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Fuel Cell Hybridization Topologies Using Various Energy Storage Technologies

A review

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***Abstract*—The main idea of this work is to review and classify the currently existing fuel cell (FC) hybridization topologies with various energy storage technologies (lithium-ion batteries (LIBs), supercapacitors (SCs), and lithium-ion capacitors (LICs)). There are presented generalized topologies of FC hybridization using LIB/SC or LIC. Also, when analyzing the energy storage technologies presented on the market, a comparison was made of LIB, SC, and LIC characteristics in the form of tables and Ragone plot. As a result, perspectives for the development of hybrid FC technologies using LIC were proposed due to the most advantageous characteristics compared to other energy storage methods.**

Keywords — PEM fuel cell; lithium-ion capacitor; hybridization source.

I. Introduction

Hybrid energy storage is a combination of energy storage devices. Hybrid energy storage can be used as a part of the system of renewable energy sources. In this case, hybrid energy storage devices may differ depending on the purpose. Renewable energy sources are currently on the rise. In recent years, there has been an increasing trend towards a reduction in carbon dioxide emissions into the atmosphere. Regarding this, the energy industry is also turning to the development of hydrogen technology [1]–[5]. In parallel, rapid technological development is stimulated by states. The development of environmentally friendly conservation methods and energy production received a new stage of stimulation and development on July 14, 2021, when the European Union presented an ambitious climate plan to transform all sectors of its economy. Every industry will be forced to accelerate the transition from fossil fuels to reduce pollution by at least 55% by 2030 from 1990 levels [6]. This plan will also affect the automotive industry, stimulating hydrogen engine development.

Using FC as a renewable source of the energy was combined with some problems. Previously, the development of industry and engines using hydrogen has been slowed down by high production costs: hydrogen engines have not been produced due to the high cost of hydrogen and the lack of infrastructure for hydrogen production, infrastructure, and production in the meantime have not been developed due to the lack of demand for hydrogen. Stimulating the production of sustainable modes of transport, in turn, is likely to stimulate infrastructure development, thereby lowering the cost of hydrogen production [1]–[3].

The efficiency of hydrogen engines is 60-80%. At the same time, the maximum efficiency for heat engines is 53%, but on average it is 35-38%. Due to the limitation on the efficiency of heat engines, internal combustion engines have no opportunity to significantly increase their efficiency and approach the performance of hydrogen fuel cells (FC). Such a high efficiency in a hydrogen FC is achieved because they immediately generate thermal energy and electricity as a result of a chemical reaction, unlike engines that convert thermal energy into mechanical energy. [7]

In addition to the advantages, FCs also have disadvantages. So, for the FC, it is destructive to work in an "idle" mode, when the energy produced is not used for operation, and to work under load conditions higher than the voltage at the output of the FC. Both modes of operation lead to the degradation of the cells of the FC, thereby shortening its life. The recuperative energy flow is also harmful to the FC when it is used in cars. The FC cannot absorb this energy, and therefore this factor also affects the rate of wear.

It is crucial to consider the hydrogen production pathways to reduce greenhouse gas (GHG) emissions when using hydrogen. Indeed, hydrogen can be generated by using different processes such as thermochemical and water electrolysis processes. Nowadays, thermochemical processes relying on coal gasification and natural gas reforming are widely employed. On one hand, the use of these processes contributes to the increase of GHG due to a large amount of CO_2 released into the atmosphere. On the other hand, these processes can be combined with carbon capture, utilization, and storage (CCUS) technologies (currently under research and development) to

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decrease drastically the GHG emissions. In comparison, the water electrolysis process coupled with low-carbon power sources (renewable energy sources, nuclear) is a promising and attractive pathway to generate decarbonized hydrogen for different applications (energy storage, transportation, power-to-gas, and industry such as the production of semiconductors and ammoniac).

Once hydrogen is generated, it can be used with a fuel cell to supply electricity. Fuel cells are electrochemical devices that can convert hydrogen and oxygen into electricity, releasing only water and heat as by-products. For this reason, the dissemination of fuel cells comes within the scope of global climate challenges since the fuel cell does not release GHG emissions. Furthermore, among all the existing fuel cell technologies, proton exchange membrane (PEM) fuel cells are the most widespread technology from the solid electrolyte, low-temperature operation, and quick start-up point of view. Hence, this technology is particularly fit for transportation applications, backup power, and distributed generation systems such as microgrids). However, PEM fuel cell technology suffers from different key challenges, especially in terms of durability and performance. To cope with these technical barriers, one of the solutions is to couple PEM fuel cells with other energy storage devices such as Li-ion batteries (LIB) and supercapacitors (SC). In the literature, the PEM fuel cell can be combined either with LIB and SC or only supercapacitors or batteries [8]–[20]. There are a lot of studies that propose different topologies for hybridization. In literature mostly proposed topologies that use DC-DC converters, while massive of them were described in a review by A. Kuperman [21], but later also proposed other topologies [22]–[26] or management systems [27]–[30].

Recently the lithium-ion capacitor (LIC) technology has been introduced and has attracted the attention of its characteristics [31]. Indeed, LIC combines LIB and SC technologies, respectively at the anode and cathode of LIC [32]. Over LIBs and SCs, LIC offers some benefits such as low self-discharge, higher energy density, and cell voltage [32], [33].

