Storage systems for transportation, land handling and naval applications

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***Abstract*— A confluence of industry, social, environmental and economical drivers is creating new interest in electric energy storage systems. The limitation in the energy resources availability, the continuing increasing of the fossil fuels cost and the more attention to the earth ecosystem, is making storage systems a suitable solution in many applications ranging from grid application toward the industrial and transportation ones. In this paper a review of actual electrical storage technologies suitable for transportation and naval applications is provided with particular attention to the functionalities that is possible to introduce according to the selected technology. Moreover, the applications of storage systems in land and naval handling will be analyzed in details underlining the advantages deriving by the introduction of opportunely chosen storage units.**

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I. Introduction

The recent evolution in the field of energy storage technologies makes new interesting possibilities arise for what concern the use of energy storage devices in road vehicles, in shipboard electrical applications and, in general, for urban mobility and good movements, i.e. cranes, forklifts and so on.

In this paper, at first it is given the scenario of the storage technologies available on the market highlighting the characteristics, the performances and the possible advancements foreseeable for the next years. Then, the different applications will be discussed emphasizing the contribute that energy storage systems can give to sustainable mobility, land handling and naval applications.

Moreover, some considerations are given about the impact due to a wide diffusion of electrical vehicles on distribution networks pointing out the new scenarios available with the transformation of the traditional networks in smart grids.

II. Storage Technologies Option

The continue research in the field of electrochemistry, in particular, but also in mechanics and new innovative materials has allowed the introduction on the market of many different storage technologies solutions. Due to their specific performances, each of them is not able to fulfill all the possible applications. A criterion to compare the different technologies is represented by the Ragone plot, Figure 1; each technology is characterized by a specific area representing the typical technical constrains in terms of specific energy versus the specific power. In this way it is possible to select the best storages according to the typical condition of use requested by the application. In addition by appropriately coupling different storage devices it is possible to realize a hybrid storage system with enhanced performances in terms of efficiency and specific energy and power [1, 2].

In the following the main storage technologies are analyzed and some highlights, as performances and future technology evolution, are discussed.

A. Electrochemical batteries

Today's secondary (rechargeable) electrochemical batteries are the most investigated storage devices. The peculiarity of these devices is they can reversibly convert electric energy in chemical energy without additional machines. Since the first battery was realized in 1799 by Alessandro Volta, many other technologies have been developed and many others are in a research phase.

The focused attention in these devices is related to the wide portfolio of applications in which they can be used, from grid stationary applications to electric vehicles market passing from quite all the industrial applications. The requirements according to the application are very different, but there are so huge industrial drivers and interests that, in the last decades, a lot of public and private funding are converging in research and develop of new electrochemical batteries.

The main motivation of this research is that, with the exception of lead acid batteries, there is not a well established

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technology able to fulfill all technical, environmental and safety requirements, even the prominent performances of each technology. As indicated in [3] there are many fundamental gaps in understanding the atomic- and molecular level processes that govern the battery operation, performance limitations, and failure. Fundamental research is critically needed to uncover the underlying principles that govern these complex and interrelated processes.

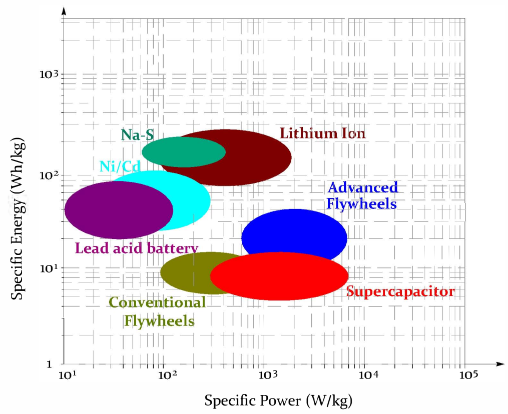

Figure 1. Ragone plot of different storage technologies.

