FUEL CELL HYBRID ELECTRIC VEHICLE: A REVIEW ON CURRENT STATUS, KEY CHALLENGES AND FUTURE PROSPECTS

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Abstract - A fuel-cell hybrid electric vehicle is an advanced type of hybrid vehicle that utilizes a combination of fuel-cell technology and electric propulsion for improved efficiency. The fuel cell generates electricity through a chemical reaction using hydrogen as the fuel source. This electricity powers the vehicle's electric motor, while a battery system stores excess energy, provides additional power during acceleration, and stores regenerative braking energy. To improve the performance of fuel cell hybrids, designing and developing efficient energy management strategies is an urgent need for current automotive manufacturers. From the perspective of energy consumption, the main work is to reduce hydrogen consumption. In recent years, energy management strategies based on intelligent connected vehicle technology have also received extensive attention. Most fuel cell vehicles are classified as zero-emission vehicles that emit only water and heat. Compared with internal combustion vehicles, hydrogen vehicles centralize pollutants at the site of hydrogen production. In an electric drive vehicle, the low-voltage auxiliary battery provides electricity to start the engine before the traction battery is engaged, it also powers vehicle accessories. This high-voltage battery stores energy from regenerative braking and provides supplemental power to the electric motor. The DC converter converts higher voltage to lower voltage DC power which is needed to run the vehicle and recharge the auxiliary battery. Using power from the fuel cell and the traction battery pack, the motor drives the vehicle's wheels. A fuel cell stack is an assembly of individual membrane electrodes that use hydrogen and oxygen to produce electricity. So the fuel cell electric vehicle is the best option to simultaneously reduce air pollution, greenhouse gas emissions, and the consumption of fossil fuels

***Key Words*:** Battery(auxiliary), Battery pack such as petroleum and natural gas., DC/DC Converter, Electric traction motor(FCEV), Fuel cell stack, Fuel filler, Fuel tank(hydrogen), Power electronics controller, Thermal system(cooling), Transmission(electric)

1.INTRODUCTION

A Fuel Cell Hybrid Electric Vehicle(FCHEV) is a type of hydrogen vehicle that uses a fuel cell to produce electricity, powering its onboard electric motor. Fuel cells in vehicles create electricity to power an electric motor using hydrogen and oxygen from the air.

All fuel cells are made up of three parts: an electrolyte, an anode, and a cathode. In principle, a hydrogen fuel cell functions like a battery, producing electricity, which can run an electric motor. Instead of requiring recharging, however, the fuel cell can be refilled with hydrogen. Different types of fuel cells include Polymer Electrolyte Membrane (PEM) Fuel Cells, Direct Methanol Fuel Cells, Phosphoric Acid Fuel Cells, Molten Carbonate Fuel Cells, Solid Oxide Fuel Cells, and Regenerative Fuel Cells. As of 2009, motor vehicles used most of the petroleum consumed in the U.S. and produced over 60% of the carbon monoxide emissions and about 20% of greenhouse gas emissions in the United States. In contrast, a vehicle fueled with pure hydrogen emits few pollutants, producing mainly water and heat, although the production of the hydrogen would create pollutants unless the hydrogen used in the fuel cell was produced using only renewable energy.

The fuel cells discussed in this paper are proton exchange membrane fuel cells (PEMFCs), which use hydrogen energy as the energy source to generate electricity. The PEMFC directly converts the chemical energy contained in hydrogen into electricity, heat, and water [3]. The fuel cell suffers from a slow dynamic response and is difficult to adapt to complex driving conditions. The chemical reaction of the hydrogen in the fuel cell which supplies electrical energy is often smaller than the rate of change of the load. At the same time, rapid acceleration and deceleration and frequent start-stop operations during driving will affect the durability of the fuel cell. Based on these characteristics, fuel cells are often used in hybrid energy storage systems with other energy sources, such as batteries and ultracapacitors, for power applications. Additionally, fuel cells are widely used in hybrid power systems with other energy sources. It is useful to reduce the consumption of hydrogen, reduce the

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size of fuel cells, and increase the economy of hybrid power systems Fuel cell-based hybrid systems are widely used not only in fuel cell hybrid vehicles but also in other transportation equipment, such as unmanned aerial vehicles (UAVs) and trams. The FCEVs use a traction system that is run by electrical energy engendered by a fuel cell and a battery working together while fuel cell hybrid electric vehicles (FCHEVs), combine a fuel cell with a battery or ultracapacitor storage technology as their energy source Instead of relying on a battery to provide energy, the fuel cell (FC) produces electricity using hydrogen.

