.
[7] Lattanzio and Clark.
[8] Lattanzio and Clark.

The lifecycle of electric vehicles (EVs) can be broadly divided into four stages - production stage, in-use stage, after-use & recycling stage and waste & disposal stage. The type and extent of environmental effects, energy use and water exploitation caused due to EVs vary widely based on the type of vehicle, type of fuel, stage in the life cycle of the vehicle and the type of electric grid.[9] This section provides an overview of environmental effects of electric vehicles during these life cycles stages.

1. Production stage

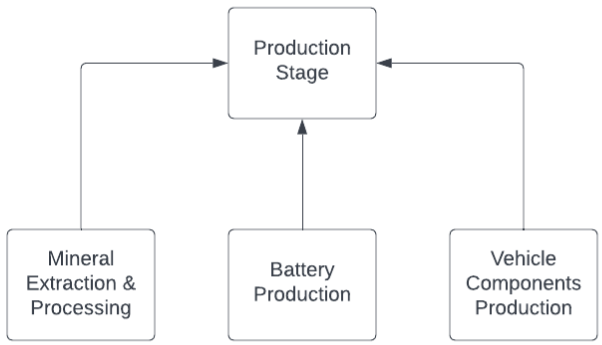

Fig #2: Key Steps in the Production Stage

The production stage includes the processing & extraction of mineral resources, the production of batteries and the production of other vehicle components. In several studies of life cycle assessment of EVs, the material extraction & processing stage is combined with the later stages of vehicle production, but since this process individually has substantial environmental effects and is also very resource intensive requiring large amounts of water and energy (electricity and labor) it is discussed separately here.[10] Most of the environmental effects in the production stages can be attributed to direct material & mineral exploitation.

Ⅰ. Mineral Resources

The production and assembly of EVs is very resource intensive with different components having their own material requirements. The material requirements for this stage has a varied range, including metals like aluminum & steel and raw materials like

[9] Lattanzio and Clark; Prantik Dutta, "Assessment of Environmental Implications of Electric Vehicles"; Burchart-Korol and Folęga, "Environmental Footprints of Current and Future Electric Battery Charging and Electric Vehicles in Poland."
[10] Lattanzio and Clark, "Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles"; Vitta, "Electric Cars – Assessment of 'Green' Nature Vis-à-Vis Conventional Fuel Driven Cars," December 2021; Ona Egbue, Suzanna Long, and Seong Dae Kim, "Resource Availability and Implications for the Development of Plug-In Electric Vehicles."

plastic and carbon fiber for the production of vehicle body parts, metals like copper, aluminum, nickel, iron for critical vehicle components, and minerals like lithium, cobalt, manganese and other rare earth elements (REE) such as dysprosium and neodymium for the production of batteries. The mining, extraction and processing of these minerals have adverse effects on the environment. In the present day, the lithium-ion battery is a core component of an EV, with over 70% of the rechargeable battery market comprising these batteries.[11] The key minerals used in EVs are discussed here.

a) Lithium

Lithium is an extremely essential material for the production of lithium-ion batteries. Most of the world's lithium is found in Bolivia on a high plateau called "The Salar", the world's largest flat surface, which is covered with a few meters of salt crust that is extremely rich in lithium, containing 50% to 70% of the world's lithium reserves.[12] Each Tesla car needs approximately seven kilograms of Lithium for its battery pack.[13] This can give us a sense for estimating the general quantity of lithium that is used in other EVs produced by different manufacturers.

The production of lithium is a water intensive process since it is done more through brine mining than rock mining.[14] Since not much data is available on the water consumption and effects of lithium mining, there is an argument put forth by many people to conduct further research to assess the real environmental impact of lithium mining including its effects on water consumption and wildlife ecosystem.[15]

b) Cobalt

Cobalt is another element which is essential for the production of lithium-ion batteries. While there are battery chemistries for the lithium-ion battery that utilize other minerals, these are not as stable. Half of the cobalt produced in the world goes into electric cars, which require around 4Kgs to 30Kgs per battery.[16] This metal is found all over the world including Australia, China, USA, Russia, Philippines, South-Africa, Canada, Cuba etc., but 70% of the world's total supply comes from the Democratic Republic of Congo (DRC).[17] The artisanal mining industry of cobalt is faced with many human rights challenges ranging from child labor to working conditions of people.[18]

[11] Coffin and Horowitz, "The Supply Chain for Electric Vehicle Batteries."
[12] Emily Achtenberg, "Bolivia Bets on State-Run Lithium Industry."
[13] Merrill et al., "We're Going To Need More Lithium."
[14] Crawford and Joler, "Anatomy of an Ai System."
[15] Agusdinata et al., "Socio-Environmental Impacts of Lithium Mineral Extraction."
[16] WION, *Gravitas Plus*.
[17] "Mineral Commodity Summaries 2022"; WION, *Gravitas Plus*.
[18] WION, *Gravitas Plus*.

While DRC has the world's largest deposit of cobalt, most of the processing of cobalt happens in China.[19] Studies and reports have linked mining of cobalt with several environmental effects such as soil pollution, surface dust, environment hazards due to tailings and slags and high biological endemism for bird species.[20]

c) Aluminum

Since aluminum is relatively light-weight that other compatible metals for production of vehicle components, it is the most apparent choice for manufacture of vehicle body parts in EVs. EVs need to have a lightweight body since the battery, which is the critical component and the powerhouse, is significantly heavy and adds considerable mass to the EV. Aluminum production and processing is energy intensive and leads to the emission of several greenhouse gasses including perfluorocarbons, which makes these emissions more intensive than in the processing of other metals like steel.[21]

d) Rare Earth Elements

The fifteen elements of the lanthanide series in the periodic table with the addition of two other elements yttrium and scandium are considered as rare-earth elements. These REEs are critical for magnets used in the production of batteries and other components in EVs. Contrary to their collective name, many of these elements are moderately available in the earth's crust, with some in greater abundance than copper, lead, gold and platinum.[22] Even though these elements are abundantly available they are sparsely concentrated making the extraction process very costly and polluting.[23]

Ⅱ. Battery Production

The battery production stage is the most energy intensive, requiring about 10% to 75% of manufacturing energy, and having the most proportions of subsequent environmental effects, with upto 70% of the manufacturing GHG emissions depending on the composition of the energy grid.[24] This process includes the preparation of anode & cathode materials, manufacturing of battery cells and assembly of these cells into a

---

[19] WION, *Gravitas Plus*
[20] Banza Lubaba Nkulu et al., "Sustainability of Artisanal Mining of Cobalt in DR Congo"; Kaniki and Tumba, "Management of Mineral Processing Tailings and Metallurgical Slags of the Congolese Copperbelt"; Edwards et al., "Mining and the African Environment."
[21] Dolin, "PFC Emissions Reductions: The Domestic and International Perspective."
[22] Lattanzio and Clark, "Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles"; Crawford and Joler, "Anatomy of an Ai System."
[23] Humphries, "Rare Earth Elements"; Crawford and Joler, "Anatomy of an Ai System."
[24] Nordelöf et al., "Environmental Impacts of Hybrid, Plug-in Hybrid, and Battery Electric Vehicles—What Can We Learn from Life Cycle Assessment?"

battery pack.[25] Since this process is energy intensive, the environmental effects also vary greatly depending on the location and the type of energy grid at the place of production.

Ⅲ. Vehicle Components Production

This stage also depends on the type of energy grid along with the addition of the physical design of the vehicle model. As a general rule, the design of a vehicle dictates how resource intensive the production of its components is going to be. The larger the vehicle the more materials it is going to need for its construction and in turn more energy is going to be expended for this process.[26] Hence the environmental effects of this process vary greatly by the model & design of the EV. Manufacturers can take advantage of the existing infrastructure that is used for the manufacture of vehicle parts for internal combustion engine vehicles, using it to manufacture similar parts in EVs such as the vehicle body & auxiliary systems.[27]

2. In-Use Stage

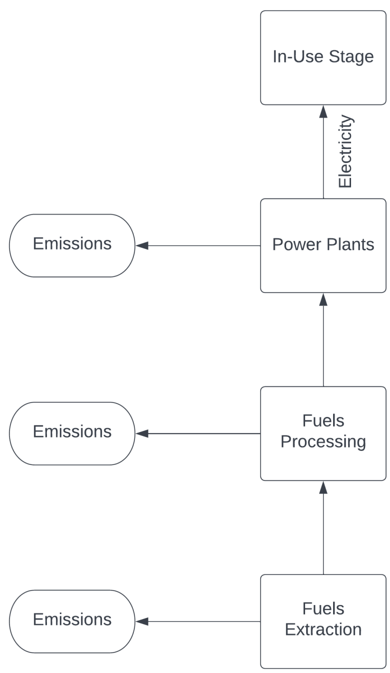

Fig #3: In-Use Stage Emissions

[25] Lattanzio and Clark, "Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles"; WION, *Gravitas Plus*.
[26] Lattanzio and Clark, "Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles."
[27] Lattanzio and Clark, "Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles."

