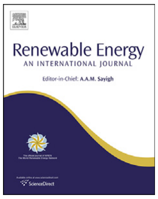
Renewable Energy 76 (2015) 375–380

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene



Review

Potential of lithium-ion batteries in renewable energy

Boucar Diouf [a], Ramchandra Pode [b], *

[a] Kyung Hee University, Department of Information Display, 26 Kyunghee-daero, Dongdaemun-gu, Seoul 130-701, South Korea
[b] Kyung Hee University, Department of Physics, 26 Kyunghee-daero, Dongdaemun-gu, Seoul 130-701, South Korea

ARTICLE INFO

Article history:
Received 6 March 2014
Accepted 18 November 2014
Available online 5 December 2014

Keywords:
Battery
Lithium-ion
Renewable energy
Electric car
Cost
Safety

ABSTRACT

The potential of lithium ion (Li-ion) batteries to be the major energy storage in off-grid renewable energy is presented. Longer lifespan than other technologies along with higher energy and power densities are the most favorable attributes of Li-ion batteries. The Li-ion can be the battery of first choice for energy storage. Nevertheless, Li-ion batteries to be fully adopted in the renewable energy sector need a price reduction that most likely will be due to the mass production. The progress in Li-ion batteries needs to be carried further to match enough energy and power densities for the electric vehicle. We present the electric vehicle sector as the driving force of Li-ion batteries in renewable energies. We believe that the development of the electric vehicle industry could be the driving force for the renewable sector making Li-ion batteries more affordable as a benefit of mass production. In the development of Li-ion technology, the electric automobile will be accompanied by other sectors such as grid storage, consumer electronics, the electric bike, military or other medical applications. We present the incomparable advantages of Li-ion batteries over other technologies even if some challenges are still to overcome for a wider usage in stationary energy storage.

1. Introduction

Photovoltaic energy is continuously proving itself efficient throughout the world. The technology had known tremendous evolution along with a huge price drop making it more and more affordable. The evolution in photovoltaic (PV) energy can be attributed to the development of the individual different parts of a standalone solar system and the expansion of grid-tie systems. Nevertheless the energy storage that largely remains based on lead-acid batteries has not known much change in the last decades. In fact the price of solar panels has considerably dropped even if the technology is still in general made of mono or polycrystalline wafer based silicone solar cells. The thin film solar panels are acquiring more and more importance but are yet to be major players in the market. The lighting technology has considerably changed from incandescent lamps to highly efficient light emitting diode (LED) lamps with a price continuously decreasing as described by Haitz's law [1]. It is the same for charge controllers and inverters in general. The weak point remains the lead-acid battery, mainly because of its shorter lifespan, especially in comparison with the other components of an off-grid system. The battery technology has undergone a lot of evolution but the photovoltaic industry still uses largely lead acid batteries because of initial cost reasons and controlled recycling. Historically, valve regulated lead acid (VRLA) batteries have had a few superior technical traits, in addition to their extremely low cost, that have kept them in the lead of the overall battery market.

In a standalone PV system the lifespan of the solar panel is more than 25 years and at least 50,000 h for the LED (about 15 years) [2]. In order to improve the longevity of such a system, the lifetime of the battery should level up from the bottom to match that of the LED lamps by reaching the 15 years target, about 5000 cycles at 80% depth of discharge.

Lithium-ion (Li-ion) is a fairly new comer in the battery technology [3–7]. Li-ion and VRLA battery markets are expected to grow over the next several years, but Li-ion is certainly to overtake VRLA in some areas as when mass, lifespan or power density is critical. Lithium based batteries with their technical characteristics have the potential to revolutionize the photovoltaic (PV) industry and renewable energies in general, provide they are affordable for common systems. The current photovoltaic market is not profitable enough to boost a new battery technology expensive to develop otherwise. The development of parallel industries as the electric automobile sector [3,8], the electric bike, especially in China [9–13],

---

* Corresponding author. Tel.: +82 10 5169 3510; fax: +82 2 957 8408.
E-mail addresses: diouf@khu.ac.kr (B. Diouf), rbpode@khu.ac.kr (R. Pode).

http://dx.doi.org/10.1016/j.renene.2014.11.058
0960-1481/

the consumer electronic industry and others such as military, space and medical applications will create a booming effect and open new opportunities to cut down the cost of rechargeable lithium batteries and make them ideal candidates for common storage in off-grid renewable energy. In fact, for this type of stationary storage application, Li-ion batteries can potentially feature two main fundamental characteristics: longer cycle life and lower life cycle cost. The cost per cycle can be less for Li-ion batteries compared to lead-acid batteries when their lifespans considered. So, even with the current status of development, for a long-term vision it may be more advisable to invest in Li-ion rather than lead-acid even if the upfront cost is higher. But the unique energy storage in renewable energies is not sufficiently appealing to Li-ion industrials for mass production.

