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A Review on the Potential of Electric Vehicles in Reducing World CO_2 Footprints

S. Alotaibi, S. Omer, Y. Su

***Abstract*—**The conventional Internal Combustion Engine (ICE) based vehicles are a threat to the environment as they account for a large proportion of the overall greenhouse gas (GHG) emissions in the world. Hence, it is required to replace these vehicles with more environment-friendly vehicles. Electric Vehicles (EVs) are promising technologies which offer both human comfort "noise, pollution" as well as reduced (or no) emissions of GHGs. In this paper, different types of EVs are reviewed and their advantages and disadvantages are identified. It is found that in terms of fuel economy, Plug-in Hybrid EVs (PHEVs) have the best fuel economy, followed by Hybrid EVs (HEVs) and ICE vehicles. Since Battery EVs (BEVs) do not use any fuel, their fuel economy is estimated as price per kilometer. Similarly, in terms of GHG emissions, BEVs are the most environmentally friendly since they do not result in any emissions while HEVs and PHEVs produce less emissions compared to the conventional ICE based vehicles. Fuel Cell EVs (FCEVs) are also zero-emission vehicles, but they have large costs associated with them. Finally, if the electricity is provided by using the renewable energy technologies through grid connection, then BEVs could be considered as zero emission vehicles.

***Keywords*—**Electric vehicle, fuel cell electric vehicle, hybrid electric vehicle, internal combustion engine.

I. Introduction

THE EV technology has emerged as a promising solution of the problem of GHG emissions [1]. Transportation sector is one of the top contributors to GHG emissions globally. According to the US Energy Information Administration (EIA), the transportation sector is responsible for 27% of total energy consumption and around 34% of total GHG emissions in the world [2]. Traditionally, vehicles have used the ICE which burn fossil fuels producing harmful gases (such as carbon dioxide and carbon monoxide etc.) Therefore, there is a need to switch from ICE to a more environment-friendly technology. EVs provide one such alternative. However, this is not the only advantage of EVs. The operating cost of EVs has also been found to be much less than ICE-based vehicles [3]. Due to their environmental-friendly nature and better fuel economy, EVs they have gained a lot of attention over the past few years.

EVs can be classified based on the degree or the way in which electricity is used as the energy source. The main types of EVs are BEVs, Hybrid/Plug-in Hybrid EVs (HEVs, PHEVs), and FCEVs. Fig. 1 shows the worldwide growth in EV stock of BEVs and PHEVs from 2013 to 2018. In 2018 there was an estimated growth of 3.3 million BEVs and an additional 1.8 million PHEVs.

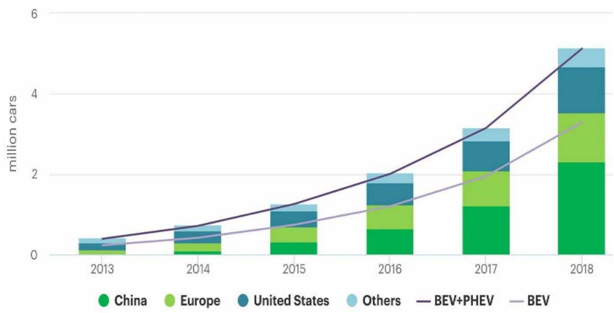

Fig. 1 Worldwide growth in BEV and PHEVs according to region [4]

Major characteristics, features and technologies used in the main types of EVs are presented in Table I. Each type of EV is unique in its characteristics and the choice is up to the consumers. The world market for the EVs increased exponentially since 2013 (see Fig. 1 [4]) but FCEVs are far less mainstream with a stock of only 12,900 vehicles worldwide with 46%, 23%, and 14% in the US, Japan, and China, respectively at the end of 2018. The target vision and projection of hydrogen council expect a significant increase in hydrogen fuel cell vehicles by 2030. Their vision predicts that by 2030, one in 12 cars in Germany, Japan, South Korea and California would be powered by hydrogen and globally 10-15 million cars and 500,000 trucks [5]. Also, their vision projects the hydrogen fuel cell vehicle market up to 2050. By 2050, the hydrogen powers more than 400 million cars, 15-20 million trucks, and around 5 million buses [6]. The BEVs completely rely on batteries for energy for propulsion [7]. The propulsion system consists of only electric motors whereas the hybrid vehicles have both electric machines and an IC engine. So, the energy sources for the hybrid engine have both batteries and IC engine. Fuel cell vehicles use fuel cell and supplementary batteries for propulsion of the electric motor which is the prime mover in fuel cell vehicles. The specific characteristics, features and technologies available in BEVs, HEVs/PHEVs and FCEVs are detailed in Table I.

The aim of this paper is to review state-of-the-art EVs. The advantages and disadvantages of different vehicle technologies are also discussed. The rest of the paper is organized as follows: in Section II, an overview of different EV types is presented. Recent trends related to the different types of EVs are presented in Section III while cost analysis is

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presented in Section IV. Finally, conclusions are presented in Section IV.

