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Analysis on the electric vehicle with a hybrid storage system and the use of Superconducting magnetic energy storage (SMES)

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Abstract

Given the current load and power density limitations in electric vehicle (EV) storage systems, it is necessary to study hybrid and control systems in order to optimize their performance and present themselves as a real alternative to internal combustion engine (ICE) vehicles. This implies the development of legislation and specific regulations that enable the research and development of these storage and management systems for hybrid systems. The research presented here aims to analyze the implementation of the SMES (Superconducting Magnetic Energy Storage) energy storage system for the future of electric vehicles. To do this, the need for a hybrid storage system has been taken into account, with several regulatory options, such as the reduction of rates or the promotion of private investments, which allow the technological development of EVs. What is sought is to achieve the market share proposed by the different countries to reduce Greenhouse Gases (GHG), according to their objectives. This approach must be taken from the legislative and regulatory perspective, specific to EVs and charging points, of several countries or regions with different cultures, management models and implementation potential, such as the United States of America (USA), Europe and China. This analysis is associated with the economic study of costs that this storage system may involve in the implementation of EVs to replace ICE vehicles, resulting in possible economic benefits as well as the environmental benefits of the use of EVs. In this analysis, the current high cost of using a hybrid system of these characteristics can be observed with the comparison of three EVs, as well as current data on GHG emissions produced by transport. All this leads to a series of advantages and disadvantages that must be taken into account in order to achieve the objectives that countries have in the coming decades of EV diffusion.

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Keywords: SMES; Hybrid storage; Electric vehicle; Economic analysis; GHG reduction

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Nomenclature

AC	Alternate Current
AFDC	Alternative Fuels Data Center
ANSI	American National Standards Institute
BEV	Battery Electric Vehicle
DC	Direct Current
DOE	Department of Energy
C2ES	Center for Climate and Energy Solutions
EDLC	Electrostatic double-layer capacitors
ETS	Emissions Trading Schemes
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FEV	Full Electric Vehicle
GHG	Green House Gas
HEV	Hybrid Electric Vehicle
HoC	Heat of Combustion
HTS	High Temperature Superconductor
ICE	Internal Combustion Engine
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LTS	Low Temperature Superconductor
mHEV	Mild Hybrid Electric Vehicle
PHEV	Plug-Hybrid Electric Vehicle
REE	Red Eléctrica de España
REEV	Range Extended Electric Vehicle
SAC	Standardization Administration of China
SAE	Society of Automotive Engineers
SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
STRIA	Strategic Agenda for Research and Innovation in Transport
Tc	Critical Temperature
TRIMIS	Transport Research and Innovation Monitoring and Information System
USA	United States of America
V2G	Vehicle to Grid
ZEV	Zero Emission Vehicle

1. Introduction

The need for the use of electric cars is becoming increasingly important. In recent years the use and purchase of electric vehicles (EV) and hybrids (HEV) is being promoted with the ultimate goal of reducing greenhouse gases (GHG), as can be the Paris Agreement [1]. In 1834, Thomas Davenport presented the first electric vehicle in the United States of America (USA) [2], and in 1851, Charles G. Page's vehicle reached a speed of 31 km/h [3] A year later, the first car was sold in the USA.

The main reasons for promoting electric and hybrid vehicles are threefold:

- Environmental sustainability: They are a sustainable alternative to internal combustion engines (ICE). The automotive sector needs to innovate towards more environmentally friendly mobility.

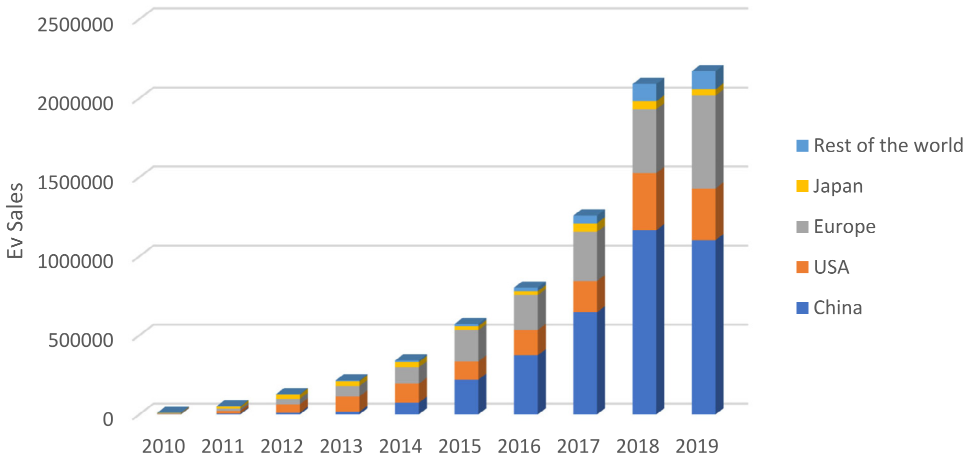

Fig. 1. EV sales by region or country [6].

- Economic sustainability: The main oil-producing countries are socio-politically unstable, which leads to fluctuations in the cost of fossil fuels.
- Energy sustainability: Electric vehicles represent an important alternative to oil and a suitable way to integrate renewable energies into transportation. It also makes it possible to improve the energy efficiency of the electricity sector through so-called V2G (Vehicle to Grid) [4,5].

Once the importance and necessity of the use of electric and hybrid vehicles for mobility in the coming years is known, this study seeks to analyze EV storage systems both economically and at a regulatory level, together with the charging systems through grid connection sockets associated with EVs. This importance is shown in Fig. 1, which shows the evolution of EV sales worldwide, and in Fig. 2, the total number of EVs in specific regions or countries.