The main battery technologies for industrial use are:

- $Pb-H_2SO_4$: Lead acid battery;
- Ni-Cd: Nickel-Cadmium battery;
- Ni-MH Nickel-Metal hydride battery;
- Na-S Sodium-Sulfur batteries;
- $Na-NiCl_2$ Z.E.B.R.A. battery;
- Li-ion Lithium ion battery;
- VRB: Vanadium redox battery;
- Zn-Br Zinc-Bromine battery;

1) Lead acid battery ($Pb-H_2SO_4$)

It is the most mature, well known electrical storage technology used in all industrial applications ranging from UPS, automotive, telecom up to naval and submarine. Many models [4 – 6] and experimental activities [7 - 10] have been conducted over the years in order to investigate and improve this technology. The main disadvantage is related to a lower energy density and cycle life compared to the newer technologies.

Significant, not for the rated power but for the system life, is the 1 MW/1.5MWh lead acid storage system located in a remote island in Alaska by GNB Industrial Power and Exide. The storage system, that has been operative for 12 years showing a limited visible performances degradation, has been finally replaced in 2008.

Due to a very low cost solution this kind of technology is on board of all internal combustion engine vehicles in order to guarantee the engine switch on and to realize the stabilization function of the automotive electric plant. The limited energy density doesn't allow to consider this technology for hybrid or pure electric vehicles.

In order to improve lead acid battery technical performances, maintaining their low system cost, researcher added carbon-enhanced electrodes to create advanced lead acid batteries. This, combined with the introduction of wounded cells, represent the actual trend evolution for this well known technology. The theoretical specific energy of lead-carbon batteries is 166 Wh/kg, but actually only the 70-80% of this value is reached [13]. Especially for the automotive market in U.S. DOE is supporting Exide Technologies with Axion Power International and East Penn Manufacturing Co. for the production of advanced lead-acid batteries; the idea is to couple the traditional lead acid technology with a carbon supercapacitor combination in order to fulfill the micro and mild hybrid applications [14, 15].

Regarding the system integration the East Penn Manufacturing Co., USA, receive another funding (2.5 million$ on a total cost project of 5 million$), [14] to demonstrate the economic and technical availability of a 3 MW grid-scale, advanced energy storage system using advanced lead-acid battery.

2) Nickel-Cadmium battery (Ni-Cd)

Nickel Cadmium batteries ranging, both the oldest type and the vented pocket-plate, are very reliable, sturdy, and long-life batteries, which can be operated effectively at relatively high discharge rates and over a wide temperature range. It is typically produced in the range of 5–1200 Ah and it is used in many industrial, military, telecommunications, UPS applications, and emergency lighting [15]. It has very good charge retention properties, and it can be stored for long periods of time in any condition without deterioration.

An important key aspect of this type of battery lies in the low cost, if compared with other innovative technologies and in any case greater than traditional lead acid storage. Limitations in using this kind of battery are related to the presence of Cadmium and a limited specific energy density if compared with the innovative ones.

Due to its particular reliability and rugged performances in terms of electrical and mechanical abuse tests, this kind of battery has been suitable for the automotive market. Deutsche Automobilgesellschaft mbH (DAUG) developed a new electrode structure, the fiber-structured electrode for Electric Vehicles applications. This technology is nowadays applied in all types of nickel-cadmium as well as nickel-metal hydride batteries.

A further innovation regards the plastic-bonded or pressed-plate electrode, where the active material, cadmium oxide, is mixed with PolyTetraFluoroEthylene (PTFE) and a solvent to produce an isotropic paste. In this way the production cycle is well standardized and issues related to dust during manufacturing are eliminated.

Fiber plate and plastic-bonded Nickel-Cadmium batteries find many applications in traction, power station and substations, aircraft and the other applications.

Typical specific energy values range are 25 Wh/kg for pocket plate batteries, 40 Wh/kg for larger fiber plate batteries up to 80 Wh/kg for plastic-bonded plates batteries.

No technology evolution is expected for this technology due to the presence of Cadmium, a toxic element for the environment and living beings.

3) Nickel-Metal hydride battery (Ni-MH)

In order to eliminate the presence of Cadmium in the active negative material and the memory effect, an evolution of traditional Nickel Cadmium battery is Nickel Metal hydride battery where the Cadmium is replaced with hydrogen absorbed in a metal alloy.

As shown in [15] industrial available Nickel Metal hydride batteries fit many of the technical requirements required by United States Advanced Battery Consortium (USABC) performance goals for the EV batteries. It can be noticed how commercial Ni-MH batteries are characterized by a specific energy of 70 Wh/kg, specific power of 220 W/kg and an environmental operating temperature between -30 to 65°C making them very suitable for the automotive market.

