Electric Vehicles and Internal Combustion Engine Vehicles:

A Quantitative Comparison

Vidit Aggarwal

Methods

The two countries that will be compared are the USA—a global superpower, with the current dominating currency—and India. India has been chosen due to high rates of growth in its economy worldwide, making it suitable for observation in the coming years (Patnaik and Pundit) along with its dire need for environment-friendly vehicles, that stems from housing the largest population in the year 2023 (Hertog et al.).

The selection of ICE (Internal Combustion Engine) vehicles was done by sorting the highest selling brands (Carlier). From these brands the highest selling sedan and SUV were chosen for the calculation of raw data. For BEVs, the company's sales were disregarded, and the cars were chosen based on the most units sold nationwide. The selection of cars was done for two categories: India and the USA. Each of these categories had further two subdivisions: sedans and SUVs. Each division consisted of four cars.

Price: The comparison of the price of cars was calculated from the average price of each category, and the averages were then compared against their fuel-based counterparts, with sedans being compared to sedans and SUVs being compared to SUVs. The upfront retail price of each car was sourced from the OEMs official website.

Range: This metric compares the range of the BEV against the range of a traditional ICE vehicle. Data was calculated in a similar way to the price by averaging the range of the selection of cars and making a direct comparison with the values. The data source was primarily the brand's website itself; however, in some cases an alternative generalized website was used. The calculation of range was done by three standard tests: NEDC, WLTP and EPA. Due to the collection of data from a variety of different websites, all the cars did not undergo the same test and thus may be a bit inconsistent.

Refueling/Recharging Times: This comparison is between the recharging time of a BEV and the refueling time of gasoline-based cars. The recharging time for a BEV can vary a lot based on the wattage output of the charger; therefore, a standard of Level 2 (240V AC) charging was assumed, as these are the most common chargers in both recharging stations and household chargers. This was calculated by using the average recharging times of BEVs in their respective categories and with a common gasoline refueling time of 2 minutes for sedans and 3 minutes for SUV to account for the larger fuel tank sizes of SUVs.

Density of Stations: The density of stations was calculated by averaging the density of stations in a metropolitan city and urban city; the density for each city was calculated by dividing the number of stations by the area of the city in square miles. The primary reason in choosing a metropolitan city stems from the large population it houses and the high income households it houses which are most likely to purchase a BEV (Davis). Urban cities were chosen because it is challenging to find viable data for rural towns, areas with low population density, especially in India where most rural towns have no charging stations at all.

Energy: This metric consists of three different comparisons. First, the cost of one kilowatt-hour of electricity sourced directly from the power grid and one kilowatt-hour of fossil-fuel based energy (petrol since most of the selected models of cars use petrol) was compared. This factor was calculated and compared separately for India and the USA, due to the difference in availability of fuel which causes a difference in cost. Secondly, a comparison between the percentage of energy that was converted into useful energy between BEVs and ICE vehicles was directly sourced from online sources. The third comparison was a combination of the first two, where the cost of the distance traveled on one kWh of energy was compared between BEVs and traditional gasoline vehicles. The data was sourced from the first two comparisons and was mathematically calculated by multiplying the percentage by the value of the first metric.

Results

Figures of Merit	INDIA		USA	
	Real values	Normalized	Real values	Normalized
Price of BEV sedan : Price of ICE sedan	35,074.02 : 9,257.50 [USD:USD] (converted from INR to USD at 1 INR = 0.12 USD)	3.78:1	34,655 : 25,625 [USD:USD]	1.35:1
Price of BEV SUV : Price of ICE SUV	27,190.77 : 12,817.56 [USD:USD] (converted from INR to USD at 1 INR = 0.12 USD)	2.12:1	48,307.5 : 30,661 [USD:USD]	1.58:1
Range of BEV sedan : Range of ICE sedan	294 : 494 [miles:miles] (converted from km to miles)	0.59:1	267.25 : 493 [miles:miles]	0.54:1
Range of BEV SUV : Range of ICE SUV	278.5 : 573.33 [miles:miles] (converted from km to miles)	0.48:1	284.5 : 452.4 [miles:miles]	0.63:1
Charging of BEV sedan : Refuelling of ICE sedan	7.7 : 0.033 [hours:hours]	233.3:1	7.75 : 0.033 [hours:hours]	234.8:1
Charging of BEV SUV : Refuelling of ICE SUV	9.9 : 0.05 [hours:hours]	198:1	6.5 : 0.05 [hours:hours]	130:1