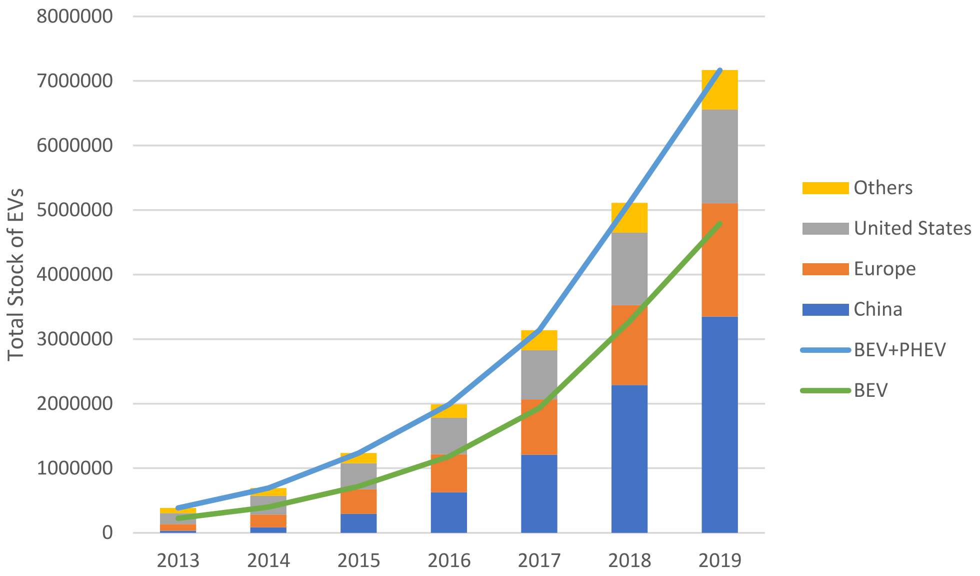

Fig. 2. Total stock of EVs by region or country [6].

Fig. 2 shows exponential growth in all countries of the world and the difference between BEVs (Battery Electric Vehicle) and PHEVs (Plug-in Hybrid Electric Vehicle). Apart from what the graphs show, the vast majority of the countries have projected that their vehicle fleets, or at least most of their vehicle sales, will be of this type.

On the other hand, given the characteristics of EVs and due to the frequent starts and stops of these vehicles, the charging and discharging profiles of the batteries suffer strong variations. The specific power of today's batteries is much lower than that required to cope with such demanding and repetitive power cycles. One option is to realize a hybrid storage system with some basic requirements [7–11]. These requirements are based on reaching a design compromise between specific energy, mainly provided by the battery, specific power, provided by another storage system, and a long lifetime.

In the hybrid systems studied for electric vehicles, mainly batteries and ultracapacitors (EDLC) are used [9,12–14]. Another option is the use of other systems with high power density, such as flywheels or SMES systems, to a lesser extent.

The main storage system with high specific power that is sought to be analyzed in this study is the SMES (Superconducting Magnetic Energy Storage) where the energy is stored in a superconducting coil at a temperature below the critical temperature, Tc. This technology is being researched and developed in order to be used in different types of applications [15–23], mainly in Smart Grid or Smart Cities application [4,15,21,24–36], although there are also researches that focus on the improvement of its technical characteristics [22]. The main characteristics available in this energy storage system (ESS) are shown in Table 1. This table shows a comparison with the main storage systems capable of providing the specific power required for a hybrid storage system for the study.

Table 1. Main characteristics of a SMES system [4,19,24,28,36–49].

	Daily self-discharge (%)	Energy density (Wh/L)	Specific energy (Wh/kg)	Power density (W/L)	Specific power (W/kg)	Response time	Discharge time	Suitable storage duration	Efficiency (%)	Lifetime (yr)	Lifetime (cycles)
SMES	10–15	0.2–6	0,5–5	1000–4000	500–2000	>10 ms	ms-5 min	min-h	<95	30+	$5 \cdot 10^5$
EDLC	20–40	2–30	2,5–15	100.000	500–5000	>10 ms	ms-60 min	s-h	<90	30+	$5 \cdot 10^5$
FlyWheel	55–100	20–80	10–30	1000–5000	400–1500	ms-s	ms-15 min	s-min	<85	>20	$1 \cdot 10^6$

It can be seen that the three storage technologies have similar characteristics but that SMES systems have very low response time and very high performance, which may favor their use in self-driving vehicle applications. In contrast, these systems can be expensive to implement and develop in vehicles.

During this study, their main advantages and disadvantages in hybrid storage systems for electric and/or hybrid vehicles, costs, application regulations and technical standards, as well as their environmental and economic benefits will be analyzed. According to [50], the aforementioned criteria, together with the technical and social criteria, allow the evaluation of an ESS.

Section 2 of this study seeks to explain the methods used in the research presented here. In this section, a review of hybrid storage systems in EVs is shown, as well as the legislation related to electric vehicles and charging points that allow enhancing the use of EVs in the main markets. Section 3 performs an economic cost analysis on the implementation of a hybrid system of this type in vehicles. During this analysis, a cost comparison of several EVs with a hybrid system consisting of a lithium battery and a SMES system will be carried out. This allows obtaining the possible economic benefits of the development of these systems due to the reduction of transportation and processing of oil to obtain gasoline or diesel, as well as other indirect benefits. It also addresses the discussion of the environmental benefits provided by the use of EV as opposed to the use of ICE vehicles, an important factor for its implementation and competitiveness with other types of systems in the case of hybrid storage in EVs.

It is in Section 4 where a brief summary is made of both the advantages and disadvantages that the SMES system presents in a hybrid storage system for this particular case. Finally, Section 5 is reserved to show the main conclusions obtained from the regulatory and economic study that may involve the study of these hybrid storage systems in the EV.

2. Materials and methods

In order to analyze electric vehicles, they must be classified according to their configuration and capabilities. For this purpose, it must be kept in mind that an electric vehicle owes its propulsion energy partially or totally to electric energy. In this sense, according to [4,44,51–53], a classification can be made as shown in Fig. 3.

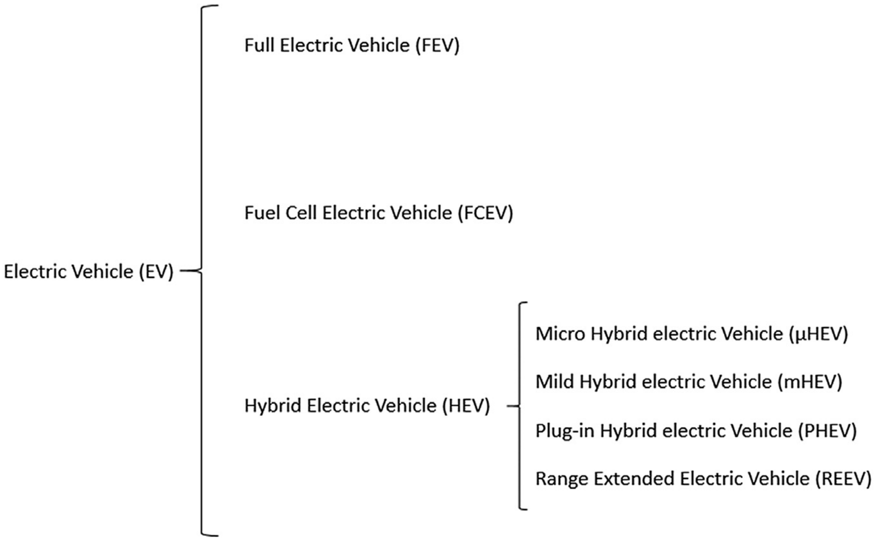

Fig. 3. Classification of electric vehicles [4,44,51–53].

