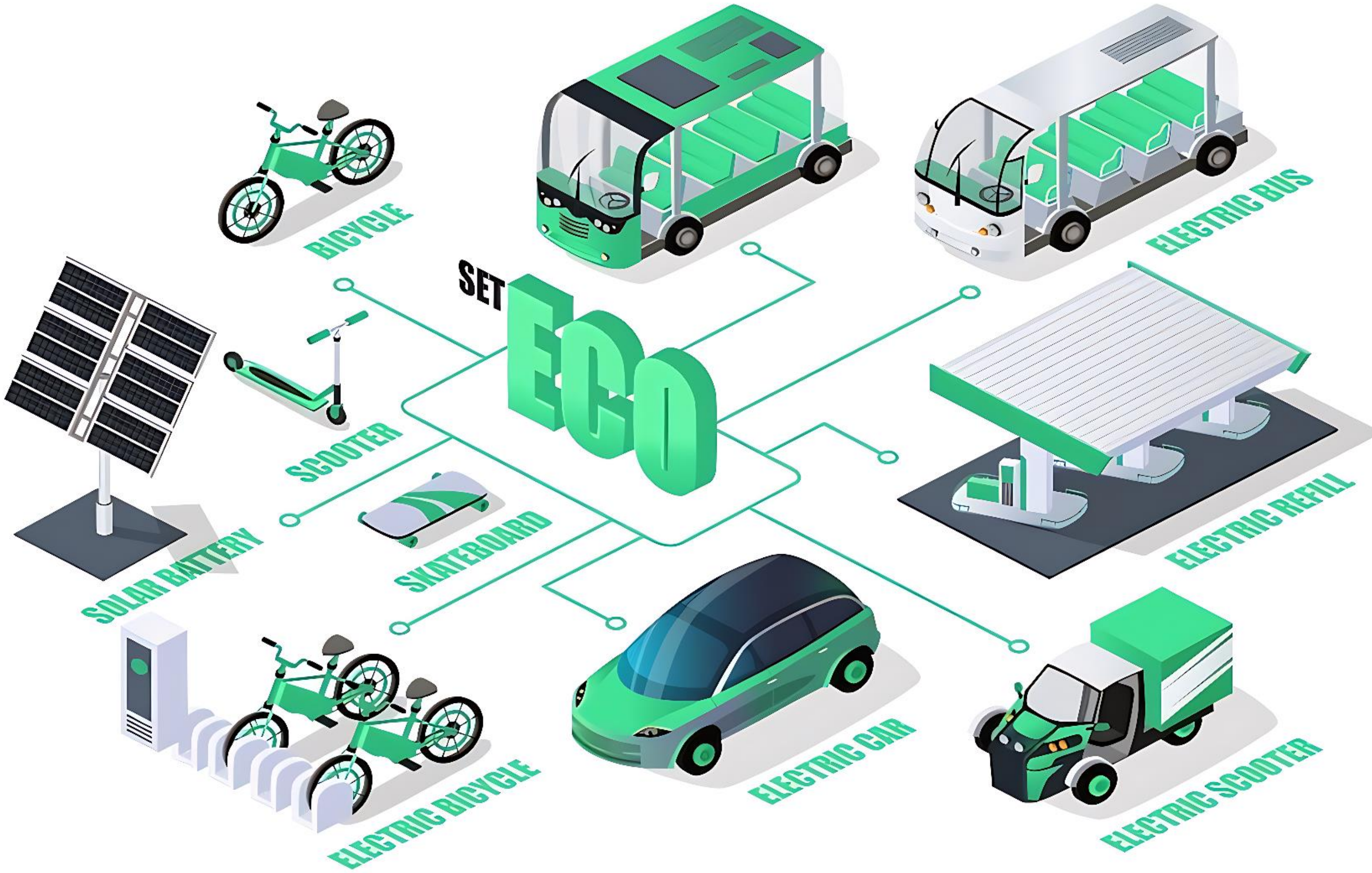

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From Diesel to Batteries: The Drive Towards Transportation Electrification

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Abstract

Transportation electrification, a significant mitigator of greenhouse gas emissions, is one of the many initiatives in moving from traditional fossil fuels to clean electricity. This is because decarbonization has become a global priority in combating global warming and securing a sustainable life on Earth. Today, electric vehicles are the most prominent and rapidly growing electrified transit mode whereas the integration of electrification in aviation, for instance, poses significant challenges. Advancements in electromobility have been ongoing and are expected to have substantial progress by 2050, such as in the micromobility, aerial, freight transport, and rail markets, which is on schedule with meeting the net zero requirement of the Paris Agreement.

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Introduction

The field of electrification has recently been reintroduced to decarbonize our planet, which is the process of reducing greenhouse gases such as carbon dioxide. The emission of such gases is caused by the burning of fossil fuels, resulting in the trapping of heat and warming of the planet. Accordingly, several initiatives have been undertaken in the field of electrical engineering, namely shifts towards electrification, renewable energy, and fuel-cells. Today, this adjustment from fossil fuel-based energy to clean energy is crucial and currently being implemented in various sectors, namely transportation, manufacturing, construction, agriculture, and others. This paper focuses on the electrification of the transportation industry by performing a holistic analysis on electric cars, bicycles, drones, airplanes, trucks, and trains.