The continuing improvement on this kind of technology and excellent performances in terms of safe operations at high voltage, safety in charge and discharge (including tolerance to abusive overcharge and overdischarge), maintenance free, excellent thermal properties, capability to utilize regenerative braking energy, simple and inexpensive charging and electronic control circuits and environmentally acceptable and recyclable materials are the main driver of this kind of technology. Active interest in research and development of Ni-MH batteries is showed by US Department of energy [14, 15] that is actually funding Johnson Controls, Inc, with an award of $299.2 for the production of nickel-cobalt-metal battery cells and packs, as well as production of battery separators (by partner Entek) for hybrid and electric vehicles.

4) Sodium-Sulfur batteries (Na-S)

A Sodium-Sulfur battery belongs to the family of Sodium batteries. In the mid of 1990 this kind of battery was the most candidate for stationary electric energy storage applications due to a potential low cost system, high cycle life, high specific energy (120 – 220 Wh/kg) and good specific power (up to 170 W/kg) as high energy efficiency (up to 90%). In addition the use of inexpensive and abundant materials avoid problems related to the availability. Due to the presence of a solid electrolyte at ambient temperature, Sodium batteries have to operate at high temperature rate (300 – 350°C) in order to maintain liquid the electrolyte; this, with the corrosion of the insulators, which is typical in the harsh chemical environment causing a gradually conductive properties and increasing the self-discharge rate, are the main issues related to this technology.

5) Z.E.B.R.A. battery (Na-NiCl$_2$)

In order to improve the performances of Na-S batteries and, in particular the issues related to the corrosion of the insulating material and the dendritic sodium growth, different makers (ABB, SPL and MES DEA) reached a relatively advanced state in developing electric-vehicle battery technologies based on Sodium battery (Zero Emission Battery Research Activity - ZEBRA battery).

ZEBRA battery operates at 245 °C and they are characterized by a specific energy range of 100-130 Wh/kg and specific power range of 170-240 W/kg [15]. The developer team efforts have been concentrated in realizing an affordable, reliable and safe sodium battery storage system. Particular significant is the comprehensive ABB experience that tested its ZEBRA batteries in a wide variety of car manufacturer's vehicles (BMW E-1 electric car, Chrysler minivan T115, the Daimler Benz 190, two VW vehicles, and a number of Ford Ecostar demonstration vehicles). Despite this, in the mid 1990s ABB and SPL discontinued their programs on this technology. Differently, after a certain period of lower interest, 1st February 2010 MES-DEA and FIAMM founded a new company called FZ Sonick SA for the production of ZEBRA batteries for the electric vehicle market and grid stationary applications. No particular technology changes are expected in this technology and the major efforts are related to the industrialization of this product especially for the automotive market penetration.

6) Lithium ion battery (Li-ion)

It's the today's most investigated electrochemical storage technology in terms of material developing, cell and system assembling.

They are characterized by a typical specific energy of 150Wh/kg, a little more than Sodium batteries, a low self discharge rate (typically 2-8% per month), long cycle life (more than 1000 cycle at 80% DOD) and extended temperature range of operation.

The main drivers making this technology more interesting than others are the high specific energy, high cell rated voltage (up to 4.2V), high rate capability, sealed cell and no maintenance required.

Actually the research is still open in defining the most suitable configuration in terms of anode and cathode material, cell geometry, system monitoring and assembly. According to

[14], Li-ion technology issues related to chemistries and associated materials can be improved and solved by means of adequate cell and system failure identification models, system optimization and system design, unfortunately the continuing presence of new electrode materials does not facilitate this process.

Until now major efforts have been devoted to design suitable Li-ion battery for the electric and hybrid vehicle market and as reported in [13] and [14] consistent public funds have been allocated to many industrial companies (more than 1 billion$ from the U.S. DOE in the last 2 years). The technology research is continuing especially in the developing of new anode and cathode materials in order to ensure more safe and stable lithium batteries. The new frontiers regard the introduction of Lithium Titanium oxide (LTO) for the anode material and Lithium Manganese oxide ($LiMn_2O_4$) for the cathode material in order to obtain more safe, performing, cost effective and extended operative temperature range lithium batteries. The growing interest, as reported in [16], is also for several utility grid-support applications such as Distributed Energy Storage Systems (DESS), transportable systems for grid support, commercial end-user energy management frequency regulation, wind and photovoltaic peak smoothing. Many experts believe stationary market for Li-ion battery could exceed those for transportation.