The study focuses on FEVs, where the true potential of a power storage system such as the SMES system can be shown. Hybrid systems are ICE-centric systems with an electrical energy storage element as a support. These hybrid systems are classified according to their degree of electrification, an example being μHEVs, where the electric systems do not reach more than 5 kW of power but without incorporating any electric drive system.

FCEVs are usually encompassed as hybrid vehicles since they are usually associated with electric batteries or power storage systems, as shown in the studies of [54]. The development of these vehicles can enhance the use of the SMES system as a secondary storage system, due to the use of hydrogen as a cooling system for the superconducting coil, as discussed later in this study.

FEVs are usually vehicles whose energy storage element is based on a chemical battery [55], either by means of Lithium, Nickel, Sodium or metal–air batteries [35,45,48], leaving aside lead–acid batteries not used for their use in the traction movement of EV engines.

In all the above cases, the use of standardized electric chargers, connectors and some degree of electrification is required, as will be seen later. In this sense, and as an example of EV charging systems, according to [56] for Spain, there are 4 types of recharging according to their connection to the vehicle:

1. Connection of the EV to the recharging station by means of a cable terminated in a plug with the cable attached to the EV (Fig. 4a).
2. Connection of the EV to the charging station by means of a cable terminated at one end in a plug and at the other end in a connector, where the cable is an accessory of the EV (Fig. 4b).
3. Connection of the EV to the recharging station by means of a cable terminated in a connector, the cable is part of the fixed installation (Fig. 4c).
4. Connection of a light EV to the charging station by means of a cable terminated in a connector, the cable incorporates the charger (for motorcycles, e.g.) (Fig. 4d).

Among all the options, it is necessary to study hybrid FEVs, i.e. having two different electrical energy storage systems. These hybrid systems are usually composed of an energy storage system, such as a Lithium battery, and a power storage system, in this sense a supercapacitor [9,12–14], a flywheel or a SMES superconducting coil, as discussed above.

2.1. Hybridization systems

Normally, the main ESSs where the energy density is high have as a counterpart a rather low power density, with the drawbacks that this can produce for starting and starting an electric motor of a vehicle [51]. Therefore, a hybrid system is sought where the power density of some systems can be combined with the energy density.

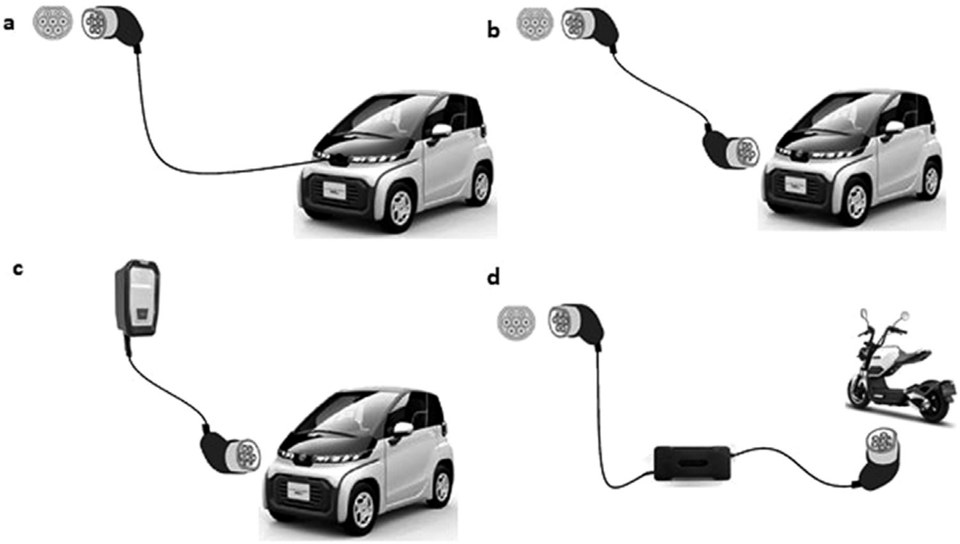

Fig. 4. (a) Type 1 EV charging; (b) Type 2 EV charging; (c) Type 3 EV charging; (d) Type 4 EV charging [56].

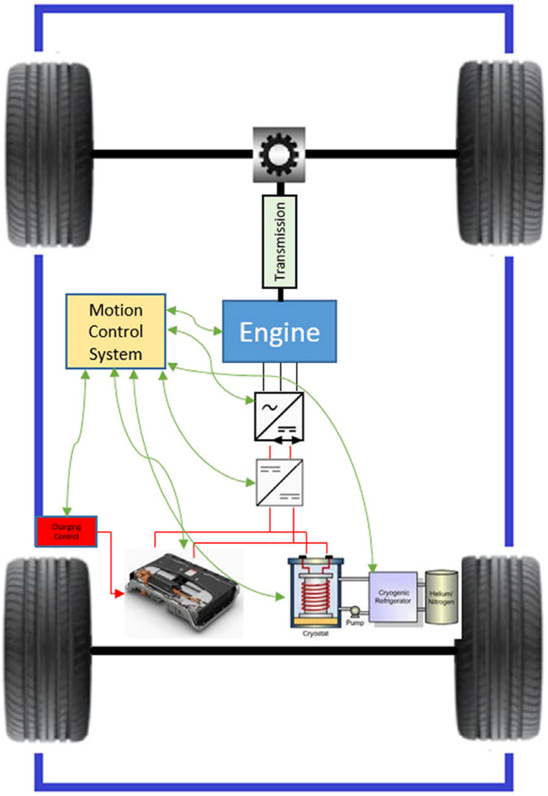

Fig. 5. Parallel configuration of the ESS for EV [44,52,53].

2.1.1. *Parallel hybrid system*

Fig. 5 shows the configuration of a parallel hybrid system of an FEV, [44,52,53]. In this case, it has been realized using a battery and the SMES power storage system.

In this case, charging is done through an interface to the battery, which is connected in parallel directly to the secondary storage system, SMES system. This parallel system is connected to a DC–DC converter to match the power to be supplied to the inverter that provides alternating current to the three-phase motor. From this motor, through gears and mechanical coupling systems, it is connected to the differential gear that transmits the motor's movement to the vehicle's drive wheels.