Electric Vehicles

The origin of electric vehicles (EVs) can be traced to the 1800s, at which point it was superior to internal combustion engine (ICE) cars. However, the cheaper price of the latter caused EVs to disappear from the market in the 1900s. Later in history and since the 1990s, interest in selling commercial EVs has been rekindled due to rising fuel prices and environmental concerns.

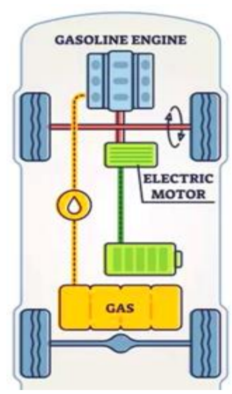
In conventional ICE vehicles, the gasoline supplied to the engine is ignited for wheel rotation, releasing emissions due to combustion. Conversely, EVs operate with batteries to supply power, which leads to prolonged durations for recharging versus refueling. On the other hand, combustion results in huge losses in the forms of heat and exhaust, making EVs a much more energy-efficient option. Moreover, EVs have higher well-to-wheel (WTW or W2W) efficiency than ICEs, which refers to how efficiently energy is used from its original source all the way to moving the vehicle's wheels.

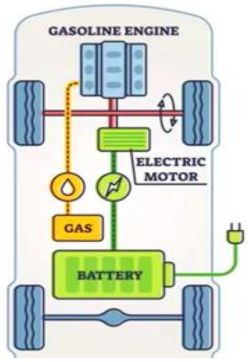
Although EVs are more expensive to purchase than ICEs, the total cost of ownership (TCO) of the former can be lower due to ICE's higher maintenance costs and prevailing fuel expenses. Therefore, with the development of e-mobility infrastructure, EVs are expected to be cheaper.

The Electric Vehicle Family

1- Hybrid Electric Vehicles (HEVs):

An HEV combines a gasoline engine, typically smaller than that of ICEs, with a small battery and an electric motor. The latter converts electrical energy into mechanical energy to propel the vehicle while the electric engine recharges the battery as the car moves. Thus, it is fueled in the same way as a gasoline-engine car. It is worth mentioning that the Toyota Highlander is a widely recognized example of an HEV.



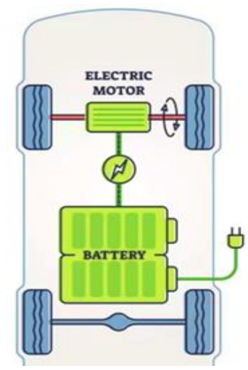


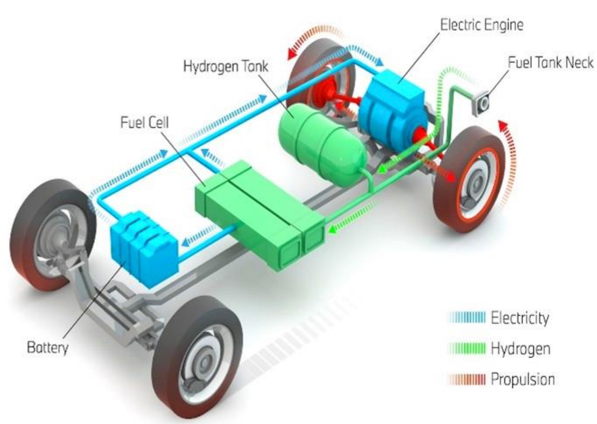
2- Plug-in Hybrid Electric Vehicles (PHEVs):

A PHEV, such as BMW 330e Sonata, is very similar to an HEV but with a larger plug-in battery, providing a relatively greater driving range. Note that the extended-range electric vehicle (EREV) is a type of a PHEV.

3- Battery Electric Vehicles (BEVs):

A BEV is a fully electric car, possessing neither an engine nor a gas tank can; thus, it be charged only from the electric grid. Accordingly, it strictly runs on a relatively larger battery and electric motor. All Tesla models are BEVs.





4- Fuel cell Electric Vehicles (FCEVs):

An FCEV, as exemplified by the Toyota Mirai, differs from all forementioned types since it produces electricity through hydrogen and air, emitting only water vapor and heat as by-products. However, the market remains small due to limited hydrogen refueling stations.

Hybrid Logic: How Series and Parallel Systems Work

Series

The electric motor is the only entity driving the wheels of the vehicle as the ICE solely recharges the battery.

A specific type of a series hybrid is the extended-range electric vehicle (EREV), with its small ICE designed to extend the battery's range.

Parallel

Both the ICE and electric motor can power the wheels, either together or separately, depending on road and vehicle conditions. For instance, over long distances and constant speeds, HEVs run on the gasoline engine whereas at low speeds, stop and go traffic, and uphill driving, the electric motor is used for fuel economy.

Series/Parallel

Also known as the power-split hybrid (PSH), the series/parallel hybrid powertrain merges both configurations, rendering it very flexible and efficient.

For example, during braking and at lower speeds, the EV operates on the series configuration while during acceleration, the parallel drivetrain is favored. One popular example is the Toyota Prius.

Not Just the Car: The Full Electric Equation

Solar roof car: As the field of photovoltaics advances, EVs such as a certain edition of the Hyundai Sonata Hybrid have implemented a solar roof to generate supplementary electricity, providing further support to the battery. However, after assessing its cost, complexity, and small-scale energy generation due to limited surface area, solar-integrated EVs are deemed neither worthwhile nor recommended.