Density of Charging Stations : Density of Gas Pumps	1.71 : 2.51 [No. per sq.mile: No. per sq.mile:]	0.68:1	18.31 : 1.95 [No. per sq.mile: No. per sq.mile:]	9.36:1
Price of Electricity per kWh : Price of Petrol per kWh	13 : 7.7 [cents:cents]	1.69:1	13 : 16.7 [cents:cents]	0.78:1
Price of Electricity per useful kWh of energy : Price of Petrol per useful kWh of energy	10 : 61.90 [cents:cents]	0.16:1	21.69 : 61.90 [cents:cents]	0.35:1

Table 1: A numerical representation of the data collected and the figures compared (https://shorturl.at/AMORT)

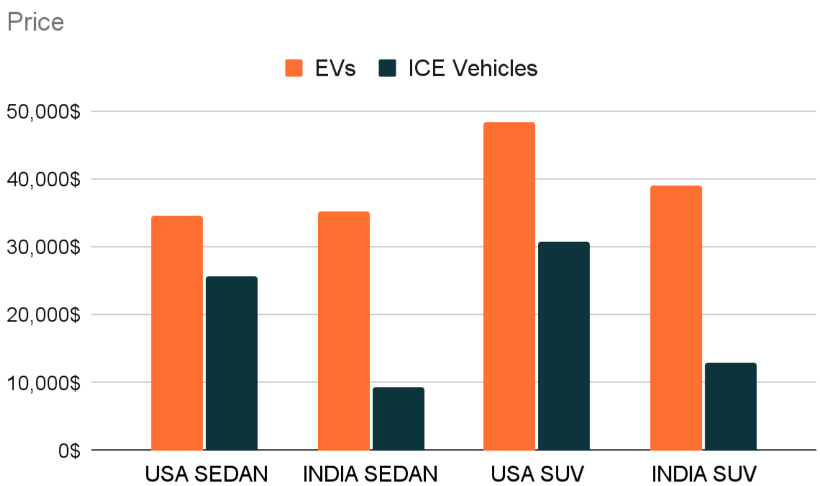


Figure 1: Representation of the average price of vehicles in dollars shows the average prices of the selection of cars. This depicts the difference between ICE vehicles in both the countries and highlights the importance of price to increase selling in low cost of living countries.

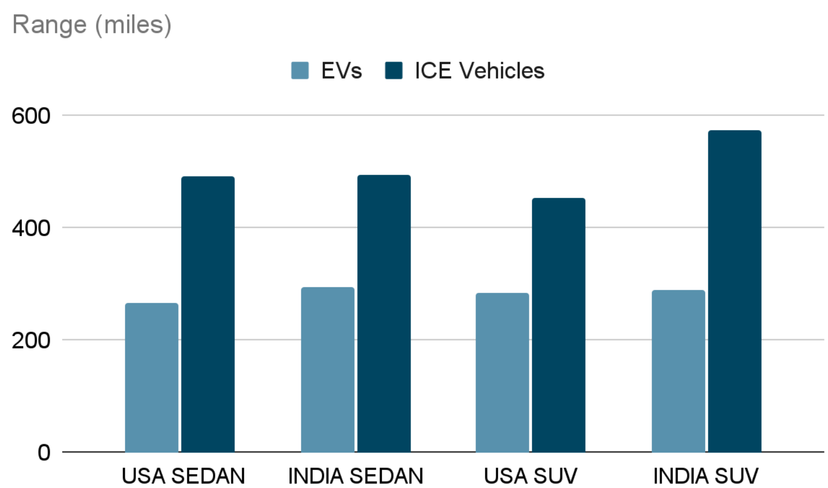


Figure 2: Representation of the range of a vehicle in miles Figure 2 compares the average range of vehicles in their respective categories. This is used to highlight the significant differences between BEVs and ICE vehicles. It also shows the similarities between entirely different OEMs in different countries.