The control system is in charge of controlling different parameters, such as temperatures, SOC or rpm to send control orders to provide optimum management and performance of the systems. It must also control the cooling system and losses that may occur in the SMES system.

As advantages, this system provides simplicity in its configuration and savings in its development but, on the contrary, in these systems, the main storage system, the one formed by batteries, and the secondary one, in this case the SMES system, must have the same nominal voltage. This is due to the use of a single DC–DC converter before the inverter that provides alternating current to the motor, assuming that a three-phase alternating motor is used and not any other type of direct current motor.

2.1.2. Serial hybrid system

Within this category are different types of variants, with ESS directly coupled to the IGBT inverter or through more complex configurations that allow for increased performance and resource optimization, as shown by [44,52,53].

The most common type of series hybrid system is the one shown in Fig. 6, where each storage system is connected to its own DC–DC converter to match the power provided to the motor through the IGBT inverter.

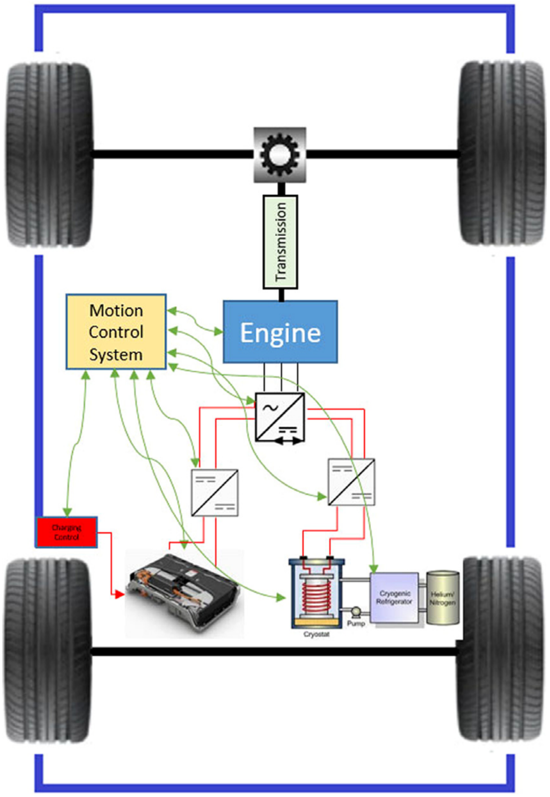

Fig. 6. Serial configuration of the ESS for EV [44,52,53].

In this system, parameters and values are also monitored and controlled from a central control module. This system provides the control with greater energy supply and storage stability, configuration flexibility and efficiency. However, there is a reduction in the battery life cycles caused by the large power supplies provided by the ESS.

For both systems there is currently a recharging system that can allow battery recharging times ranging from several hours to a full recharge in several minutes. So-called ultra-fast recharging is still being researched and developed, as it is one of the major problems with all EVs.

In addition, the electric motors used perform generator functions for energy recovery through the KERS system, or regenerative braking, [9,14,51], by which they transform the energy of the vehicle's motion into electrical energy that is stored in the accumulators, controlled by the central motion control system to store this energy in the accumulators.

2.2. Regulatory framework

Due to the different EV alternatives and their configurations, it is possible to see the legislative and economic limitations that this causes. For this, it is necessary to know the standardization and regulatory options that affect each country or territory, summarized in [57].

In terms of this regulation and legislation, we seek to expose three countries or regions from different continents, where EVs are currently more widespread and where their use is being promoted the most. The objective of this comparison is to observe the different ways in which three completely different regions are promoting the development, purchase and use of EVs. In principle, these countries have completely different social and resource management characteristics that are reflected when it comes to encouraging EVs, although they also have similarities and points in common.

2.2.1. Chinese legislation

The New Energy Vehicle (NEV) program supports the promotion policy for the acquisition of EVs in China. In this sense, the Chinese central government encourages research by EV manufacturers through subsidies, credits or tax exemptions [58], and other aid through the Ministry of Transport (MOT) [59], the Ministry of Finance (MOF) [60] or the Ministry of Industry and Information Technology (MIIT) [61], whose main objectives are to clean the air in China's cities, reduce oil imports and position China for world leadership in a strategic industry such as the automotive industry. Also from the Chinese government, it is sought to encourage the development and inclusion in energy storage systems, at a general level, which can directly or indirectly affect EVs [62].

In the case of China, the calculation to incentivize the purchase of EVs is based on the energy density of ESSs and their energy efficiency. It seeks to subsidize a maximum of 2 million EVs per year.

On the other hand, it is also sought to encourage the purchase of this type of vehicles through provincial governments, through exemptions from traffic restrictions or reductions in parking fees, even with free parking, such as [63].

As for EV-related standards, they are developed by the Standardization Administration of China (SAC), a member of the International Organization for Standardization (ISO) [64]. In relation to EVs, and their storage systems, the standards that affect in their construction are very varied, from those related to battery safety requirements (GB 38031-2020) to the accumulator control and management system (GB/T 38661-2020), even the requirements of electromagnetic compatibility in EVs (GB/T 36282-2018). On the other hand, there are also standards affecting vehicle charging systems, such as NB/T 33020-2015 or NB/T 33021-2015, or storage systems, such as supercapacitors for EVs (QC/T 741-2014) or for the manufacture and calibration of SMES superconductor systems (GB/T 30109-2013) [65].

2.2.2. U.S. Legislation

At the US level, there are also various levels of assistance and support for EVs. At the federal government level, tax improvements, R&D investments and different programs have been promoted to enable the competitive development of EV technology, although in the last year the US Congress decided not to extend the federal credit [6]. Both the Alternative Fuels Data Center (AFDC) of the Department of Energy (DOE) [66] and the Center for Climate and Energy Solutions (C2ES) [67] show the regulations at both federal and state level, where it can be observed that there are only four cases where the commercial deployment of alternative vehicles, not only EVs, is not supported. Virtually all states have measures in place to encourage the purchase and use of EVs, such as tax advantages subsidies or other measures [68].

Several states joined together to sign a program called ZEV (Zero Emission Vehicle) in 2014 where those states are sought to encourage the purchase of EVs and the installation of grid chargers, or failing that refueling infrastructure [69]. This program has been led by the state of California, along with others such as Massachusetts, New York or Connecticut, among others.

Even so, government incentives have been reduced since 2019, both in the USA and in China, despite which an increase in EV purchases is still being seen in these countries [6]. The increase in sales may be due to financial supports at the local government level.