In the last years another prominent evolution of the lithium batteries is in the lithium-air batteries. In this system, that is an open system using air as reagent, during discharge, oxygen from the air reacts with lithium ions, forming lithium peroxide on a carbon matrix. Upon recharge, the oxygen is given back to the atmosphere and the lithium goes back onto the anode. A big role in this technology is played by IBM with its 'The battery 500 project' [17], in order to develop a battery that can reach a theoretical energy density up to 1000 times grater than traditional lithium ion batteries, making this technology suitable for the electric vehicle market. The actual main technical issue is related to the chemical stability of the electrolyte and, in particular, it has been noticed that oxygen doesn't react only with the carbon electrode but with the electrolyte too, causing a quick life reduction of the system.

B. Supercapacitor

These devices are characterized by a greater energy density, about two orders of magnitude, than traditional electrolytic capacitors. As a traditional capacitor the energy is stored in an electrostatic field, so that no electrochemical reactions take place during the charging and discharging process; for this reason the process is highly reversible and the charge-discharge cycle can be repeated frequently and virtually without limits (typically today is a lifespan up to 1 million cycles).

The today's most common supercapacitors for industrial application are based on carbon for the electrode materials and an organic solution for the electrolyte. In this way typical values of specific energy and specific power are 5 Wh/kg of 4 kW/kg respectively.

An important characteristic of these storage devices is a well established production process, so that in the last 10 years no significant variations on the chemical and material design are detectable. In this way a lot of significant experiences have been conducted on transportation, automotive and industrial applications.

Actual research in supercapacitor technology is all oriented in increasing the energy density of these devices. In particular two research lines are under investigation, the first one is related to the use of the nanotechnology to realize the carbon electrode increasing the usable electrode surface, the second one is investigating the possibility to introduce the lithium to one electrode. In the latter solution the increasing in the energy density pay a reduction in the cycle life.

Anyway, in the last years, a growing interest in using the supercapacitor technology takes place. In this direction it's important to underline the ongoing U.S. DOE funding on supercapacitor applied research granted to EnerG2, Inc. (21 million$) and to the FastCap System Corp., (5.35 million of $) in order to produce a nanotube enhanced ultracapacitor with a higher energy density comparable to standard batteries, but, compared to the latter, with a greater power density and thousands of times of cycle life. The interest is related to the potential cost reduction on hybrid and electric vehicles and on grid-scale storage applications.

C. Fly Wheel

Flywheels are electromechanical devices able to store energy as kinetic by means of a spinner rotor. In order to exchange this energy, a motor/generator machine is coupled with the flywheel; in the most of the application a power converter is added in order to enlarge the working machine operative range. During charging phase electricity is converted into kinetic energy and the rotor speed is increased, while in discharge the opposite process takes place.

The electric machine and rotor are well integrated and the bearings are often a magnetic type in order to optimize the total system efficiency and reduce the device noise.

In designing the device two strategies can be adopted in order to increase the specific energy [18]. The first one consists in increasing the rotor inertia by acting on the rotor diameter, typically steel, with a rotational speed up to 10000 rpm. This kind of device is typically used as UPS and its main limitation is due to its weight and size. The second designing approach uses smaller diameter rotor and increases rotational speed up to 100000 rpm; in this way it is possible to realize more compact and modular flywheels suitable for transportation [19-22] and naval applications [23-24]; in particular in naval applications flywheel seems to be prominent but until now no significant industrial applications have been realized.

Due to the high fast response of these devices, up to 4 milliseconds, a system efficiency up to 0.93 and an estimated lifetime up to 20 years, these systems could be an alternative solutions to supercapacitors storage systems. They can be sized with a rated power between 100kW and more than 1MW up to 1 hour.

Actual research on flywheel is continuing oriented in new rotor material and electromagnetic bearings able to support increasing rotational speed to realize more compact and reliable flywheels.