Most developed countries to support renewable energies production and distribution promote grid-tie systems with “net metering” type concepts that do not require a battery, the energy transformed is directly injected in the grid via a controller [14]. Such policies had created the conditions for the boost in the PV panel industry and the consecutive mass production dragged the prices down. In developing countries where batteries are more needed because generally PV systems are off-grid, they are less affordable due to populations' revenues [15,16]. This is an important limitation for what should have been a large market for Li-ion storage and is a limiting factor in the mass introduction of Li-ion batteries as primary storage systems in renewable energy. It appears that the renewable energy sector will only benefit of the development of the Li-ion batteries but will not be the driving objective of industries. It is then important to understand and follow the evolution of the sectors that will drive the cost, technical achievements and solutions for safety issues obtained from research and development in the Li-ion batteries. Upfront price will remain an important parameter in the choice of the battery in a standalone system. At the moment the market of electric vehicles seems to be the strongest driving force for the development of Li-ion batteries capable of bringing change in renewable energies. Therefore the future of renewable energy may be looked at as tightly correlated with the future of the electric and hybrid vehicles. To achieve the popularization of li-ion batteries, it is necessary to make them safer and pricewise more competitive. The market expansion of the electric car will accompany the mass production of Li-ion batteries. Furthermore, to replace the internal combustion engine, the development of the electric car itself, is conditioned by the achievement of longer autonomy range, faster charge, good acceleration and longer lifespan, so better energy and power densities but that increases as well the safety challenges to overcome [17]. Academic institutions and industries are currently developing innovative materials and design to the reach that goal [4,6].

2. The driving sectors of Li-ion batteries

The automobile industry is persistently looking for an alternative to the internal combustion engine. It is now admitted that greenhouse gases do not just pollute [5] but more, they hold important responsibility in global warming with terrible consequences. According to a report from Wards Auto, the global number of cars exceeded 1.015 billion in 2010, jumping from 980 million the year before. The OECD's International Transport Forum forecast that the number of cars worldwide would reach 2.5 billion by 2050.

Electric vehicles are drawing more and more attention due to their potential in the reduction of greenhouse gases in one hand and the current dependence and limitation of oil resources in the other that brings national vulnerabilities. The current limitation for the development of the electric automobile is the storage battery. The development of Li-ion batteries will certainly be decisive for larger scale commercialization of electric vehicles [18]. Li-ion battery technology for electric vehicles (EVs), hybrid electrics vehicles (HEVs) and plug in hybrid vehicles (PHEV) is still in its infancy, it started in 2009 [5,8,19].

Compared with other technologies, Li-ion batteries are the most suitable for electric vehicles [7,20] because of their capacity for higher energy and power output per unit of battery mass (Fig. 1). It makes them lighter and smaller than other rechargeable batteries for the same energy storage capacity [21,22]. It is foreseen that by 2020, more than half of new vehicle sales will likely consist of HEVs, PHEVs and EVs. At the moment majority of all hybrids on the market uses nickel metal hydride (NiMH) batteries. According to studies, this may change within a decade, 70% of hybrids, and 100% of plug-in hybrid and all-electric vehicles are expected to run on Li-ion batteries [23].

Currently, the HEV uses mostly the battery to save fuel in acceleration phases and charges it while braking [8]. For example a Toyota Prius can travel only 2–3 miles in all-electric mode. Both, the Chevy Volt and Nissan Leaf are electrically powered by Li-ion batteries [8]. The Chevy Volt a PHEV has autonomy of about 35 miles in all-electric mode before switching to gasoline, while the Nissan Leaf, an EV, can run approximately 70 miles between charges [8].

The higher energy and power densities are the same reasons why Li-ion batteries are already widely dominating the consumer electronics market such as cell phones, laptop computers, digital cameras and many other portable electronic devices [7,24]. Strong demand for Li-ion batteries in the consumer electronics sector will help electric vehicle batteries move down cost/experience curve [25]. Other advantages of Li-ion batteries compared to lead acid and nickel metal hydride batteries (NiMH), summarized in Table 1 below, relate to their high-energy efficiency, no memory effects, and a relatively long cycle life. Furthermore, the flat discharge curve of the Li-ion cell offers effective utilization of the stored power while the voltage remains almost constant.

