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ETM 671 – Managing
Emerging Technologies
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[SOLID STATE BATTERIES]

Contents

Electric Vehicles

Global usage of fossil-fuel based energy consumption is unsustainable —due to limited supply, increased global demand, and the negative environmental effect of greenhouse gases (GHGs). To manage this situation the major economies of the world are considering other sources of energy and requiring suppliers to utilize new technologies to effect change and widespread deployment.

As part of this global trend, all types of vehicles are being redesigned for countries to run on electricity as a plug-in or hybrid-with-reduced-fuel-usage. The International Energy Agency recently published the "Technology Roadmap: Electric and Plug-in Hybrid Vehicles" which describes the trends for electric vehicles up to 2050 (IEA, 2011). This roadmap is based on a vision that these electric vehicles (EVs) and plug-in hybrid vehicles (PHEVs) will represent 50% of annual light duty vehicles (LDVs) by 2050 (Figure 1).

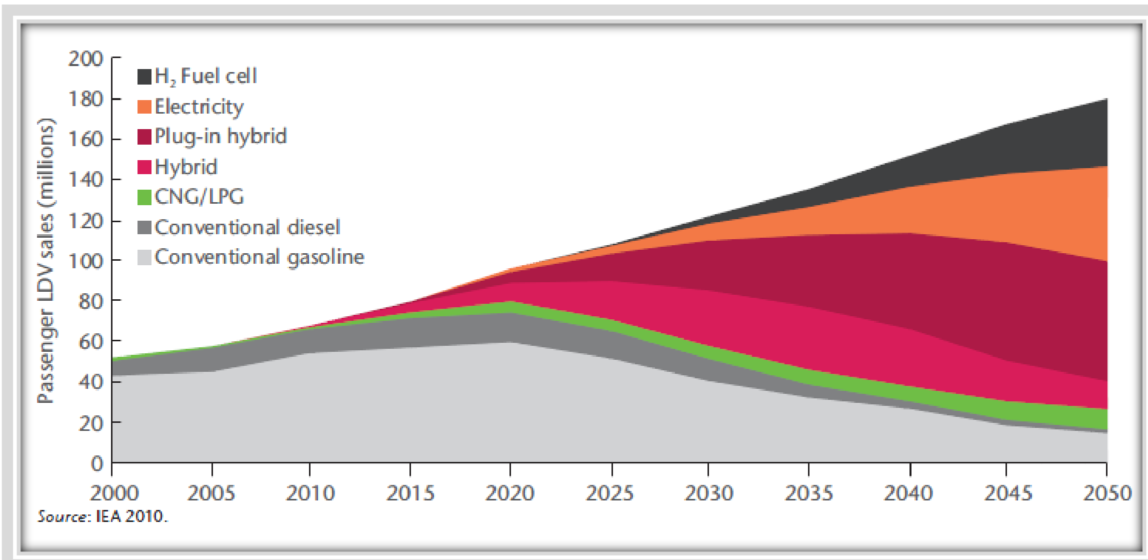


Figure 1: Annual light-duty vehicle sales by technology type - One Scenario [Source: IEA 2010]

Besides setting targets, policy support, and recharging infrastructure, the key findings include battery requirements for vehicle performance and energy storage research, development, and demonstration (RD&D) initiatives to bring down costs. This is critical for overall market entry and penetration of EVs. Currently, battery costs are in range of \$500 – \$800 per kilowatt-hour (kWh) and need to be reduced to \$300 - \$400 per kWh by 2020 to be comparable to a break-even cost of the internal combustion engine (ICE). RD&D efforts also need to address resource requirements and ensure secure supply chains and avoid bottlenecks. Lithium and rare earth metals supply should be specifically monitored.

Electric vehicles (EVs) are propelled by an electric motor and use batteries for electricity storage. Battery provides the vehicle motive and auxiliary power. Batteries are typically recharged from power grid electricity and brake energy recuperation. EVs have the advantage of high efficiency, zero GHG vehicle emission and air pollutants, very low noise, and a low cost electric motor. The main disadvantage is the dependence on batteries with low energy and power densities compared to liquid fuels.