To compensate for these factors and extend the life of the system, hybridisation of the system is used. To quickly increase the current at the output of the FC, it is necessary either to significantly increase the power of the FC itself or to create hybrid systems. Typically, lithium-ion batteries (LIB) or supercapacitors (SCs) are used to create a hybrid FC system [8]–[12]. In addition to them, a flywheel [34] and superconducting magnetic energy storage devices are used in hybrid systems. LIBs have a larger energy reserve and can compensate for the lack of power for quite a long time; however, LIBs cannot quickly respond to a large jump in the required energy. SCs, on the other hand, have a lower energy reserve compared to LIBs, but they can deliver a higher charge of power when needed at one point in time. The addition of a battery and/or SC to the system allows excess energy to be absorbed. This energy can either come from the FC itself, which is operating in an "idle" mode, or it can be recuperative – which is directed back to the FC during braking and accumulates in the battery. A further issue is connecting FC and the hybridisation storage energy device properly. There are different configurations for the hybridization of the FC: passive, active, and semi-active topologies.

Recently, the hybridization between lithium-ion capacitors (LIC) and FCs has been introduced in the literature [31]. LICs feature higher energy density than SCs while offering a suitable power density. Moreover, the LIC presents a low self-discharge compared to SCs, which feature high self-discharge. Also, in previous papers, the advantages and disadvantages of these schemes have been discussed, mainly based on LIBs and SCs. Previous papers have been compared and analyzed, research papers about active and semi-active configurations were structured in Table A 1 (appearing in Appendix A).

Table A 1 shows the comparison of different papers dedicated to passive configuration schemes. By looking at Table A 1 one can see the different abilities and characteristics of passive topology examined in different papers. Furthermore, this table summarizes control strategies for those passive connection schemes, and the type of work with those schemes: part of reviewed papers is dedicated to experiments only, another part of the papers describes simulations based on experimental results, and some of the reviewed papers combine models and hardware tests. The table brings out the advantages that have been highlighted for those schemes in the original papers. Applications that are meant for those schemes are mostly for different types of vehicles.

There are two works dedicated to the experimental testing of passive connection schemes: one of them is about FCs and LIBs, and the other one is about FCs and SCs. As the result of comparing those papers can be seen that the key factor is the ability of these hybridization schemes to compensate for the voltage drop in the dynamics. And both of those experimenters proved that LIBs or SCs can compensate for the shortage of voltage caused by the dynamic load. For the SC, the compensation of the voltage drops is 5% of the fuel consumption [35], [36].

For modeling that has been mentioned in the reviewed papers, it is possible to divide it into two methods: modeling based on the experimental results and modeling before experimenting. Each of those methods is represented by two papers in Table A 1. Also, there is a paper that makes modelling and then validates the results in real-time.

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In the case of modeling before experimental research Table A 1 presents two papers [20], [37]. One of them is dedicated not only to the passive hybridization scheme but there is also to an active type while using the battery. In another work, the hybridization is made using a SC. In both those works is present control of supply valves and cooling fans. Due to those two research works, it is possible to conclude that passive configuration allows for avoiding FC degradation [20], [37].

The other two research papers [31], and [38] shown in Table A 1 are dedicated to modeling that is based on the results of the experimental tests. One of these works has used a passive hybridization scheme while the other all the types of hybridization. Both works have been oriented toward FC electric vehicle applications. Both works have demonstrated that hybridization contributes to preventing FC degradation. The paper [31], has also exhibited that passive topology increases the efficacy FCs by decreasing hydrogen consumption. At the same time, another paper [38] has pointed out the increased cost of the FC system. Also, it has been stated that active topology is the most effective hybridization scheme for the FC.

Finally, Table A 1 presents a study of a passive connection scheme with a pre-charged SC including modeling and real-time validation [39]. It has been highlighted the advances in reducing the FC degradation rate and increasing the efficiency of the system by operating SCs discharge ratio higher than 50%.

Hence, the main idea of this paper is to compare, analyze various hybrid energy systems using LIBs, SCs, and LICs, and highlight superior technology and new perspectives for fuel cell hybridisation.

This article is divided into 4 sections. As a result of the introduction providing relevant information about the hybridization of the FC, Section 2 is focused on the classification of configurations, in which all currently existing FC hybridization methods are considered. Then, in Section 3, the advantages and disadvantages of various connection schemes are highlighted Furthermore, this section presents the comparison results of LIBs, SCs, and LICs. Besides, a table comparing the results of experiments in various scientific works for passive connection schemes is given. In Section 4, a discussion is provided to analyze the reported works about passive configuration and to emphasize the benefits of using LIC instead of SC and LIB for the hybridization of the FC.

II. CLASSIFICATION

The circuits for connecting LIBs, SCs, and LICs to the FC are divided into 3 main types: passive, semi-active, and active. They are divided into types depending on the availability and connection method of the DC-DC converter. In this part, only the connections of SCs or LIC to the FC are considered. Indeed, the connections considered LIB have already been reported in previous review works.

Also, the FC must maintain a constant average current despite terminal losses. At the same time, the SC or LIC must provide a dynamic current in the system. In a passive connection system, the SC must be voltage matched to the FC [19].

A. Passive connection scheme

The circuit is called passive in the absence of a DC-DC converter in the connection diagram (Fig. 1). The SC or LIC is connected directly to the FC. Circuits of this type are characterized by ease of connection and low cost due to the absence of additional power electronics However, the disadvantage of this type of circuit for connecting the FC and SCs or LIC is that the load current is distributed uncontrollably. The only thing that determines the load current for the FC and the SC or LIC is the internal resistance [21]. At increased workload, both the FC and the battery or capacitor give off charge. When the load drops, the FC provides energy to both the load itself and the capacitor [21].

In this case, the battery voltage must correspond to the required load range on the FC. To do this, it is needed to either connect the LIBs in series, thereby increasing the internal resistance. Or choose LIBs with the required characteristics, which will affect the cost of the system.