To have a better market penetration, the relatively high cost of Li-ion batteries for vehicles is one of the main parameter to adjust to make the technology more competitive despite its incomparable technical advantages. According to recent estimates for vehicles' batteries, the cost of Li-ion is four to eight times the price of lead-acid and one to four times the price of NiMH [26]. However, the cost of lithium batteries is expected to drop significantly because the batteries will be increasingly used for many applications, along with the electric car, such as in medical equipment, uninterruptible

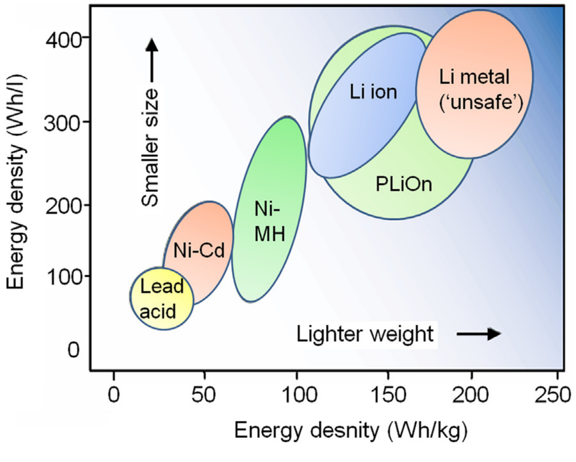


Fig. 1. Comparison between different battery technologies in term of volumetric and gravimetric energy densities.

Table 1
Comparison between different battery technologies.

Specifications	Lead acid	NiCd	NiMH	Li-ion		
				Cobalt	Manganese	Phosphate
Specific energy density (Wh/kg)	30–50	45–80	60–120	150–190	100–135	90–120
Internal resistance (mΩ)	<100	100–300	200–300	150–300	25–75	25–50
	12 V pack	6 V pack	6 V pack	7.2 V	per cell	per cell
Cycle life (80% discharge)	200–300	1000	300–500	500–1000	500–1000	1000–2000
Fast charge time	8–16 h	1 h typical	2–4 h	2–4 h	1 h or less	1 h or less
Overcharge tolerance	High	Moderate	Low	Low. Cannot tolerate tickle charge		
Self-discharge/month (room temp.)	5%	20%	30%	<10%		
Cell voltage (nominal)	2 V	1.2 V	1.2 V	3.6 V	3.8 V	3.3 V
Charge cutoff voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20		3.60
Discharge cutoff voltage (V/cell, 1C)	1.75	1.00		2.50–3.00		2.80
Peak load current	5C	20C	5C	>3C	>30C	>30C
Best result	0.2C	1C	0.5C	>1C	<10C	<10C
Charge temperature	−20 to 50 °C (−4 to 122 °F)	0 to 45 °C (32 to 113 °F)		0 to 45 °C (32 to 113 °F)		
Discharge temperature	−20 to 50 °C (−4 to 122 °F)	−20 to 65 °C (-4 to 49 °F)		−20 to 60 °C (-4 to 140 °F)		
Maintenance requirement	3–6 months (topping charge)	30–60 days (discharge)	60–90 days (discharge)	Not required		
Safety requirements	Thermally stable	Thermally stable, fuse protection common		Protection circuit mandatory		
In use since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very high	Very high	Low	Low		

power supply (UPS), forklifts, consumer electronics and other backup power supplies.

As the market grows and production scales up; manufacturers will take advantage of economies of scale and put on the market products of lower prices. According to studies, the cost of Li-ion batteries will decrease from US$650/kWh in 2009, the start of their introduction in the electric car, to US$325/kWh by 2020 [23]. We should point out that there is a wide range of prices for batteries depending on manufacturers and quality; the above prices represent an average price. Component costs may go down 20–30% in the next few years due to purchasing economies of scale that will lower prices for material suppliers [23]. Li-ion battery technology is still relatively new so there are potentially many opportunities for cost reduction. Material substitution could have an important impact since a large part of the total battery cost is due to materials [27]. Research and development efforts are focused on using more inexpensive and chemically stable materials. Nevertheless, durability, safety, and performance will all be paramount research objectives above simple cost calculations [23].

The price of batteries is less dependent on the active material costs than on their production volume [28]. It is consecutively expected to have a price decrease as the batteries mass production takes place. The mass production will be supported by the development of manufacturing equipment or processes to decrease linetime requirements for the fabrication of the different components of the cells, primarily the electrodes [28].

Beside the cost reduction due to mass production, the price of Li-ion batteries can also decrease with improvement of design [28] and integration of the battery packs based on management of the power potential and pack sizes.

Batteries for different applications have different costs due to the requirements for different output rate capabilities. Li-ion cells are generally made of a thin laminate electrodes to allow the kinetic of electro–chemical reactions to take place at appropriate rates. Thinner electrodes will provide higher power densities while thicker electrodes are for higher energy densities.

Cells with thinner electrodes are more expensive to fabricate [28]. Reduction of cost may come from developing materials that allow thicker electrodes in a cell to still achieve power requirements. Cost reduction can also be achieved by designing application-specific battery packs employing different types of cells: thicker electrode cells for energy storage requirements for all electric range and thinner electrode cells for higher power requirements for acceleration needs as in HEV. Cost reduction may come as well come from evolution in the development of cells to operate in a wider range of applications.

As the energy storage capacity of Li-ion batteries improves and cost decreases, these batteries will be more and more attractive for energy storage for other applications. Indeed, some analysts estimate that electric grid applications could eventually create a larger market than vehicles [7,29–32]. Non-vehicle uses will likely include backup power supply, military, and aerospace applications [32–35]. Most such applications currently use lead-acid or NiMH, but are expected to move to Li-ion batteries in the future.