In order to provide greater power when accelerating, FCEVs are also built to recover braking power. Since hydrogen serves as the FCEV's primary fuel, the magnitude of the hydrogen fuel tank involved determines how much energy can be delivered to its system This means that the size of the battery has no bearing on the amount of energy that is available. By the end of 2020, about 35,000 FCEVs were in operation globally in the conveyance zone, representing a rapid expansion of this technology. While HEVs play a role in the transition toward wide electric mobility, shortcomings of BEVs remain. This includes a limited driving range in comparison to HEVs and the additionally needed charging infrastructure. The requirement of sufficient mileage per battery charge for individual mobility seems to be met by BEVs through research and future development of battery technolo- gies, which leads to higher gravimetric and volumetric energy density. In contrast, for heavy-duty and long-haul trucks, the available battery technology may be insufficient in regard to the combination of high power and long distances forming challenging requirements. Here, the deployment of FCS technology as the main energy source may be a favorable solution for heavy-duty vehicles due to the high gravimetric energy density of hydrogen and the ability for fast refueling. In order to provide greater power when accelerating, FCEVs are also built to recover braking power. Since hydrogen serves as the FCEV's primary fuel, the magnitude of the hydrogen fuel tank involved determines how much energy can be delivered to its system This means that the size of the battery has no bearing on the amount of energy that is available. By the end of 2020, about 35,000 FCEVs were in operation globally in the conveyance zone, representing a rapid expansion of this technology. While HEVs play a role in the transition toward wide electric mobility, shortcomings of BEVs remain. This includes a limited driving range in comparison to HEVs and the additionally needed charging infrastructure.

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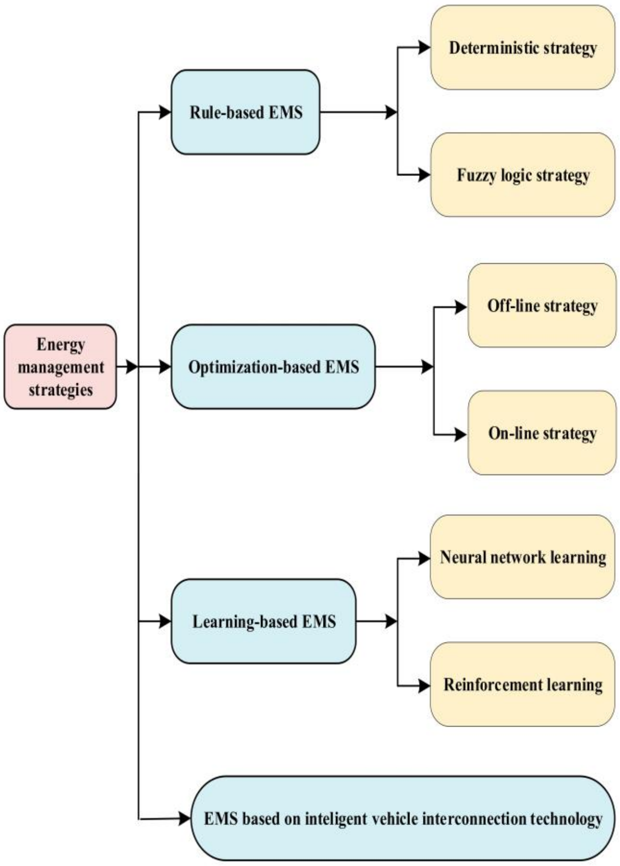