TABLE I. ENERGY STORAGE COMPARISON CHART

Technology		Lead Acid	Ni-Cd	Ni-MH	Z.E.B.R.A.	Li-ion	Supercap	Flywheel
Specific Energy	[Wh/kg]	30-50	25-80	60-120	100-130	90-190	2-5	10-50
Specific Power	[W/kg]	10-100	60-150	150-250	170-240	200-800	100-4000	500-3000
Cycle life		200-300	1000	300-500	1000-3000	500-2000	1000000	20 years
Fast charge time		8-16 h	1 h	2-4 h	1 h	1-4 h	5 s	10 s
Overcharge tolerance		High	Moderate	Low	Moderate	Low	Low	N.A.
Self discharge/month (room temperature)		5%	20%	30%	10% per day	<10%	50%	15%
Nominal cell voltage	[V]	2	1.2	1.2	2.58	3.3-3.8	2.5-3.0	N.A.
Charge temperature	[°C]	-20 +50	0 +45	0 +45	270-350	0 +45	-40+60	-20 +50
Discharge temperature	[°C]	-20 +50	-20 +65	-20 +65	270-350	-20 +60	-40+60	-20 +50
Maintenance required		3-6 months	30-60 days (discharge)	60-90 days (discharge)	6 days (discharge)	Not required	Not required	Not required
Safety requirements		Thermally stable	Thermally stable	Thermally stable	Monitoring	Monitoring and management	Thermally stable	Stable
In use since		Late 1800s	1950	1990	1970	1990	1999	1950
Toxicity		High	High	Low	Low	Low	Very Low	Low

III. ELECTRIC STORAGE APPLICATIONS

The obtainable advantages arising from the integration of electrical storage systems in transportation, industrial an naval handling are related to the possible reduction of the energy consumption maintaining the same performances of the application. According to the application the storage integration can be realized in order to obtain:

- Pure electric system
- Hybrid electric system.

In the first case the storage system has to fulfill all the power and energy system requirements, while in the second case the storage system has to realize a specific power/energy mission in order to support the main source in supplying the load. In this way it is possible to ensure a power mission by the energy storage system while the energy mission is ensured by the traditional primary energy source that is typically an internal combustion engine (ICE) or the primary electric grid. The correct integration of the energy and power sources let to optimize the overall system in terms of energy consumption, efficiency and emissions.

In this general approach, according to the specific application, different usage of the storage can be realized.

A. Automotive application

The main categories of electric vehicle can be summarized as:

- Pure electric vehicle
- Hybrid electric vehicle
- Plug-in hybrid electric vehicle

The distinction among the two categories is related to the amount of storable electrical energy in the vehicle. In pure electric vehicle, storage is the unique reserve of energy able to fulfill all the vehicle functionalities; in hybrid vehicles, according to the level of hybridization (Micro, Mild, Strong, Plug-in Hybrid) the electric storage system, that can fulfill an electric mission in the range of 0-70 km, is coupled to a traditional fuel storage with its Internal Combustion Engine (ICE). In particular in actual automotive applications there are two concepts of hybridization: the first one sees the presence of the power storage system in order to only fulfill all the power transient demands under ten seconds, while in the second concept the presence of the storage system is considered more an alternative energy reservoir to fulfill the vehicle mission. It is clear that in the first solution the presence of the traditional energy source is mandatory to realize the vehicle mission, but in this way a greater system optimization it is obtainable due to the fact the power and energy mission can be satisfied by two distinct system properly sized and operated.

In Table 2 a summary of technical specifications of the Electrical ESS for different kind of electrical vehicles is reported [25]. In hybrid and plug-in application the presence of the electrical storage aims to optimize the primary energy source according to the scheme of Figure 2, in fact the presence of a dynamic energy storage let to achieve two goals:

- a recovery energy function during the braking phases
- a peak shaving function of the power/energy supplied by the primary energy source.

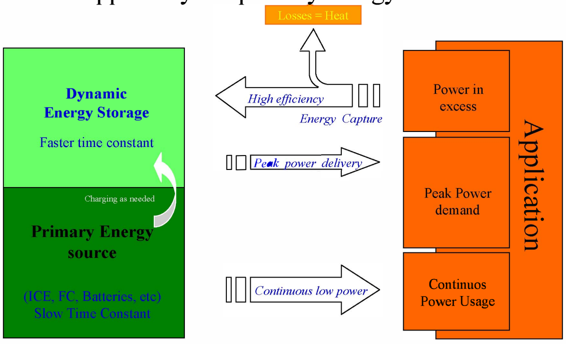

Figure 2. System layout in presence of the electrical storage system coupled to the primary energy source.