The electric bike industry is another sector that will probably allow mass production and consecutively cost reduction of Li-ion batteries. In fact, as an example there is an important expansion of the Chinese electric bike market since the end of the 1990s' from nearly 40, 000 in 1998 to an estimated 15 million in 2006 [12,36].

Improvement in technology and lower cost will bring transition from VRLA to Li-ion batteries and have an impact on the future growth of the electric bike market; it may as well influence the future of the electric cars.

Indeed, Li-ion cells, whether for electric vehicles, electric bikes or consumer electronics, are all fabricated based on the same processes. For the batteries, the difference lays in the battery management system (BMS). It would be more convenient to produce the same battery for a number of different applications, from portable consumer electronics to electric vehicles. Li-ion batteries can be designed for high power or high energy depending on cell size, thickness of the electrodes, and relative quantity of materials used [27]. High power cells are generally smaller in order to dissipate the higher heat load. Both types use the same current collectors and separators in the cell.

Today's state of art in Li-ion batteries with a specific energy of 150 Wh kg^{-1}, widely used for small-scale devices, it is not enough to match the performance of internal combustion vehicles as shows (Fig. 2) below. It is therefore necessary to sustain the efforts in research and development to improve the battery technology in one hand and the efficiency of the electric engine in the other. To

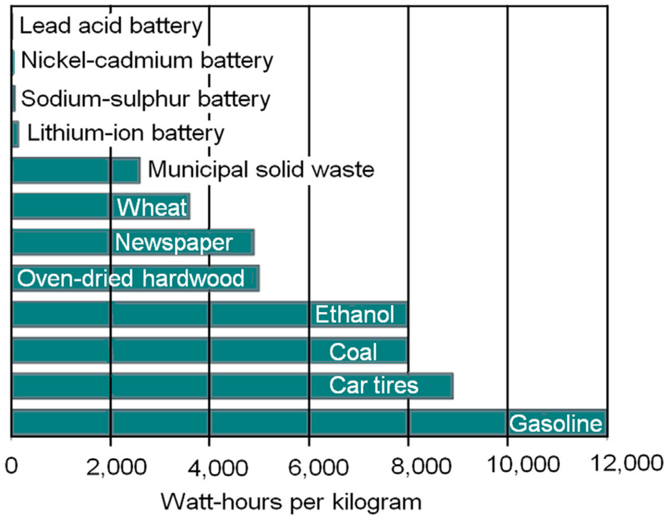


Fig. 2. Comparison between energy densities of different materials.[39].

reach that goal, the energy density needs to be doubled for the future generation of PHEVs with 40–80 miles all-electric range and multiplied by 5 for the future EVs with 300–400 miles autonomy range [8].

So far, major advances in lithium-battery technology were made based on the discovery of new materials, as $LiFePO_4$, and efficient designs. That path may further improve the technology to achieve density of energies greater by a factor 2 to 3 but a greater progress may need to adopt a new technology as lithium–oxygen, ideally lithium air [4], or lithium-sulfur [6,37], all within a window of good safety [6,38], they are both under development. For example a lithium–oxygen cell can theoretically output up to 1752 Wh kg^{-1} (Fig. 3) specific energy if the oxygen electrode is discharged to lithium peroxide. This reaction is reversible if side reactions with the electrolyte solvents can be avoided [8].

3. Lithium-ion batteries based stationary energy storage

An ideal energy storage setup should present certain fundamental features as safety, affordability, efficiency, tolerance to external parameters variations as temperature and humidity, good energy and power densities, long lifespan and no or low maintenance requirements.

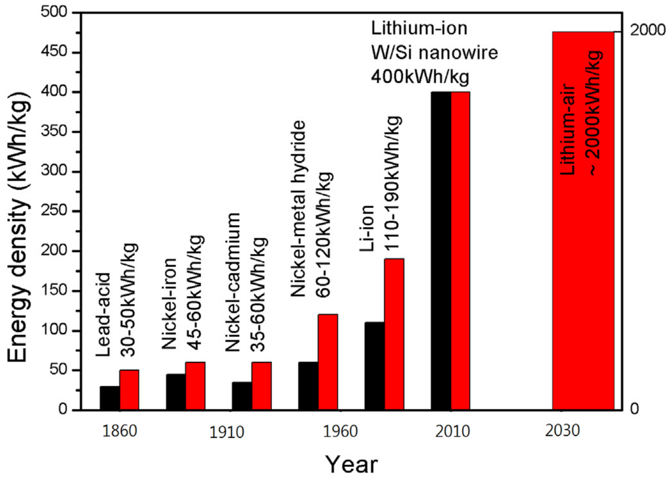


Fig. 3. Evolution of battery technologies by their density of energy.[40].