Fig:1 Energy management systems

2. LITERATURE REVIEW

To fulfill the performance requirement in vehicle propulsion and portable fuel cell applications, a fuel cell stack is typically coupled with a battery through a DC/DC converter to form a hybrid power system. Defining the fuel cell performance and identifying the limitations are critical in designing fuel cell hybrid power applications. Otherwise, unnecessary protection with conservative FC operation may result in lower overall efficiency. However, FC system identification and performance validation outside the safe limits might cause stack degradation or failure. Therefore, a physics-based model is necessary in designing a FC hybrid power system. The fuel cell model developed in the literature can be classified into two main categories, namely, microscopic and macroscopic models. The microscopic model deals with the performance of the local area in the cell. For example, the FC model predicts the spatial distribution of current density . Due to computational load, the microscopic model is not suitable in system integration studies. The macroscopic model is generally defined by global pressure, temperature, and flow conditions. The electrochemical reactions are considered instantaneous Recent research also shows a lot of results in modeling the transient behavior of fuel cells based on reactants supply dynamics temperature dynamics and humidity . Amphlett et al. showed the temperature dynamics of fuel cells. Wang et al. also presented that the fuel cell dynamics associated with humidity exhibit a time constant that is far slower than the ones of reactants supply even though humidity has a direct effect on the membrane conductivity and thus internal resistance. Transient power performance is highly related to the reactant pressure and flow dynamics . Modeling and control of the air supply that can respond to transient load is emphasized in "In most fuel cell models, exogenous input is current, and the resulting output is either cell or stack voltage Rarely voltage is defined as the input load . The past models consider exogenous input to interface the FC with the external power demand. Independently from the input, the internal dynamics of the FC follow the same physical principles. Performance limitations due to the air supply in PEM FC have been reported previously. Regulating air flow based on the flow rate measurement at the supply manifold inlet introduces a limitation because the actual air flow at the cathode inlet is not the same as the one at the compressor outlet This mismatch introduces a significant complexity in tuning the air flow controller for the actual in-stack performance objective. On the other hand, high compressor control effort, which draws current directly from the stack, can cause instabilities in the FC power delivery system Two performance variables, air flow and cathode pressure, become both critical to the fuel cell performance and the system efficiency . Note that the hydrogen supply is more important than the air supply when reformer is used due to the slow dynamics of the reformer

The integration and associated dynamics of the fuel cells in the hybrid power system depend highly on the electric architecture and specific load conditions. Various electric connections between the fuel cell and battery have been proposed in the literature. Parallel connection between the fuel cell and the battery with the electric load without any DC/DC converter is originally proposed for submarine applications . Although parallel connection does not provide active control in power management, this design provides a first-order RC (resistor-capacitor) filter to the fuel cell stack This way, the battery can cover the transient power demand. However, this passive connection limits the fuel cell stack and battery size and imposes constraints on their operation and, hence, performance The past models consider exogenous input to interface the FC with the external power demand. 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Although parallel connection does not provide active control in power management, this design provides a first-order RC (resistor-capacitor) filter to the fuel cell stack [50]. This way, the battery can cover the transient power demand. However, this passive connection limits the fuel cell stack and battery size and imposes constraints in their operation, and hence, performance . The DC/DC converter isolates the voltage range of the fuel cell from the battery, offering more flexibility and the potential for optimized performance. Hence a DC/DC converter is almost always considered in FC hybrid system studies. A large number of studies on the DC/DC converters for fuel cells is focused on soft voltage sources, which accounts for the cell voltage variation due to the electrochemical characteristic at different operation conditions . There is another functionality, however, that a DC/DC converter has to perform. The DC/DC converter in FC hybrid system handles power split and active fuel cell management. The operation principles of power split in FC hybrid vehicle power are well summarized in . In the same paper, several electric architectures are presented with signal flows associated to interacting current and voltage, pointing to the lack of appropriate dynamic model for analysis and control design. Since the control bandwidth of the DC/DC converter is faster than any other dynamics in the FC, battery and electric load, the DC/DC converter is sometimes modeled as static conversion of power. Based on quasi-steady state assumption, noncausal optimization methods have been used to evaluate the supervisory control in energy storage and regenerative braking strategies . Most hybrid strategies associated with fuel cell applications mainly focus on protection of the FC stack. Therefore the control command to the DC/DC converter is determined by the fuel cell system. To prevent abrupt changes in current load to the fuel cell, first-order current load filter is proposed in Load governors and model predictive control have been also proposed for current control. The control objective of the DC/DC converter varies with the specification of the electric loads. The duty cycle control of the DC/DC converter is proposed for the purpose of maintaining battery stage of charge Two different DC/DC converters are proposed with its own control objective, namely, fuel cell objective and power bus objective . Specifically, conventional DC/DC converter manages the current drawn from the fuel cell based on a supervisory control command, whereas a bidirectional DC/DC converter draws power from the battery to maintain the DC bus voltage. The small volume and weight of a bidirectional DC/DC converter make it lucrative for FC hybrid vehicle The bidirectional DC/DC converter controls fuel cell voltage instead of current load . In most of FC hybrid power studies, the fuel cell stack is modeled with a static polarization relationship assuming fixed fuel cell operating parameters and avoiding the dynamical variations. 6 Introduction Thus, the major objective of protecting the fuel cell from harmful transition cannot be evaluated.