The environmental effects in this stage for any vehicle arise from the type of fuel used by it, in the case of EVs it is electricity or fuel used to generate electricity. While EVs do not emit any GHGs during their operation or in-use stage, emissions may occur during the extraction, refining and transportation of fuels used by the power plants and during the power generation in these power plants.[28] Hence, most of the environmental effects in this stage can be attributed to the composition of the energy grid and the type of fuel used to generate electricity for charging EVs. For instance, results show that the future carbon footprint in Poland for EVs is less than that for petrol vehicles but future water footprint of EVs is greater than for petrol vehicles.[29] In this case the calculations are done with the future projections of the energy grid from 2035 which is expected to be composed of alternate green energy and nuclear sources.[30]

The environmental effects associated with EVs from the in-use stage include effects on terrestrial and aquatic ecosystems, emissions from GHGs, terrestrial acidification, terrestrial and freshwater ecotoxicity and freshwater eutrophication.[31] The emission of nitrogen and sulfur oxides from coal powered electric grids counterbalance the nitrogen oxide savings from the absence of tailpipe emissions in EVs.[32] One noteworthy point in this context is that there are laws and regulations already in place in many countries to mitigate the effects of air pollution and water pollution arising from the refining and consumptions of various fuels.[33]

People from different cultures with varied backgrounds have contrasting considerations when making decisions about using EVs. While people from the global north may consider the adverse environmental effects caused by EVs, people from the global south may have other considerations including monetary reasons. Since the monetary cost of EVs in the operation stage is considerably less than that of ICEVs of similar capacity, this can make EVs attractive to people who want cheaper means of transportation. Many countries from the global south, who do not have considerable local oil reserves, have higher fuel costs which can be a significant burden for its people. This burden is also compounded by the low per capita income in these nations. Understandably, the low operation costs and economic sustainability of EVs make them a readily lucrative choice for people. Additionally, to provide a sustainable means of transportation in these

[28] Efstathios E. Michaelides, "Primary Energy Use and Environmental Effects of Electric Vehicles"; Prantik Dutta, "Assessment of Environmental Implications of Electric Vehicles"; Lattanzio and Clark, "Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles."
[29] Burchart-Korol and Folęga, "Environmental Footprints of Current and Future Electric Battery Charging and Electric Vehicles in Poland."
[30] Burchart-Korol and Folęga.
[31] Lattanzio and Clark, "Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles."
[32] Lattanzio and Clark.
[33] Lattanzio and Clark.

countries (from the global south) a well established support infrastructure is essential for such technologies like EV.

There are several arguments and strategies from studies regarding the infrastructure needed to support EVs.[34] These strategies are aimed at various aspects of the charging infrastructure ranging from studies focusing on improving the efficiency of charging stations to studies more focused on placement of these stations in an urban environment. Studies have found that a two fold increase in charging stations could lead to more than doubling the EV drivers.[35] From these strategies it can be concluded that if we want to scale the use of EVs, one possible solution is to develop and build the support infrastructure for EVs simultaneously with the introduction of EVs in the market. Some countries have already started formulating policies to adopt EVs in their public transportation systems. Some have also started acquiring EVs as a cheaper means of transportation for their citizens. Most of the EVs used for public transportation are Electric Buses but there are also examples of electric bikes, electric scooters & electric rickshaws.

A disparity in value systems can be observed in the assignment of value to the factors, which are considered for using EVs, by people from developed nations vs the people from developing nations. While people from developed nations put a high value on factors like environmental effects, sustainable transportation and energy intensivity; the people from developing nations assign high value to economic sustainability and accessibility. One group is concerned about long term environmental goals while other is concerned about short-term monetary relief. These long environmental goals are focused on the survival of future generations while the short-term monetary relief is focused on the survival in the present.

It can be readily inferred that not all people have the luxury to think about the effects of environmental damage in the future, some people put more value in their needs of the present trying to satisfy them. How people from different demographics perceive “value” is a very subjective question. It is therefore not easy to generalize which assignment of “value” is more valuable in the context of EVs.

---

[34] Jerome and Udayakumar, “A Study on Cost-Effective Electric Vehicle Charging Infrastructure in India Through Open Access Power Procurement”; Ashfaq et al., “Assessment of Electric Vehicle Charging Infrastructure and Its Impact on the Electric Grid”; Wolbertus et al., “Charging Infrastructure Roll-out Strategies for Large Scale Introduction of Electric Vehicles in Urban Areas”; Hemant Harishchandra Kore and Saroj Koul, “Electric Vehicle Charging Infrastructure”; Baum, Darvish, and Schulz, “Mobile AC/DC Test Device for Electric Vehicle Charging Infrastructure Communication”; Zeng et al., “Optimization of Future Charging Infrastructure for Commercial Electric Vehicles Using a Multi-Objective Genetic Algorithm and Real Travel Data”; Schulz and Rode, “Public Charging Infrastructure and Electric Vehicles in Norway”; Desai et al., “Using Connited Vehicle Data for Assessing Electric Vehicle Charging Infrastructure Usage and Investment Opportunities.”

[35] Wolbertus et al., “Charging Infrastructure Roll-out Strategies for Large Scale Introduction of Electric Vehicles in Urban Areas.”

3. After-Use & Recycling Stage

The proportion of environmental effects from this stage is a smaller percentage than that from the other stages of the EV life-cycle, towards the total lifecycle environmental effects.[36] These effects depend on the ways in which the EVs are disassembled, repurposed or reused. This stage involves the process of collection of EVs after they are no longer operational, dismantling these vehicles in parts and separating critical & hazardous vehicle components, like batteries, from the ones that can be reused or repurposed, like tires and vehicle body. The leftover vehicle structures are then shredded.

Recyclable materials are collected from the materials which are separated from vehicles in the previous step of this stage for further processing & recycling. EVs are more material intensive than fuel intensive,[37] and if they are to be adopted in large scale this material intensive portfolio makes recycling a high priority to make their adaptation sustainable as possible. Recycling processes for certain resources, like aluminum, are well established and can significantly reduce the resource intensity in its supply chain. But EV components like batteries are not readily recyclable. Additionally, several methods for recycling these batteries have their drawbacks for example hydrometallurgical recycling is very water intensive, and pyrometallurgical, while cost-effective, is more energy intensive and emits more air pollutants.[38] Consequently, There are some people that emphasize the importance of having efficient recycling processes.[39]. Moreover, the REEs used in the production of magnets in EVs have only limited recyclability.[40]

There are reports estimating the recycling rates for these lithium-ion batteries to be less than 5% in the United States.[41] Studies have shown that recycling and reuse of materials from these batteries can reduce the GHG emission from battery production to 50%, which already has the most emission in the whole lifecycle of EV, as well as reduce the ecological impact of these batteries by more than 20%.[42]

---

[36] Tagliaferri et al., "Life Cycle Assessment of Future Electric and Hybrid Vehicles."
[37] Lattanzio and Clark, "Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles."
[38] Hendrickson et al., "Life-Cycle Implications and Supply Chain Logistics of Electric Vehicle Battery Recycling in California"; Jacoby, "It's Time to Get Serious about Recycling Lithium-Ion Batteries."
[39] Ellingsen and Hung, "Research for TRAN Committee-Resources, Energy, and Lifecycle Greenhouse Gas Emission Aspects of Electric Vehicles."
[40] Tsamis, Strategy, and Llp), "Recovery of Rare Earths from Electronic Wastes."
[41] Jacoby, "It's Time to Get Serious about Recycling Lithium-Ion Batteries."
[42] Hendrickson et al., "Life-Cycle Implications and Supply Chain Logistics of Electric Vehicle Battery Recycling in California"; Unterreiner, Jülch, and Reith, "Recycling of Battery Technologies – Ecological Impact Analysis Using Life Cycle Assessment (LCA)."

Furthermore, there is also active research being conducted on closed-loop recycling, where materials from spent batteries are recycled directly into new batteries in the manufacturing process, this would help in reducing the energy and material resources by eliminating the mining and processing steps.[43] This will in-turn help to ameliorate the negative environmental effect caused by these processes.

Additionally, there is a strong economic incentive for recycling these materials as the recovered minerals can be used to make new batteries, lowering manufacturing costs.[44] Moreover, in many types of Li-ion batteries the concentration of the constituent metals (like Li, Co, Mn etc.) exceed the concentration in natural ores, making these spent batteries akin to highly concentrated and enriched ore.[45] If these metals can be extracted on a large-scale and economically than that from a normal ore, the price of these batteries will drop significantly.[46] This inturn will reduce the prices of EVs. In addition to these economic benefits, recycling these minerals will also reduce the amount of minerals that ends up in landfills.[47]

Apart from recycling these batteries some people are also looking into "second life" or secondary use in stationary energy storage applications for them past their useful life in their intended use for EVs.[48]

4. Waste & Disposal Stage

Since the recycling industry for lithium-ion batteries is not yet developed these batteries end up as waste. Improper disposal of these batteries may add to the environmental effects of this stage.[49] This battery waste is hazardous and toxic in nature and most of the time in several countries it is disposed of by either burning or dumping in landfills, which inturn causes more emissions and ecological damage to the environment. Co, Ni, Mn and other battery metals can readily leak from casings of the buried batteries and contaminate the soil and groundwater, threatening the local ecosystem and human health.[50] The same is true for other salts and solvents used on these batteries.[51] Hence, design of better battery chemistry from sustainable materials which can be recycled will go a long way to mitigate the toxic effects from the batteries of EVs.

[43] "DOE Launches Its First Lithium-Ion Battery Recycling R&D Center."
[44] Jacoby, "It's Time to Get Serious about Recycling Lithium-Ion Batteries."
[45] Jacoby.
[46] Jacoby.
[47] Jacoby.
[48] Stringer and Ma, "Where 3 Million Electric Vehicle Batteries Will Go When They Retire."
[49] Lattanzio and Clark, "Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles."
[50] Jacoby, "It's Time to Get Serious about Recycling Lithium-Ion Batteries."
[51] Jacoby.