Hybrid electric vehicles (HEVs) have an engine and a motor with limited battery capacity for energy storage. The electrical energy is generated by the engine or brake energy recuperation. The batteries provide on-demand power to the motor for auxiliary motive power. Future generations of PHEVs are expected to have much higher battery capacities.

Electric vehicles (HEVs/PHEVs/EVs) have been in the marketplace for ten years and the current market penetration is 2% in the United States and 9% in Japan (IEA, 2011). Worldwide cumulative sales of electric vehicles exceed 2.5 million units. IEA presents a forecast of all types of light duty vehicle sales till 2050 based on their "BLUE map" scenario which assumes that EV/PHEV technologies will improve rapidly and allow for fast market penetration with 2.5 million EVs and 5 million PHEVs by 2020.

Batteries

Batteries and energy storage are critical to the successful adoption of EVs. For today's drivers the batteries need to have a capacity of 75 kWh or more and at $500/kWh this would translate to a battery cost of around $35,000. To make EVs affordable automakers produce vehicles for shorter driving distances (less than 120 miles). Initially, the cell R&D and production are the key factors for new battery technologies; however the entire value chain needs to be kept in view for the successful deployment of the new battery cells (Dinger et al., 2010). The Boston Consulting Group has outlined the value chain of electric vehicle batteries as seven steps (Dinger et al., 2010, Figure 2).

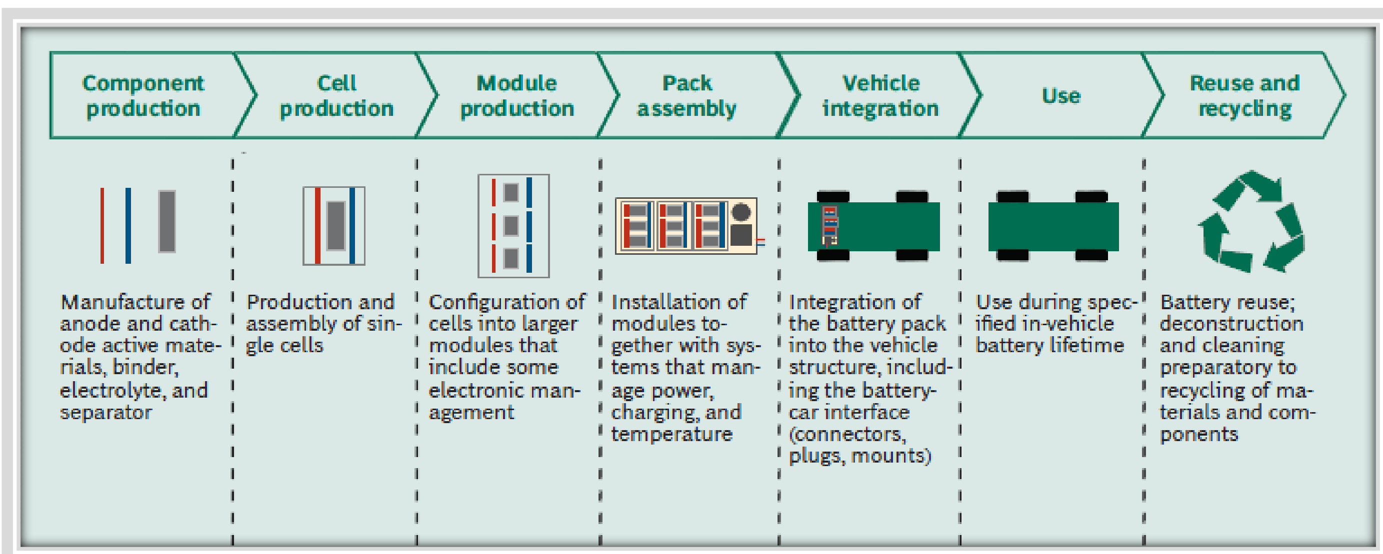


Figure 2: The Value-Chain of Electric-Car Batteries Comprises of Seven Steps (Dinger et al., 2010)

The major battery technology challenges that need significant improvement (especially for lithium-ion (LI-ion) batteries) include:

Storage Capacity. EVs require batteries with higher energy density while PHEVs require higher power density. This may require different battery technologies but for commercial reasons it may mean that one type of battery should cater for both markets.