TABLE I
SUMMARY OF THE MAIN CHARACTERISTICS OF EACH EV TYPE, THEIR MAIN FEATURES, AND ADVANTAGES/DISADVANTAGES

EV Type	BEV	HEV/PHEV	FCEV
Energy source(s)	Battery	Battery/ultra-capacitors, ICEs	Fuel cells, supplementary battery
Propulsion technique	Electric motor drives	Electric motor drives, ICEs	Electric motor drives
Main features	Zero emission, short driving range, higher initial costs	Low emission, longer range, complex	Zero emission, high initial costs, moderate driving range
Major techniques	Electric motor control, battery management, charging device	Electric motor control, battery management, managing multiple energy sources, optimal system efficiency, components sizing	Fuel processor, fueling system, fuel cell cost
Regenerative braking	Yes	Yes	Yes
Battery capacity	20-100 kWh	5-20 kWh	2-20 kWh
Number worldwide	3.3 million	1.8 million	12,900

II. OVERVIEW OF EV TYPES

In this section, the four different types of EV technologies (i.e., BEV, HEV, PHEV, and FCEV) are reviewed.

A. Battery EVs

The BEV does not use a traditional ICE. Instead, it uses an electric motor and battery. In order to recharge its battery, it requires plugging in into an external source of electricity (see Fig. 2 [8]). An alternative way to recharge the batteries of a BEV is to use 'regenerative braking' [9]. In regenerative braking, the vehicle's electric motor is used to help slow down the vehicle and to recover some of the energy which is usually lost as heat generated by the brakes.

Advantages of a BEV are zero emissions, no gas or oil changes, the ability to conveniently charge at home, fast and smooth acceleration due to lack of gears, and low operating costs. Some disadvantages are shorter ranges than gas vehicles and slightly higher cost than their gasoline equivalents although the gas savings typically make up for the difference in 2-3 years.

Over the past few decades, the number of BEVs has increased significantly and by 2030 the projection estimates that there will be more than 125 million BEVs across the globe. The development of the Lithium-ion batteries acts as the heart of these advancements in EVs [10]. BEVs use the batteries to store the electric energy and need to be plugged in to charging stations to recharge the batteries. In this type of EVs the electric motor is very efficient and usually uses 90-95% of the input power. This power is used to move the vehicle, and which always results in zero emissions while driving [11].

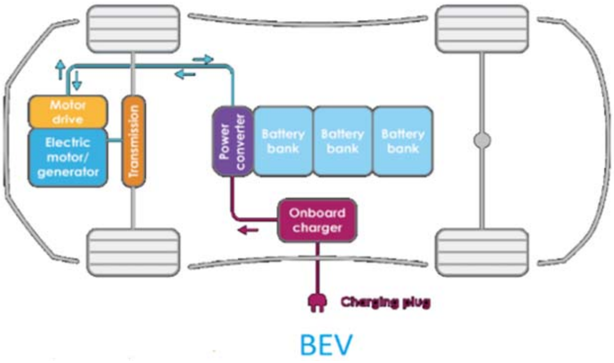

Fig. 2 Diagram of a BEV [8]

The main challenges associated with the BEVs are the cost and driving range associated with the batteries. The majority of models of BEVs are not able to store more energies and driving range is limited below 160 miles or 250 km, whereas some advanced new models offer substantially more range up to 400 km, and the upcoming models are predicted to range beyond 400 km.

Apart from the concern on range, consumers are also concerned on the cost of batteries. In 2015, the cost for the battery was US $350/kWh, which added the total price for a 40 kWh capacity battery to US$ 14,000. This cost on battery lead to an additional increase in cost of EVs by at least US$ 12,000 in comparison to the similar price range ICE vehicles. [12].

Deloitte estimation predicts that the market for BEVs will reach the peak point in 2022 when the cost of the ownership of the BEV is in par with its IC engines counterparts. The consumer concern regarding the utility of the BEVs is shown in Fig. 3. The majority of the countries in Fig. 3 are more concerned on the driving range, cost and the lack of the infrastructure for charging. In India, 25% of the EV customers are more concerned on lack of EV charging infrastructure [13].

Fig. 4 shows the driving range of the next generation BEV for the most popular car manufactures in the world like Nissan, Ford, Tesla, GM, Daimler, Hyundai, Tata motors, Volkswagen and Geely. Among all these car manufactures the Tesla motors are expected to reach 1000 km of range in 2020 with their 'next generation Roadster'.