Li-ion Battery

The Li-ion battery was born after several years of R&D in the Sony Corporation in the 90's. Li-ion batteries require certain sophisticated minerals materials which makes a broad domain knowledge in material science a necessity for their development. After several years of development work on electroacoustic materials the R&D team at the Sony Corporation focused on investigating novel electrochemical cells.[52] These efforts on utilizing nonaqueous electrolytes resulted in the development of a high-performance cell with $LiCoO_2$ (LCO) cathodes and lithiated carbon anodes - first Li-ion battery system.[53] These batteries have undergone several developmental changes since Sony announced the successful development of first gen Li-ion batteries in 1990. The first gen Li-ion batteries had energy densities of 80 Wh/Kg and 200 Wh/dm^3, whereas the energy densities of the latest versions of these batteries are greater than 230 Wh/Kg and 620 Wh/dm^3.[54]

The present-day technology and assembly practices are represented by BatPaC, with efficiency improvements that yield a more energy-dense battery which is suitable for large-scale production to satisfy growing demand.[55] In BatPaC, Al foil is the current collector at cathode and Cu foil or Al foil is the current collector at anode.[56] BatPaC allows for several choices for the cathode material including lithium manganese oxide, lithium iron phosphate, lithium nickel manganese cobalt oxide or lithium nickel cobalt aluminum oxide.[57] Anode has graphite coats on both the sides and a polymeric material binds together the active-material particles.[58] The battery assembly process uses certain solvents to facilitate contact between materials.[59] A porous polymer membrane separates the two electrodes.[60] An electrolyte composed of $LiPF_6$ and other solvents fills the pores in the separators and active materials.[61] A pouch made up of polyethylene terephthalate, Al and polypropylene encloses the cells.[62] Multiple cells are combined into a module housed in aluminum.[63] This BatPac design is used to construct batteries on a large scale.

---

[52] Nishi, "2 - Past, Present and Future of Lithium-Ion Batteries"; Pistoia, *Lithium-Ion Batteries*.
[53] Nishi, "2 - Past, Present and Future of Lithium-Ion Batteries"; Pistoia, *Lithium-Ion Batteries*.
[54] Pistoia, *Lithium-Ion Batteries*; Nishi, "2 - Past, Present and Future of Lithium-Ion Batteries."
[55] Gaines and Dunn, "21 - Lithium-Ion Battery Environmental Impacts"; Pistoia, *Lithium-Ion Batteries*.
[56] Gaines and Dunn, "21 - Lithium-Ion Battery Environmental Impacts"; Pistoia, *Lithium-Ion Batteries*.
[57] Gaines and Dunn, "21 - Lithium-Ion Battery Environmental Impacts"; Pistoia, *Lithium-Ion Batteries*.
[58] Gaines and Dunn, "21 - Lithium-Ion Battery Environmental Impacts"; Pistoia, *Lithium-Ion Batteries*.
[59] Gaines and Dunn, "21 - Lithium-Ion Battery Environmental Impacts"; Pistoia, *Lithium-Ion Batteries*.
[60] Gaines and Dunn, "21 - Lithium-Ion Battery Environmental Impacts"; Pistoia, *Lithium-Ion Batteries*.
[61] Gaines and Dunn, "21 - Lithium-Ion Battery Environmental Impacts"; Pistoia, *Lithium-Ion Batteries*.
[62] Gaines and Dunn, "21 - Lithium-Ion Battery Environmental Impacts"; Pistoia, *Lithium-Ion Batteries*.
[63] Gaines and Dunn, "21 - Lithium-Ion Battery Environmental Impacts"; Pistoia, *Lithium-Ion Batteries*.

Since more and more technologies have started to depend on these batteries as well as the increase in demand of these batteries, further improvement of this battery technology is needed. For this, it is recognised that investigation of new active materials is essential to further develop the Li-ion battery's performance, including energy density and safety characteristics.[64] To this goal several novel materials are being investigated, these include, Sn-based Anode, Si-based Anode, Ti-based Anode, Li-ion Battery with gelled polymer electrolyte and $LiFePO_4$ cathode for Li-ion batteries.[65]

In addition to these material investigations, development of new technologies is also essential for newer generations of these batteries. Some new technologies that are being developed for this purpose are - Positive Electrode with Excess Lithium, Organic Positive Electrodes and Ceramic-Coated Separators.[66] While these mentioned technologies in development are scientifically attractive, they have certain drawbacks and do not meet certain technical requirements in the present day.

Development of these technologies and resolving the conflicts of these technologies with technical requirements can certainly give a huge boost towards the creation of newer generation of Li-ion batteries. Some of these technologies include organic materials as battery components which may reduce the hazardous environmental effects that arise from the inorganic materials during the lifecycle of these batteries.

In the coming years the following factors will contribute equally in lowering the cost of Li-ion batteries for vehicles - Increased process knowledge and manufacturing scale, Engineering advances in electrolyte, cell, and pack designs & Introduction of new materials with increased performance.[67]

[64] Pistoia, *Lithium-Ion Batteries*; Nishi, "2 - Past, Present and Future of Lithium-Ion Batteries."
[65] Nishi, "2 - Past, Present and Future of Lithium-Ion Batteries."
[66] Nishi.
[67] Gallagher and Nelson, "6 - Manufacturing Costs of Batteries for Electric Vehicles"; Pistoia, *Lithium-Ion Batteries*.

Energy Generation

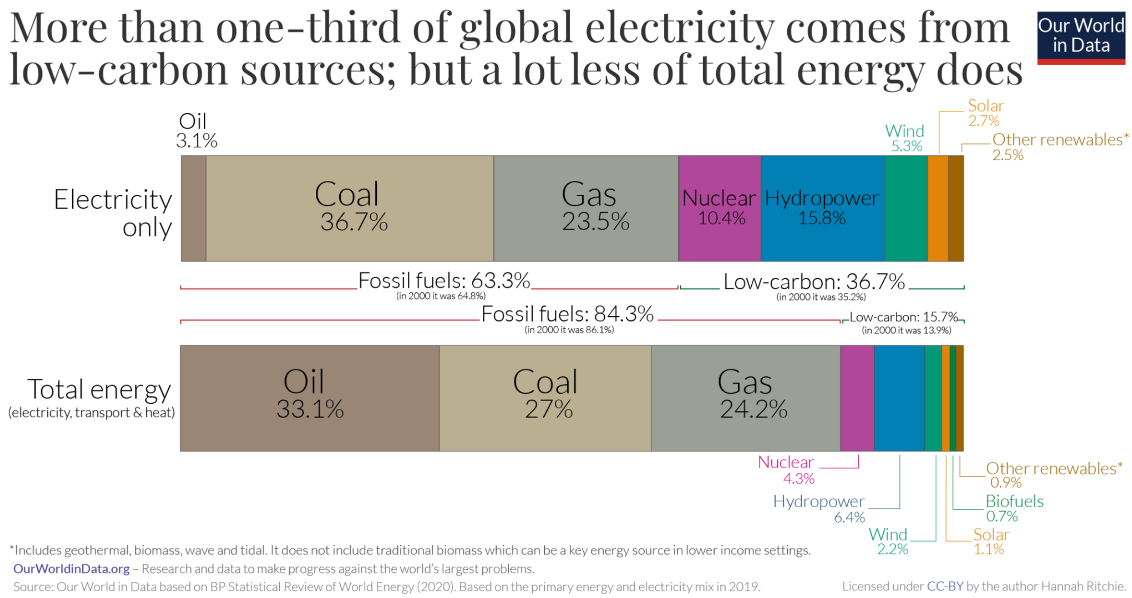

Fig #4: Global Energy vs Electricity breakdown.[68]

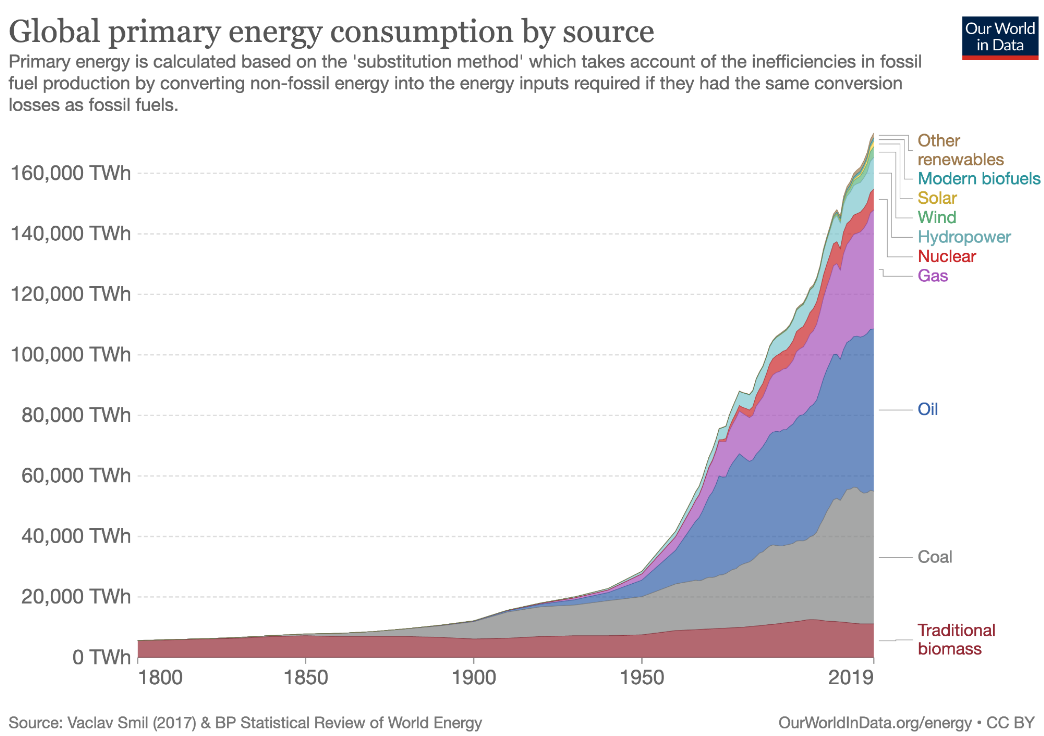

Fig #5: Global Energy Consumption Breakdown.[69]

[68] Ritchie, Roser, and Rosado, "Energy Mix."
[69] Ritchie, Roser, and Rosado.