3. METHODOLOGY:-

In this work an economic and environmental analysis of a hybrid fleet composed of FCHEVs and BEVs has been carried out. First, various representative driving cycles have been created, using a Markov Chain approach, starting from on-road GPS data employed to determine BEVs energy consumption, FCHEVs hydrogen consumption and distance travelled within the time horizon. Economic and environmental analysis have been performed starting from the reconstructed driving cycles characteristics knowing the technical features of fleet and charging columns. 2.1. Markov Chain method for driving cycles creation In order to define the input of the optimization algorithm, reference driving cycles are needed to simulate vehicles missions. Markov method allows to reconstruct potential predict driving cycles through the correlation between adjacent probability states defined based on the acceleration and velocity. Firstly, the real GPS data have been discretized with an appropriate step size, obtaining velocity-acceleration states probability distribution. The transitions between individual states are described by a probability distribution, defined through the transition probability matrix (TPM) obtained from real driving data. Joining the probability distribution of velocity-acceleration states and the transition probability matrix, a driving cycle is created for the performance evaluation . Further details of the proposed approach can be found in . 2.2. Battery Electric Vehicle and Fuel Cell Hybrid Electric Vehicle models. All the inputs of the optimization algorithm are obtained through the simulation of FCHEVs and BEVs platforms. The two models share the same framework with some differences that account for the different type of powertrain. The models have been implemented in Matlab/Simulink/Simscape framework and the general layout of the vehicle is presented in Figure 1 for the FCHEV. In particular, it refers to a light-medium duty commercial vehicle, considering a weight of nearly 3500 kg, with a parallel architecture between the FC and the battery pack. It is equipped with a 130 kW permanent magnet motor, a battery pack with 104 Ah capacity and 350 V rated voltage and a 99 kW PEM fuel cell (more details can be found in previous work [17]). The main differences between the FCHEVs and BEVs can be understood looking at the scheme. Firstly, the BEV model has no parts strictly related to the fuel cell stack. Then, the battery packs have been doubled (from a single pack of 104 Ah up to a double pack of 208 Ah capacity), together with a reasonable sizing of the thermal circuit. For what concern the e-motor, this has been kept equal among the two models

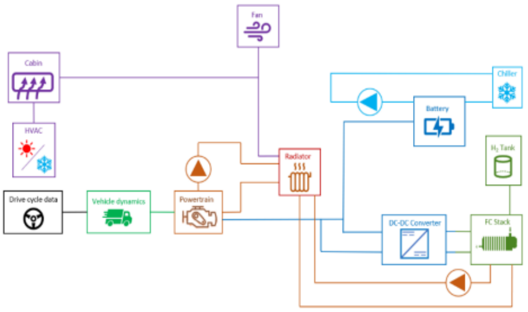

Fig 2: FCHEV Chain approach

The methodology for developing a fuel cell hybrid electric vehicle (FCHEV) involves several key steps. First, the selection and integration of various components are essential. This includes choosing suitable fuel cell technology, energy storage systems (such as batteries or supercapacitors), and electric motors. The design should optimize power distribution and control strategies to maximize efficiency and performance. Next, vehicle architecture and packaging play a critical role in ensuring space for components and achieving the desired weight distribution. Careful consideration must be given to safety and crashworthiness while maintaining the vehicle's aerodynamics.