The passive connection scheme is the most common and a lot of research has been devoted to it: [20], [21], [31], [37], [39]. Also, this scheme is already used in practice in many commercial products [21], which also proves its consistency and efficacy.

B. The parallel semi-active connection scheme

Adding a DC-DC converter to the passive circuit in parallel with the FC allows it to move to a parallel semi-

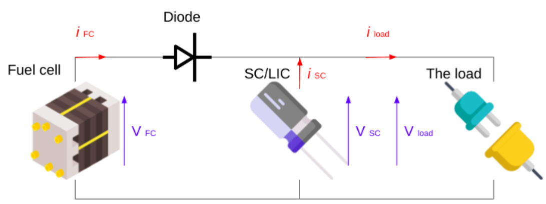

Fig. 1 Passive connection scheme

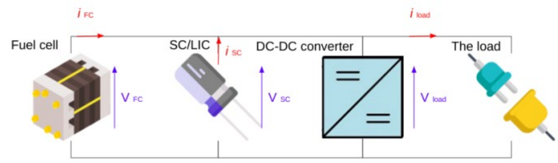

Fig. 2 Parallel semi-active connection scheme

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active connection. With this type of connection (Fig. 2), it is no longer necessary to match the voltage of the load on the FC. Also, in this configuration, the voltage mismatch between the SC and the FC is allowed, in contrast to the passive connection scheme. However, even under these conditions, the current that can be drawn from the SC is limited. This limitation is because the current cannot freely change as it is determined by the voltage at the FC terminals. As a result of this current limitation for the SC with this connection scheme, part of the dynamic current still must be provided not by the SC, but by the FC.

C. The semi-active supercapacitor connection scheme

The semi-active SC connection scheme differs from the parallel semi-active connection system in the location of the DC-DC converter. If in the previous circuit, the converter was located parallel to the FC, then in this circuit the converter is located parallel to the SC (Fig. 3).

When using this connection scheme, it becomes possible to control the SC current. This possibility favorably distinguishes this connection scheme in front of the parallel connection scheme, where the SC current was not regulated. Thereby, the parallel semi-active connection scheme improves the possibilities of energy use of the SC in tandem with the FC. This configuration also allows the SC to be charged with regenerative energy, regardless of load [21].

This configuration uses the principle of active filtering. Bypassing an active filter connected to a DC source and a non-linear load is used [21], [40]. Also typical is

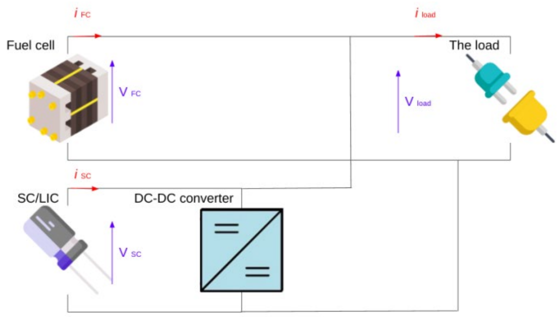

Fig. 3 Supercapacitor semi-active connection scheme

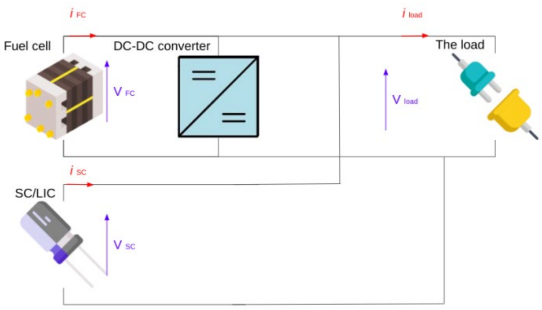

Fig. 4 Fuel cell semi-active

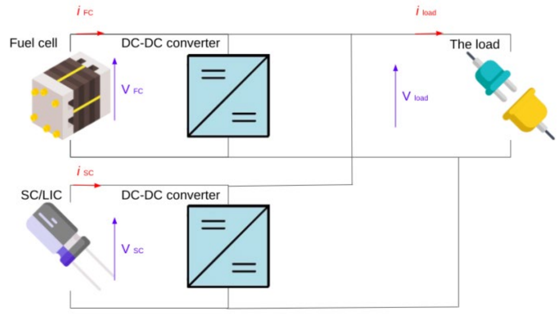

Fig. 5 Parallel active connection scheme

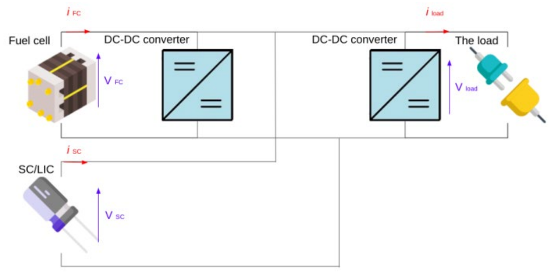

Fig. 6 Fuel cell series active connection scheme

the SC operation in the range of 50-100% of its nominal voltage, thereby allowing the use of 75% of its total energy.

D. Semi-active fuel cell connection

A semi-active FC connection scheme (Fig. 4) takes place in the case of a parallel connection between a FC and a SC. The DC-DC converter is located between the FC and the load. Using this topology does not control the energy use of the SC. This scheme uses control of the parameters and energy use of the FC. This allows controlling the current at the outlet of the FC. In this type of connection, the rated voltage of the SC must match the voltage of the load. Matching the load voltage and charge/discharge voltage of the SC is key. If it is impossible to reach these values, it is necessary to consider other topologies of FC hybridization [21].