To meet the next generation driving range by major car manufacturers shown in Fig. 4, the improvement in the energy density can be achieved for the lithium ion batteries by optimizing the existing Li-ion cells or introducing new battery materials with enhanced charge, discharge and thermal performance. Better battery management system can enhance the driving range; simultaneously can improve the safety and life extension [14]. Optimized cooling and improved pack design will improve the driving range. Significant reduction in the vehicle and battery pack mass can also improve the driving range. Beyond 2023, Lithium-air, solid state technologies, high energy capacitors can improve the BEV's range [13]. From Fig. 4, it can be seen that the BEVs by automakers such as Tesla, Volkswagen and ford are expected to provide a minimum of range 400 km with their variant of Roadster, ID Crozz and concept and Mach 1 respectively. Among these variants, Tesla Roadster is expected to cross the range of 1000 km. This expected increase in Tesla variant towards the end of 2020 would be due to their technological improvement in batteries. As this technology is patented by Tesla motors, it becomes difficult for other motor companies to compete with Tesla motors in the BEV market. It took another two to three years for the motor companies like the General Motors and Volkswagen groups to reach the present driving range of Tesla motors [13]. To overcome these concerns, the biggest car manufacturers and new entrants are expected to increase the production capacity of the EVs. Fig. 5 shows the EV production capacity increase in millions for 17 years since 2013. This indicates that all the car manufacturers increase their production capacity gradually which in turn makes the IC engine cars obsolete in future markets.

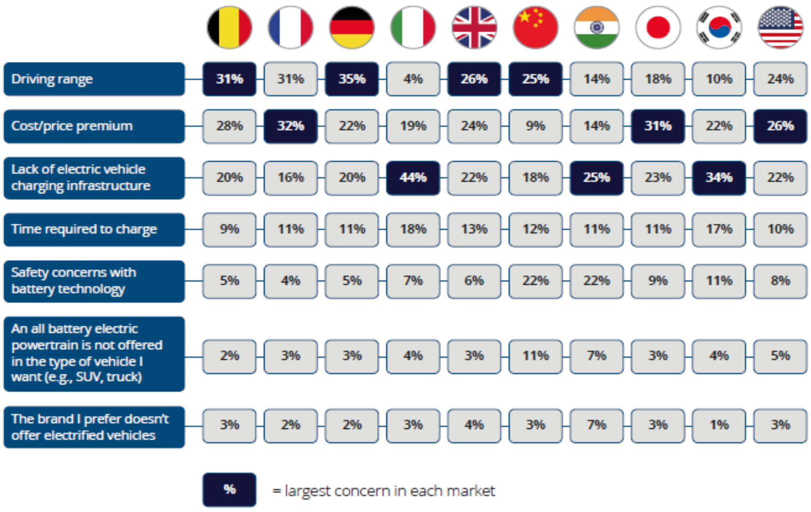

Fig. 3 The percentage of concerns of customers in regard to buying BEVs in different countries [15]. Each country is represented with their national flags

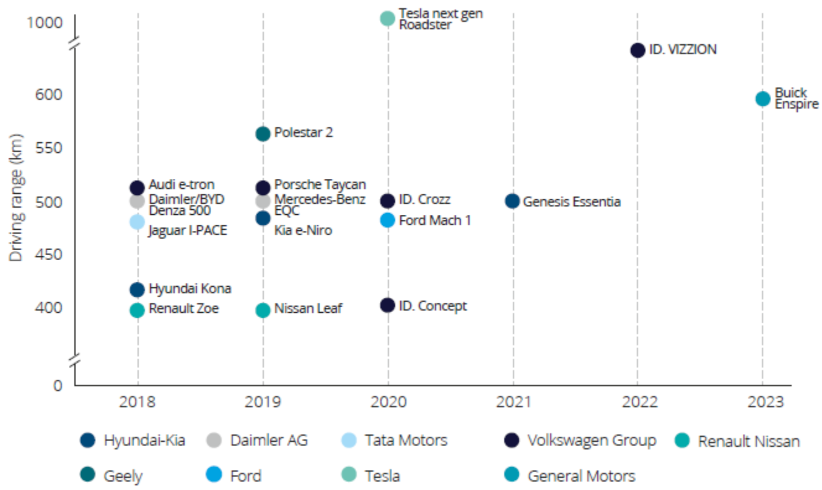

Fig. 4 The driving range for the next generation BEVs [13]

There are numerous battery manufacturers in the world who deliver commercially available EV batteries, for example Samsung and Panasonic. On the other hand, the majority of car makers already have their own battery development plants, such as Tesla. Some of the commercially available batteries and projected specifications are shown in Table II. The batteries such as Al-air and Li-air are under development and not yet commercialized. And also, the batteries that are commercially available are still being developed, among the batteries currently available, the Li-ion batteries dominates all other in its energy features, which makes it a suitable candidate for the application in all type of EVs [11].