Additionally, the development process involves extensive simulation and testing to evaluate the FCHEV's performance, energy efficiency, and emissions. Prototyping and validation of the powertrain system are crucial, along with real-world testing to fine-tune operational parameters. Finally, data collection and analysis help refine the FCHEV's design and performance to achieve a sustainable and efficient hybrid electric vehicle. There are various methodologies for developing fuel cell hybrid electric vehicles (FCHEVs), each with its own unique approach and advantages. Here are some of the key methodologies along with explanations:

1.Parallel Hybrid FCHEV (PHEV) : In a PHEV FCHEV, both the fuel cell and the battery-electric system are connected to the vehicle's drivetrain in parallel. This means that both power sources can drive the vehicle simultaneously, and the control system manages their interaction. The advantage of this approach is that it allows for a seamless transition between power sources and offers enhanced performance and efficiency. The fuel cell can provide continuous power for cruising, while the battery can assist during acceleration or regenerative braking.

2. Series Hybrid FCHEV :In a series hybrid FCHEV, the fuel cell is the primary power source, while the battery-electric system is used to assist during periods of high power demand, such as acceleration. The fuel cell generates electricity, which is then used to power the electric motor driving the wheels. The battery serves as a buffer and stores energy from regenerative braking. This approach is highly efficient as the fuel cell operates in its sweet spot most of the time.

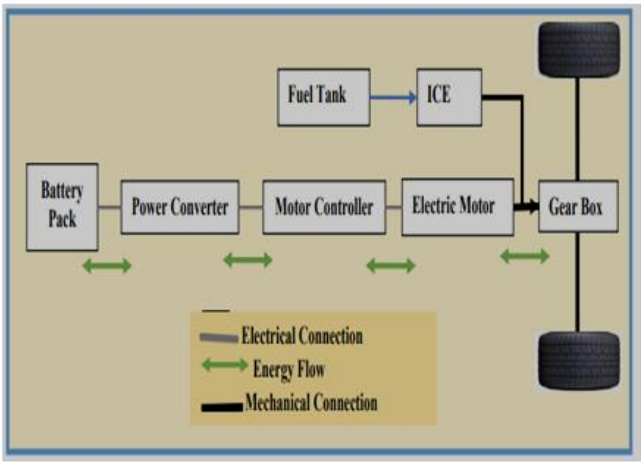

Fig 3: Series Hybrid FCHEV

3. power-Split Hybrid FCHEV : Power-split FCHEVs combine elements of both series and parallel configurations. They typically have a planetary gear set that allows for various operating modes. The fuel cell can directly power the wheels, and excess energy can be used to charge the battery. This flexibility optimizes the vehicle's efficiency by utilizing the fuel cell and battery in the most efficient way for different driving conditions.

4. Plug-In FCHEV : This methodology involves a FCHEV with a larger battery pack that can be charged via a plug-in connection. These vehicles offer extended electric-only driving range when the battery is charged and can operate in a variety of modes, including all-electric, series hybrid, or parallel hybrid, depending on the driving conditions and user preferences. Plug-in FCHEVs offer the benefits of reduced greenhouse gas emissions and increased energy efficiency.

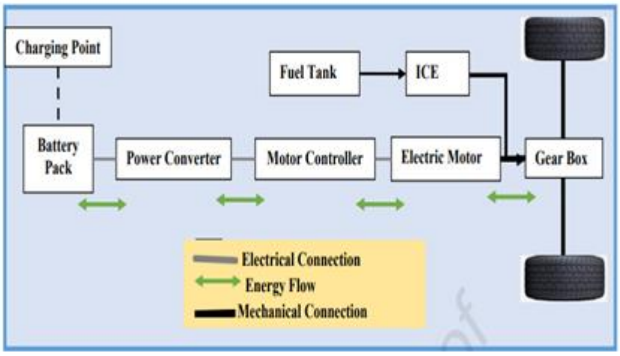

Fig 4: Power-Split Hybrid FCHEV

5. Hydrogen Fuel Cell Range Extender FCHEV : In this approach, the fuel cell acts as a range extender for a battery-electric vehicle. The primary power source is the battery, and the fuel cell is used to generate electricity when the battery's state of charge is low, thereby extending the vehicle's range. This configuration can provide the advantages of zero emissions while offering the security of longer driving distances.

Each of these methodologies has its own set of advantages and trade-offs, and the choice depends on factors like vehicle design goals, driving patterns, and infrastructure availability. FCHEV development requires a detailed analysis of these methodologies to determine the best approach for a particular application, considering factors like efficiency, emissions, cost, and overall performance.