Almost two-thirds ~63.3% of the global electricity came from fossil fuels in 2019.[70] Of the ~36.7% low carbon sources, renewables accounted for only ~26.3% and nuclear energy for ~10.4%.[71] Although solar, wind and other renewable sources are growing quickly around the world with more countries trying to actively switch their energy grids towards low carbon sources, the percentage of low carbon sources are still very less in the total breakdown of the energy mix.

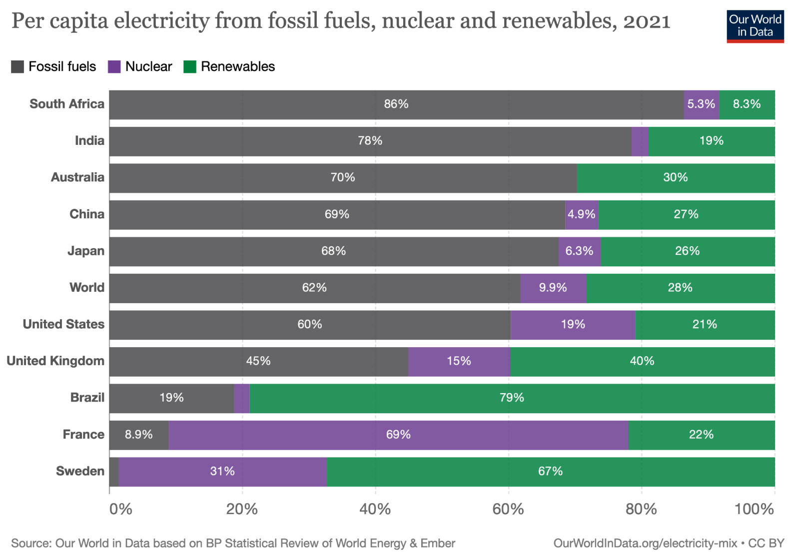

Fig #6: Per capita electricity from fossil-fuels, nuclear and renewables, 2021.[72]

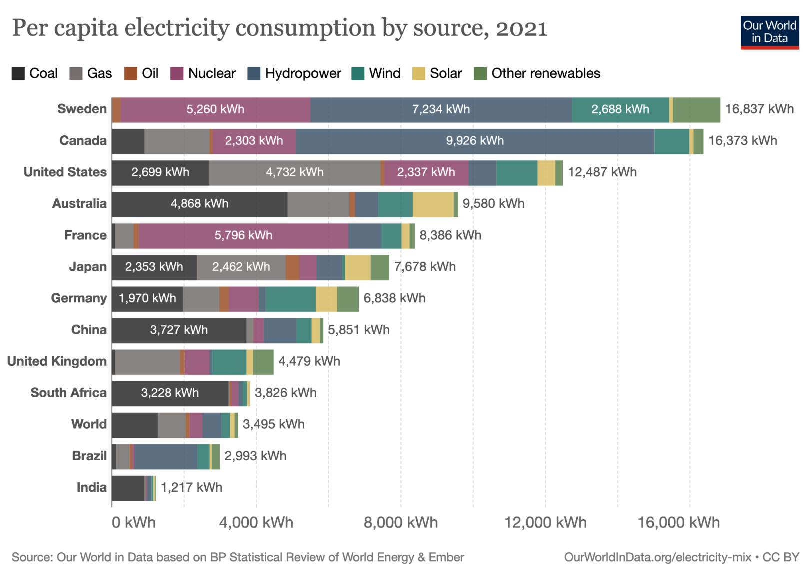

Fig #7: Per capita electricity consumption by source, 2021.[73]

70 Ritchie, Roser, and Rosado.
71 Ritchie, Roser, and Rosado.
72 Ritchie, Roser, and Rosado.
73 Ritchie, Roser, and Rosado.

As you can see in the Fig #6, many of the large consumers of electricity still have a huge dependency on fossil-fuels for satisfying their energy needs. It can be also be inferred from Fig #7 that many European countries have almost switched towards renewable and low carbon sources for electricity generation. While countries such as the USA, China and Germany have a lot of renewable sources along with a considerable amount of fossil-fuel generation. Whereas countries like India are still dependent on fossil-fuels, even though the total energy generation is significantly lower than that of countries in Europe, USA and China.

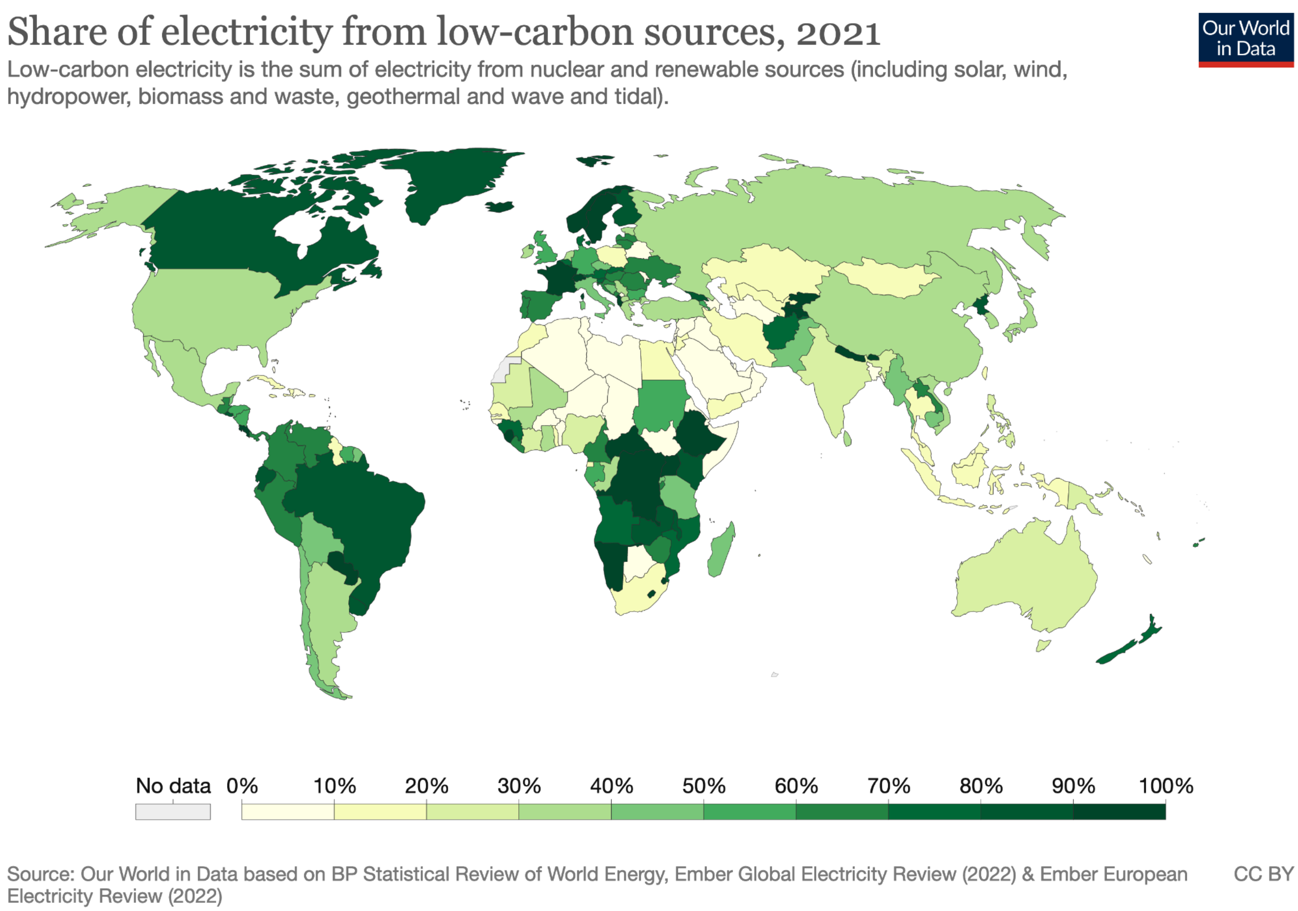

Fig #8: Share electricity from low carbon sources.[74]

[74] Ritchie, Roser, and Rosado.