At the standardization level, the USA has the American National Standards Institute (ANSI) for the development of standards [70]. This institute belongs to ISO, so ISO norms are related to these standards.

On the other hand, in the USA there is also the Society of Automotive Engineers (SAE) [71] specialized in the automotive and aerospace industry whose manufacturing standards are usually considered as standard for use in these industries. Among these standards are some such as Life Cycle Testing of Electric Vehicle Battery Modules (J2288) or Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing (J2464), among others.

2.2.3. European legislation

As for the European Union (EU) there are also several levels, and the first of all is the one created by the European Council together with the European Parliament that creates regulations and guidelines, which must be adapted by the member states to their internal legislation, which would be the second legislative level in the EU.

The main document created by the EU is the so-called White Paper on Transport, of 2011, where it indicates the need to reduce GHGs in Europe by 60% in 2050 in relation to 1990 levels [72]. As a result, Europe defined the Strategic Transport Research and Innovation Agenda (STRIA) [73], which defines seven areas where the EU should concentrate its efforts to achieve these transport objectives, monitored by the Transport Research and Innovation Monitoring and Information System (TRIMIS) [74].

In relation to the promotion of the use and development of EVs in Europe, there are regulations aimed at the design of electric motors and variable speed drives [75] or the promotion of these vehicles itself [76]. This is derived from regulations for the reduction of GHG emissions, such as [77] for commercial vehicles and [78] for heavy-duty vehicles. These regulations also include a mechanism to incentivize the adoption of zero- and low-emission vehicles in a technology-neutral manner.

At the EU member country level, laws have been implemented to incentivize the purchase of EVs and to prohibit the purchase of vehicles with gasoline or diesel engines before 2030–2040, depending on the case [79].

Likewise, incentives have been provided for member countries to develop a network of alternative fuel infrastructures through Directive 2014/94 [80] with a ratio of one recharging point for every ten EVs. The aim is to have 1 million charging points in the European Union by 2025.

At the standardization level, the European Union, and its members, rely mainly on the standards made by the International Electrotechnical Commission (IEC). As in the rest of the international standardization organizations, they are divided into Committees, among which TC 69, on "Electric power/energy transfer systems for electrically propelled road vehicles and industrial trucks" [81] stands out at the EV level, where the standards applied to the EV power supply, the internal communication bus or the EV charging system are described.

Apart from these three large blocks, there are also other large consumers or producers such as South Korea, Japan or India, but the generic regulations of the main countries seek to promote the purchase of EVs in one way or another.

2.3. Economic analysis

For a hybrid storage system to be implemented in vehicles, they must be economically viable, as well as technically feasible to use. SMES systems for small applications have not yet been tested with the necessary efficiency.

To analyze the cost of a hybrid EV storage system, the hybridization configuration of the component systems and the characteristics of these systems must be taken into account. The calculations have been based on [12,24,45,47,48,82–84], and are based on manufacturing and investment costs and financial costs.

$$TSC(\$) = C_I(\$) + C_F(\$) \tag{1}$$

In this case, operation and maintenance (O&M) costs are not considered since these costs should not be reflected in the final cost of an EV. These costs are related to energy storage plants that require infrastructure and specialized personnel for their maintenance.

As for the investment cost, C_I, it takes into account the materials used, as mentioned above, their construction and commissioning of all the auxiliary systems and subsystems they may have. Investment costs can be broken down into three subsets:

$$C_I\left(\$\right) = C_{st}\left(\$\right) + C_e\left(\$\right) + C_{AUX}\left(\$\right) \tag{2}$$

where:

C_{st} (\$) is the cost of materials and construction of the ESS,

C_e (\$) is the cost of the electrical system of the device, and

C_{AUX} (\$) is the cost of auxiliary systems not included in the above items.

If we break down each subassembly, the cost of materials can be further subdivided, at the level of the construction of the coil or battery, the construction of the hydraulic cooling system, the pump, the materials that compose them and the design itself. In spite of that, prices are usually taken per kW or kWh unit, so the value of the cost of materials would be:

$$C_{st}\left(\$\right) = \left(C_{E1}\cdot E_1\right)/\eta_1 + \left(C_{E2}\cdot E_2\right)/\eta_2 \tag{3}$$

where:

C_E is the materials cost per unit energy of the primary system, possibly a Lithium battery, and the secondary system, in this case a downsized SMES system. It is measured in \$/kWh.

E is the storage of the primary and secondary system, respectively. It is measured in kWh.

η is the efficiency of the primary and secondary system, respectively

On the other hand, the cost of the electrical system depends on the raised configuration and the vehicle management and control system. The term of the electrical system cost would be:

$$C_e\left(\$\right) = \varepsilon\cdot\left(C_{P1}\cdot P_1 + C_{P2}\cdot P_2\right) \tag{4}$$

where:

ε is a hybridization factor, i.e., depending on the system used, the system can be made more expensive or cheaper.

C_P is the power cost of the system. It is measured in \$/kW.

P is the stored power capacity. It is measured in kW.

Finally, there is the auxiliary system, where the focus is on the strategy for storing and supplying and monitoring the energy flow. This value is also usually obtained as a function of power or stored energy.

$$C_{AUX}\left(\$\right) = C_{AUX}\left(\$/kWh\right)\cdot E_T \tag{5}$$

where:

E_T is the total energy stored in the system. It is measured in kWh.

As for the second summand of Eq. (1), the financial or investment cost, where there are purely economic components, such as investment interest, or the years to amortize the storage system

$$C_F\left(\$\right) = \delta\cdot C_I\left(\$\right) \tag{6}$$

With the multiplying factor δ produced by:

$$\delta = \frac{r\cdot(1+r)^k}{(1+r)^k - 1} \tag{7}$$

where:

r is the investment interest,

k is the useful life, in years.

With the above approach and with the price information of storage systems in [43,44,51,83,84], it can be obtained that the cost of the hybrid electric storage system using a Lithium-Ion battery system and SMES would be as shown in Table 2.

On the other hand, a 10% interest rate and costs that are expected to be reduced by 50% in the future in the manufacture of batteries and storage systems have been considered, as shown in [6,83]. Considering the previous

Table 2. Costs of vehicles with hybrid storage system [43,44,51,83,84].