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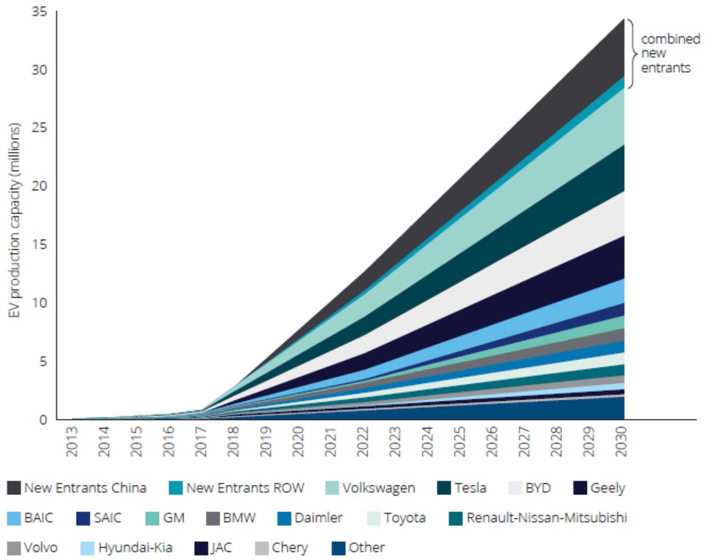

Fig. 5 EV production forecast of the big car manufacturers and new entrants [13].

TABLE II
THE PAST, PRESENT AND PROJECTED BATTERY SPECIFICATION IN EVS [11]

	Now			Projected		
	Specific power (W/kg)	Specific Energy (Wh/kg)	Cycle life (deep cycles)	Specific power (W/kg)	Specific Energy (Wh/kg)	Cycle life (deep cycles)
Pb/A (VRLA)	200	35	600	300	45	1500
NiMH	200	65	1000	300	75	1200
NaNiCl2	150	100	1000	400	120	1500
Li-ion	300	100	NA	500	150	1500
Zn-air	90	100-200	NA	110	300	600
Al-air	10	200-300	NA	16	1300	NA
Li-air				Low	600-1000	NA
Fe-air	90	80	600	100	120	1000

Note: NA means the parameter is not applicable

The vehicle efficiency and the power generation efficiency are the factors which determine the energy consumption of BEVs. The energy consumption of the BEVs varies with the driving conditions, speed and with the use of heaters or air conditioning. The energy consumption and the BEVs specifications by car manufacturers are shown in Table III. The energy consumption can be as high as 200 Wh/km for EV variants like Mitsubishi iMiev. The range of BEV varies with the velocity, so the longest BEV range is achieved in city driving conditions where the speed does not exceed 50 km/hr. When the Drag Coefficient (Cd) decreases, the fuel consumption decreases with approximately same battery capacity and same battery type, comparing Ford Focus and Nissan Leaf. In fact, the frontal area increases the drag directly [11].

TABLE III
BEVS OF DIFFERENT GLOBAL MANUFACTURERS AND THE SPECIFICATION OF THE COMPONENTS AND DESIGN

	Max. Power (kW)	Weight (kg)	Frontal Area (m2)	Cd	Battery type	Battery capacity (kWh)	Motor	Fuel Consumption (Wh/km)
Smart Fortwo Electric	30	854	1.95	0.38	Sodium-nickel-chloride (Zebra)	14	BLDC	120
Mitsubishi iMiev	47	1080	2	0.3	Lithium-ion	16	BLDC	125
Think city	30	1038			Sodium-nickel-chloride (zebra)	28.3	AC-Induction	157
Ford Focus	100	1550	2.26	0.32	Lithium-ion	23	BLDC	190
Nissan Leaf	80	1585	2	0.28	Lithium-ion	24	BLDC	150
Fe-air	90	80	600			100	120	1000

Note: Fuel consumptions are based on new European driving cycle and the specifications are by the car manufacturers. Cd- is the drag coefficient, aerodynamic friction term, depends on velocity, BLDC is the Brushless Direct Current motor.

B. Hybrid EVs

In HEVs, the power for propulsion is harnessed from both batteries and gasoline by employing the electric machines and IC engines respectively. A schematic diagram of an HEV powertrain is shown in Fig. 6. The ICE in HEV harnesses the power from gasoline and drives the wheel. The electric motor additionally supports the IC engine in power transmission whenever required or the motor drive the car independently depending upon the charge state of the battery and electric power train considerations. When the charge is below the threshold, the engine turns the motor to generate electric power to charge the battery pack. Motor control unit and power converter unit help in switching between these requirements. The combination of IC engine and electric power train can be of different forms such as series hybrid, parallel hybrid, series-parallel hybrid and complex hybrid configurations. All these configurations have advantages and disadvantages [8]. HEVs utilize electric propulsion systems only when there is a demand for power and it is generally advantage in low speed conditions like in urban areas, it reduces the fuel consumptions as the engine stops during the idling period especially in traffic jams. This also helps in reducing the GHG emissions. During high speeds the electric system switches to the IC engine. Two drive trains can work simultaneously to improve the performances of the configuration technologies generally used in HEVs, which are explained below [8].