E. Parallel active connection

Among all parallel connection topologies, the active parallel scheme (Fig. 5) is the most optimal. The presence of a DC-DC converter makes it possible to control the energy parameters of both the FC and the SC. With an active parallel connection, there is no need to match the voltage of the FC, SC, and load. Moreover, the voltage of the SC can be mismatched with the voltage of the load. This possibility is due to the presence of a voltage converter, which in turn provides a constant current to the FC. Also, there is no voltage fluctuation in the SC, which could have occurred in the topologies described above.

F. Fuel cell series active hybridisation scheme

At Fig. 6 is shown the result of adding a DC-DC converter between the SC and the load, it eliminates

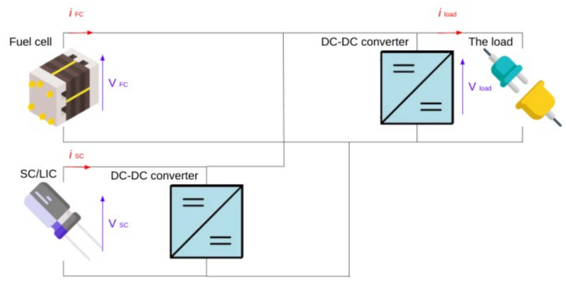

Fig. 7 Supercapacitor series active connection scheme

the voltage fluctuation problem on the SC. The received topology is called an active sequential FC connection. The disadvantage is that the efficiency is reduced due to the additional DC-DC converter.

G. Active series supercapacitor connection

In an active series capacitor circuit (Fig. 7), an additional DC-DC converter is positioned between the FC and the load. As a result, the voltage variations and matching to the load of the SC is regulated, however, the efficiency decreases due to the greater number of energy conversions.

III. SUMMARY

The schemes described before have a lot of advantages but at the same time disadvantages.

For the passive connection scheme, representative advantages are the lowest price and the easiest way of connecting parts. The small number of parts that are needed for the realization of this scheme makes this scheme the cheapest among other types of hybridization schemes. Also, the small number of parts makes calculations of this scheme easier in comparison to other types of schemes. Contrariwise, this type of connection has the lowest level of control for the parameters. This leads to the fact that the current and voltage flow in an uncontrolled way and they are limited only by the internal resistance.

Each of the few types of semi-active connection schemes described above has some advantages and disadvantages. The main common advantage is the higher number of possibilities of control. Added DC-DC converter allows controlling the current flowing from the capacitor (in case of capacitor semi-active hybridization scheme) or current of the battery (in case of battery semi-active hybridization scheme). At the same time, the parallel semi-active hybridization scheme allows the mismatching of the voltage between the battery and the load. In the case of a semi-active FC connection, it is possible to control the current between the FC end of the load. Per contra, for the battery or capacitor semi-active hybridization scheme the voltage is not regulated and is affected by the current flow from the FC.

The capacitor or the battery series active scheme of hybridization typically has better characteristics in comparison with semi-active topologies because of the acceptance of voltage variations. But at the same time in this topology efficiency is reduced because of two stages of conversion. In the case of the parallel active hybridization scheme, efficacy is the highest among all types of hybridization schemes. Moreover, this type of topology combines the possibility of a mismatch of the voltage of the source and/or battery (or capacitor) and at the same time, the DC-DC converter provides an almost stable shape of the current. The disadvantage of the active topology schemes is their price which is caused by two DC-DC converters used in one scheme. Also, the disadvantages are the complicity of the schemes and difficulties in calculations that are caused by them.

For hybridization purposes, different energy storage technologies can be used. The choice of energy storage technology is guided by its features and cost. Firstly, SCs are known for their high-power density advantages, higher than 10 kW/kg. Also, SCs have long-life energy storage (up to 20 years, around 1.000.000 cycles), high reliability and efficiency (>98 %), very low equivalent series resistance (ESR), wide operation temperature range (from -40 °C to 85 °C), low operating costs, maintenance-free, and environmentally friendly materials [41], [42]. On the other side, their energy-storing is limited to the range of 5-10 Wh/kg [41], [43]. Their advantages and disadvantages are reported in Table A 1, including also for LIB and LIC. In comparison, LIBs have a higher energy density (150-200 Wh/kg) but suffer from low power density [44], [45]. Besides, LIBs feature lower energy efficiency and lifetime than SCs and a slower response to dynamic solicitations. In addition, they request the use of a battery management system (BMS) to monitor their states according to voltage, current, and temperature.

In a closer look at the LIC technology, Jagadale et al. [32] have shown that LIC can be called the result of integrating technologies of LIB and SC. Especially anode was borrowed from LIB and the cathode was borrowed from EDLC (SC). The same review paper also analyzed materials that were used in different types of LIC. There was shown that a breakthrough in the characteristics of LIC was made when a new highly effective material was used: heteroatom-doped carbon which was used as the cathode for LIC. Generally, for LIC prominent cathode materials were used Graphene, porous carbon, and bifunctional cathodes. It also was highlighted that the fabrication of LIC allows for increasing the energy density while keeping the same advantages in terms of power density. Thus, benefits in terms of energy density and power density can be obtained. The principle of realization with LIC is shown in Fig. 8, which is based on materials presented in [32], [33].