	BYD Tang EV600	Model 3 T	EQC 400 4MATIC Mercedes Benz
Power (kW)	182.7	261	304.24
Capacity batteries (kWh)	82.8	75	88
Lifetime (yr)	20	20	20
C_I ($)	47.666,44 $	62.755,85 $	65.009,05 $
C_F ($)	5.598,88 $	7.371,28 $	7.635,94 $
Total ($)	53.265,32 $	70.127,13 $	72.644,99 $

point, three vehicles from the three regions indicated in the previous section have been assumed. In this case, we have looked for vehicles with a very similar range, about 500 km, from the companies BYD [85] from China, Tesla [86] from USA and Mercedes-Benz [87] at European level. It must be taken into account that the costs shown are relative to the current prices of the technologies used, and only of the ESS, so the complete vehicle would be somewhat more expensive, considering that energy storage is the most expensive part of this type of vehicle.

3. Results

Bearing in mind the different models of hybrid storage systems for EVs and the regulations that seek to promote the purchase of these vehicles and their development, the costs of using a hybrid storage system with an SMES system must be analyzed.

For this, we must keep in mind that SMES systems are formed from a coil with superconducting materials, divided between LTS (NbTi) and HTS (YBCO or BSCCO) [16–19] according to their Tc. There are different studies that seek to analyze the optimization of this ESS [22]. They also have a container where to contain such coil and the coolant, which can be Helium, Nitrogen or liquid Hydrogen (LIQHYSMES) [21], in this last case Hydrogen can also be used to supply a fuel cell (FC) [20], as well as a coolant reservoir and a suitable pump to recirculate the coolant [35].

A flow management and electronic control system that allows monitoring of temperature, voltages, currents and other variables for proper operation, must control all this. These management strategies for charging, discharging and optimal control of storage systems are encompassed in stochastic control, linear programming, dynamic programming or Pontryagin's minimum principle. These management and control systems for both hybrid systems and for a single ESS come from different studies, both for individual uses and applications, such as EV, as well as in the electrical grid itself, [10,13,23,45,49,53,54,88–94].

3.1. Environmental benefits

Among the main benefits found with the use of EVs, and discussed above, is the use of electricity as fuel. The use of electricity as a fuel in transportation can lead to a very considerable decrease in GHG.

If we take into account the use of fossil fuels such as gasoline, diesel or LPG for vehicle transport, whether for private or professional use, there is data such as that shown in Fig. 7. In this case, the energy consumption in Spain during the last decade has been taken into account as an example.

As the consumption data are in MWh, the amounts of GHG and harmful gases, such as CO_2, SO_2 or NO_x, can be calculated using the so-called emission factor (χ), which indicates the amount of a substance for each kg of fuel consumed. A summary table of these values depending on the type of fuel can be seen in Table 3. These values may vary over time due to improvements made by manufacturers due to environmental restrictions in different countries.

To obtain the total amount per year of the different substances that have been generated due to the use of these fuels, the following formula must be taken into account.

$$R_x = \frac{E_{Cx} \cdot \chi_x}{HoC_x} \tag{8}$$

where:

E_C is the energy consumed by that fuel,

χ is the emission factor of the fuel, and

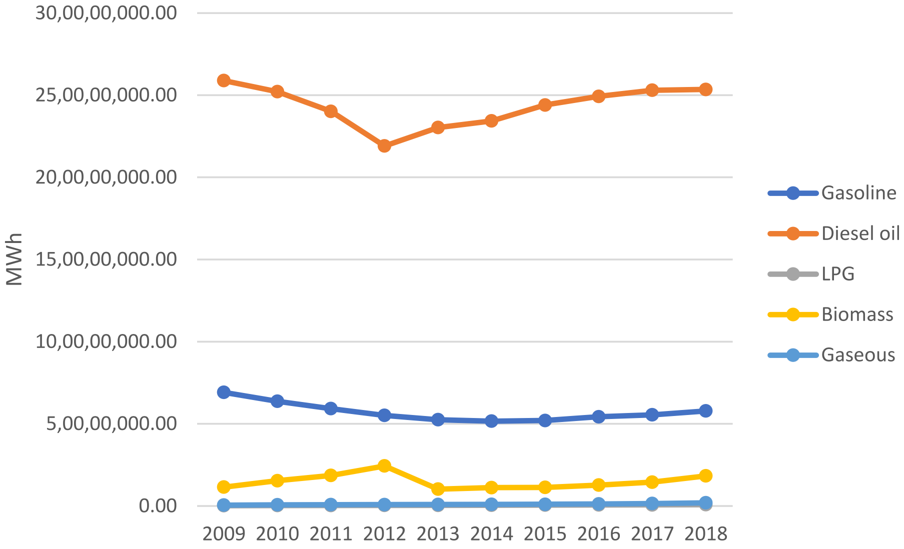

Fig. 7. Energy consumption in transport in Spain (MWh) [95].

Table 3. Emission factor, by IDAE [96].

	Kg CO_2/kg of fuel	kg SO_2/kg of fuel	kg NO_x/kg of fuel
Gasoline	3.1800000	0.0000150	0.0087300
Diesel Oil	3.1400000	0.0001500	0.0129600
LPG	3.0170000	0.0000000	0.0152000
Biomass	0.0180000	0.0000736	0.0014160
Gaseous	2.4664000	0.0000000	0.0530000

Table 4. Heat of Combustion, by IDAE [96].

	kWh/kg of fuel
Gasoline	12.3060
Diesel oil	11.9440
LPG	13.1390
Biomass	3.9330
Gaseous	12.2780

Table 5. Tons of CO_2, SO_2 and NO_x produced by transport in Spain (Tn), by IDAE [96].

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
CO_2	86 143.24	83 012.35	78 736.75	72 194.57	74 422.72	75 295.56	77 967.71	80 010.92	81 359.65	82 230.56
SO_2	3.55	3.53	3.44	3.27	3.15	3.21	3.34	3.43	3.52	3.60
NO_x	336.77	327.66	312.90	289.54	295.12	299.57	310.76	319.71	326.24	331.92

HoC is the calorific value of the fuel

Considering the calorific value obtained from the Institute for Energy Diversification and Saving (IDAE), belonging to the Ministry for the Ecological Transition and Demographic Challenge of Spain [96], shown in Table 4, the tons produced of CO_2, SO_2 and NO_x in Spain by transport are obtained. Table 5 shows the amounts of these gases produced between 2009 and 2018.

It can be observed the large amount of GHG generated per year only by vehicles with ICE in a country like Spain, a member state of the EU. In addition, it should be noted that these values do not show other gases or particles that can be generated, such as CO or NH_3. On the other hand, it is also possible to see the reduction of emissions produced by an economic crisis. It can also see the economic recovery with the growth of these levels as of 2018. It is in these situations where the strengths and weaknesses of the technologies can be seen and where one must bet on some technologies or others to be able to position oneself in the market.