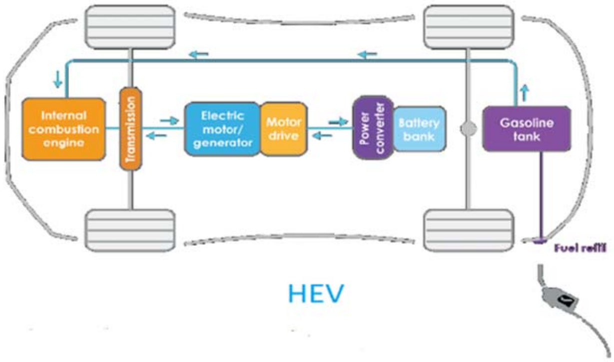

Fig. 6 Diagram of a HEV [16]

In these vehicle systems, the battery minimizes idling and enhances the vehicle's ability to stop and go which is important in city driving. The electric battery can accelerate the car to about 40 mph, then the combustion engine takes over. Since HEVs cannot be recharged from the electricity grid, all of their energy comes from gasoline and regenerative braking. Advantages of HEVs are longer ranges than BEVs and less gas consumption and emissions production than gas only vehicles. Disadvantages are non-zero emissions and complex mechanics with the gasoline and electric systems able to turn the transmission simultaneously which can lead to higher risk of failure and high repair costs. Additionally, like PHEVs, HEVs are 8-10 times more expensive to operate than BEVs since they use gasoline and require oil changes. Also, a disadvantage over a PHEV is that there is no ability to charge an HEV from the electric grid [8].

C. Plug-in HEVs

This technology also uses both ICE and an electric power train same as that of HEVs, but the main difference between these two technologies is that PHEVs use electric propulsion as the main driving force, and it demands a bigger battery capacity than that of HEVs. These PHEVs start in electric mode, run in electric mode and when the batteries are low of charge then the electrical system calls on the IC engine to boost the propulsion system or to charge the batteries. A schematic diagram of a PHEV is shown in Fig. 7. The main use of the ICEs is to enhance the range of the trip. The batteries of the PHEVs can be charged directly from the grid or it can be charged using the regenerative braking. So, it contributes less to the carbon footprint as it consumes less fuel than that of the HEVs.

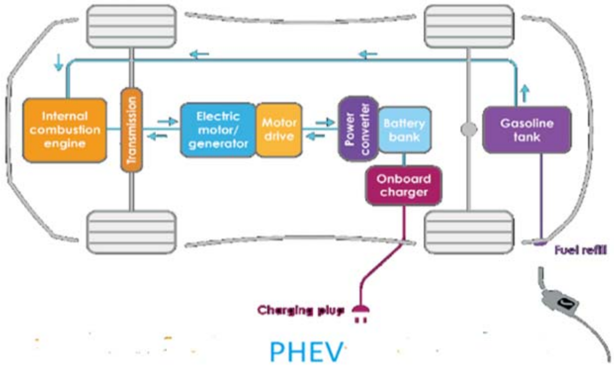

Fig. 7 Diagram of a plug-in HEV [16]

D. Fuel Cell Vehicles

FCEV is also known as the Fuel Cell Vehicles (FCV). As the name suggest this type of vehicles depends on the fuel cell that uses the chemical reactions to produce electricity. A schematic diagram of a fuel cell car is shown in Fig. 8.

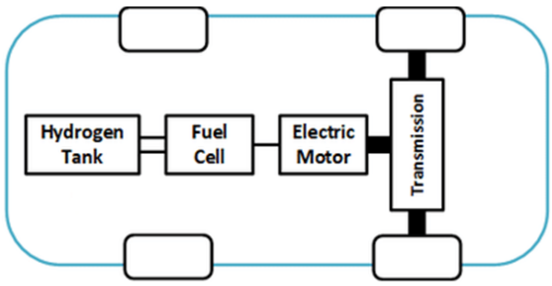

Fig. 8 Diagram of FCEV [16]

Hydrogen is the fuel used in the fuel cell, so generally these types of vehicles are also known as the hydrogen FCVs. Hydrogen located in a special high-pressure tank is the fuel. The other ingredient in addition to hydrogen to produce the power is oxygen, which is generally sucked into the cell system from the atmosphere. The electricity generated from the fuel cell drives an electric motor and the excess energy produced will be stored in the batteries or the supercapacitors [17]. Some of the examples of commercially available FCVs with batteries are the Toyota Mirai and Honda Clarity. The only byproduct of the power generation process using the fuel cells is water [17].

FCVs use chemical reactions to produce electricity [18]. They only produce water as a byproduct of its power generating process which is ejected out of the car through the tailpipes [19]. Advantages of FCVs are that they produce their own electricity through a process which emits no carbon pollutants and refilling takes a similar amount of time as conventional gas vehicles. Disadvantages include the scarcity of hydrogen fuel stations, high cost of fuel cells, and safety concerns regarding hydrogen leaks [8]. The cost of the fuel cell is more than US$ 200 per kW which is far greater than the IC engine which is US$ 50 per kW.

The main characteristics of FCV in comparison with HEV and BEVs are shown in Table IV [20].