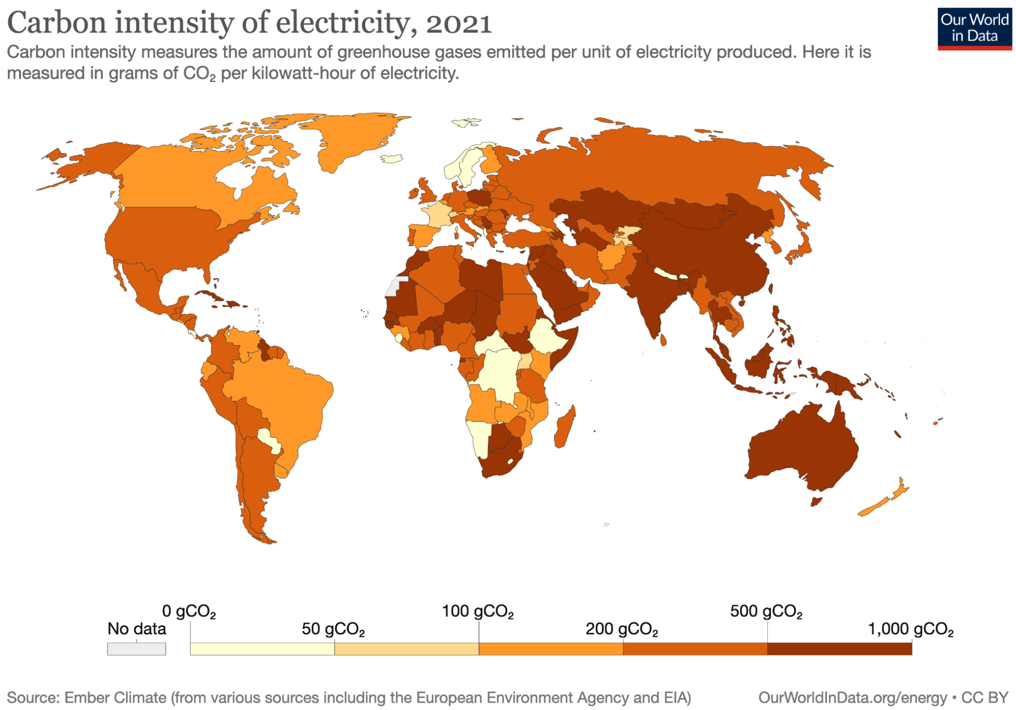

Fig #9: Carbon intensity of electricity, Map, 2021.[75]

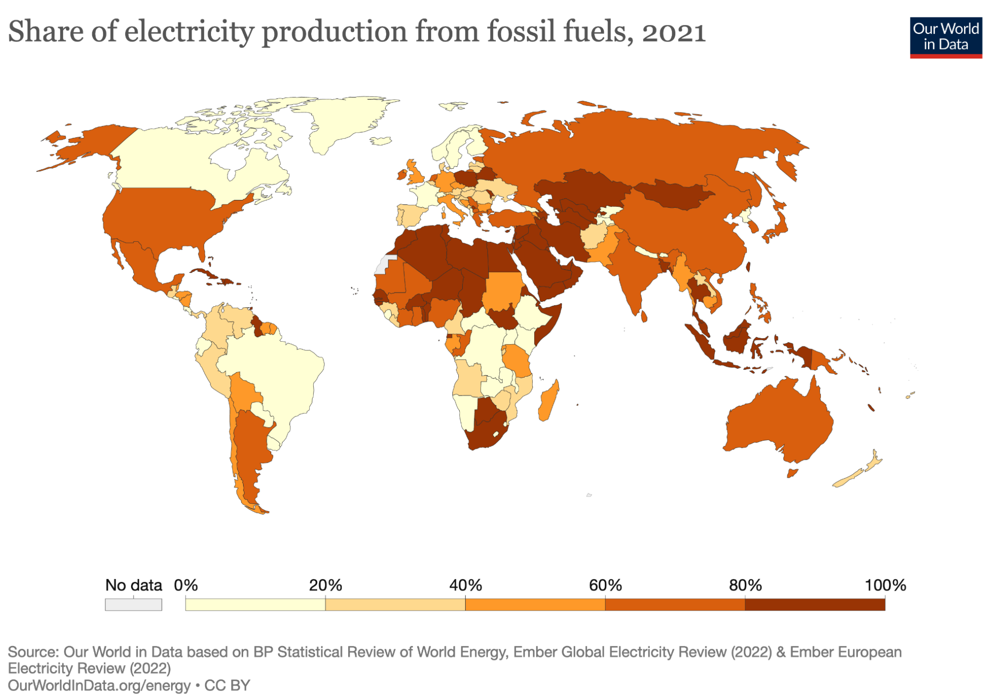

Fig #10: Share of electricity from fossil fuels, Map, 2021.[76]

[75] Ritchie, Roser, and Rosado.
[76] Ritchie, Roser, and Rosado.

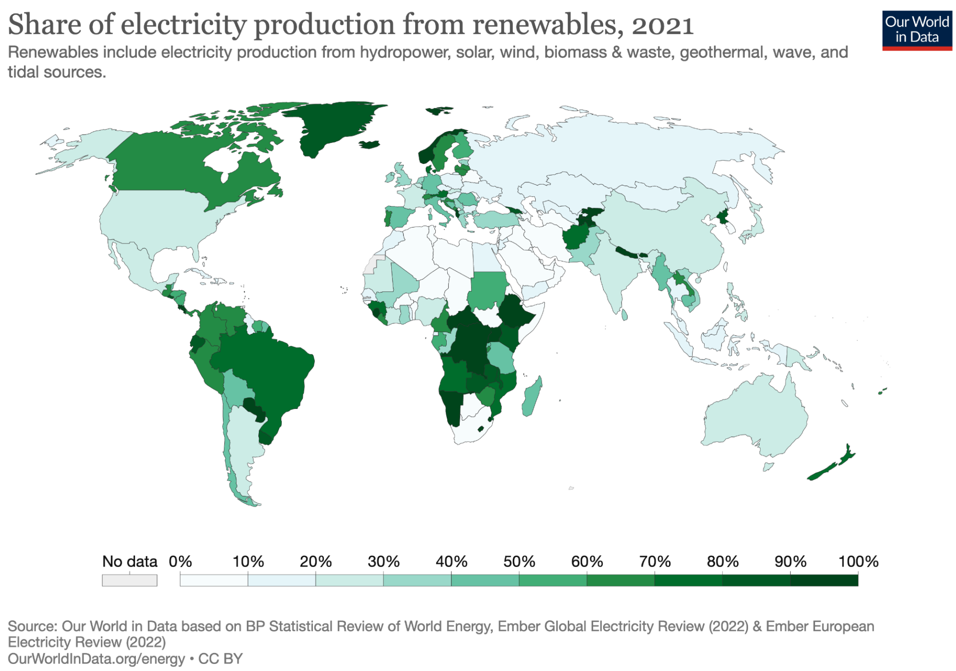

Fig #11: Share of electricity from renewables, Map, 2021.[77]

As you can see from Fig #11, many countries are increasing their renewable sources for electricity needs. Their dependency on high carbon fuels also remains significant as seen in Fig #10. Hence just looking at the numbers of renewables and their growth can be misleading, we also have to take into account the total distribution as well as change in the fossil fuel sources for generation of electricity. This variable distribution of the energy grid around the world makes it difficult to generalize the efficacy of EVs as a solution for environmentally friendly means of transport.

Even if most of the world actively wants to transition towards renewable and low carbon sources for electricity production, it is always difficult to have future projections. Sometimes unforeseen events in global geo-politics or unforeseen trends in the global economy can be the driving factors for several decisions that can change or hinder the transition of countries from high carbon fossil fuels to renewable sources or low carbon sources for electricity generation. For instance, in the present day in 2022 (at the time this paper is being written), more and more countries in Europe are re-transitioning towards coal powered electricity from natural gas due to the sanctions on Russia for invading Ukraine.[78] Another instance can be of India, where it does not operate its

[77] Ritchie, Roser, and Rosado.
[78] ThePrint, *Power Cuts, Coal Shortages, Burning Summer, Putin & Our Freebie Politics*.

natural gas plants (which are cleaner than coal) because of the high price of its fuel which makes it economically impracticable.[79]

The overall emissions and environmental sustainability of EVs in the In-Use stage is dependent on the type of energy grid.[80] Hence it is essential to convert the primary means of electricity generation into renewable sources of energy, countries with more proportion of renewable and nuclear energy sources have a significant positive impact on reducing the CO_2 emissions with the use of EVs.[81] For example, studies on environmental effects from EVs in Poland based on future projections for the energy grid (2035) have shown positive results for reducing emissions if the energy generation from renewables and nuclear power is increased with the simultaneous decrease in electricity generation from solid fuels.[82]

Alternatives

In reaching the goal of achieving environmentally sustainable transportation, EVs are posited as a viable solution to reduce carbon emissions. Alongwith the several drawbacks of EVs as described in this paper, they are not the only technology that can be a possible solution for sustainable and environmentally friendly transportation.