Battery Discharging. PHEV batteries require both deep discharging as well as shallow cycles (for power assist and regenerative braking). These requirements are quite different than that for the current ICE-based HEVs use only shallow discharging.

Durability. Batteries need to improve in durability and total life expectancy over a wide range of operating conditions.
Other Challenges. Other areas of improvement are: energy density (specific energy) to reduce footprint and weight, power density (specific power) to increase acceleration, temperature sensitivity, reducing time to recharge, and battery costs.

Battery Technologies

An introduction to the different types of battery technologies is helpful in gaining insight into battery options as well as the value of Li-ion technology (Figure 3). Specific energy is inversely proportional to specific power, however both are important and that is why Li-ion technology is more optimal than the other electrochemical methods. Hence lithium-ion batteries have gained an important place in powering electronics and hold a good future for EV applications (Bruno Scrosati & Garche, 2010).

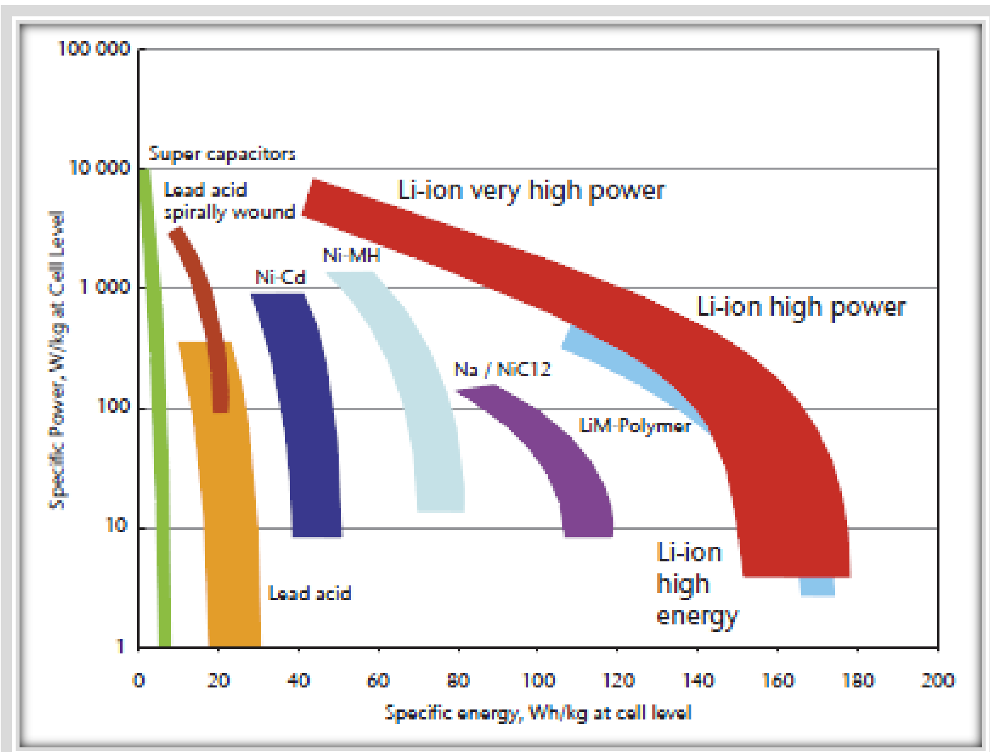


Figure 3: Specific Energy and Specific Power of Different Battery Types [Source: Johnson Control - SAFT 2005 and 2007]

The commonly used Li-ion batteries used for most consumer electronics consists of a graphite anode and a $LiCoO_2$ cathode (3.6 V system) and can reach a practical energy density of 150 Wh/kg in a single cell. However, this current battery technology is not sufficient for EVs due to its limited life and missing safety features (Marom, Amalraj, Leifer, Jacob, & Aurbach, 2011). Marom et al have suggested a technology roadmap for the direction of Li-Ion research with the indication that the cathode material is the limiting factor (Figure 4).