Since its introduction in the market in 1991 by Sony, Li-ion technology has fascinated scientists with its fast ramp-up in gain of energy density within a modest volume and weight increase when compared with existing lead-acid, NiCd or NiMH rechargeable batteries Fig. 2 [21,22]. These features made it the ideal companion for wireless applications and digital electronics that demand lightweight small volume and long battery run time. Moreover, Li-ion chemistry offers other interesting advantages over its competitors (Table 1): that of no memory effects, no need of special maintenance for extending service life and relatively longer shelf life due to very low self-discharge rates and especially density of energy presently and more for the future as shows Fig. 3.

Through the development of parallel sectors such as the automobile industry, decreasing usage cost will boost the application of Li-ion batteries to other industrial and residential energy storage applications. Li-ion batteries have potential to increase the efficiency, lifespan and reliability of alternative systems such as off grid photovoltaic and wind power that currently almost exclusively uses lead-acid.

If the cycle durability of Li-ion batteries improves significantly, it might also be possible to find a second use of vehicle batteries as a home energy storage device or emergency power supply, once the initial capacity drops under a certain level and the batteries no longer efficient enough for vehicles.

In addition, Li-ion batteries because of their high density of energy can be applied to the so called “vehicle-to-grid” [41–44]. In this application electric vehicle batteries are charged during off-peak hours and the energy is sold back to utility companies during peak hours. In the USA, the federal government as well as utility companies considers “vehicle-to-grid” as a market driver for PHEVs. In July 2010, the Department of Energy set an objective of 40 million smart meters and one million PHEVs by 2015 [45]. Several utility companies have started testing the “vehicle-to-grid” concept, associating with local governments. PG&E, a California utility company, has demonstrated “vehicle-to-grid” with the Bay Area Air Quality Management District [46]. Xcel Energy has begun commercial testing of “vehicle-to-grid” using 60 PHEVs with the city of Boulder and Boulder County, state of Colorado [47]. The firm Google is also testing “vehicle-to-grid” concept (Addison, 2009) [48]. According to Zpryme Research & Consulting, “vehicle-to-grid” market size will be $26 billion by 2020 [45].

The initial cost is still much higher for Li-ion than for lead-acid batteries. Nevertheless, there are situations where their features such as longer lifespan, higher energy density, tolerance to higher temperature or possibility of deeper cycles offer advantages that largely surpass the initial investment difference when choosing Li-ion over other technologies. For example concerning solar streetlights where maintenance has a real high cost, the longer lifespan, the higher energy density and the fact that no maintenance is required are decisive factors of choice for city planners. In this case, the design is generally so that the battery due to its size can be incorporated in the light pole directly compared to a bulky lead-acid battery for which generally an extra storage box is needed. The volume needed for VRLA batteries is 5.6 times that of Li-ion, estimating a density 3.5 times higher for Li-ion than for VRLA and a depth of discharges of 80% and 50% respectively. As well, when using Li-ion batteries due to their lifespan, the frequency of battery service is much lower, this is a very important aspect of cost in city planning and management. This is why in modern solar streetlights a LED lamp and a lithium based battery pack are combined for high efficiency and long lifespan.

In opposite, in solar home systems for example, the storage space is not generally an issue for the battery even if the lifespan remains of high importance along with the upfront cost. Introduction of Li-ion batteries in off grid solar home systems may mostly be seen under the angle of gain in lifespan as storage space may not be a challenge. For example when using Li-ion batteries for energy storage system it becomes possible to match the period of mortgage payment if the gain in lifespan continues. In fact, when in deep discharge it is possible to reach 5000 cycles of life we can theoretically foresee a system installed for 20 years without maintenance and no electricity bill to pay. The current limitation of lead-acid batteries generally used in home systems is their lifespan and in some extend their low power density. Nevertheless, major price drop and extended lifetime are needed before the Li-ion batteries become the main batteries for home systems. Furthermore, there is a good match between lead-acid and Li-ion batteries for most of voltage ranges, so it is for most charge controllers and power inverters, more and more of them can be adjusted to operate with either one of the chemistries. The economics of the batteries is not just the cost but will include transportation, installation and other maintenance fees when necessary. So, the choice of batteries with the current technical development will depend on many factors, as cost and safety but they can all be affected by environmental parameters, VRLA has a lower initial cost but suffers of a higher sensitivity to high temperatures. The lifespan of the lead-acid batteries is typically between 3 and 5 years. It's closer to 3 years or 5 years depending on the environment and the number of cycles. For cooler operating environments, with fewer discharge/recharge cycles on well-maintained batteries, the life expectancy of a battery can approach up to 5 years. On the contrary, in operating environments with extreme heat and moisture and numerous discharge/recharge cycles with poorly stored and maintained batteries the life of a battery can drop to two years.