BEV charging time	sedan	SUV
a. USA	7.75 Hrs	6.5 Hrs
b. INDIA	7.7 Hrs	11.125 Hrs
Fossil Fuel refueling time	0.033 Hrs	0.05 Hrs

Table 2: Representation of the charging times of BEVs and refueling times of gasoline based vehicles

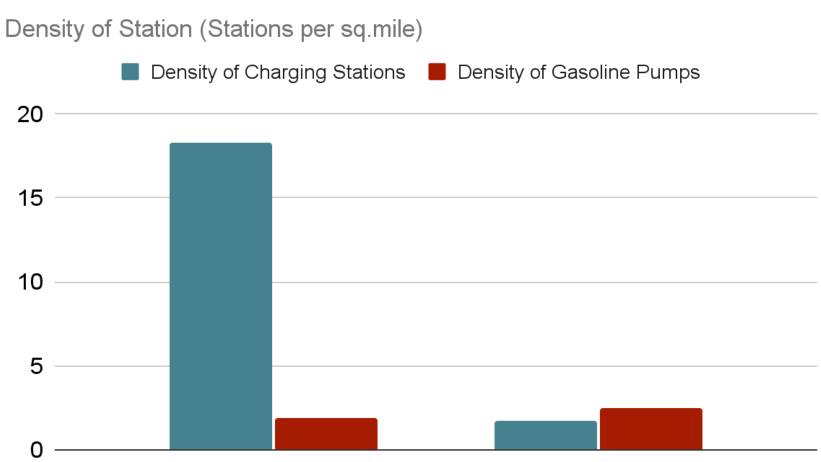
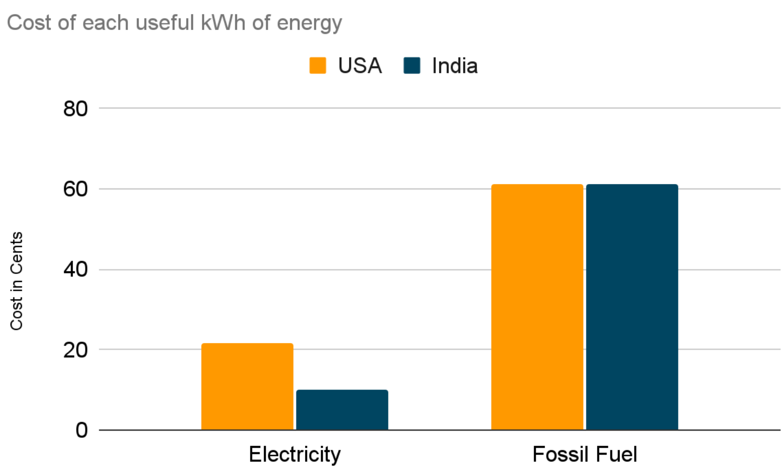


Figure 3. Represents the number of stations per square mile in highly populated areas
Figure 3 shows the density of stations on average in the respective countries. Its main purpose is to show the difference between a developed country and a developing country by highlighting the significant difference between the density of charging stations.

Figure 4: A comparison between the cost of electricity

In Figure 4 the first graph represents the cost of one kWh of energy in the USA and India between fossil fuels and electricity supplied directly from the power grid. The second graph depicts the cost of ‘useful’ energy – energy used in moving the car – for the respective vehicles. This cost was derived from the efficiency of the vehicle – which refers to the energy conserved for the wheels after factoring in energy loss from various sources: heat, friction and other accessories such as speakers – this was typically around 77% for BEVs and can range between 12-30% for ICE vehicles (US dept. of Energy)



Analysis and Discussion

The results from the collection of data have highlighted a series of factors which indicate the reasons for the slow adoption and subpar selling of BEVs in developing countries, in this case India. The comparison of India to the US, assists us in separating factors that may have affected the data such as higher cost of living.