Vehicle-to-Grid (V2G) and Vehicle-to-Home (V2H) technologies: Similar to the procedure of selling electricity back from solar cells, V2G and V2H are two types of bidirectional charging whereby EV batteries send excess energy back to the electricity grid and to a home's electrical network, respectively. This way, one can sell stored energy during peak demand and buy during off-peak periods, generating revenue. Through minimizing the load on the grid, V2G (and V2H) assist in reducing electricity costs and foster a more sustainable energy future.

Wireless charging: It uses electromagnetic induction to deliver power from a transmitter coil to a receiver coil, electromagnetically charging the battery. Its integration is particularly beneficial at public transport and taxi stops, enabling vehicles to maintain their charge and avoid unnecessary lengthy charging durations. Furthermore, wireless charging reduces the risk of electrical hazards due to the absence of the inconvenient high voltage charging cables and keeps roads visually pleasing, bypassing the need for bulky charging stations.

Autonomous vehicles (AVs):

AVs or self-driving cars operate without human intervention and are equipped with Artificial Intelligence (AI) systems to minimize unnecessary braking and acceleration mechanisms, improving energy efficiency. The integration of autonomous systems in EVs is motivated by several factors: First, since EVs are environmentally friendly, the implementation of autonomous fleets with these drivetrains is coherent with this drive for sustainability. Second, given the reliance of AVs on numerous sensors such as LiDAR (Light Detection and Ranging), a reliable power source such as batteries is required. Third, because EVs are more responsive than ICEs, they are the ideal choice for the incorporation of AI systems.

One promising technology with the potential to obstruct fleet electrification and preserve the familiarity of ICEs is electrofuels, which are low-carbon substitutes for fossil fuels. Also known as synthetic fuels, e-fuels are produced by combining harvested carbon dioxide or nitrogen with green hydrogen, with the latter being generated through the electrolysis of water with renewable energy. One major attraction of e-fuels is their direct influence on lowering greenhouse gas (GHG) emissions without the need for adjustments on existing gasoline engine vehicles.

Watt Connects Us: The Charging Infrastructure

EVs can be charged using one of two types of electrical power: AC (alternating current) or DC (direct current).

AC Charging

The electrical grid feeds AC to the EV's onboard charger (OBC), which is a power electronics device placed inside the car to convert AC to DC. This device is crucial as batteries can only store DC. AC chargers are mainly installed in homes and are relatively slower than DC charging due to the various size and weight restrictions of EVs.

DC Charging

Since the charging experience of EVs is regarded as an impediment to its purchase, it is necessary to improve the charging rate through the implementations of an offboard charger. In DC (fast) charging, the OBC is placed inside the charging station, converting AC power from the grid into DC power outside the EV. Hence, this type of charger enables accelerated charging and mainly appears on highways.

A crucial component of the charging process is the "battery management system" (BMS), which supervises key parameters in the batter pack to ensure its efficiency, safety, and lifespan. For example, it automatically stops the charging process when the battery reaches full capacity.

Goodbye, Gasoline

EVs offer numerous new technological advancements over ICEs:

1- Regenerative braking: When the driver decelerates or breaks, the electric motor reverses in function and acts as a generator, converting kinetic energy into electrical energy and storing it in the battery (regeneration). Hence, the motor is a bidirectional power converter, enabling drivers to gain range when braking.

2- Greener Gears: Unlike ICEs, electric motors produce a full torque right from zero RPM, a characteristic known as instant torque. Therefore, there is no requirement for a gearbox, clutch, and mechanical transmission system.

Electric Revolution: The Growing EV Market

In 2024, the market share of BEVs started gaining momentum in China, spiking to about 27% while that of Europe and the United States (U.S.) trailed behind at just 13% and 8% respectively. Chinese government strategies were behind this surge, assisting both emerging automakers and EV purchasers through direct and indirect incentives, which include providing relatively inexpensive public and home charging networks (Grosvenor et al., 2025).

According to a Boston Consulting Group (BCG) survey conducted in 2025 on customers who were aiming at buying EVs during the upcoming year across the regions, three resemblances appeared (Grosvenor et al., 2025):

OVER 33% OF PARTICIPANTS PLAN TO BUY A BEV

While China holds the leading market share, there is an equal engagement in buying BEVs in all three locations.

RANGE ANXIETY AMONG TWO-FIFTHS OF BEV OWNERS

Due to range limitations, 80% of current U.S BEV owners are not willing to reinvest in a BEV.

LESS TECH-DRIVEN PEOPLE ARE HESITANT ABOUT BEVS

Western automakers must not drive their faithful consumers away while seeking to boost BEV sales.

Particularly due to range anxiety, sales of PHEVs and EREVs in China and the US have surpassed all others. On the other hand, the market expansion of BEVs in Europe represents an obvious countertrend (Grosvenor et al., 2025). However, it is vital to expand the charging infrastructure, provide high-speed charging, and upgrade battery capacity to solve the first two problems simultaneously.

Although EREVs improve the range of EVs, the issues of range anxiety and lengthy charging periods remain. To tackle the first issue, additional fast charging networks are required outside workplaces, supermarkets, and on highways. To overcome the second, more challenging problem, individuals must recognize the sustainability benefits of this new mobility plan. The adoption of EVs is comparable with the everyday use of mobile phones; users charge their smartphones regularly because they see significant advantages of owning them.