One can see that LIBs are great in energy characteristics such as density, voltage, and self-discharge. But in the case of characteristics and technology, those

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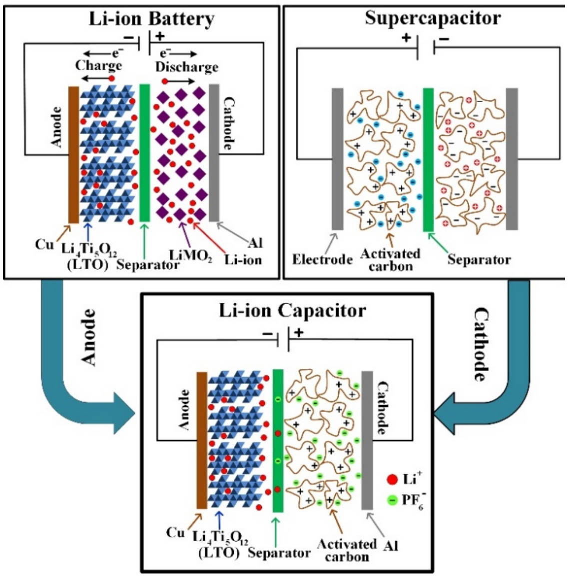

Fig. 8 The fabrication of LIC is based on LIB and SC inspired by [32]

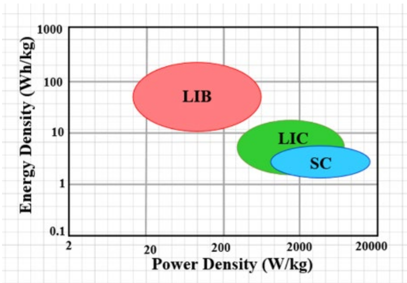

Fig. 9 Ragone plot

advantages were gained by sacrificing physical characteristics: LIBs are big, slow, not efficient, and also have low power density.

On the other hand, one can see that SCs have high rates of such characteristics as efficiency, dynamics, power density, capacitance value, and lifetime. Moreover, SCs are smaller than LIBs. Also, SCs do not require voltage monitoring. The main disadvantage of SCs is low cell voltage, which is the lowest compared to LIBs and LICs.

At the same time, by looking at Table 1, one can see that LICs have better characteristics than LIBs and are very similar to SCs but has fewer drawbacks. The one disadvantage compared to LIBs is lower energy density. Compared to SCs, LICs require voltage monitoring.

Table 1 shows the comparison of features and technologies in LIB, SC, and LIC presented on the market these days. By analyzing this table, can be seen that the highest cell voltage range is presented by LIB and the lowest – by SC. At the same time, can be seen that power density is the highest at SC and the lowest at LIB. Also, one can see that the lifetime of LIB is much lower than the lifetime of LIC and SC. As has been mentioned before, only the SC does not require voltage monitoring. SC has the shortest charging time, while LIB needs the longest charging time in comparison.

Characteristics of the LIB, LIC, and SC presented on the market were analyzed. The results of comparing those characteristics are shown in Fig. 9 as the Ragone plot. As this figure presents can be seen that LIBs have the biggest energy density, but at the same time, the power density is the lowest. LICs, on the other hand, have higher power density, compared to LIB, but the energy density is smaller. Also, one can see that the higher power density is presented by SCs. At the same time, SCs have the narrowest range of energy density compared to LIBs and LICs. In conclusion, can be seen that SCs are the best option if the key characteristic is the power density. Otherwise, if the most important characteristic is energy density, the LIB is the best option presented nowadays. At the same time, LIC is a compromise solution that combines both characteristics in the mid-range.

The information before shows that LIC is the best option if one is looking for an option with a small size and good capacitance. Also, one can see that the passive topology is the cheapest option but still with good characteristics.

Also, by analyzing the energy storage technologies presented in the market, a cost comparison has been carried out. The comparison allows specifying the advantages and disadvantages in the price range when comparing the LIB, LIC, and SC.

For comparing prices to minimize inaccuracy, it has been decided to compare prices within one store. As li-ion capacitors are mostly presented with a voltage of 3.8 V, Li-ion batteries and supercapacitors were reviewed in the same voltage range.

Table 1 Comparison of LIB, SC, and LIC by features

Features\Technologies	LIB	SC	LIC
Cell voltage range	2,5-4,3	1,35-3	2,2-3,8
Power density range (W/kg)	18-316	1280-18835	604-10000
Energy density range (Wh/kg)	10-225	2-7	2,2-18
Self-discharge	6-10%/month	1-2,5%/month[32], [46]	3-8%/ month (after 6 months at 25 C)
Lifetime	1000 - 1200 cycles	>1M cycles	>1M cycles
ESR (Ohm)	≤0,25	0,0008-0,2	0,002-0,7
Operating temperature, C	60 to -20	65 to -40	85 to -35
Voltage monitoring required	Yes (BMS)	No	Yes (CMS)

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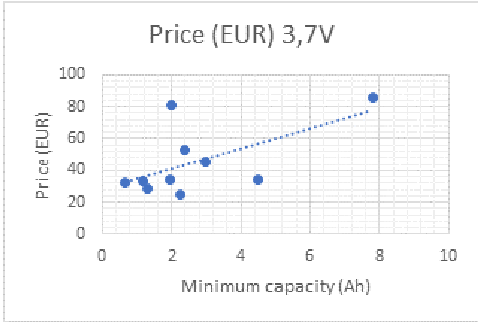

Fig. 10 LIB dependence of the price from the available minimum capacitance for voltage 3.7 V

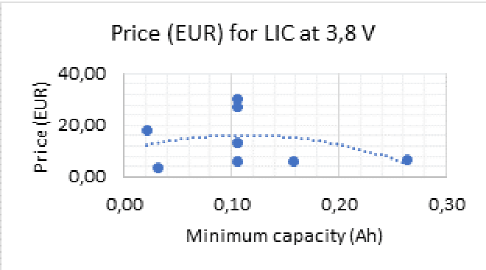

Fig. 11 LIC dependence of the price from the available minimum capaci-tance for voltage 3.8 V

Features\Technologies	LIB	SC	LIC
Charging time	In terms of hours or tens of minutes	In terms of seconds	In terms of tens of seconds or tens of minutes