Price

Price is the most important factor when comparing cars; approximately 42% of buyers in 2022 stated this to be the largest factor considered when making a purchasing decision (Autolist Editorial Staff). It can be concluded that BEVs have a higher upfront cost. Electric sedans are 35% more expensive than ICE sedans, and electric SUVs are 58% more expensive than ICE SUVs (See Figure 2). This increase in price makes BEVs unfavorable to the majority of low income households, especially in India where low and middle income households make up a majority of the population and only 3% of the population made over $3600 annually in 2021 (Rathore). While this is enough to sustain an adequate life in India, it is in no way enough to purchase a BEV that retains similar upfront costs to the US. The large contingent of the low and middle income households also support the data from Figure 2 where Indian ICE vehicles are only a fraction of the US ICE vehicles; this is a result of adaptation in a low income environment, and BEVs have yet to see this form adaptation and revolution.

Range

Range is a core performance measure for every car, and approximately 39% of buyers in 2022 stated range as their second biggest concern when making a purchasing decision (See Figure 3). ICE vehicles almost doubled their respective counterparts in terms of range. This difference in range can be attributed to their smaller energy capacity, as the average BEV has a storage of only 60 kWh and up to 75 kWh for SUVs (IEA) as compared to ICE vehicles that can store up to 50-60 L of fuel (Wikipedia contributions). Therefore, since one liter of petrol contains 8.9 kWh of energy this amounts to 445-534 kWh of energy in the average fuel tank which is several times more than BEVs, this displays the huge gap in storage capacity that BEVs still have to make up. This gap is extremely difficult to make up due to a variety of reasons, which stem from the chemical composition of the battery.

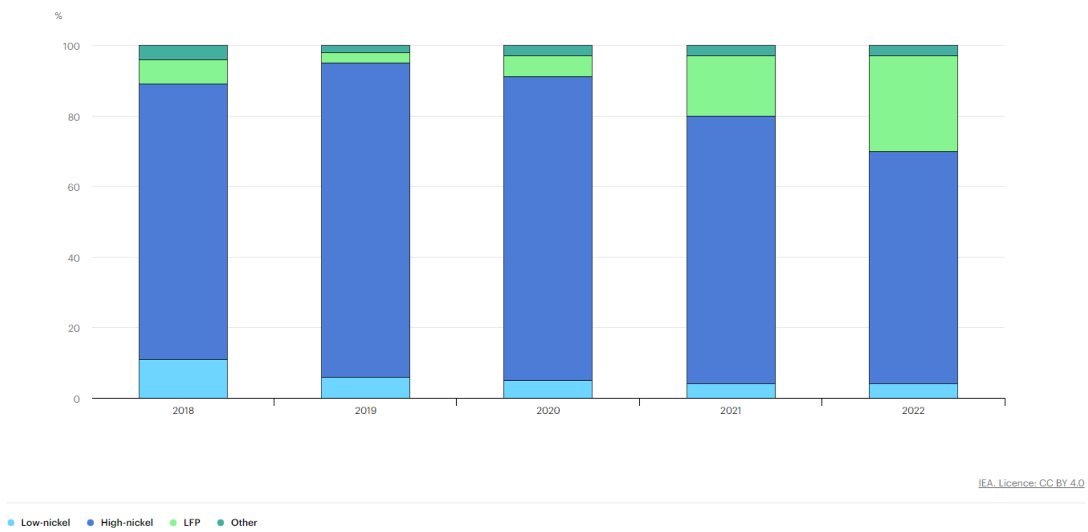


Figure 5: Chemical composition of batteries by IEA: https://www.iea.org/data-and-statistics/charts/electric-ldv-battery-capacity-by-chemistry-2018-2022

Lithium nickel manganese cobalt oxide (NMC) has been the most common choice for the battery, with a market share of 60% due to its high energy density. The second most common choice is lithium iron phosphate (LFP) with a market share of 30% in 2022. LFP has seen significant growth due to Chinese OEMs, especially BYD, which alone requires up to 50% of the demand (IEA). This is because BYD has made breakthroughs in LFP battery technology with their blade battery, which takes care of two major problems: the reliability of the battery, and the usage of nickel—a rare metal with depleting sources. Innovative solutions such as this indicate the start of a revolution in the automotive industry.