Another BCG analysis revealed that Chinese PHEV/EREV consumers typically belong to single-vehicle households and favor these markets over ICE, thanks to the cost advantage of electricity over gasoline. Simultaneously, they can bypass the discomfort of prolonged charging on longer trips, an impediment that they would normally have to tolerate with a BEV. Given these advantages, the Chinese PHEV/EREV markets have just more than doubled in compound annual growth rate between 2020 and 2024, compared to 55% for BEVs. This pattern is consistent but on a small scale in the U.S. (Grosvenor et al., 2025).

Upon witnessing the success of the Chinese EV market, western "original equipment manufacturers" (OEMs), among which are BMW and Volkswagen, are evaluating similar approaches to overcome the three forementioned problems (Grosvenor et al., 2025):

1. Implementing a micro-marketing approach to address different client groups for each EV powertrain.
2. Pioneer new technologies to ensure EVs comply with customer price and performance criteria. For instance, the battery range and power of Chinese PHEV SUVs substantially surpass those of all PHEVs in the European Union.
3. Due to the discrepancies in enthusiasm for technology, EVs might need to be equipped with different navigation features such as advanced car assistance.

Micromobility

Not all vehicles that were electrified depended on fuel, diesel, or fossil fuels, namely bicycles and scooters. According to Oxford Languages, micromobility is defined as transportation using light vehicles to be used for limited distances. Alternatively, it can be classified according to its parking flexibility as these vehicles can be parked anywhere. Therefore, micromobility also encompasses e-mopeds. Light electric vehicles (LEVs) have numerous advantages discussed below:

Low-Impact Exercise — 1
Since they require less physical effort than traditional bikes, they are optimal in assisting the elderly and inexperienced riders.

Efficient Uphill Riding — 2
The harder the rider pedals, the greater the help provided by the motor, leading to increased velocity.

Helping Mobility Needs — 3
Promotes universal access by including those suffering from asthma, joint pain, and mobility issues.

One popular brand is Trek Bikes, which designs e-bikes for all needs, ranging from low assist to high modes. While the majority of support levels are activated by pedaling, others offer the throttle assist mode, enabling bikers to ride without pedaling.

To realize where micromobility could fit, some problems affiliated with the current mobility network will be discussed.

First, due to the ever-growing population, the demand for urban passenger-miles in all means of transport could increase by 100% between 2015 and 2050. Of course, the ideal transit mode remains mass transit, but challenges related to First-Mile (FM) and Last-Mile (LM) make it less appealing to the public. The FM/LM challenge refers to the mismatch between someone’s location with the public transport system, where LM refers to the destination. This inconvenience is a universal issue as every location cannot

always be accommodated for; thus, people are obliged to take an extra step to arrive at a bus stop which might be a walking distance away (Zarif et al., 2019). Multimodal transport might be a solution, as LEVs help bridge the gap between its users and public transport locations, making short-distance travel more convenient and enjoyable.

Second, more than half of the car rides in the U.S. span less than five miles, which is not the ideal form of transit for this short of a distance. According to micromobility investor Oliver Bruce, LEVs could cover more than 4 trillion miles worldwide, presenting an enormous market potential worth hundreds of billions (Zarif et al., 2019). Given the scale of the presented statistics, converting even a fraction of these miles from cars to LEVs would significantly reduce GHG emissions, make cities healthier, and decrease congestion and pollution.

E-scooter Shutdown in Paris

Launched in 2018, this pilot program consisted of the public rental of e-scooters via a mobile application. Users were allowed to abandon them anywhere they desired, which resulted in messy streets and "scooter littered" pavements. Due to the dearth of bike lanes, people rode on sidewalks instead, increasing the risk of injuries. After five years of regulatory concerns, the verdict resulting from 90% of the public votes was to prohibit the use of electric scooters. Hence, it is ironic that while Paris was the first European city to establish an e-scooter market, it became the first to outlaw it (Chrisafis, 2023).

Some of these challenges can be mitigated through various cutting-edge features. In the case of private LEVs, it proves hard to regulate them after their purchase while when it comes to shared LEVs, parameters such as speed limit, maintenance checks, and parking restrictions can be enforced. Therefore, shared micromobility can even be considered over-regulated in this sense, an option that is lacking in other transport modes.

For generations, cars have been the king of vehicles; thus, all other smaller vehicles are bound to share the remaining space, which mainly constitutes sidewalks and then bike lanes if available. It follows that micromobility is impractical for sidewalks and traditional roads that are dominated by pedestrians and heavier vehicles respectively. Therefore, securing reserved lanes is as important of an infrastructure for LEVs as charging stations for EVs.

Speaking of bicycle lanes and charging stations, engineers have pioneered the bicycle dock technology which addresses both requirements and more. For instance, “Bluebikes” has developed a smart bicycle dock, thus upholding safety standards and solving both issues of scooter littering and charging stations.

Delivery Drones

It might sound futuristic, but the days of waiting for a shipment are gone as delivery drones have become a reality. While EV technology has significantly evolved, a different approach is needed to deal with air mobility. In the air, it is crucial to oppose gravity to maintain balance and altitude. Other challenges in aviation include the weather.