In this way it is possible sizing the primary energy source on the average power requested by the application and designing the system control in order to ensure the functioning of the primary energy source close to the maximum efficient point at constant power, while all the other power fluctuations are guaranteed by the presence of a faster dynamic energy storage. According to the behaviors of the available technologies, see Figure 1, it's clear that the more appropriate candidates electrical energy storage systems in this kind of applications are supercapacitors and flywheels only for the hybrid applications and the electrochemical batteries for pure electric and plug in vehicle. However, at present, flywheels are not available in standard size, so they should be designed ad hoc for the application while supercapacitors can be bought more simply on the market.

Another important application of the electric energy storage system in automotive regards the more and more diffused start&stop application. In this case the requirements in terms of high numbers of start&stop cycles (at least 250k) and high peak power demands configure supercapacitors as the best technical compromise in terms of weight, volume and cost.

TABLE 2. ELECTRICAL ESS REQUIREMENTS FOR PURE ELECTRIC, HYBRID AND PLUG-IN VEHICLES [25]

	Pure Electric		Hybrid		Plug-in	
Parameter	**Minimum Goals**	**Long Term Goal**	**Minimum Goals**	**Long Term Goal**	**High Power/Energy Ratio Battery**	**High Energy/Power Ratio Battery**
Power - Discharge	60 kW	80 kW	25 kW (10 s)	40 kW (10 s)	45 kW (10 s)	38 kW (10 s)
Power - Regeneration	40 kW	40 kW	20 kW (10 s)	35 kW (10 s)	30 kW (10 s)	25 kW (10 s)
Available energy	20 kWh	40 kWh	0.3 kWh	0.5 kWh	3.4 kWh	11.6 kWh
Calendar Life	10 years	10 years	15 years	15 years	15 years	15 years
Cycle life	1000, 80% DOD	1000, 80% DOD	300k 25Wh cycle	300k 50Wh cycle	-	-
Operating Environment	-40 to +50	-40 to +85	−30 to +50	−30 to +50	-30 to +50	-30 to +50
Production price	< 6000 $ 25k units/year	4000 $ 25k units/year	500 $ 100k units/year	800 $ 100k units/year	1700 $ 100k units/year	3400 $ 100k units/year

The wide diffusion of electrical vehicles will have an important impact on distribution networks and will make necessary a review of designing and managing criteria. In particular, in designing an innovative distribution network it has to be taken into account: i) the total number of electric vehicles (EVs), ii) the daily charging needs and iii) the spatial and temporal distribution of the energy request.

The last two factors are closely related to the size of batteries installed in cars, distance covered by each vehicle, type of contract with the Distribution System Operator (DSO) and type of charge point, for example domestic charging at home or in next-to-come "energy stations".

The current structure of the distribution system, radial or open-loop, in fact, sets constrains on the total number and/or on recharging power of the vehicles depending on their location along the distribution feeder due to existence of temporary bottlenecks (limited hosting capacity). This matter is, at present, object of deep analysis of technicians in order to define efficient strategies for charging the vehicles respecting grid ties.

However, significant changes in distribution networks are happening in these years. Indeed, the distribution networks are becoming active networks for the presence of Distributed Generation (DG) and are more and more "smart" because each device exchanges information with the others in order to ensure the required levels of efficiency and quality of the network itself.

Although the local production of electricity displays interesting positive aspects from an energetic viewpoint as it envisages the use of clean sources and losses reduction, the diffusion of renewable energy sources (RESs) can result in a significant criticality associated with the random nature of their availability, strongly influenced by weather conditions. To overcome this drawback, it is now widely accepted that the use of storage devices may offer interesting opportunities. These storage devices would allow to decouple, at least partially, the production from the usage, thus implying a better exploitation of RESs from both technical and economical viewpoints.

Experimentations are being carried out in this research field, to test the opportunities offered by the introduction of dedicated energy storages devices interfaced with the network with advanced electronic converters; their presence allows not only to regulate active power flows, but also to supply ancillary services such as harmonic filtering and voltage regulation.