Several alternative technologies are being developed from a varied domain range of fields. There is a vast amount of ongoing work carried out for the development of scalable high performance battery technologies from materials like sodium and aluminum for creating viable Na-ion and Al-ion batteries.[83] Additionally, alternative fuel technologies like hydrogen fuel cells, ethanol from crops like sugarcane and corn, and

---

[79] ThePrint, *Power Cuts, Coal Shortages, Burning Summer, Putin & Our Freebie Politics*.
[80] Efstathios E. Michaelides, "Primary Energy Use and Environmental Effects of Electric Vehicles"; Prantik Dutta, "Assessment of Environmental Implications of Electric Vehicles"; Burchart-Korol and Folęga, "Environmental Footprints of Current and Future Electric Battery Charging and Electric Vehicles in Poland"; Lattanzio and Clark, "Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles."
[81] Vitta, "Electric Cars – Assessment of 'Green' Nature Vis-à-Vis Conventional Fuel Driven Cars," December 2021; Efstathios E. Michaelides, "Primary Energy Use and Environmental Effects of Electric Vehicles."
[82] Burchart-Korol and Folęga, "Environmental Footprints of Current and Future Electric Battery Charging and Electric Vehicles in Poland."
[83] Tan et al., "Compact Sn/C Composite Realizes Long-Life Sodium-Ion Batteries"; Zhang et al., "Evidence for Dual Anions Co-Insertion in a Transition Metal Chalcogenide Cathode Material NiSe2 for High-Performance Rechargeable Aluminum-Ion Batteries"; Wang et al., "Initial-Anode-Free Aluminum Ion Batteries"; Qin, Qin, and Li, "Metal–Organic Framework-Derived CuTe@porous Carbon Composites as Novel Cathodes for Aluminum Ion Batteries"; Zhou et al., "Review on Mn-Based and Fe-Based Layered Cathode Materials for Sodium-Ion Batteries"; Nurohmah et al., "Sodium-Ion Battery from Sea Salt"; Tong et al., "Superior Conductivity and Accelerated Kinetics Na3V2(PO4)2F3@CNTs with High Performance for Sodium-Ion Batteries."

edible oils as engine fuel are also being developed.[84] Furthermore, innovative engine design technologies are being developed like that of the hybrid engines that can run on multiple fuels, hybrid cars that take advantage of both batteries & fuels.[85]

Development of these technologies may pave the way for transition towards more sustainable transportation. Many of these technologies are in the prototype stage while some are already being implemented in some scale in select countries. The use of ethanol as an engine fuel as well as hydrogen fuel cell vehicles have already started to make an appearance in the commercial market.

These transitions towards sustainable transportation can be attributed to the efforts by governments to give incentive for the development of alternative technologies for transportation by actively formulating policy in this direction. The disparity in the development of alternative technologies in transportation amongst nations can be readily seen in their policies. These policies are in turn the reflection of the dominant culture and market viability of these countries. Several countries around the world, along with the development of alternative technologies, have also started to simultaneously invest in building support infrastructure for these technologies.

Conclusion

It is evidently clear that the promotion of EVs by manufacturing companies as eco-friendly means of transportation is flawed. EVs are not net zero emissions throughout the lifecycle.[86] The lifecycle GHG emissions in the operation or in-use stage

---

[84] Foorginezhad et al., "Sensing Advancement towards Safety Assessment of Hydrogen Fuel Cell Vehicles"; Mario Ortiz and Erazzú, "Sugarcane Energy"; Murta et al., "The Use of Palm Oil Biodiesel Blends in Locomotives"; Jiao, Li, and Bai, "Ethanol as a Vehicle Fuel in China"; Zang, Martins, and Fonseca-Zang., "Life Cycle Inventory for Biomethane as a Diesel Substitute for the Brazilian Ethanol Industry - Case Study"; Dwivedi and Sharma, "Potential and Limitation of Straight Vegetable Oils as Engine Fuel – An Indian Perspective"; Xue, "Combustion Characteristics, Engine Performances and Emissions of Waste Edible Oil Biodiesel in Diesel Engine"; Demirbas, "Future Fuels for Internal Combustion Engines"; Aso, Kizaki, and Mizuno, "Development Progress of the Toyota Fuel Cell Hybrid Vehicle"; Hordeski, *Hydrogen & Fuel Cells*; Yu and Tao, "Simulation-Based Life Cycle Assessment of Energy Efficiency of Biomass-Based Ethanol Fuel from Different Feedstocks in China"; Hua et al., "University of Waterloo's Hydrogen Fuel Cell Choice Meets the Reality of Canada's Winter by Using Model-Based Design"; Whitmarsh and Wietschel, "Sustainable Transport Visions."

[85] Sidharthan Panaparambil, Kashyap, and Vijay Castelino, "A Review on Hybrid Source Energy Management Strategies for Electric Vehicle"; Dathu and Christy, "Advanced Plug-in Hybrid Electric Vehicle with Multiple Source's"; Sarvaiya, Ganesh, and Xu, "Comparative Analysis of Hybrid Vehicle Energy Management Strategies with Optimization of Fuel Economy and Battery Life"; Verbelen et al., "Comparison of an Optimized Electrical Variable Transmission with the Toyota Hybrid System"; Guan and Chen, "Adaptive Power Management Strategy for a Four-Mode Hybrid Electric Vehicle."

[86] Burchart-Korol and Folęga, "Environmental Footprints of Current and Future Electric Battery Charging and Electric Vehicles in Poland."

of EVs are lesser than that of ICEVs.[87] The GHG emissions from the production stage including the extraction and processing of minerals for EVs is usually 1.3 to 2.0 times that of ICEVs.[88] The local air quality is found to be better with the use of EVs than with the use of ICEVs.[89]

The CO_2 emission avoidance from EVs depends on the composition of the energy grid and the technology used to generate electricity, the countries which have more nuclear, renewables and low carbon generation sources have more significant CO_2 emission avoidance from EVs.[90] Transitioning to a green energy grid for primary energy generation will reduce emissions, but it is essential to note that these technologies will only reduce emissions and not reverse it. In order to combat global warming carbon sequestration of the existing emissions is essential.[91]

The energy and emissions of EVs scale linearly with the number of vehicles, therefore unless there is a first order change in battery manufacturing or significant improvement in battery recycling, EVs will have more emissions than ICEVs and will not be able to compete with them.[92] If alternate battery chemistries are developed which substitute Nd, Dy, Co & Ni with sustainable minerals the contribution towards eco-sustainability will be significant.[93] Studies have shown that recycling and reuse of materials from these batteries can reduce the GHG emission from battery production to 50%, which already has the most emission in the whole lifecycle of EV, as well as reduce the ecological impact of these batteries by more than 20%.[94]

Another strategy of using EVs in mass transportation with last mile connectivity with electric bicycles & bikes will be effective in combating emissions.[95] Several other alternative technologies like hydrogen fuel cells, ethanol for vehicle engines, novel

[87] Lattanzio and Clark, "Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles."
[88] Lattanzio and Clark.
[89] Lattanzio and Clark.
[90] Efstathios E. Michaelides, "Primary Energy Use and Environmental Effects of Electric Vehicles"; Burchart-Korol and Folęga, "Environmental Footprints of Current and Future Electric Battery Charging and Electric Vehicles in Poland"; Prantik Dutta, "Assessment of Environmental Implications of Electric Vehicles"; Vitta, "Electric Cars – Assessment of 'Green' Nature Vis-à-Vis Conventional Fuel Driven Cars," December 2021; Lattanzio and Clark, "Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles."
[91] Vitta, "Electric Cars – Assessment of 'Green' Nature Vis-à-Vis Conventional Fuel Driven Cars," December 2021.
[92] Vitta.
[93] Vitta.
[94] Hendrickson et al., "Life-Cycle Implications and Supply Chain Logistics of Electric Vehicle Battery Recycling in California"; Unterreiner, Jülch, and Reith, "Recycling of Battery Technologies – Ecological Impact Analysis Using Life Cycle Assessment (LCA)."
[95] Vitta, "Electric Cars – Assessment of 'Green' Nature Vis-à-Vis Conventional Fuel Driven Cars," December 2021.

hybrid engines and new sustainable battery chemistries; can also be developed for tackling the problem of global warming and achieving the goal of emission reduction.

Hence, in order to make EVs environmentally sustainable, considerable improvements need to be done in the manufacturing and recycling processes. Additionally, sustainable forms of batteries need to be developed along with the transition towards green energy grids. Furthermore, nations also need to reduce their electricity generation from solid and high carbon fuels. In addition to these, countries will also have to simultaneously develop support infrastructure for EVs to make their large-scale expansion possible.

References

Agusdinata, D.b. (1), W. (1) Liu, H. (1) Eakin, and H. (2) Romero. "Socio-Environmental Impacts of Lithium Mineral Extraction: Towards a Research Agenda." *Environmental Research Letters* 13, no. 12 (01 2018). https://doi.org/10.1088/1748-9326/aae9b1.

Ashfaq, Muhammad, Osama Butt, Jeyraj Selvaraj, and Nasrudin Rahim. "Assessment of Electric Vehicle Charging Infrastructure and Its Impact on the Electric Grid: A Review." *International Journal of Green Energy* 18, no. 7 (April 15, 2021): 657–86. https://doi.org/10.1080/15435075.2021.1875471.

Aso, Shinji, Mikio Kizaki, and Hideaki Mizuno. "Development Progress of the Toyota Fuel Cell Hybrid Vehicle." *SAE International Journal of Engines* 1, no. 1 (January 1, 2009): 296–303.

Banza Lubaba Nkulu, Célestin, Lidia Casas, Vincent Haufroid, Thierry De Putter, Nelly D. Saenen, Tony Kayembe-Kitenge, Paul Musa Obadia, et al. "Sustainability of Artisanal Mining of Cobalt in DR Congo." *Nature Sustainability* 1, no. 9 (September 1, 2018): 495–504. https://doi.org/10.1038/s41893-018-0139-4.

Baum, Lukas, Sahar Darvish, and Detlef Schulz. "Mobile AC/DC Test Device for Electric Vehicle Charging Infrastructure Communication: Mobiles AC/DC-Testgerät Für Ladeinfrastruktur-Kommunikation in Der Elektromobilität." *E & i Elektrotechnik Und Informationstechnik*, March 8, 2022, 1–6. https://doi.org/10.1007/s00502-022-01008-1.

NACLA. "Bolivia Bets on State-Run Lithium Industry." Accessed April 24, 2022. https://nacla.org/news/bolivia-bets-state-run-lithium-industry.