Because of these hurdles, delivery drones are still not prevalent, although, Amazon has been using Prime Air since 2022, delivering goods in the span of thirty minutes using drones. Another example is Zipline Rwanda, an autonomous drone delivery service which transports medical supplies such as blood transfusion products and vaccines.

Before expanding this new technology, it is crucial to develop unmanned traffic management (UTM) infrastructure. First, unmanned aerial systems (UAS), implemented in unmanned aerial vehicles (UAVs) and adopted in the military, controls aircraft without the intervention of an on-board human pilot. Via UAS, remote pilots can closely monitor drones to detect obstacles, prevent collisions, and redirect the aerial route. Second, to achieve larger distances, unmanned traffic management (UTM) is required. This includes surveillance and tracking systems, radars, flight planning, communication systems, and servers to supervise all aerial congestion. Concerning location, air-mobility solutions can be comparatively uncomplicated in rural areas than urban ones due to fewer obstructions and flight activity. Therefore, UTM systems must run more frequent checks for barriers and deal with more complex aerial trajectory in cities (Duvall et al., 2019).

In villages, UAS could deliver packages anywhere near someone's location, namely front yards or doorsteps. In cities, on the other hand, drones need to deliver the parcel at certain drop-off points, namely rooftops, for deliveries without a clear unloading spot (Duvall et al., 2019). Hence, shipping to urban areas would cost more due to this additional last-mile delivery, to be conducted by either delivery drones (droids) or delivery personnel. Because of such a short distance, package transportation can be carried out on LEVs.

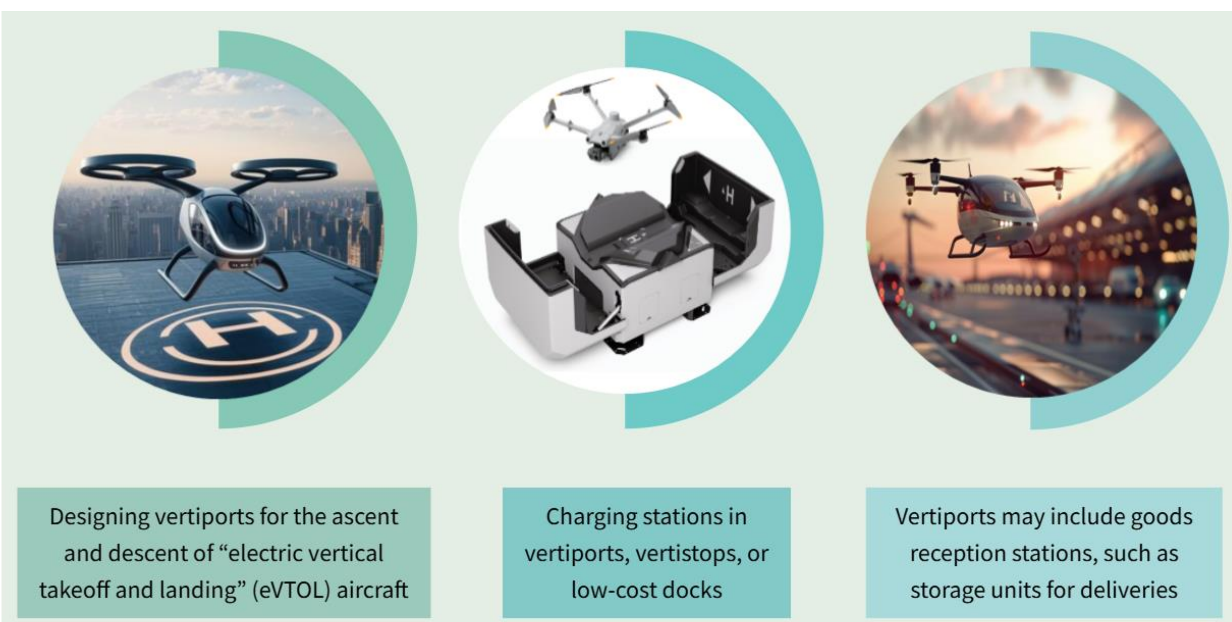
Some key infrastructure requirements for UTM systems are outlines below (Duvall et al., 2019):

Navigation planning — UTM must weigh all limiting factors, such as weather conditions, and find the quickest path to the destination (but not necessarily the shortest one).

Backup plan — In case of component or mechanical failures, an emergency mode must be activated whereby drones land immediately.

Spacing Management — To avoid getting stuck in turbulence and prevent catastrophes, it is forbidden for drones to tailgate and approach nuclear plants without keeping a certain proximity.

Three physical infrastructure necessities for delivery drones (Duvall et al., 2019):



Electric Airplanes

As the pursuit for reducing the carbon footprint persists, electric airplanes prove to be a promising solution. To provide some historical context, the concept of electrifying flights is not a new one but dates to 1883 with the Tissandier electric airship, which was the first time electricity propelled a flying machine. Although the replacement of large commercial airplanes is not anytime soon, optimistic progress is underway with small "electric vertical takeoff and landing" (eVTOL) aircraft (Carter et al., 2023).

To begin with, electric airplanes are relatively quieter and cheaper than jet-fueled aircraft. For instance, Beta Technologies' Alia CX300, the world's first all-electric aircraft to successfully take off with four passengers, is dramatically more affordable than a conventional helicopter.