Another sector of interest is grid storage. Energy storage for grid is generally used to support the grid to match the needs at all moment with reliability. It can be in hydroelectric form with pumped hydroelectric power, it is the most common, mechanical with compressed air, chemical, electrical or in electrochemical form as sodium–sulfur, Na–S, the most frequent currently but they suffer of safety deficit [7]. Due to their high energy and power densities, Li-ion batteries can also be applied to grid energy storage. They can be used in micro-grid applications or just as grid support in peak consumption hours. In case of grid support, the usage will range potentially from frequency regulation and load following, when short response times are needed, to peak shaving and load shifting, both of which can lead to improvements in grid reliability, stability and cost [49]. In general the usage of rechargeable batteries in energy storage can allow better integration of renewable energy resources to the grid and be used to accommodate peak loads [7]. For example among others, a new, state-of-the-art, 5 MW Li-ion energy storage system was recently unveiled in South Salem, Oregon, USA. The new energy storage system will allow the storage of the excess electricity occasionally produced by some intermittent renewable energy sources, such as wind and solar, as well as providing other services. The energy storage system is integrated with a localized power zone, standing for a microgrid, which means that depending on the size of the system, a number of customers in the area will be able to retain power even during regional electrical blackouts. The energy storage system will respond to regional grid conditions with the help of a key aspect of the demonstration called transactive control. The technology helps power producers and users decide how much of the area's power will be consumed, when and where. This is done when producers and users automatically respond to signals representing future power costs and planned energy consumption. The automated signals allow participants to make local decisions on how their smart project can support local and regional grid needs. The new energy storage system should give grid operators the information they need to design better, larger systems and offers means of exploring different ways to integrate solar or wind power with the grid. Photovoltaic or wind turbine systems are widely installed worldwide. This makes electricity grids “smarter” and facilitates them with integration of renewable energy sources; this may be a necessary step to achieve a sustainable power industry. But, renewable energy sources as sun radiations or wind are not constant and intrinsically dependent on environmental conditions. Serious concerns about reliability and performance require integration of energy storage as a critical part to buffer energy or provide arbitrage. Direct connections of renewable energy sources to the grid can lead to stability issues of the utility network or even its failure. Battery energy storage system can be used to control the output fluctuations of renewable energy sources. It can be based on Li-ion battery and power conditioning system. Lithium-based battery offers high specific power/energy density, and gains popularities in many applications, such as small grids and integration of renewable energy in grids [30–32].

In deep discharge applications Li-ion batteries has significantly higher cycle life than lead-acid batteries. This difference is enhanced as the operation temperature increases. The cycle life of each one of the chemistries can be increased by limiting the depth of discharge rate and temperature, but lead-acid is generally much more sensitive to each of these factors. Lead-acid and Li-ion batteries both offer pros and cons for stationary storage applications. When making a choice for one or the other number of factors should be taken into consideration as: safety, reliability, initial cost including installation, lifespan, weight and volume especially to consider for shipping cost and storage availability, temperature sensitivity, environmental impact and maintenance. Li-ion batteries perform better as temperature is higher as in hot climates but their initial cost is much higher. Rural electrification is sector continuously growing is in developing countries, with a main demand is for lighting and cell phones [15]. In this case energy storage plays a fundamental role and generally populations have to deal with remoteness, making services not available, furthermore, high temperatures limit the lifespan of lead-acid batteries generally used, particularly in Africa. Such situations call in favor of Li-ion batteries rather (Table 1). For example, in fee-for-service, one of the rural electrification models [50–52] the adoption of Li-ion batteries will have the benefit of no maintenance needed, the lifespan is much longer (currently up to 2000 cycles for a depth of discharge at 80%) and a better tolerance to high temperatures. The adoption of Li-ion batteries will bring major advantages to overcome the initial cost. In fact, in the fee-for-service model private companies install solar home systems at the end users' domicile but remain the owner of the equipment. The private companies are in charge of the maintenance or repair of the systems if needed and the end users have to pay fees in exchange of the electricity service. One of the problems of these rural areas that weaken the fee-for-service model is their remote character. There is no technical service or parts available in case of breakdown; the systems should be built in order to minimize technical failures. It will reduce the expenses of the private companies and the fees paid by the end users. The battery, as in most of photovoltaic off-grid systems, remains the weak point, especially because of its short lifespan generally about 500 cycles for a depth of discharge at 50% of its capacity.

Among the different Li-ion batteries $LiFePO_4$ seems to be the most promising for large capacity energy storage [53,54]. This is due to its lifespan and safety compared to other Li-ion batteries. So, it should be expected that in the near future with the current trend in research and development for the automobile industry the prices will be continuously dropping and Li-ion batteries, particularly $LiFePO_4$, will gain popularity in renewable energy storage and particularly in off grid solar home systems. Nevertheless to operate Li-ion batteries safely, it is needed to protect them with an electronic circuit as they do not tolerate overcharge or discharge and extreme temperatures that can lead to serious issues [55].