In Fig. 10 is shown the dependence for LIB for voltage 3.7 V as the closest voltage for 3.8 V presented in the market. This graph shows the rise of the price while raising the minimum capacitance of the Li-ion batteries. One can see that the presented minimum capacitance for LIBs changes from 0.66 Ah to 2 Ah while prices change from 24.95 EUR to 86.21 EUR. The rising of the price, in general, is presented by the line of the trend and shows

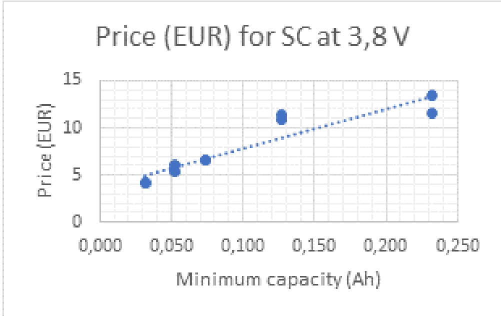

Fig. 12 SC dependence of the price from the available minimum capaci-tance for voltage 3.8 V

that price rises while minimum capacity rises. Also, Fig. 10 was shown that mostly minimum capacitance is presented in a row from 0.66 Ah to 3 Ah and the price varies in a row from 2.25 EUR to 80.89 EUR [47].

Fig. 11 presents the prices of Li-ion capacitors depending on the minimum available capacitances. The dependence is nonlinear. It can be seen that price changes nonlinearly: the unit with the lowest capacitance has a price of 18.18 EUR. Then, one can see that units with the same capacitance are presented with different prices from 5.88 to 13.37 EUR, while LICs with the highest capacitances are presented with the prices in a row from 6.02 to 6.58 EUR [48].

Fig. 12 shows the prices for supercapacitors at a voltage of 3.8 V. For supercapacitors the dependence of the price on the minimum capacitance is almost linear. Capacitances are presented in a row from 0.032 Ah to 0.232 Ah with prices from 4.22 to 13.49 EUR [49].

For comparing the price dependencies of LIB, LIC, and SC a compilation of the graphs has been made, which in Fig. 13 and Fig. 14 is presented. Fig. 13 shows the dependence of the prices on the minimum capacitance for the voltage of 3.8 V. One can see that the row of the capacitance for 3.8 V for the LIB is the biggest but at the same time prices are the highest. Also, it is shown

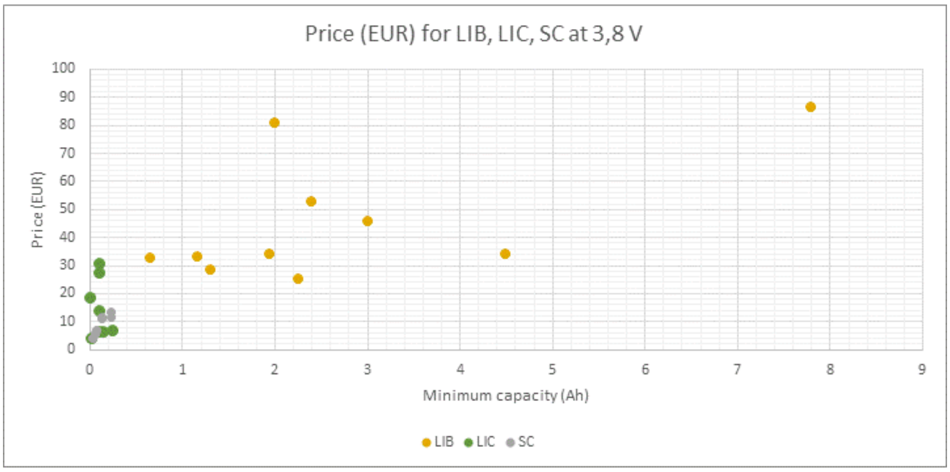

Fig. 13 LIB, LIC, SC normal dependence of the price from the available minimum capacitance for voltage 3.8 V

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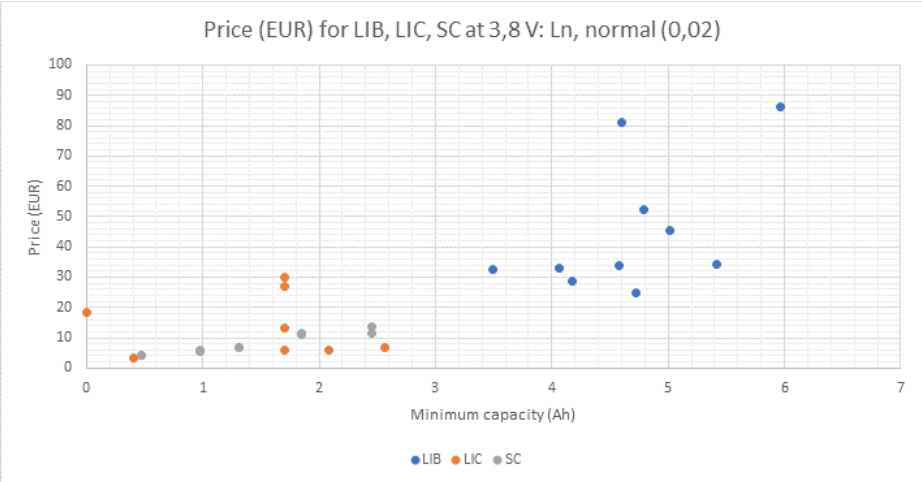

Fig. 14 LIB, LIC, SC dependence of the price from the available minimum capacitance for voltage 3.8 V with Ln capacitance, normalized by 0.02 Ah

that the capacitance provided by SC and LIC has the smallest width, but the prices rise slowly. Comparing the LIC and SC, one can see that their prices rise almost the same.