However, unlike traditional airplanes which get lighter the more distance they cover, electric planes' batteries maintain the same weight. In contrast, its electric motor is compact and light; as a result, it can be mounted anywhere in comparison with the storage of fuel in the wings of conventional airplanes.

It follows that strictly relying on electricity for heavy aircraft could be challenging due to the need for hefty batteries, unrealistically increasing their weight. Although swapping empty batteries with pre-charged ones might be a solution, many batteries grouped together could be hazardous.

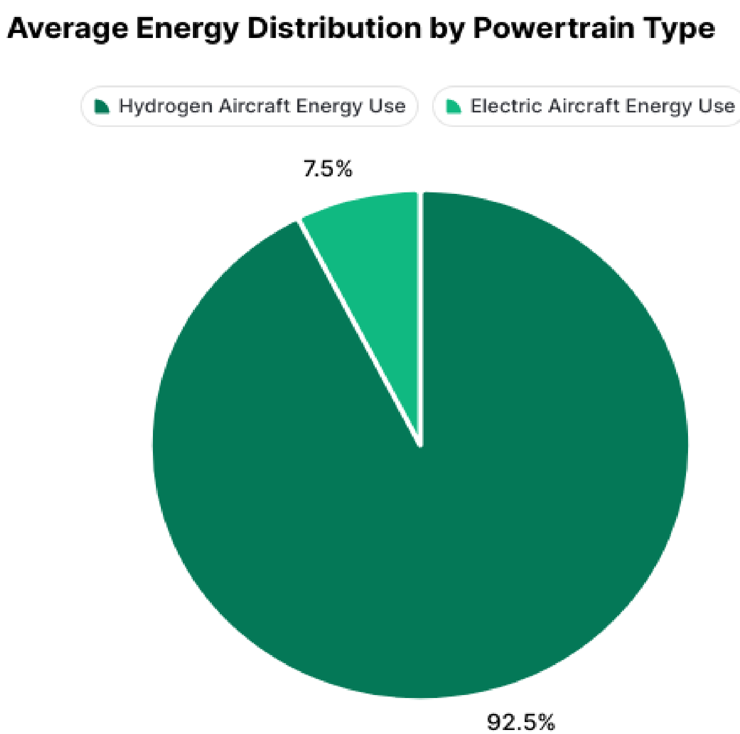
For this reason, instead of electrification, airlines such as Delta Air Airlines rely on biofuels or sustainable aviation fuels (SAF) which are derived from biomass or algae; however, their mass-production presents difficulties affiliated with availability and cost. On the other hand, it might address the issue of longer flights and can be combined with partial use of hydrogen.

Given that eVTOLs are designed for short-range flights, they can address the major problem of prolonged charging periods. In comparison with extremely short non-electric flights that emit more GHG in terms of their duration, eVTOLs demonstrate greater potential for large-scale integration. Furthermore, one notable characteristic of eVTOLs is their ability to hover and thus land in areas lacking airports.

According to Mission Possible Partnership's energy estimates, 21% to 38% of all aviation vehicles could be battery-electric and hydrogen by 2050. To meet this threshold, green energy between 600 to 1,700 TWh (Terawatt-hours) is needed worldwide. This huge number is comparable to that generated by about ten to 25 renewable energy sites as large as Belgium (Carter et al., 2023).

Alternative propulsion could be accomplished in two different technologies: battery-electric and hydrogen-powered aviation. To build this infrastructure by 2050, capital expenditure in the range of $700 billion to $1.7 trillion would need to be allocated (Carter et al., 2023).

The following chart illustrates how this energy would be distributed according to the used powertrain (Carter et al., 2023):



It is noticeable how hydrogen aircraft needs the most energy as battery powered aircraft have limitations pertaining to their range, charging duration, along with the number of passengers. Two promising models of battery-powered planes include Pipistrel Alpha Electro and Eviation Alice.

Concerning energy requirements, because airplanes need substantial clean energy to operate especially for longer distances, securing external electricity providers is crucial. For instance, for the operation of the Paris Charles De Gaulle Airport which spans around 3,300 hectares, approximately 5,800 hectares of solar panels would need to be constructed (Carter et al., 2023).

eTrucks

Almost all cargo trucks in the US are ICEs, emitting more than 25% of the overall GHGs of the transportation sector. To combat this problem, zero-emission trucks (ZETs) are introduced: vehicles that produce zero tailpipe emissions or none whilst functioning through the technologies of BEVs and FCEVs (Breiter et al., 2023).

In November 2022, it was estimated that the sales of ZETs would double across the U.S. by 2040. Hence, ICE trucks could be gradually eliminated as both medium-duty trucks (MDTs) and heavy-duty trucks (HDTs) are expected to become zero emission (ZE). To clarify their differences, MDTs are designed for short distance and light regional hauling while HDTs are intended for cross-country lengthy and heavier hauls, requiring a larger battery capacity (Breiter et al., 2023).

Concerning the powertrain, it is essential to understand the strengths and weaknesses of BEVs and FCEVs. Analogous to the section on electric airplanes, BEVs have slower charging times and are expected to be more common in MDTs, ideal for a typical San Francisco to Los Angeles regional drive. Therefore, the battery pack must accommodate the whole ride without unnecessary lengthy stops.