Burchart-Korol, Dorota, and Piotr Folęga. "Environmental Footprints of Current and Future Electric Battery Charging and Electric Vehicles in Poland." *Transport Problems: An International Scientific Journal* 15, no. 1 (January 2020): 61–70. https://doi.org/10.21307/tp-2020-006.

Coffin, David, and Jeff Horowitz. "The Supply Chain for Electric Vehicle Batteries." *Journal of International Commerce & Economics*, December 2018, 1–21.

Crawford, K. (1), and V. (2) Joler. "Anatomy of an Ai System." *Virtual Creativity* 9, no. 1–2 (01 2019): 117–20. https://doi.org/10.1386/vcr_00008_7.

Dathu, K. P. M. Y. V., and A. Ananthi Christy. "Advanced Plug-in Hybrid Electric Vehicle with Multiple Source's." *Journal of Cardiovascular Disease Research (Journal of Cardiovascular Disease Research)* 12, no. 5 (November 2021): 622–27.

Demirbas, A. "Future Fuels for Internal Combustion Engines." *Energy Sources Part A: Recovery, Utilization & Environmental Effects* 32, no. 14 (September 2010): 1273–81. https://doi.org/10.1080/15567030903060317.

Desai, Jairaj, Jijo K. Mathew, Howell Li, and Darcy M. Bullock. "Using Connited Vehicle Data for Assessing Electric Vehicle Charging Infrastructure Usage and Investment Opportunities." *ITE Journal* 92, no. 3 (March 2022): 22–31.

"DOE Launches Its First Lithium-Ion Battery Recycling R&D Center: ReCell | Argonne National Laboratory." Accessed May 4, 2022. https://www.anl.gov/article/doe-launches-its-first-lithiumion-battery-recycling-rd-center-recell.

Dolin, Eric Jay. "PFC Emissions Reductions: The Domestic and International Perspective." *LIGHT METAL AGE*, 1999, 7.

Dwivedi, Gaurav, and M.p. Sharma. “Potential and Limitation of Straight Vegetable Oils as Engine Fuel – An Indian Perspective.” *Renewable and Sustainable Energy Reviews* 33 (May 1, 2014): 316–22. https://doi.org/10.1016/j.rser.2014.02.004.

Edwards, David P., Sean Sloan, Lingfei Weng, Paul Dirks, Jeffrey Sayer, and William F. Laurance. “Mining and the African Environment.” *Conservation Letters* 7, no. 3 (May 2014): 302–11. https://doi.org/10.1111/conl.12076.

Efstathios E. Michaelides. “Primary Energy Use and Environmental Effects of Electric Vehicles.” *World Electric Vehicle Journal* 12, no. 138 (August 1, 2021): 138–138. https://doi.org/10.3390/wevj12030138.

Ellingsen, L. A. W., and C. R. Hung. “Research for TRAN Committee-Resources, Energy, and Lifecycle Greenhouse Gas Emission Aspects of Electric Vehicles.” *Policy Department for Structural and Cohesion Policies, European Parliament, Brussels*, 2018.

Foorginezhad, Sahar, Masoud Mohseni-Dargah, Zahra Falahati, Rouzbeh Abbassi, Amir Razmjou, and Mohsen Asadnia. “Sensing Advancement towards Safety Assessment of Hydrogen Fuel Cell Vehicles.” *Journal of Power Sources* 489 (March 31, 2021). https://doi.org/10.1016/j.jpowsour.2021.229450.

Gaines, Linda L., and Jennifer B. Dunn. “21 - Lithium-Ion Battery Environmental Impacts.” *Lithium-Ion Batteries Advances and Applications*, January 1, 2014, 483–508. https://doi.org/10.1016/B978-0-444-59513-3.00021-2.

Gallagher, Kevin G., and Paul A. Nelson. “6 - Manufacturing Costs of Batteries for Electric Vehicles.” *Lithium-Ion Batteries Advances and Applications*, January 1, 2014, 97–126. https://doi.org/10.1016/B978-0-444-59513-3.00006-6.

Guan, Jen-Chiun, and Bo-Chiuan Chen. “Adaptive Power Management Strategy for a Four-Mode Hybrid Electric Vehicle.” *Energy Procedia* 105 (May 1, 2017): 2403–8. https://doi.org/10.1016/j.egypro.2017.03.689.

Hemant Harishchandra Kore and Saroj Koul. “Electric Vehicle Charging Infrastructure: Positioning in India.” *Management of Environmental Quality: An International Journal* 33, no. 3 (February 9, 2022): 776–99. https://doi.org/10.1108/MEQ-10-2021-0234.

Hendrickson, T.p. (1, 2), O. (1 Kavvada 2), N. (1) Shah, R. (1) Sathre, and C. (1) D Scown. “Life-Cycle Implications and Supply Chain Logistics of Electric Vehicle Battery Recycling in California.” *Environmental Research Letters* 10, no. 1 (01 2015). https://doi.org/10.1088/1748-9326/10/1/014011.

Hordeski, Michael F. *Hydrogen & Fuel Cells : Advances in Transportation and Power*. Lilburn, GA: Fairmont Press, 2009. https://login.ezproxy.pratt.edu/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=e000xna&AN=254082&site=eds-live&scope=site.

Hua, C., C. Haliburton, E. J. Wilhelm, C. J. Mendez, M. B. Stevens, M. Fowler, and R. A. Fraser. “University of Waterloo’s Hydrogen Fuel Cell Choice Meets the Reality of Canada’s Winter by Using Model-Based Design.” *SAE International Journal of Engines* 1, no. 1 (January 1, 2009): 346–51.

Humphries, Marc. “Rare Earth Elements: The Global Supply Chain.” Congressional Research Service (CRS) Reports and Issue Briefs. Congressional Research Service (CRS) Reports and Issue Briefs, June 1, 2012.

Jacoby, Mitch. “It’s Time to Get Serious about Recycling Lithium-Ion Batteries.” Chemical & Engineering News. Accessed April 25, 2022. https://cen.acs.org/materials/energy-storage/time-serious-recycling-lithium/97/i28.

Jerome, Sajan, and M. Udayakumar. “A Study on Cost-Effective Electric Vehicle Charging Infrastructure in India Through Open Access Power Procurement.” *Arabian Journal for Science and Engineering* 46, no. 12 (December 1, 2021): 12509–24. https://doi.org/10.1007/s13369-021-06012-9.

Jiao, Jianling, Jingjing Li, and Yu Bai. “Ethanol as a Vehicle Fuel in China: A Review from the Perspectives of Raw Material Resource, Vehicle, and Infrastructure.” *Journal of Cleaner Production* 180 (April 10, 2018): 832–45. https://doi.org/10.1016/j.jclepro.2018.01.141.

Kaniki, Arthur Tshamala, and Kaniki Tumba. “Management of Mineral Processing Tailings and Metallurgical Slags of the Congolese Copperbelt: Environmental Stakes and Perspectives.” *Journal of Cleaner Production* 210 (February 10, 2019): 1406–13. https://doi.org/10.1016/j.jclepro.2018.11.131.

Lattanzio, Richard K., and Corrie E. Clark. “Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles.” Congressional Research Service (CRS) Reports and Issue Briefs. Congressional Research Service (CRS) Reports and Issue Briefs, June 1, 2020. https://login.ezproxy.pratt.edu/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=edsgao&AN=edsgcl.661400073&site=eds-live&scope=site.

Lifang Wu and Wei Yang. “Tackling Supply Chain Challenges of Tesla Model 3.” *Operations Management Education Review*, no. 11 (January 2017): 5–34.

Mario Ortiz, Joaquín, and Luis Erazzú. “Sugarcane Energy: Potential Electricity Production from Vinasse Produced by the Ethanol Industry.” *Sugar Journal* 84, no. 5 (October 2021): 8–11.

Merrill, Dave, Jess Shankleman, Thomas Biesheuvel, and Joe Ryan. “We’re Going To Need More Lithium.” *Bloomberg Businessweek*. Bloomberg L.P., September 11, 2017.

“Mineral Commodity Summaries 2022.” USGS Numbered Series. *Mineral Commodity Summaries 2022*. Vol. 2022. Mineral Commodity Summaries. Reston, VA: U.S. Geological Survey, 2022. https://doi.org/10.3133/mcs2022.

Murta, Aurélio Lamare Soares, Marcos Aurélio Vasconcelos De Freitas, Carla Guimarães Ferreira, and Mariana Marinho Da Costa Lima Peixoto. “The Use of Palm Oil Biodiesel Blends in Locomotives: An Economic, Social and Environmental Analysis.” *Renewable Energy: An International Journal* 164 (February 2021): 521–30. https://doi.org/10.1016/j.renene.2020.08.094.

Nishi, Yoshio. “2 - Past, Present and Future of Lithium-Ion Batteries: Can New Technologies Open up New Horizons?” *Lithium-Ion Batteries Advances and Applications*, January 1, 2014, 21–39. https://doi.org/10.1016/B978-0-444-59513-3.00002-9.

Nordelöf, Anders, Maarten Messagie, Anne-Marie Tillman, Maria Ljunggren Söderman, and Joeri Van Mierlo. “Environmental Impacts of Hybrid, Plug-in Hybrid, and Battery Electric Vehicles—What Can We Learn from Life Cycle Assessment?” *The International Journal of Life Cycle Assessment* 19, no. 11 (November 1, 2014): 1866–90. https://doi.org/10.1007/s11367-014-0788-0.