3.2. Economic benefits

The economic benefits that the use of EV can bring about can be monetized by considering the phases of the fossil fuel process, extraction, processing, transportation and distribution and storage. Added to this are taxes, customs, regulatory changes and other factors that cause uncertainty in this type of energy vector [97]. Due to the complexity and great variability of these factors, it is difficult to make an exhaustive study of each case. When it comes to monetization, in the EU there is the actor of Emissions Trading Schemes (ETS) [98], where CO_2 is priced per ton of emission. Fig. 8 shows the evolution of its price in recent years.

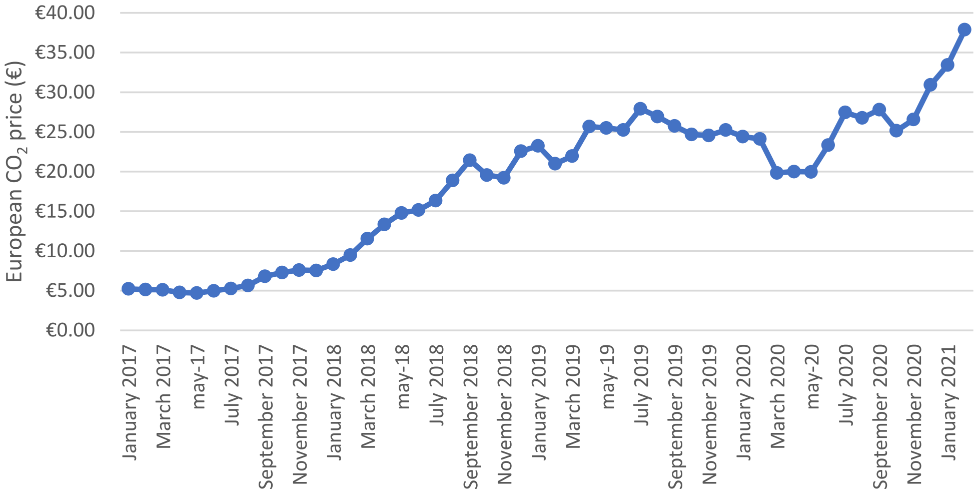

Fig. 8. European CO_2 price [98].

The price of CO_2 emissions in the EU with the amount of tons of CO_2 emitted due to ICE vehicles is a biased way of looking at the cost of using these vehicles. In order to promote EV and zero emission energy sources, it is estimated that this "emission tax" should be increased to 80 €/ton. These costs are usually borne by the fossil fuel energy generating companies. In contrast, other harmful emissions such as PM10 or NO_x emissions cannot be monetized. To this should be added the costs of energy, caused by generation and distribution, depending on the energy mix, in the Spanish case, where 44% of electricity generation was from so-called renewable sources [99].

On the other hand, the possibility of EVs can also be seen in the so-called V2G, where EVs are used as support elements of the power grid. This system can reduce power outages [43] or smooth the energy curve to avoid stressing the power system [100]. In this sense, and for reference, in a member state such as Spain, an availability of 97.9% was obtained in the peninsular grid, according to *Red Eléctrica de España* (REE) in 2020 [99]. That 2% can cause economic losses in the millions in continuous manufacturing processes, such as.

On the other hand, the cost of using EVs must take into account the investment, both public and private, made in the development of EVs with greater autonomy and greater reliability, as well as the development of a supply network as dense as possible. This is associated with inflation, payback time and investor profitability. It should be borne in mind that for the private investor, any operation must produce a return in a reasonable period, so regulatory and economic uncertainty can make many investors wary of investing. Therefore, if demand for EVs and competition between manufacturers is encouraged, private investment for the technological development of the industry will be boosted, helping the research community to develop an EV with similar performance to a conventional vehicle at a similar cost.

Despite this uncertainty, there are a large number of projects in Europe focused on the development of EV-related technologies, such as the development of batteries, over €300 m, EV charging and infrastructure, over €200 m, or the development of engines, electronics and transmission systems to increase the efficiency of EVs, over €500

m. According to [79], around 450 projects related to the development of technology to make EVs competitive with ICE vehicles

4. Discussion

The use of EV provides great advantages, where the great environmental benefits stand out, and important disadvantages to be taken into account. Specifically, a hybrid storage system consisting of a lithium battery [55,101], proposed in this case, and a SMES system.

4.1. Advantages of the hybrid system

Among the advantages that can be obtained from this system are, very extensible to EVs in general:

- Environmental benefit: This type of advantage is applicable to the substitution of ICE vehicles by EVs, as seen above. Even so, it should be kept in mind that in the manufacture of EVs, procedures and materials are used that produce GHG emissions and other products that can negatively affect the environment, but this is beyond the scope of this research. On the other hand, the considerable reduction of noise pollution due to the use of EVs should be commented. It is such that, as an example, European legislation requires EVs and HEVs to make a minimum noise level between 0–20 km/h. This noise must be between 56 and 75 dB's [102].
- Durability: With the choice of a suitable management and control system, [13,23,53,88], and the right materials, they are very reliable systems with fairly basic maintenance. This can provide more than 20 years of trouble-free use with little maintenance.
- Higher performance: The use of hybrid systems, with a proper management and control system, as well as the appropriate hybridization configuration for each use, can provide higher performance and efficiency in EV use.
- Helping the energy system: The use of EVs with high power and energy density can help the electric system through the so-called V2G, as a storage source and grid overload regulation system. This system is associated with Smart Grids and electricity distribution, allowing the development of an energy system less dependent on fossil fuels.

4.2. Disadvantages of the hybrid system

Despite the many advantages, these systems have many other disadvantages that need to be solved. This section focuses on the disadvantages that the SMES system can provide in the EV. Among them are:

- Health problems: the use of the SMES system produces high magnetic fields, although they are being the subject of studies and research, with uncertain results and without any evidence of possible health effects, it must be taken into account. In this case, the EU drafted a recommendation regarding public exposure to magnetic fields [103].
- Technical complexity: The hybridization system can be complicated depending on the method of administration and control of the storage components. To this, we must add the intrinsic complexity of the SMES system because the coil must be kept at a temperature below Tc to have the necessary performance to make this system useful. All this influences the following point.
- Economic cost: It has been seen above that the storage system can be around 80%–90% of the cost of an EV. This is because SMES systems are not fully developed for the particular use in EV. It is also due to all the systems associated with the superconducting coil, such as the coolant reservoir, booster pump or hydraulic system, apart from the coolant temperature control and pressurization system. It should also be borne in mind that the materials used for their manufacture and processing are often difficult to obtain, which can significantly increase costs in this regard.
- Storage volume: This point is derived from the technical complexity and lack of development of the SMES system, discussed above. If the power density values provided are taken into account, where the power density is around 1000–4000 W/L, it is obtained that for a system such as those studied in the Economic Analysis, of about 250 kW of power, a volume of between 62.5–250 L is obtained for the SMES system alone. This is also associated with the specific power, around 500–2000 W/kg, which would weigh this system around 125–500 kg, only this storage system, which would cause the vehicle to be quite heavy.