4. RESULTS AND DISCUSSIONS:-

In this section the results and the relative discussion are reported and commented. First of all, the results related to the energy and hydrogen consumption varying the ambient temperature are presented. Then, the influence of the fleet configuration on the specific costs is commented to select the best configuration. Finally, the evaluation of the FCHEVs penetration impact on the grid is presented with a future consideration related to the hydrogen costs

In Figure 3 the variation of FCHEVs and BEVs consumption with the temperature is reported.

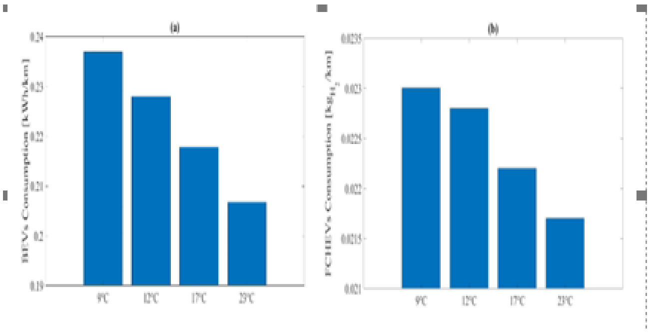

Fig 5: FCHEV and BHEV consumptions graph

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1. A deeper insight can be obtained looking at Figure 4 and Figure 5, representing the BoP of the vehicles by means of pie charts. The results have been obtained by simulating the mission in Figure 2. "Vehicle distribution" subfigures represent the global BoP of the vehicles, and it can be seen that BEV-relative figure presents only two terms, namely "Traction" and “Vehicle Aux,” while the one relative to FCHEV shows also the internal auxiliaries demand of the FC (computed separately from the others) and the term accounting for battery inefficiencies. The other subfigures (“Aux Distribution”) stand for the energy sharing among the vehicle auxiliaries.

2. In both cases, there is a dependence of the vehicle's consumption on the external operating temperature.

3. It is now clear the increment in consumption of the 9 °C cases respect to the 23 °C ones. The 0 % of HVAC request is due to the fact that cabin target temperature is nearly the same as the environmental temperature in the case of higher temperature, while the other case shows an extensive use of the cabin conditioning (93,2 % of auxiliaries demand) to reach the comfort regime: this is translated into an increase of the total request from 2,4 % up to 15,2 %, strongly impacting the BEVs consumption.

4. In the case of BEVs, there is a reduction in consumption of 13% in the highest temperature (23 °C) compared to the lowest (9 °C), while there is a decrease of 6% in the case of hydrogen vehicles.

5. Similar considerations can be drawn for FCHEVs. Here, the major contribution from the energy standpoint is given by HVAC, accounting for nearly 50% of the auxiliaries demand; however, the FC warm-up phase (to avoid excessive power derating and degradation) has a strong role in increasing the consumption as well (from 6,5% for 23 °C up to 14,3% for 9 °C).

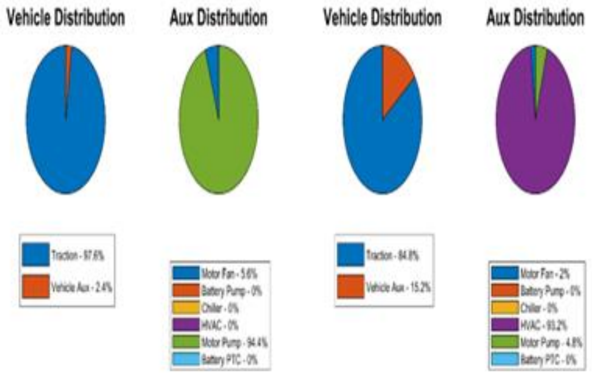

Fig 6: BHEV Piechart

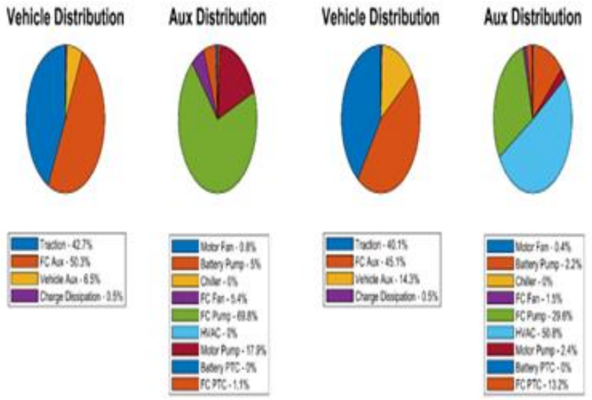

Fig 7: FCHEV and BHEV Distribution Piechart

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1. Figure 6 shows how this behavior is reflected in the variation of the fleet-specific costs.