TABLE IV
MAIN CHARACTERISTICS OF BEVS, HEVS AND FCEVS [20]

	BEV	HEV	FCV
Propulsion	Electric motor drives	Electric motor drives	
ICEs	Electric motor drives		
Energy Storage subsystem	Battery and Supercapacitors	Battery, supercapacitors and Fossil fuels	Hydrogen tank, battery and supercapacitors to enhance power density
Energy source and infrastructure	Electrical grid charging facilities	Gasoline stations, electrical grid facilities (PHEV)	Hydrogen, hydrogen production and transportation infrastructure
Characteristics	Zero local emissions, High energy density, independent of fossil fuel, relatively short driving range, high initial cost, commercially available, safer.	Low local emissions, high fuel economy, long drive range, dependence on fossil fuels, higher cost than ICE vehicles, Commercially available, less safe than BEVs	Zero low local emissions, high energy efficiency, independent of fossil fuels (if not using gasoline to produce H2), high cost, under development, Highly risk

III. RECENT TRENDS

In this section, a discussion of the recent trends related to the different types of EVs is given.

A. Battery EVs

Present BEVs such as the Tesla Model S and Model X can cross the range of 600 km and 525 km, respectively, on a single charge of 100 kWh battery pack. Their dependence on cylindrical high capacity 18650 batteries sets them apart from other EV manufacturers. A typical method of arranging 18650 batteries in Tesla BEVs is shown in Fig. 9 [8]. They have enhanced the charging by 50% with using V3 and V2 superchargers [21].

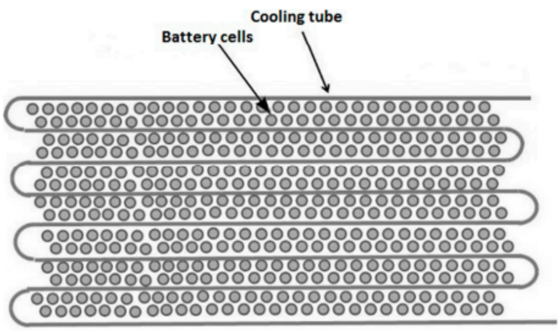

Fig. 9 Battery arrangements in Tesla BEVs. The cooling tubes are used to remove the heat

The biggest BEV manufacturer in the world Tesla is claiming that their future batteries are going to run a car for almost 1 million miles, as part of their research in pact with Dalhousie University already published a paper in the Journal of Electrochemical Society [22]. This improvement in life is possible with numerous electrolyte additives. Tesla submitted the patent on Dioxazolones and Nitirle Sulfites as Electrolyte additives for future Lithium ion batteries [23]. Tesla's previous patent is on the cooling system which improved the performance and lifespan without any noticeable increase in the cost [24]. This cooling system along with the novel battery chemistry is expected to be commercialized soon on next variant of Tesla motors [25].

Apart from Tesla motors, Honda is another EV manufacturer mainly producing HEVs. They unveiled their complete electric Honda Clarity recently. The driving range for the Honda Clarity electric is approximately 89 miles, so Honda BEVs are ideal for short and predictable trips and it runs on the power drawn from high voltage Lithium ion batteries [26]. They are capable to recover the lost energy through regenerative breaking [27]. This type of vehicles can be charged through a household outlet or a charging station or else DC fast charging which is the latest charging technology in Honda EVs [28].

Another global EV manufacturer is Toyota, also popular for their HEVs; they have started developing BEVs to improve the mobility and to reduce pollution in urban areas. Their target market in chronological order is China, Japan, India, United States and Europe. Their compact zero emission vehicles for city transportation are powered with batteries which are quick to recharge and improve the air quality.

B. HEVs

The latest Toyota hybrid Camry comes with a 4th generation gasoline - hybrid electric engine, which can deliver about 160 kW of power [29]. The battery used is a nickel-metal hydride and the motor generator used is permanent magnet synchronous motor [30]. Almost all the models of Toyota hybrid range can provide a range of 100 km for a gallon of fuel. This range or the fuel consumption is combined effect of both electrical system and conventional IC engine system [30]. Nickel metal hydride batteries are made up of nickel hydroxide as positive electrodes and alloys of nickel, titanium, vanadium as negative electrodes [31]. The main advantages of metal hybrid batteries are high operating temperature range, recyclable and ecofriendly nature, resistance to over-charge and discharge, and longer cycle life [8].

Honda hybrid vehicles are suitable for any range of trip with impressive miles per gallon (mpg) ratings and cost savings. The high voltage Lithium ion batteries are specifically designed for longer life span minimum of 8 years. Their products cause lesser impact on the environment as they harvest metals and components from the batteries of the electrified vehicles and repurpose these into other product [28].

The global HEV manufacturers are Ford, Nissan, Honda, Toyota, Lexus, Mercedes, Hyundai, BMW, Kia, Volkswagen, Infiniti, Lincoln, Cadillac, Porsche, GMC, and Chevrolet. Their popular HEV models are shown in Table V [32]. Among all these variants of hybrid cars, Toyota, Honda and Nissan are the most common HEVs in the market. The auto makers such as Jaguar, Land Rovers and Tata are developing their future hybrid and complete EVs. Honda and Toyota have many variants of hybrid cars in comparison with other global HEV manufacturers.