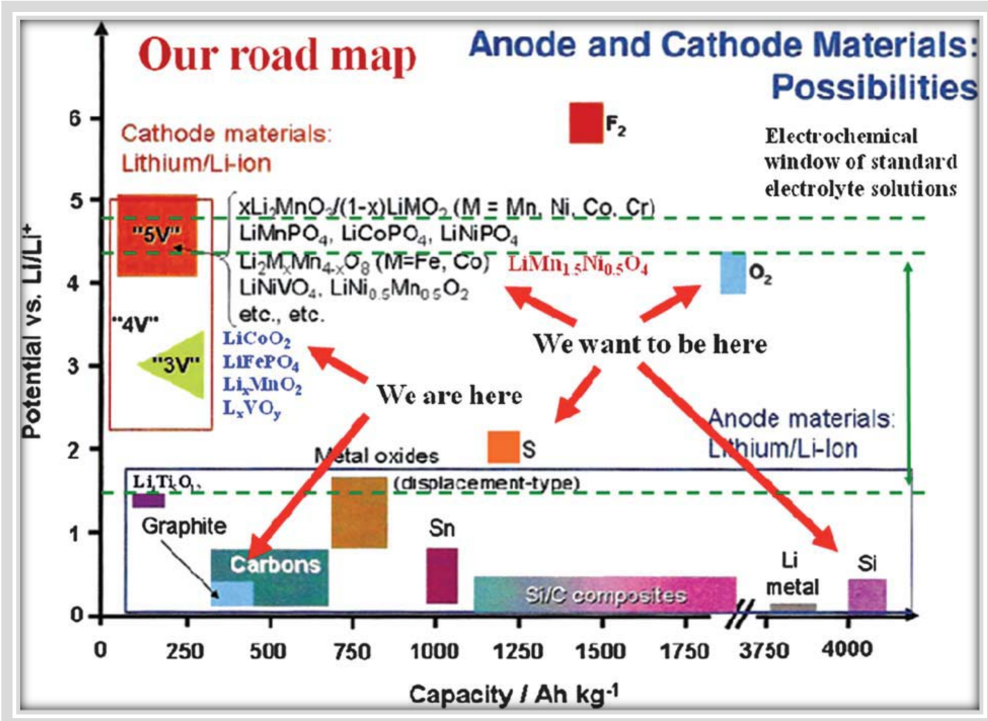


Figure 4: R&D Roadmap for New Electrode Materials Compared to Today's State-of-the-Art (Marom et al., 2011)

Lithium-based batteries are likely to be sufficient for the near-term till 2015 but after that new battery chemistries need to be developed for long-distance driving as shown in Figure 5 (Miller, 2009).

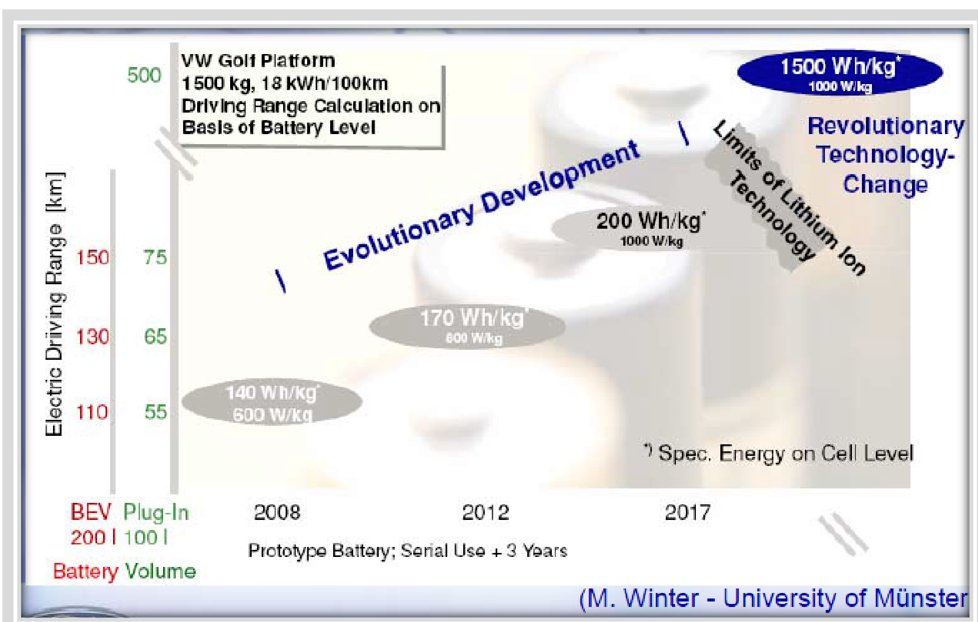


Figure 5: Evolutionary Versus revolutionary Development for Lithium-Ion (Miller, 2009)