4. Conclusion

We have presented the potential for a wide use of Li-ion batteries as primary storage in the renewable energies, replacing the very common lead acid batteries. Favorable attributes of Li-ion batteries are longer lifespan, higher densities of energy and power. These are the principal weak points of batteries at the moment used in off grid renewable energies. Nevertheless, the take-off is yet to be seen because of the cost competitiveness of Li-ion chemistry that is still high and in some extend shows safety issues. The cost and safety issues are most likely be overcome with the development of the electric vehicle that will trigger a mass production in the near future. Li-ion batteries are more environment friendly than lead-acid batteries. Because of the density of energies, lead-acid batteries require more raw materials to achieve the same energy storage capacity which may affect environment due to more mining.

The sustainability of Li-ion batteries and a real sense of their application as ideal batteries in renewable energy, despite their unique technical features, requires for them to use abundant row material, to be recyclable. Replacing more than 1 billion cars in the world with electric vehicles or plug-in hybrids powered by 15-kWh lithium-ion batteries would use up to 30% of the world's known reserves of lithium. Nevertheless, other sources are available as lithium is also found in unlimited quantities in sea water, and concentrating it from brines is more environment friendly than conventional mining. The production of lithium could also be based partly on recycling as already done with lead–acid batteries. Lithium battery technology will also need to achieve lower carbon footprint, it is currently about 70 kg CO_2 per kWh.