Nurohmah, Anisa Raditya, Shofirul Sholikhatun Nisa, Khikmah Nur Rikhy Stulasti, Cornelius Satria Yudha, Windhu Griyasti Suci, Kiwi Aliwarga, Hendri Widiyandari, and Agus Purwanto. “Sodium-Ion Battery from Sea Salt: A Review.” *Materials for Renewable and Sustainable Energy* 11, no. 1 (April 1, 2022): 71–89. https://doi.org/10.1007/s40243-022-00208-1.

Ona Egbue, Suzanna Long, and Seong Dae Kim. “Resource Availability and Implications for the Development of Plug-In Electric Vehicles.” *Sustainability* 14, no. 1665 (January 1, 2022): 1665–1665. https://doi.org/10.3390/su14031665.

Pistoia, Gianfranco. *Lithium-Ion Batteries: Advances and Applications*. Oxford, NETHERLANDS, THE: Elsevier, 2014. http://ebookcentral.proquest.com/lib/pratt/detail.action?docID=1583621.

Prantik Dutta. “Assessment of Environmental Implications of Electric Vehicles: A Review.” *Journal of Research in Engineering and Applied Sciences* 6, no. 4 (October 1, 2021): 188–95. https://doi.org/10.46565/jreas.2021.v06i04.008.

Qin, Te, Lu Qin, and Jianling Li. “Metal–Organic Framework-Derived CuTe@porous Carbon Composites as Novel Cathodes for Aluminum Ion Batteries.” *Ionics: International Journal of IonicsThe Science and Technology of Ionic Motion*, March 29, 2022, 1–11. https://doi.org/10.1007/s11581-022-04530-6.

Ritchie, Hannah, Max Roser, and Pablo Rosado. “Energy Mix.” *Our World in Data*, November 28, 2020. https://ourworldindata.org/energy-mix.

Sarvaiya, Shradhdha, Sachin Ganesh, and Bin Xu. “Comparative Analysis of Hybrid Vehicle Energy Management Strategies with Optimization of Fuel Economy and Battery Life.” *Energy* 228 (August 1, 2021). https://doi.org/10.1016/j.energy.2021.120604.

Schulz, Felix, and Johannes Rode. “Public Charging Infrastructure and Electric Vehicles in Norway.” *Energy Policy* 160 (January 2022): N.PAG-N.PAG. https://doi.org/10.1016/j.enpol.2021.112660.

Sidharthan Panaparambil, Vishnu, Yashwant Kashyap, and Roystan Vijay Castelino. “A Review on Hybrid Source Energy Management Strategies for Electric Vehicle.” *International Journal of Energy Research* 45, no. 14 (November 2021): 19819–50. https://doi.org/10.1002/er.7107.

Smith, William J. “Can EV (Electric Vehicles) Address Ireland’s CO.Sub.2 Emissions from Transport?” *Energy* 35, no. 12 (December 1, 2010): 4514.

Stringer, David, and Jie Ma. “Where 3 Million Electric Vehicle Batteries Will Go When They Retire.” *Bloomberg.Com*, June 27, 2018, N.PAG-N.PAG.

Tagliaferri, Carla, Sara Evangelisti, Federica Acconcia, Teresa Domenech, Paul Ekins, Diego Barletta, and Paola Lettieri. “Life Cycle Assessment of Future Electric and Hybrid Vehicles: A Cradle-to-Grave

Systems Engineering Approach.” *Chemical Engineering Research and Design* 112 (August 1, 2016): 298–309. https://doi.org/10.1016/j.cherd.2016.07.003.
Tan, Mingdong, Shuanghui Han, Zhenbang Li, Hao Cui, Danni Lei, and Chengxin Wang. “Compact Sn/C Composite Realizes Long-Life Sodium-Ion Batteries.” *Nano Research*, March 19, 2022, 1–10. https://doi.org/10.1007/s12274-022-4255-0.
ThePrint. *Power Cuts, Coal Shortages, Burning Summer, Putin & Our Freebie Politics*, 2022. https://www.youtube.com/watch?v=0H68w6Fjcuo.
Tong, Haitao, Haowei Han, Guangying Zhang, Kefu Gao, Qingyu Dong, Fangdong Hu, and Xiaolei Jiang. “Superior Conductivity and Accelerated Kinetics Na3V2(PO4)2F3@CNTs with High Performance for Sodium-Ion Batteries.” *Ionics: International Journal of IonicsThe Science and Technology of Ionic Motion*, March 18, 2022, 1–9. https://doi.org/10.1007/s11581-022-04511-9.
Tsamis, Achilleas, Mike COYNE (Centre for Strategy, and Evaluation Services Llp). “Recovery of Rare Earths from Electronic Wastes: An Opportunity for High-Tech SMEs,” February 5, 2015. https://policycommons.net/artifacts/1336635/recovery-of-rare-earths-from-electronic-wastes/1943961/.
Unterreiner, Lea, Verena Jülch, and Sören Reith. “Recycling of Battery Technologies – Ecological Impact Analysis Using Life Cycle Assessment (LCA).” *Energy Procedia* 99 (November 1, 2016): 229–34. https://doi.org/10.1016/j.egypro.2016.10.113.
Verbelen, Florian, Walter Lhomme, Emmanuel Vinot, Jeroen Stuyts, Majid Vafaeipour, Omar Hegazy, Kurt Stockman, and Peter Sergeant. “Comparison of an Optimized Electrical Variable Transmission with the Toyota Hybrid System.” *Applied Energy* 278 (November 15, 2020). https://doi.org/10.1016/j.apenergy.2020.115616.
Vitta, Satish. “Electric Cars – Assessment of ‘Green’ Nature Vis-à-Vis Conventional Fuel Driven Cars.” *Sustainable Materials and Technologies* 30 (December 2021): e00339. https://doi.org/10.1016/j.susmat.2021.e00339.
———. “Electric Cars – Assessment of ‘Green’ Nature Vis-à-Vis Conventional Fuel Driven Cars.” *Sustainable Materials and Technologies* 30 (December 1, 2021). https://doi.org/10.1016/j.susmat.2021.e00339.
Wang, Lei, Xinmei Song, Yi Hu, Wen Yan, Zuoxiu Tie, and Zhong Jin. “Initial-Anode-Free Aluminum Ion Batteries: In-Depth Monitoring and Mechanism Studies.” *Energy Storage Materials* 44 (January 1, 2022): 461–68. https://doi.org/10.1016/j.ensm.2021.10.044.
Whitmarsh, Lorraine, and Martin Wietschel. “Sustainable Transport Visions: What Role for Hydrogen and Fuel Cell Vehicle Technologies?” *Energy & Environment* 19, no. 2 (March 1, 2008): 207–26.
WION. *Gravitas Plus: The Dark Side of Electric Vehicles*, 2022. https://www.youtube.com/watch?v=RFHvq-8np1o.
Wolbertus, Rick, Robert van den Hoed, Maarten Kroesen, and Caspar Chorus. “Charging Infrastructure Roll-out Strategies for Large Scale Introduction of Electric Vehicles in Urban Areas: An Agent-Based Simulation Study.” *Transportation Research Part A: Policy & Practice* 148 (June 2021): 262–85. https://doi.org/10.1016/j.tra.2021.04.010.
Xue, Jinlin. “Combustion Characteristics, Engine Performances and Emissions of Waste Edible Oil Biodiesel in Diesel Engine.” *Renewable and Sustainable Energy Reviews* 23 (July 1, 2013): 350–65. https://doi.org/10.1016/j.rser.2013.02.039.
Yu, Suiran, and Jing Tao. “Simulation-Based Life Cycle Assessment of Energy Efficiency of Biomass-Based Ethanol Fuel from Different Feedstocks in China.” *Energy* 34, no. 4 (April 2009): 476–84. https://doi.org/10.1016/j.energy.2008.12.015.
Zang, Joachim W., Kairo F. Martins, and Warde A. Da Fonseca-Zang. “Life Cycle Inventory for Biomethane as a Diesel Substitute for the Brazilian Ethanol Industry - Case Study.” *Energy Procedia* 153 (October 1, 2018): 444–49. https://doi.org/10.1016/j.egypro.2018.10.048.
Zeng, Li, Timo Krallmann, Andrea Fiege, Marek Stess, Timo Graen, and Michael Nolting. “Optimization of Future Charging Infrastructure for Commercial Electric Vehicles Using a Multi-Objective Genetic Algorithm and Real Travel Data.” *Evolving Systems: An Interdisciplinary Journal for Advanced Science and Technology* 11, no. 2 (June 1, 2020): 241–54. https://doi.org/10.1007/s12530-019-09295-4.
Zhang, Hao, Yongshuai Liu, Li Yang, Linyi Zhao, Xiaotong Dong, Huaizhi Wang, Yuhao Li, Tianxiang Sun, Qiang Li, and Hongsen Li. “Evidence for Dual Anions Co-Insertion in a Transition Metal Chalcogenide Cathode Material NiSe2 for High-Performance Rechargeable Aluminum-Ion Batteries.” *Energy Storage Materials* 47 (May 1, 2022): 336–44.

https://doi.org/10.1016/j.ensm.2022.02.026.
Zhou, Dengmei, Chong Zeng, Jing Xiang, Tao Wang, Zitian Gao, Chunlian An, and Wanxia Huang. "Review on Mn-Based and Fe-Based Layered Cathode Materials for Sodium-Ion Batteries." *Ionics: International Journal of IonicsThe Science and Technology of Ionic Motion*, March 16, 2022, 1–12. https://doi.org/10.1007/s11581-022-04519-1.