Even within the lithium-ion battery family, there are multiple lithium chemistry combinations and configurations with varying characteristics such as energy density, power, low temperature operations, life cycle, safety, cost, and technology maturity (Table 1).

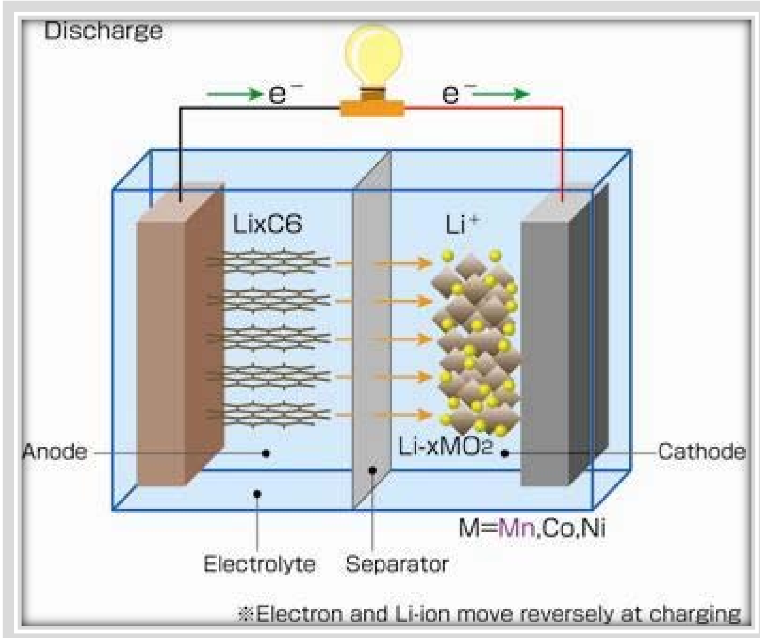
Table 1: Lithium-ion Battery Characteristics, By Chemistry

Characteristics	Lithium Cobalt Oxide (LicoO2)	Nickel, Cobalt And Aluminum (NCA)	Nickel-Manganese-Cobalt (NMC)	Lithium Polymer (LiMn2O4)	Lithium Iron Phosphate(LiFePO4)
Energy Wh/kg or L	Good	Good	Good	Average	Poor
Power	Good	Good	Good	Good	Average (lower V)
Low Temperature	Good	Good	Good	Good	Average
Calendar Life	Average	Very Good (if charge at 4.0 V)	Good	Poor	Poor above 30°C
Cycle Life	Average	Very good (if charge at 4.0 V)	Good	Average	Average
Safety*	Poor	Poor	Poor	Average	Good
Cost/kWh	Higher	High	High	High	High
Maturity	High	High	High	High	Low

Source: Guibert, Anne de (2009), “Batteries and supercapacitor cells for the fully electric vehicle”, Saft Groupe SA. (Guibert, 2009)

How does a lithium-ion battery work?

The current lithium-ion battery cell contains four main components: cathode, anode, electrolyte and separator (Figure 6) and is rechargeable where the lithium ions move between the anode and cathode, creating electricity flow to power electronics or motors (Lowe, Tokuoka, Trigg, & Gereffi, 2010). In the discharge cycle, lithium in the anode (carbon material) is ionized and emitted to the electrolyte. Lithium ions travel through a porous plastic separator and insert into atomic-sized cavities in the cathode (lithium metal oxide). Simultaneously, electrons are released from the anode and become the source of the electric current of an outside electric circuit (Figure 6). During the charge cycle, lithium ions go from the cathode to the anode through the separator. Since this is a reversible chemical reaction, the battery can be recharged.