- Slow recharging: Current EV recharging systems are quite slow compared to those related to ICE vehicles. Currently recharging systems can recharge an average battery between 8 h and 30 min, the fastest and reaching 80% SOC, State of Charge, of the batteries [104]. This can be a major drawback if the vehicle is used for long journeys where time is of the essence. Even so, it is a field that is developing algorithms for fast vehicle charging, such as [28,105,106].

Despite all the drawbacks, it is estimated that in the coming years the cost will be reduced [6,83] and will be developed at a technical level so that the SMES system can be presented as a viable alternative to other high power density systems, such as the supercapacitor [46]. This is propitiated by the bet made by the different governments for the development and implementation of EV to replace vehicles with ICE, as for example Norway that in 2019 had 55.9% of EV, either BEV or PHEV, according to [6].

4.3. Factors to enhance EV

Considering the advantages and disadvantages of EVs, it is necessary to analyze the factors and fields that should be focused on to achieve greater EV implementation. Fig. 9 shows a summary of the main factors and their relationships.

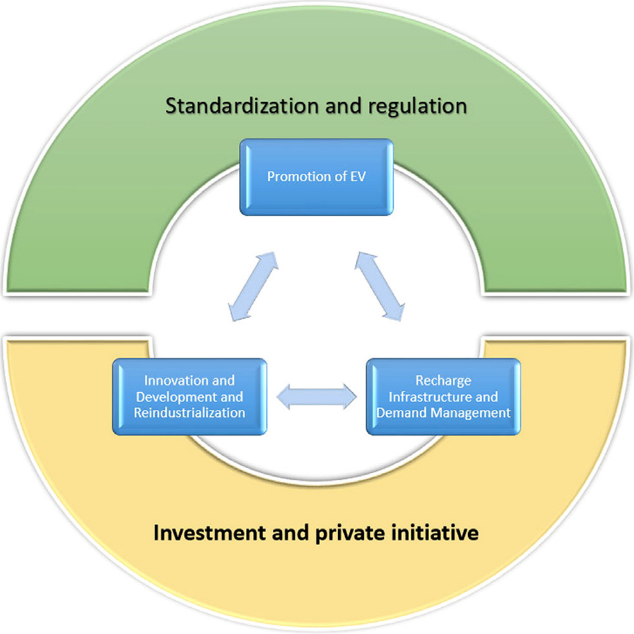

Fig. 9. EV implementation factors.

The three main blocks are promotion, R&D and reindustrialization of the sector and, finally, recharging infrastructures and the electric system. These three blocks are interconnected because many initiatives and projects are interrelated and depend on each other. Encompassing them are regularization, standardization, and private investment. This is because private investment and the public sector must go hand in hand in order to develop the EV and increase EV deployment.

Many of these measures have been developed in different countries for years, as we have seen. Within the different factors to be enhanced, some measures can be listed:

- Promotion of EV:
  - Public/private advertising campaigns with the aim of showing the great advantages of EV.
  - Incentivize the purchase of EVs through tax reductions, or through direct purchase aid for cab fleets, delivery vehicles, among others.

  - Agreements between manufacturers and major brands to reduce the selling price to companies or institutions.
  - Purchase, by the cities, of the electric public transport fleet. Large parts of the trips are urban or peri-urban.
  - Development of mobility benefits for EV owners in cities.

- R&D and Reindustrialization:
  - Re-industrialization can increase the strategic value of regions and increase the formative potential of society.
  - Reindustrialization leads to the development of ancillary companies specialized in recharging systems or specific EV modules to manufacturing plants, which allows for a decrease in unemployment.
  - Collaboration agreements between EV component manufacturing companies and public research entities, such as foundations or universities, with the aim of developing the academic field.
  - Development of research into recharging points or storage systems.
  - Reduction of administrative procedures to develop components or private initiatives in the field of mobility.

- Recharging infrastructures and demand management:
  - Implementation by municipalities of a network of public recharging points.
  - Regulatory development of standardization and normalization of the technical elements of charging points, both connectors and feeders.
  - Private development of electric recharging stations by fuel retailers to increase the number of recharging points.
  - Strengthening of the renewable electricity system with the aim of reducing electricity supply costs. It should be borne in mind that these vehicles are connected to the grid.
  - Creation of reduced tariffs during off-peak hours to flatten the electricity demand curve.

All these factors, with their initiatives, are interrelated and therefore depend on each other. They are also dependent on the regulation and standardization to be done by public entities, from the highest level to the level of municipalities, and on private investment and initiative, which has the potential to develop a large number of innovation projects, both in terms of knowledge and material.

The relationship between the public and private sectors is essential to achieve the degree of implementation of EV that is sought in the coming years. If agreements are not reached, it will take much longer to reach the targets for the reduction of GHG produced by transport, and EV may be limited to the urban environment.

5. Conclusions

According to this study, it can be seen that the development of EVs involves investing in research on their energy storage elements and the performance of the vehicle's control and drive system. The aim is to increase the autonomy of these vehicles and reduce recharging time, in order to gain ground on ICE vehicles and meet CO2 emission reduction targets in the coming years. Economic support from the public and private sector is necessary to achieve the development and inclusion of EVs through research into hybrid storage components and technologies that can respond to the challenges facing EVs. In the same sense, the public sector should facilitate, at the regulatory level, investment in technological research, either through direct aid or through tax reductions, with the idea that private investment should be involved in EV development projects. Adequate regulation can reduce the costs of storage systems, and therefore of EVs, so that they can be competitive in the market compared to ICE vehicles. At present, it can be said that FEVs are far from being competitive, they are more expensive, they have less autonomy, the recharging of accumulators is very slow compared to the refueling of a vehicle with ICE and the network of EV refueling stations is quite limited compared to the network of fossil fuel refueling stations. These problems are being solved due to the industry's large investment in solving them, with countries aiming to have the vast majority of vehicles on the road being EVs, or at least HEVs, in the coming decades, to reduce GHG emissions from the transport sector.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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