References

[1] Steele RV. Nat photonics 2007;1:25–6.
[2] Pode Ramchandra, Diouf Boucar. Solar lighting. Springer; 2011.
[3] Dahn J, Jiang J, Morshurchak L, Buhrnester C, Wang RL. The electrochemical society interface. Winter 2005. p. 27–31.
[4] Armand M, Tarascom JM. Nature February 2008;451/7:652–7.
[5] Goodenough JB, Kim Y. Chem Mater 2010;22:567–603.
[6] Tao H, Feng Z, Liu H, Kan X, Chen P. Open Mater Sci J 2011;5(Suppl. 1: M2): 204–14.
[7] Dunn B, Kamath H, Tarascon JM. Science 18 November 2011;334:928–35 [Science 334, 928 (2011)].
[8] Thackeray MM, Wolverton C, Isaacs ED. Energy Environ Sci 2012;5:7854.
[9] Weinert JX, Burke AF. ECEEE 2007 Summer study, saving energy, 1801–1810.
[10] Weinert J, Ma C, Cherry C. J Transp Special Issue: Mot Asia 2007;34(3):26.
[11] Weinert J, Ma C, Yang X, Cherry C. The transition to electric Bikesin China and its effect on travel, transit use, and safety. Washington D.C: Transportation Research Board; 2006.
[12] Cherry C. Implications of electric bicycle use in China: analysis of costs and benefits. In: UC Berkeley Center for future Urban Transport-Volvo Summer Workshop, Berkeley CA; 2006.
[13] Center for battery quality inspection quality of lead-acid batteries of electric-assist bicycle analysis report. 2006. Beijing.
[14] Edison electric institute, http://www.eei.org.
[15] Diouf B, Pode R, Osei R. J Energy Policy 2013;59:926–30.
[16] Youm I, Sarr J, Sall M, Kane MM. Renewable energy activities in Senegal: a review, renewable and sustainable energy reviews, vol. 4; 2000. p. 75–89.
[17] Wen J, Yu Y, Chen C. Mater Express 2012;2(No. 3):197–212.
[18] Armand M, Tarascon JM. Nature 2008;451:652.
[19] Electro-to-Auto Forum. Electric vehicles: 200km cruise range enabled; cost of Li-ion batteries reduced by 90%. 2009. Retrieved June 1, 2010, from http://e2af.com/review/090930.shtml.
[20] Yang P, Tarascon JM. Nat Mater 2012;11:560.
[21] Marsh RA, Vukson S, Surampudi S, Ratnakumar BV, Smart MC, Manzo M, et al. J Power Sources 2001;25:97–8.
[22] Ratnakumar BV, Smart MC. Aerospace applications. II. Planetary exploration missions (orbiters, landers, rovers and probes). In: Brousely M, Pistoia G, editors. Industrial applications of batteries: from cars to aerospace and energy storage. Amsterdam: Elsevier; 2007. p. 327–87.
[23] Deutsche Bank. Autos & auto parts electric cars: plugged in 2. 2009. From, http://www.db.com.
[24] Tarascon JM, Armand M. Nature 2001;414:359–67.
[25] Anderman M. High-power NiMH and Li ion batteries. In: Tutorial 3A for the 3rd Advanced Automotive Battery Conference, Nice, France (June 2003); 2003.
[26] H. Nishino, Key Technology for EVs; Lithium-Ion secondary battery. Retrieved June 25, 2010, from http://mitsui.mgssi.com/issues/report/r1005j_nishino.pdf.
[27] Gaines L, Cuenca R. Costs of lithium-ion batteries for vehicles: Center for Transportation Research, Energy Systems Division, Argonne National Laboratory. 2000.
[28] Barnett B, Rempel J, Ofer D, Oh B, Sriramulu S, Sinha J, et al. PHEV battery cost assessment. Lexington, Mass: TIAX, LLC; 2010. Presentation es001, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2010/electrochemical_storage/es001_barnett_2010_o.pdf.
[29] Engardio P. The electric car battery war – Business Week. Business week – business news, stock market & financial advice. Feb 12 2009.
[30] Roberts B. Capturing grid power. IEEE Power Energy Mag Jul-Aug, 2009;7(4): 32–41.
[31] Moncrieff WA. Energy storage—applications in the smart grid. Mod Electr Power Syst 2010. Wroclaw, Poland.
[32] Smart MC, Ratnakumar BV, Whitcanack LD, Puglia FJ, Santee S, Gitzendanner R. Int J Energy Res 2010;34:116–32.
[33] Ratnakumar BV, Smart MC, Kindler AFH, Ewell R, Surampudi S. Lithium batteries for aerospace applications: 2003 Mars exploration rover. J Power Source 2003;119–121:906–10.
[34] Ratnakumar BV, Smart MC, Ewell RC, Whitcanack LD, Chin KB, Surampudi S. Lithium-ion rechargeable batteries on Mars rovers. In: Second International Energy Conversion Engineering Conference (IECEC), Providence, Rhode Island; 18 August 2004.
[35] Smart MC, Ratnakumar BV, Ewell RC, Whitcanack LD, Chin KB, Surampudi S, et al. Ground testing of the Li-ion batteries in support of JPL's 2003 Mars exploration rover mission. In: Third International Energy Conversion Engineering Conference (IECEC), San Francisco, CA; 19 August 2005.
[36] Jamerson F, Benjamin E. Electric bicycle world report. 7th ed. 2005.
[37] Lin Z, Liu Z, Fu W, Dudney NJ, Liang C. Angew. Chem. Int. Ed. 2013;52:7460–3.
[38] Ribiere P, Grugeon S, Morcrette M, Boyanov S, Laruelle S, Marlair G. Energy Environ Sci 2012;5:5271.
[39] Source, DOE (Department of Energy).
[40] Source, Power magazine, http://www.powermag.com.
[41] Rahman S, Teklu Y. Role of the electric vehicle as a distributed resource. In: 2000 IEEE Power Engineering Society Winter Meeting, Singapore, vol. 1; 2000. p. 528–33.
[42] Kempton W, Tomic J. J Power Sources 2005;144(1):280–94.
[43] Kempton W, Letendre SE. Electric vehicles as a new power source for electric utilities. Transp Res Part D: Transp Environ 1997;2(3):157–75.
[44] Kempton W, Tomic J. J Power Sources 2005;144(1):268–79.
[45] Environmental Leader, Global V2G Market to Reach $26.6 B by 2020. Retrieved August 17, 2010, from http://www.environmentalleader.com/2010/07/20/global-v2g-market-to-reach-26-6-b-by-2020/.
[46] PG&E. Pacific Gas and electric company energizes Silicon Valley with vehicle-to-grid technology. 2007. Retrieved August 17, 2010, from, http://www.pge.com/about/news/mediarelations/newsreleases/q2_2007/070409.shtml.
[47] Xcel Energy. News releases. 2008. Retrieved August 17, 2010, from, http://www.xcelenergy.com/New%20Mexico/Company/Newsroom/Pages/NewsRelease20081023Vehicletogrid.aspx.
[48] Addison John. Google energy could be a smart charging and V2G provider. 2009. From, http://www.cleanfleetreport.com/clean-fleet-articles/google-energy-v2g/.
[49] Basic research needs for electric energy storage. Washington DC: Office of Basic Energy Sciences, U.S. Department of Energy; July 2007.
[50] EDRC (Energy and Development Research Centre). A review of international literature of ESCOs and fee-for-service approaches to rural electrification (solar home systems). 2003. Cape Town.
[51] IEA. Summary of models for the implementation of solar home systems in developing countries, Part 1 and 2, International Energy Agency—PVP Task 9. 2003.
[52] Lemaire X. Off-grid regulation and rural electrification in developing countries. 2010. A Literature Review, REEEP-SERN.
[53] Wu D. Lithium-ion phosphate batteries: enviro-friendly technology offered by Pihsiang energy technologies. In: Light Electric Vehicle Conference: Battery Safety, Taipei, Taiwan; 2007.
[54] Yang M-h. In: Outlook of future Li-ion battery chemistries for safety improvements. Light Electric Vehicle Conference: Battery Safety, Taipei, Taiwan; 2007.
[55] Kim KS, Hyun DS. International Conference on Renewable Energies and Power Quality (ICREPQ'12) Santiago de Compstela (Spain), 28th to 30th March, 2012.