Source: (Automotive Energy Supply Corporation, 2007)

Figure 6: Discharging Mechanism of a Lithium-Ion Battery

Solid State Batteries

A solid-state battery has both solid electrodes and solid electrolytes . As a group, these materials are good ion conductors but are essentially insulating toward electrons, properties that are prerequisites for any electrolyte. The high ionic conductivity minimizes internal resistance to enable high power densities and the high electronic resistance minimizes its self-discharge rate, thus enhancing its shelf life. Solid-state batteries generally fall into the low-power density and high-energy density category. The low-power density is due to the high resistance across solid-to-solid interfaces. However, their benefit is that they are easy to miniaturize, there is no electrolyte leakage problem, and they tend to stable over a wide temperature range (and hence avoid electrolyte boiling or freezing).

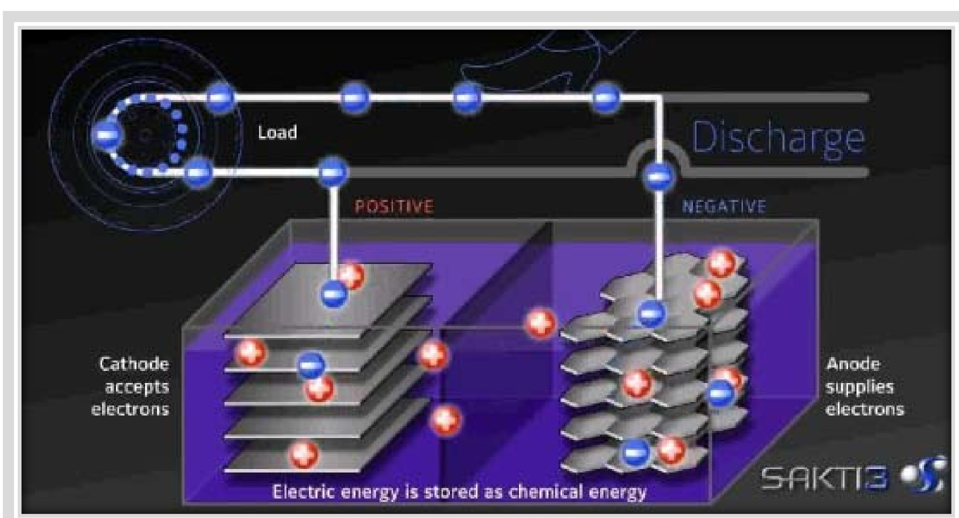


Figure 7: Solid State Battery Diagram (Source: Sakti3)

Nanotechnology Battery

Using nanotechnology in the manufacture of batteries offers multiple benefits such as: ability to use inflammable electrode materials, decreasing recharge time by using nanoparticles and increasing surface area, and decreasing current leakage using nanomaterials. Researchers at Stanford University have grown silicon nanowires on a stainless steel substrate and demonstrated that batteries using these anodes could have up to 10 times the power density of conventional li-ion batteries. At MIT research is being conducted to deposit aligned carbon nanotubes on a substrate for use as the anode, and possibly the cathode. Multiple startups already use nanomaterials in their Li-ion battery design. These include: A123Systems, NanoEnerTechnologies, Mphase Technologies, Altairnano, Naoexa, EcoloCap Solutions, Zpower, Nexeon, NanoAmor, NEI, and Contour Energy.

Vehicle Battery Patent Trends

The web-based software, Boliven (www.boliven.com) was used to search the following national and international patent databases:

United States (USPTO)
International (PCT)
Europe (EPO)
Japan (JPO)
Korea (KIPO)
INPADOC

The following keywords were then used to analyze the patents and patent trends:

Vehicle Battery
Solid State Vehicle Battery
Lithium-Ion Solid State Vehicle Battery
Sakti3

The results indicated very strong activity in both “vehicle battery” patents (Figure 8) and “solid state vehicle battery” (Figure 10) with Toyota and Denso dominating the field (Figure 9, Figure 11). However, for “lithium-ion solid state batteries”, it appears the patents are about 3% of the vehicle battery patents (Figure 12) and that Qualcomm is the top patent assignee is this area (Figure 13).