2. It can be noticed how for Case IV the operative fleet costs are directly related to the external temperature, with limited variation among the coldest and hottest conditions (about 7%).

3. On the contrary, cases with a higher number of EVs within the fleet showed a significant influence also from the electricity price variation.

4. Comparing the specific costs in terms of €/km for different configurations of the hybrid fleet with a hydrogen price of 8.5 €/kgH2, it can be seen that the best situation with the lowest costs is still represented by the fleet composed of only BEVs.

5. Indeed, with the current hydrogen price, the specific cost of FCHEVs is still not competitive (Table 4).

6. Analysis of the fleet performance foreseeing future hydrogen prices will be revealed next in the text.

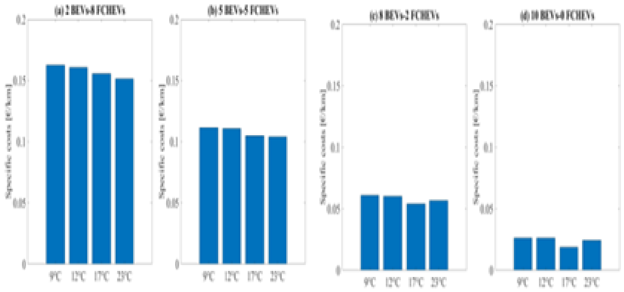

Fig 8: Analysis of Hydrogen Performance

An environmental assessment has been performed considering the CO2 reduction due to the hybridization of the fleet and Figure 7 shows the relative emissions reduction with respect to the reference target of the full thermal vehicle fleet.

5. CONCLUSION:-

This paper summarizes and concludes various energy management strategies at the current stage and analyses the advantages and disadvantages, as well as the main roles of various energy management strategies. A brief introduction to the latest energy management strategies based on intelligent vehicle interconnection technology is provided. In the complex urban traffic environment, there are a variety of unexpected situations, such as vehicle collisions, road gradients, dynamic changes in road coefficients, and traffic congestion that occur at signalized intersections. If V2V and V2I interconnection technologies can be utilized, information about the current driving status of the vehicle can be more accurately predicted. This leads sto better optimization of the energy distribution of the hybrid powertrain. Although researchers have conducted some research on fuel cell hybrid power system structures and their energy management strategies, there is still much research work to be carried out. The following is a discussion of future trends in energy management strategies for FCHEVs:

To achieve a synergistic optimization of hydrogen consumption as well as the durability of hybrid powertrain components, using a combination of multiple algorithms for energy management strategies, will be helpful. The multi-algorithm combination of energy management strategies has outstanding advantages over single-method energy management strategies in terms of real-time performance and level of optimization. For example, genetic algorithms are used to optimize rule-based energy management policies. The resulting new energy management strategy has the advantage of real-time and optimization. Researchers extensively combine various algorithms to develop better energy management strategies, which is a worthy research direction;

Current V2V, V2I, and vehicle-to-everything (V2X) interconnected technologies, are developing rapidly. V2V communication enables vehicles to wirelessly exchange information about their speed, position, and heading, making vehicle speed predictions more accurate. At the same time, the current road information can be obtained in real time through V2I communication to make a more accurate judgment on the driving state and driving mode recognition of the vehicle. With the additional input of environmental information, the energy management strategy provides better real-time and optimization performance for FCHEVs;

An energy management strategy is the core issue of a fuel cell hybrid power system. It is meaningful to ensure the efficiency of the energy management strategy in the whole life cycle scale of the system. Energy management strategies that can coordinate changes in internal parameters of energy storage components, and external multiple load scenarios in different use phases, will be an important direction. It is of great importance in the future health and safety of power battery systems, as well as efficient management aspects.

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