The presence of a large distributed storage capacity of the EVs on the one hand can be, as above said, a source of problems for the network, but, on the other hand may offer opportunities. In fact energy storage aboard may partially cooperate with dedicated energy storage devices installed by distribution companies, when imbalances between the generated and the total power occur, thus resulting in a reduction of the total amount of load shedding and in quality of supply improvement. The distributed storage devices, even if small-sized may be able to play an important role on the distribution network supplying other ancillary services. Between them, it can be mentioned the voltage regulation. As is well known, the presence of DG can cause problems to the traditional voltage regulation. So, it is often required the reactive power supplying service to DG units. However, the injection of reactive power is not an efficient voltage regulation technique in distribution networks due to the low ratio between line inductance and resistance. So, the presence of the storage units on board the EVs, in proximity of the loads, can represent an optimal solution for voltage regulation.

It is worth noting that a storage system can supply reactive power to the network both during charge and discharge phases. This service can be activated in few seconds and can last all the time necessary to stabilize the network (eventually reducing the loads). However, the cost of this service, consisting in a reduced increasing of sizing of the power devices, can be paid by the DSO.

The research topic should be approached with a systemic point of view envisaging a smart management of the multiple players that must interact with each other and, likely, it will be more profitable for clusters of vehicles than for singles EVs.

Finally, it is worth noting that a situation that shows some similarities with the above–described scenario may occur also in harbor areas. In fact, storage capacity aboard yachts is likely to increase in order to allow "electric" navigation, characterized by low levels of polluting emissions.

These types of loads can then play an interesting role in providing services similar to the above described ones by EVs.

B. Railway application

This represents another important field of application of energy storage systems, both for electric grid supplied railway system and ICE equipped railway vehicles.
In this case the general framework in which the storage can optimize the overall system efficiency is the same reported in Figure 2. Also in this case the possibility to recover the regenerated braking energy of the railway vehicle in order to reuse this energy amount in the following accelerating phase, represents the system integration goal. In case of railway application the storage system can be installed on board vehicle or stationary; in the first case the additional storage weight on board vehicle let to store a certain amount of energy to be used in case of necessity as the absence of the catenary, in addition the energy can be recovered with a greater efficiency due to a shorter path followed by the energy during the recovering phases toward the storage and vice versa toward the electric drive. Dually in case of stationary storage where the main advantage is related to the possibility of sizing a unique centralized storage system to supply different trains. Significant are the experiences in Dresden –since September 2002- and Cologne –since July 2003- cities (Germany) and Madrid city –since July 2003- (Spain) where are installed different stationary energy storage systems to realize the energy recovery and peak shaving function of the power supplied by the electric grid, Figure 3.

Figure 3. Stationary energy storage system based on the supercapacitor technology realized in Dresden city (Germany). Maxwell Technologies Supercapacitor and Siemens power electronics.

In all these applications the storage system commercially named as SISTRAS is produced by Siemens and, in particular, in Table 3 are summarized the main data of the 750V nominal voltage version.

TABLE 3. MAIN DATA OF THE SISTRAS STATIONARY ENERGY STORAGE SYSTEM PRODUCED BY SIEMENS

Voltage	[V]	750
Number of cells		1344
Capacitance	[F]	80
Usable energy	[kWh]	2.5
Max energy saving	[kWh/h]	80
Peak power	[MW]	1
Auxuliary supply		3-phase 416V
Temperature	[°C]	-20 to 40
Dimensions	[m]	1.4 X 0.9 X 0.7
Weight	[ton]	4.3

Also for diesel electric trains the presence of a high dynamic storage system let to hybridize the system power train in order to ensure greater system efficiency, as demonstrated by Bombardier that declared the possibility to save up 30% energy on its Diesel Multiple Unit (DMU) train. In particular the train is a 4 coaches train equipped with 6 boxes of energy storage system based on supercapacitor technology consisting of 384 cells of 3000F@2.7V each with a total available energy of 7kWh.
In all significant trains hybridization the best candidate storage system is based on supercapacitor technology due to the fact that the charge and discharge cycles last about different tens of seconds maximum and in addition a greater number of life cycles is required.