Fig. 14 shows the graph made for visibility: capacitance was normalized (to the smallest capacitance of 0.02 Ah) and transferred to ln. But at the same time, it becomes clear that prices and provided capacitance for LIC and SC are almost the same, while prices of LIBs are quite higher but at the same time, the provided capacitances are higher. As a result, it can be seen, that it can be possible to use smaller LICs or SCs to combine and get the same capacitance value as LIB but at a lower price. Or, otherwise, LIBs can be used as a simple alternative but at a higher price. Taking into account other characteristics of batteries and capacitors discussed above, the price is also taken into account when choosing a technology.

By looking at Table A 1 one can note that passive topology gives the ability to make schemes light, cheap, effective, and fast [20] as in [37] have shown that passive topology is the most effective type of scheme compared to ones, that use DC-DC converters. The disadvantage of using LIC is the need for the current controlling added scheme. But in comparison with other types of energy-storing technologies, it is still the best option. The combination of LIC and passive topology prevents the degradation of the FC without a big battery pack. Because of the necessity to control the current LIC, the resulting scheme will be semi-active.

IV. Discussions and Future Challenges

By reviewing the literature, this paper has shown that there are different topologies of hybridization FCs with different problems for each of them and many issues with storing energy. Those schemes and technologies of storing energy have restricted the way of choosing the convenient technology for each application area. In future works can be shown the analysis of certain topologies with certain types of energy storage.

As has been mentioned before, in the case of the passive connection scheme for the hybridization of the FC, the internal resistance defines the load current. As can be seen in Table 1, LIBs have high internal resistance. This means that LIBs will have the lowest load current in passive topology. In a passive connection scheme, the LIC will have a higher load current, while the SC will have the highest load current in case of the lowest internal resistance. At the same time, the LICs have the highest power density range. That means having the same ability to store the energy will be needed in many ways bigger battery or even SC, than LIC.

At the same time, it is necessary to consider the analysis of the cost of energy storage devices on the market. Depending on the task, a different approach to the choice of energy storage devices can be chosen. As noted above, LIB provides more capacity at a high price, while SC and LIC are in the lower-cost sector but provide significantly less capacity. In the future, the feasibility of using a complex of SC and/or LIC in comparison with single LIBs may be investigated.

From the perspective of improving FC characteristics by hybridization with various energy storage technologies, LIC seems to be the promising alternative to replace a SC for FC vehicle application. In future studies, it is possible to develop hybridization schemes specifically for LICs. Now, the specificity of the hybridization of LIC is poorly studied in the literature, since the main studies were focused on LIB and SC. While LIC has characteristics average between LIB and the electrical double-layer capacitor, which can be used in the development of hybridization schemes.

In this paper, three main energy storage technologies and hybridization schemes for FCs were compared. By analyzing papers was discovered, that the easiest and cheapest scheme is the passive connection scheme. That

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scheme is perfect for use in cases when no voltage control is required. In a comparison of energy storing technologies was shown that LIB has the biggest energy density and the biggest size, while LIC has the smallest size but the highest power density. At the same time, LIB only does not require any control strategy. This means that even in the case of using the passive connection scheme voltage monitoring will be required in any case but using LIBs. On the other hand, LIBs have the lowest power density and the biggest sizes in comparison with the same power density of SCs and LICs. By all these aspects was shown that passive topology with LIC is the best option in the case of the cheapest topology and the smallest sizes with enough energy density for saving FCs from degradation.

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Appendix A

TABLE A 1 COMPARISON OF PASSIVE TOPOLOGIES THAT HAVE BEEN TESTED IN DIFFERENT PAPERS

Author	Topology	Control strategy	Simulation/hardware	Application	Advantages
Yong-Song Chen, Sheng-Miao Lin and Boe-Shong Hong	Passive Fuel Cell/Battery Hybrid	The fuel cell could provide the maximum power to the load before any power was drawn from the battery. [36]	Experimental	transportation applications	The battery can compensate for the shortage of supplied power for the load demand during the start-up and acceleration. [36]
Clement Depature, Alvaro Macias, Andres Jacome, Loïc Boulon, Javier Solano, Joao P. Trovao	Fuel cell/supercapacitor passive configuration	Energy management is not required. The power distribution only depends on the FC and SC impedance characteristics [39]	Modeling and Real-time validation	for vehicular applications	1) Reducing the FC degradation rate because the current slope, OCV, and stop-start operation are limited, 2) Improving system efficiency because the SCs operate at a voltage discharge ratio higher than 50%. [39]
Alvaro Macias, Nagham El Ghossein, Joao Trovao, Ali Sari, Pascal Venet, Loïc Boulon	Passive fuel cell/lithium-ion capacitor	Any power electronic device is not needed. Due to the different impedance of the components, the system is self-management, in which FC supplies the average power component and LIC operates as a low-pass filter [31]	Modeling, based on experimental tests	for vehicular applications	Is lighter, compact, more efficient, and simpler to implement. passive topology can supply the requested power along different FC stages of life and reported just an increment of 12% of hydrogen consumption at the oldest condition compared to the new condition. [31]
P. Di Trolio, P. Di Giorgio, M. Genovese, E. Frasci, M. Minutillo	a hybrid fuel cell/battery power unit (passive and active)	Each FC stack is controlled by a 12 V control unit that controls the hydrogen supply valves, the electrical connection of the stack, and the cooling fans. The connection in the series of the fuel cell stacks is challenging since the ground of each control unit is in common with the fuel cell one. [20]	Modeling and Experimental testing	for light-weight vehicles	The proposed power-unit configuration does not need costly power converters and has higher overall performances concerning active DC-DC controlled configurations. the power-unit configuration can limit very well the fuel cell stack dynamic operation also when strong load power variations occur. The high capacity of the battery pack works as a lowpass filter and avoids fuel cell performance degradation. These results show how the fuel cell efficiency in the passive power unit configuration is higher than the one of corresponding configurations that include a DC-DC converter (estimated to be 43.5%). [20]
Qian Xun, Stefan Lundberg, Yujing Liu	The fuel cell/supercapacitor passive configuration without using any DC-DC converters	The FC controller is used to control the supply valve, purge valve, and air fans as well as to detect the voltage, current, and temperature of the FC stack. [37]	Modeling and Experimental testing	for a light vehicle	The FC/SC passive configuration allows the FC to have a long stabilization time and to avoid the OCV operation, which can reduce the FC degradation and improve the FC lifetime. Results show that the lowpass filter effect makes it possible to downsize the FC stack, which only needs a peak power of one-third of the load peak power. The SC evens out the current and power from the FC to prevent the FC from experiencing large currents and power variations. [37]