TABLE V
GLOBAL CAR MANUFACTURERS AND THEIR POPULAR HYBRID CAR MODELS

Honda	Accord, Civic, Insight, CR-Z, Fit, CRV, NSX
Toyota	Prius Eco, Prius, Camry, Highlander, Sienna
Nissan	Altima
Lexus	LS600h L, GS 450h, HS 250h, CT200h
Mercedes	S400 Blue Hybrid, ML 450
Hyundai	Sonata, Ioniq
Ford	Fusion, Escape, C-Max
BMW	Active Hybrid, X6 Hybrid
Kia	Optima Hybrid,
Volkswagen	Jetta, Touareg
Infiniti	MKZ
Lincoln	MKZ
Porsche	Cayenne S
GMC	Yukon, Sierra
Chevrolet	Tahoe, Silverado
Cadillac	Escalade

Note: GMC-General motors Corp.

C. Plug-in HEVs

Chevrolet Volt and Toyota Prius are examples of PHEVs [8]. Almost all the PHEV models of Honda and Toyota provide good range. Recently, the US claimed a patent on a four-wheel drive powertrain configuration which can be applied for PHEVs and HEVs which would be possibly applied in future HEVs [33]. This powertrain configuration consists of a two motor and two clutch hybrid system, Fig. 10 [34].

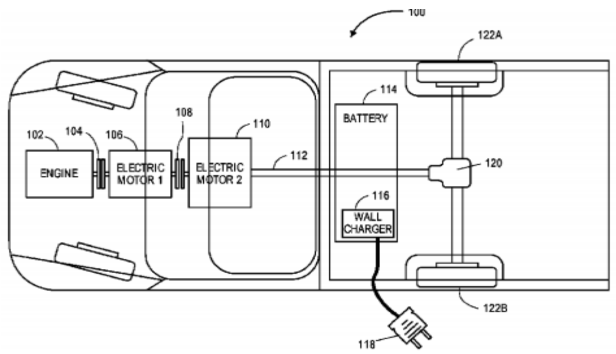

Fig. 10 Two motor two clutch 4WD Hybrid configuration [34].

The Toyota Prius plug-in hybrid can give a range of 100 km for 1 liter of fuel consumption [30]. This implies that the fuel consumption is reduced, and hence the rate of carbon emissions. Honda plug-in hybrid cars also run on a stored electricity first and then automatically switches to the gas when needed. Their models also recover the lost energy through regenerative braking. As explained, the PHEVs run using an electric motor and battery that can be plugged into the power grid to charge the battery, but also have the support of an ICE that may be used to recharge the vehicle's battery and/or to replace the electric motor when the battery is low. Electric-only driving with a reduced range (typically 25-40 km) is also possible. Advantages of a PHEV are a longer range than a BEV, less gas consumption, and fewer emissions than gas only vehicles. Because PHEVs use electricity from the power grid, they often realize more savings in fuel costs than traditional HEVs. Disadvantages of PHEVs when compared to BEVs are that PHEVs still produce emissions from the ICE, need gas and oil changes, and are 8-10 times more expensive to operate [8].

IV. COST ANALYSIS

Global EV sales are shown in Fig. 11. Many automakers have shown their intention in increasing EV sales over 15 million per year by 2025. From Fig. 11, it can be seen that electric car sales have increased to 2 million in 2018 from 1.2 million in 2017. This increase in the magnitude of EV sale is directly proportional to the expected decline in battery pack cost during this period. So, the cost of battery pack has a greater impact on the sale of EVs.

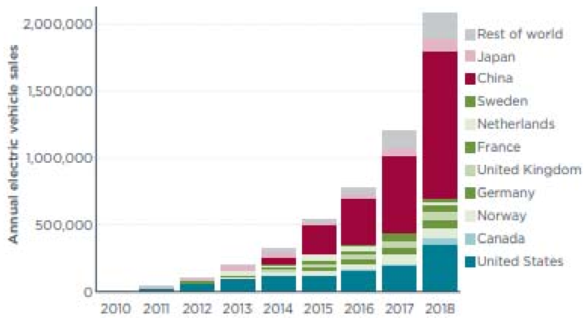

Fig. 11 The global EV sales during the period from 2010-2018 [35]

The expected cost of battery pack ($/kWh) during the period 2020 to 2030 is shown in Table VI [35]. From this table it can be seen that the cost of the battery pack reduces marginally irrespective of the battery material chemistry or geometry. This implies that with next few years, battery research and development is significantly escalating with new technological manufacturing and abundant battery material production scale. It is clear that within next 5 to 10 years (2025-2030) battery costs will be reduced by 50% which ensures that the average customer could afford the BEVs much more easily than they can today. Consequently, the conventional IC engines will become obsolete as it becomes more expensive than BEVs and due to increased concerns over pollution.