C. *Industrial applications*

Beside the above mentioned application in transportation there are many industrial handling applications where the concept of hybridization or full electric vehicle can be realized with the same improvement and advantages already discussed. The new legislative emission requirements also for industrial handling vehicles are addressing many manufactures in increasing the system efficiency of these vehicles by adopting diesel electric hybrid solutions, or improving the system efficiency and dynamic by coupling traditional energy storage system as lead acid batteries or fuel cells with high dynamic storage solutions as lithium electrochemical batteries or supercapacitors. Some examples of hybridization are the bridge cranes with hybrid diesel-electric power train, and the industrial forklift with a hybrid power train consisting of fuel cells coupled with a supercapacitor storage system.

D. *Naval applications*

In the last years, due to the more and more opportunities offered by DC technology for electric systems, innovative functionalities for the grid management are considered when efficiency, energy sources integration, storage system integration and easy system reconfiguration are key aspects. In this general framework the electric system of naval ships is a suitable candidate for this kind of innovation. In particular the possibility to introduce energy storage systems on the electric ship system can mitigate and solve the voltage fluctuations caused by modern high-power pulse electrical equipment [23, 27]. Due to the fact the network of integrated electric propulsion ship is a finite grid with a limited power reserve, the possibility of introducing an energy storage system, with adequate control strategies, can reinforce and stabilize the power system during all the operative working conditions [28]. Even if there are many publications investigating the opportunities offered by the integration of storage systems, mainly fly wheel storages, in the electric system of ships [23, 24, 27], the unique real experience, in which electrical storage systems are integrated on board of ship equipped with a DC grid solution, is represented by the ABB Onboard DC Grid, Figure 4.

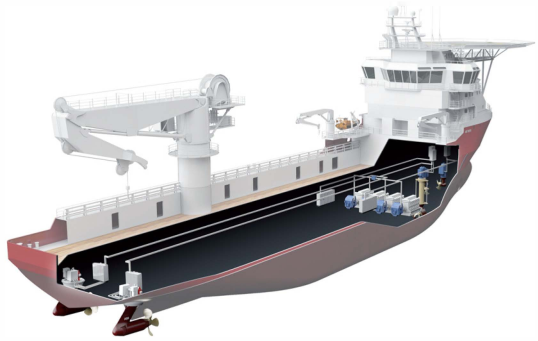

Figure 4, Onboard DC Grid propulsion system manufactured by ABB.

In the Onboard DC Grid solution, energy storages can improve the system's dynamic performances. In particular Diesel engines are characterized by slow dynamic variation when quick load changes. By using batteries or supercapacitors it is possible to provide power for a short time so that the ship's control capabilities can be improved. This will benefit especially vessels with dynamic positioning. Energy storage can also be used to absorb rapid power fluctuations seen by the diesel engines, thereby improving their fuel efficiency.

IV. CONCLUSIONS

The actual potential market for energy storage systems is huge considering the transportation applications. The general above overview underlines how all the technology options need a further enhancement in order to fulfill the related application performance requirements. If the common research driver is a lower power and energy cost, from a technical point of view, different technical improvements for transportation are needed.
In transportation major attention is devoted to Supercapacitor and Electrochemical storage devices, in particular on lithium ion technology. If for Supercapacitor the main limitation is related to the *low* energy density, the main issues related to lithium-ion technology regards the safety of this technology when used in stressed operative condition and the acceptable operative working temperature. In grid applications, characterized by a stronger system vision, the main needs concern not only the

development of new material and technology options in order to increase the system performances, but, in addition, new methodologies for optimal sizing, placements and control strategies to maximize the value of storage is needed [26].

Another common point of storage applications regards the real potential benefits achievable by an integrated use of storage systems. Analyzing single benefits is not typically possible achieving a consistent economical advantage from the use of storage devices, but when multiple benefits are considered highest revenues are obtained [17]. These general consideration underline why the actual research objectives are not only on new innovative storage technologies but also on the development of adequate diagnostic and modeling tools, system analysis, advanced control system and power electronics and, demonstrations and deployments experiences in order to really understand the potentiality of a single storage technology and the real benefits in using it in real applications [12, 17, 26].

Finally, the wide diffusion of storage systems connected to distribution networks (i.e. EVs) makes new regulation problems arise. However, an intelligent use of these storage systems can lead to advantages in terms of stability and quality of the networks. In the vision of future "smart grids", with large diffusion of DG, this point has to be taken in the right account.

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