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Author	Topology	Control strategy	Simulation/hardware	Application	Advantages
Billy Wua, Michael A. Parkes, Vladimir Yufit, Luca De Benedetti, Sven Veismann, Christian Wirsching, Felix Vesper, Ricardo F. Martinez-Botas, Andrew J. Marquis, Gregory J. Offer, Nigel P. Brandon	9.5 kWe proton exchange membrane fuel cell supercapacitor passive hybrid system	For an FC, the voltage is a function of temperature, hydration, and a range of other external conditions. The optimum operating temperature of a conventional PEMFC is generally regarded as being in the range of 60-80 C. [35]	Experimental	as a possible replacement for the Internal Combustion Engine (ICE)	Passive coupling of an FC with a supercapacitor pack allowed for the reduction of dynamic loading experienced by the FC. EIS measurements of a 1500 F Maxwell supercapacitor indicated a proportional relationship between the DL capacitance and cell voltage with 3 pseudo-linear regions. Operation at potentials lower than 1.3 V resulted in the greatest decrease in DL capacitance and therefore offered reduced buffering. Efficiency gains achieved through passive hybridization under step loads have been demonstrated to be approximately 5% concerning fuel utilization. The FC load showed an 18.4% decrease in peak loads with an average of 2% lower. [35]
A. Macias, M. Kandidayeni, L. Boulon, J.P. Trovao	three optimal hybrid energy system configurations, namely full-active, semi-active and passive	Active topology is a common choice in the literature as it has the flexibility to actively control the power split between the FC stack and the ESS and enhance the lifetime of the system. In the semi-active category, the FC is normally connected to the DC bus via a DC-DC converter while the ESS is directly connected there. This configuration is extensively used because the passive component absorbs the surplus energy in the bus, which facilitates the power split control over the FC. [38]	Modeling, based on experimental tests	a three-wheel electric vehicle composed of a fuel cell (FC) and a supercapacitor	The obtained results show that passive topology can reduce the trip cost by 14.8% and 6.4% compared to full-active and semi-active ones, respectively. However, the active architecture results in less degradation in the FC compared to the other two topologies. [38]

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Топології гібридизації паливних елементів із використанням різних технологій зберігання енергії

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Анотація—Ця оглядова стаття зосереджена на класифікації та аналізі топологій гібридизації паливних елементів (FC) з використанням різних технологій зберігання енергії, включаючи літій-іонні батареї (LIB), суперконденсатори (SC) і літій-іонні конденсатори (LIC). Мета полягає в тому, щоб зрозуміти переваги та недоліки кожної технології та запропонувати перспективи розвитку гібридних технологій FC з використанням LIC.

Пасивна схема з'єднання є найдешевшим варіантом серед схем гібридизації, з найпростішою реалізацією. Він не потребує керування енергією та дозволяє підключати різні компоненти імпедансу. Однак йому бракує контролю над такими параметрами, як струм і напруга, які обмежені лише внутрішнім опором.

Напівактивна та активна топології пропонують більше контролю над розподілом потужності та узгодженням напруги. Напівактивна топологія дозволяє контролювати потік струму від конденсатора або батареї, тоді як активна топологія забезпечує найвищу ефективність серед схем гібридизації. Однак ці схеми є більш складними та дорогими через використання DC-DC перетворювачів.

LIB мають найвищу щільність енергії, але страждають від низької щільності потужності. СК мають високу щільність потужності, але обмежену здатність зберігати енергію. LIC пропонують компромісне рішення з меншим розміром, вищою щільністю потужності, ніж LIB, і кращими характеристиками, ніж SC. LIC потребують моніторингу напруги, а SC — ні. Вибір технології залежить від конкретних вимог застосування.

Порівнюючи ціни на LIB, LIC і SC, можна побачити, що LIB мають найвищі ціни, але також найвищу щільність енергії. LIC і SC мають нижчі ціни, але забезпечують меншу потужність. Можна використовувати менші LIC або SC, щоб досягти того самого значення ємності, що й LIB, за меншу вартість. При виборі технології зберігання енергії слід враховувати фактор вартості.

Висновок: Пасивна схема підключення з LIC є найкращим варіантом для випадків, де контроль напруги не потрібен. LIC пропонують компроміс між щільністю енергії та щільністю потужності. LIBs підходять для застосувань, де щільність енергії є найважливішою характеристикою, тоді як SCs перевершують щільність потужності. Вибір технології залежить від конкретних вимог застосування. Необхідні подальші дослідження, щоб вивчити гібридизацію LIC і розробити конкретні схеми гібридизації для LIC.

Ключові слова — Паливний елемент PEM; літій-іонний конденсатор; джерело гібридизації.