Several estimates indicate that the cost of the batteries will decrease to $130-$160/kWh in 2020-2022 and further the cost will reach in a range of $120-$135/kWh by 2025. Tesla states that with their NCA-based battery technology, the cost will reach to $100/kWh by 2022. With the transition of anode material from graphite to silicon alloy and with NMC cathode material, the cost reduction of batteries can be achieved [35]. Depending upon the driving range and vehicle capacity the cost of the battery pack varies (see Table VII). From Table VII, for the same capacity battery pack it is clear that the cost of the battery pack reduces by ~50% within next 10 years. This expected decrease in battery pack cost reduces the vehicle cost significantly and implies that the majority of new car buyers could afford BEVs. The increase in sale of BEVs can be expected based on good performance, cost, driving range and maintenance.

TABLE VI
EV BATTERY PACK COST IN USD/KWH

Battery type	2020	2022	2025	2030
Pouch NMC-622	143	134	122	NA
Cylindrical 21700, NCA 83134	NA	142	NA	NA
Pouch NMC 811	160	NA	128	NA
Pouch NMC 622- Graphite anode	191	165	120	80
Pouch NMC 622 – Silicon alloy anode	317	131	85	50
Car manufacturer				
Volkswagen	152	NA	NA	NA
General motors	160	133	NA	NA
Tesla motors	130	100	NA	NA

Note: NMC = Nickel Manganese Cobalt, NCA = Nickel Cobalt Aluminum, NA – Not Available

TABLE VII
BATTERY PACK COST ($/KWH) & PACK CAPACITY (KWH) FOR SHORT, MEDIUM, LONG RANGE CARS, CROSSOVER AND SUV

Range	Car		Crossover		SUV	
	2018	2030	2018	2030	2018	2030
Short	177 & 42	74 & 39	175 & 50	74 & 46	175 & 72	73 & 66
Medium	175 & 58	73 & 54	175 & 69	73 & 64	167 & 99	72 & 92
Long	175 & 75	73 & 69	172 & 90	73 & 83	154 & 128	64 & 119

TABLE VIII
MODELS, DRIVING RANGE AND COST OF THE HEVS [36]-[40]

Make	Model/Variant	Engine size (All 4 cylinder Automatic)	Estimated mpg	MSRP ($)
Hyundai	Ioniq Blue	1.6L	58	$22,200
Toyota	Prius Eco	1.8L	56	$25,165
Hyundai	Ioniq	1.6L	55	$22,000
Hyundai	Ioniq PHEV	1.6L	125	$26,500
Toyota	Camry Hybrid LE	2.5L	52	$27,950
Toyota	Prius	1.8L	52	$23,475
Kia	Niro FE	1.6L	50	$23,340
Kia	Niro	1.6L	49	$23,340
Honda	Accord Hybrid	2.0L	47	$25,100
Chevrolet	Malibu Hybrid	1.8L	46	$27,920
Chevrolet	Volt	1.5L	42	$34,395
Toyota	Camry Hybrid LXE	2.5L	46	$32,400
Toyota	Prius C	1.5L	46	$20,630
Kia	Niro Crossover	1.6L	52	$30,000
Ford	C-Max	2.0L	47-56	$24,995
Ford	C-Max PHEV	2.0L	85	$27,995
Ford	Escape			

The cost of the HEVs varies with the manufacturing companies, potential driving range and the IC engine capacity. Some of the most popular non-plug-in hybrid vehicles are shown in Table VIII [36]. With the engine capacity and mileage (mpg), the cost of each variant of the manufacturer changes, when the capacity and mileage is more, the cost will be more. Most of HEV variants in Table VIII show an average mileage of 50-55 mpg. The cost of all the middle HEVs and PHEVs varies with in a range of $22,000-$32,000. The PHEVs are having more fuel economy than normal HEVs, Hyundai Ioniq PHEV can deliver a range of 120-125 mpg and the price is reasonable when compared with other PHEVs and HEVs. This advantage in driving range in both HEVs and PHEVs are due to the technological advancement in battery material chemistry.

V. CONCLUSIONS

In this paper, state-of-the-art EV technologies have been analyzed, which include PHEVs, HEVs, BEVs, and FCEVs. It is concluded that when considering the emissions, BEVs result in zero emissions while HEVs and PHEVs have less emissions associated with them compared to vehicles of conventional engines. The charging time is more for the BEVs and the fuel cost is less for the HEVs and PHEVs compared to conventional ICEs. The cost of the BEVs, HEV/PHEVs are higher than the conventional ICE vehicles. HEVs and PHEVs based vehicles are relatively expensive, but they have higher driving range, better fuel economy and low emissions. On the other hand, the cost of batteries adds to the overall cost of a BEV based vehicle. BEVs require larger batteries, have low driving range and require more charging time. FCEVs are also zero emission vehicles and have good driving range but due to the hazards of hydrogen gas and its storage, its application in automobiles is limited. It is expected that within next five to 10 years, the battery cost will be reduced by around 50% of the current price which would reduce the price of the BEVs significantly. So, in the near future, BEVs are expected to be the primary mode of transportation technology.

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