Recharging and Infrastructure
The recharging process is a fundamental drawback of BEVs, as fossil fuel powered vehicles can refuel within a matter of minutes while BEVs may take up to 23,000% more time than standard refueling. Chargers have been divided into 3 levels and these levels are the defining factors for faster charging times. Level 1 chargers are the most basic chargers, with 1 kW of power output and 120V AC voltage; these typically add 2 - 5 miles per hour of charging. Level 2 chargers are the industry standard and the most common ones, and you can usually find these at your home and the nearest charging station, that typically have a power output of 7 - 19 kW with 240V; these chargers add 10 - 20 miles per hour of charging. Level 3 chargers are the fastest chargers and place an immense burden on the grid. Their power output can vary anywhere from 50 - 350

kW and can add anywhere between 180 - 240 miles per hour of charging (US Dept. of Transportation). While level 3 chargers seem like the obvious solution for reduction of charging times, they are extremely expensive to construct and place a huge burden on the power grid, which results in problems with scalability. This also correlates to the “chicken egg problem,” where the lack of BEVs causes the lack of infrastructure and vice-versa. From Figure 5, it is apparent that the US has made great strides in their infrastructure, with almost 10 times the number of charging stations to gas stations; however, the graph also shows the dire situation in India, which in contrast has more gas stations than charging stations. The foremost reason for increasing the number of charging stations is to become free of range anxiety. Rather than depending on larger batteries, it is better to always have a charging station nearby since larger batteries cost more and require more expensive rare earth metals. Therefore, better infrastructure could solve a variety of problems, especially since chemical composition of a battery is no longer a bottleneck for faster charging but rather the grid and charging stations with low power output (Carrington).

Energy and efficiency
BEVs now have a better cost per mile which had not been possible up until 2022 (Reuter). The average cost of one kWh of energy can vary between 7.7 - 16.7 cents; the same cost per kWh of energy in fossil fuels when calculated had a cost of 13 cents. The difference between these vehicles originates from their percentage of ‘useful energy.’ For BEVs this percentage averages around 77%, and for ICE vehicles it can vary anywhere between 10-30% due to specific environmental conditions: terrain, highways and a variety of other such factors. This results in BEVs costing between 10 - 21 cents for each kWh of ‘useful energy’ depending on the country and location; the same measure for ICE vehicles would average around 61 cents. In layman's terms, this would mean that depending on the car and electricity prices, locally BEVs can travel 3 to 6 times further for the same cost as one would have to pay for the fuel of an ICE vehicle.

Conclusions and Recommendations

We have taken a series of factors into account—price, range, charging times, energy efficiency, and costs— which provide a quantitative comparison between BEVs and ICE vehicles. These factors represent each vehicle and their characteristics, and they also allow us to understand the logic behind the cultural shift from ICE vehicles to BEVs. However, as seen from the data presented, BEVs are still lagging behind and to make up for this they need to improve the overall infrastructure or lose their dependence and reliance on the infrastructure. This can also be done by recharging the battery without a charging station, such as with the help of photovoltaic panels embedded in the body of the car.

The concept of solar cars has been around for a long time; however, due to high cost and low energy generation from solar panels, complete self sustainability is not possible. From a recent study it was found that the number of required grid charging events per year can be reduced from 104 to 34 in The Netherlands. Photovoltaic (PV) charging can reduce CO_2 emissions of BEVs by 18% to 93% as compared with ICE vehicles. This information supports PV-powered BEVs to be impactful with some technological breakthroughs in reduction of cost for their upfront cost and improving energy generation in the PV cells. These vehicles could revolutionize the industry by reducing the fear of range anxiety and reducing the overall grid charging events (Rodriguez et al.).

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