Alternatively, FCEVs will dominate in HDTs, suitable for the lengthier San Francisco to New York journey due to their higher range and quicker refueling times. Although the cost of refueling is more expensive than recharging, the shorter duration of the former reduces travel time by 25%, thus deceasing labor requirements (Breiter et al., 2023).

The progression toward eTrucks in the U.S. necessitates an estimated expenditure of around $20-$30 billion for charging and refueling hubs. Alongside this major expenditure, complementary infrastructure will be indispensable; for example, grid upgrades are vital to supply substantial amounts of electricity at a high speed (Breiter et al., 2023).

Finally, a favorable outcome will be seen through the development of autonomous trucks, addressing the issues of driver scarcity as well as transportation costs. Without the need for human drivers and relaxation periods, long-haul trips become faster, safer, and more economical.

Electric Trains

Unlike diesel-powered locomotives, electric trains neither carry fuel nor emit smoke as they do not combust fossil fuels. Two primary methods to power electric trains are the overhead line and third rail systems, with the latter being less popular.

First, railway overhead lines or catenary systems are used to power locomotives using a pantograph; the latter runs along these wires and transmits electricity to a transformer, which steps down the transmission-line voltage to the desired one. Some of their benefits over third rail include being a more efficient power transmission system and providing a safe elevation which is out of the reach of individuals.

Second, the third rail system employs an additional conductor rail placed along the running track, used to deliver electric power to the train. A few of its advantages over overhead lines are its cheaper installation price, more aesthetic appeal, and lower maintenance costs due to its robust design.

Inherently, rail is one of the most energy-efficient ways of transport and holds the greatest potential to combat global warming. Therefore, it can build on this eco-friendly drive by captivating more commuters who are willing to decrease their carbon footprints and lower their commuting expenditure (Zawadzki et al., 2022). Nevertheless, rail is a capital-demanding industry with high initial costs, given the necessity to acquire land to build tracks, tunnels, as well as bridges.

Regrettably, data from 2022 demonstrates the declining state of the international rail industry. Traveler and freight rail in Europe have been dropping by one and three percentage points, respectively, between 2000 and 2018 (Zawadzki et al., 2022). The main culprit of this loss was ascribed to COVID-19, as travelers avoided public exposure at the time. However, even after the end of the pandemic, survey suggested that passengers were reluctant to return to public transport. Conversely, e-commerce shipments delivered by trucks in the U.S.

have skyrocketed during the coronavirus significantly faster than other industries (Zawadzki et al., 2022).

Meanwhile, all transportation modes are committing to sustainability. For this reason, anything electrified, from cars to trucks, is gaining market share; thus, an apparent solution to increase the adoption of trains is the development of electric locomotives.

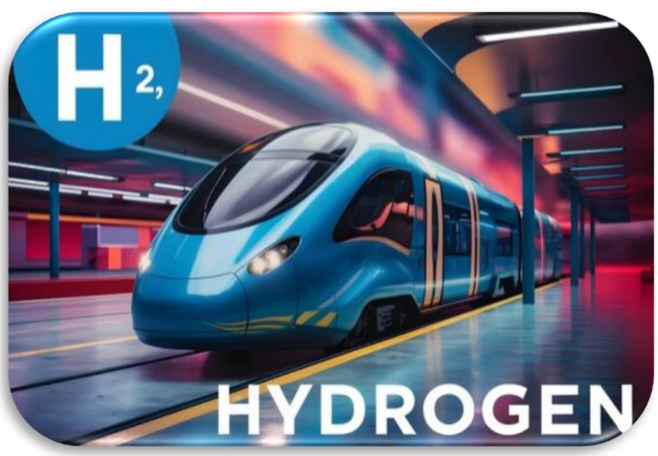
Locomotive Emissions: What You See and What You Don't

Introducing a carbon-free railway industry means not just focusing on direct train emissions but also on the indirect emissions used for administrative operations such as train maintenance (Zawadzki et al., 2022).

1- **Direct emissions** (Zawadzki et al., 2022):

Based on the findings of the International Energy Agency (IEA), diesel was used to power more than half of the world's railway operations in 2020. Therefore, carbon-neutrality can be achieved by 2050 only if diesel utilization is minimized to a mere 4% of the entirety of energy used, replacing it with either green energy or another type of locomotion.

Just like HEVs, trains can be engineered to switch between diesel power and electrified track, depending on availability, although hybrid locomotives are not entirely emission-free.

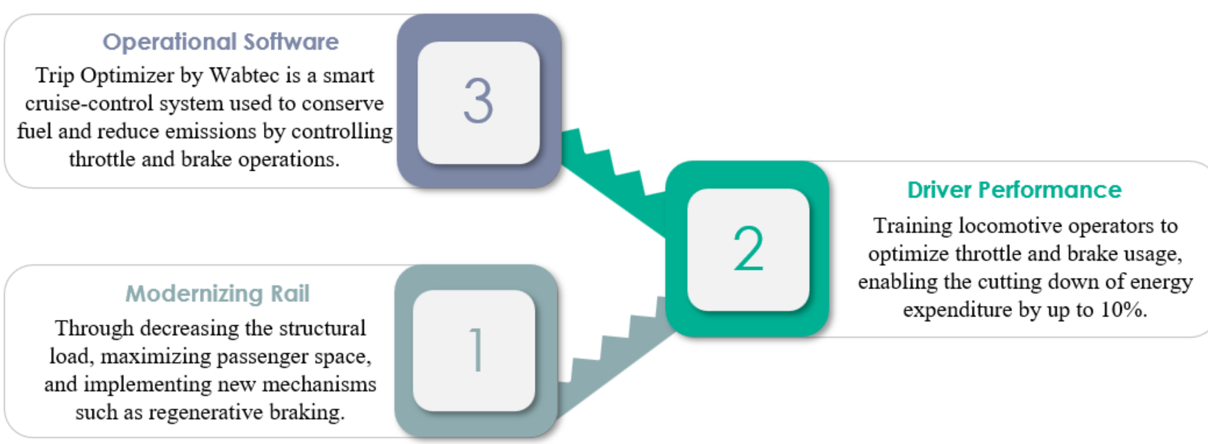


Alternatively, hydrogen gas can act as an energy source. For example, in Germany, a hydrogen train has been operating for some time now, with anticipated expansion to the Netherlands and the European Union (EU). Despite these endeavors, the technology needed for supplying, storing, as well as delivering hydrogen is costly and still in its early stages.

2- **Indirect Emissions** (Zawadzki et al., 2022):

For the rail industry to reach net zero emissions, not only does it have to be electrically powered but also substantially increase the percentage of electricity generated from renewable energy. For instance, Network Rail, the main owner of UK's train infrastructure, aims at becoming exclusively renewable by 2030. To achieve this, Network Rail is striving at incorporating solar and wind power plants into its structural assets as well as purchasing energy from external renewable electricity suppliers (Zawadzki et al., 2022).

Different techniques to increase railway's energy efficiency (Zawadzki et al., 2022)



Electric Road System

Other than securing amenities such as adequate charging stations, the electric road system (ERS) program might be beneficial for all types of land transportation systems, as it requires only slight incremental upgrades to the established infrastructure. According to Lara Erixon (2017), the director general of Swedish Transport Administration (Trafikverket), ERS possesses the capacity to lower GHG emissions, minimize energy use, and result in enhanced air quality.

For this purpose, two pilot technologies were chosen in 2015: one using an "elevated line", discussed in the electric trains section, and the other using "a rail in the roadway", both applying the concept of conductive transfer to charge driving vehicles. One year later, the first electric road for heavy-duty vehicles was publicly accessible (Erixon, 2017).

The first one employs overhead electric lines and provides two main advantages: it keeps the road undamaged and can benefit from the previously built overhead lines for rail applications. However, it remains exclusive to heavy-duty vehicles as they must be attached to these lines via a pantograph (Erixon, 2017).

On the other hand, the road-bound ERS utilizes a rail embedded in the road which is connected through a mobile arm beneath the vehicle. While this system offers accessibility to both heavy and light vehicles, it introduces difficulties such as additional upkeep costs for resurfacing and snow removal. Note that these two systems have been installed on a section of a highway and dedicated lane respectively (Erixon, 2017).

Electric Vessels

As discussed in all the above sections, land transport is phasing out of fossil fuels. The maritime industry, on the other hand, is not fully electric primarily due to the immense power requirements of large vessels, battery technology limitations, and infrastructural obstacles.

To operate watercraft on only batteries, the battery must be so substantial in size that it exceeds the spatial constraints of the ship. However, initiatives are being undertaken to support this transition. For example, the world's first fully electric, autonomous, and ZE container ship is “Yara Birkeland”, which has commercially been operating since 2022. While smaller boats are partially relying on electricity through hybrid powertrains, battery-electric propulsion is currently not feasible for long-distance shipping due to the lack of charging infrastructure at sea.

Conclusion

Transportation electrification has the potential to replace the vast majority of conventional mobility options, from airplanes to trains, and assist in achieving greenhouse gas neutrality. While challenges related to the upfront cost, battery range, and charging infrastructure exist, technologies such as electric road systems and hybrid drivetrains help mitigate these issues and achieve the net zero goal of the Paris Agreement. As indicated in the different fields, the answer to sustainability does not reside in finding one optimal form of clean energy but rather in finding the most effective combination. As battery technology advances and prices drop, e-mobility will become more prominent, prepared to shape the future of transportation.

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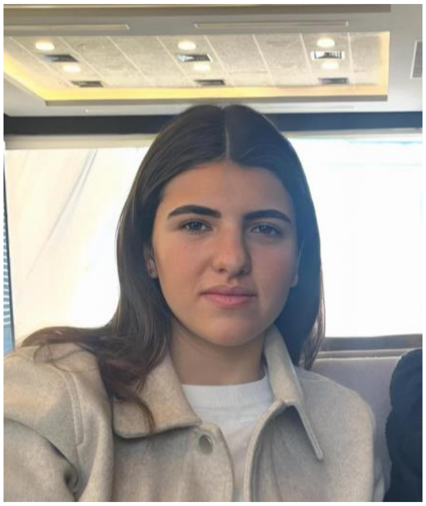
About the Author



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Nathalie Jouljian is an Electrical Engineering student at the Lebanese American University with a keen passion in renewable and sustainable energy. Having developed a particular curiosity in transportation electrification, her research explores how electric mobility can drive cleaner and more efficient transport systems. She envisions a world where roads hum with quiet energy, and every electric mile brings us closer to a greener tomorrow.