Vehicle Battery – Patents (170, 051 documents as of 06/28/2011)

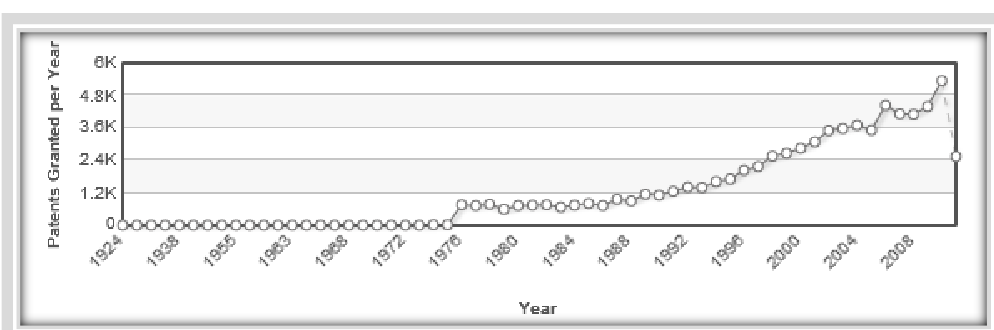


Figure 8: Worldwide Patent Granted Per Year - Vehicle Battery

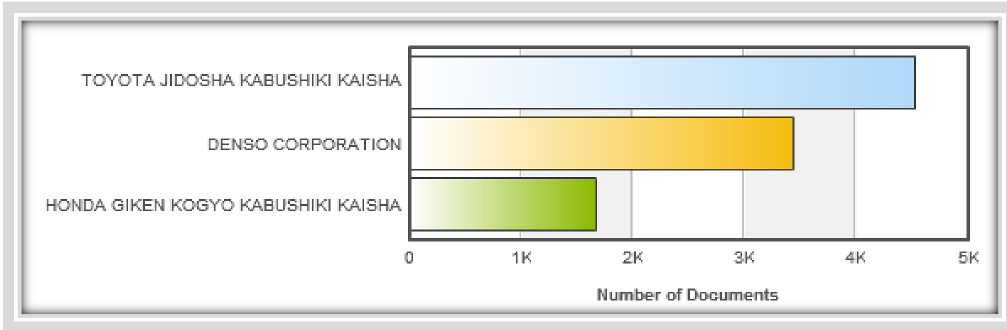


Figure 9: Worldwide Patent Granted Per Year - Vehicle Battery - Top Three Assignees

Solid State Vehicle Battery – Patents (33, 730 documents as of 06/28/2011)

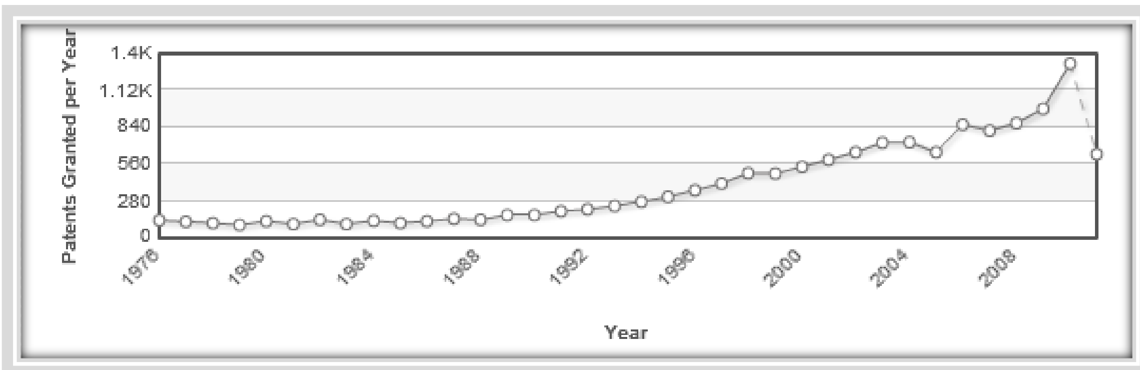


Figure 10: Worldwide Patent Granted Per Year - Solid State Vehicle Battery

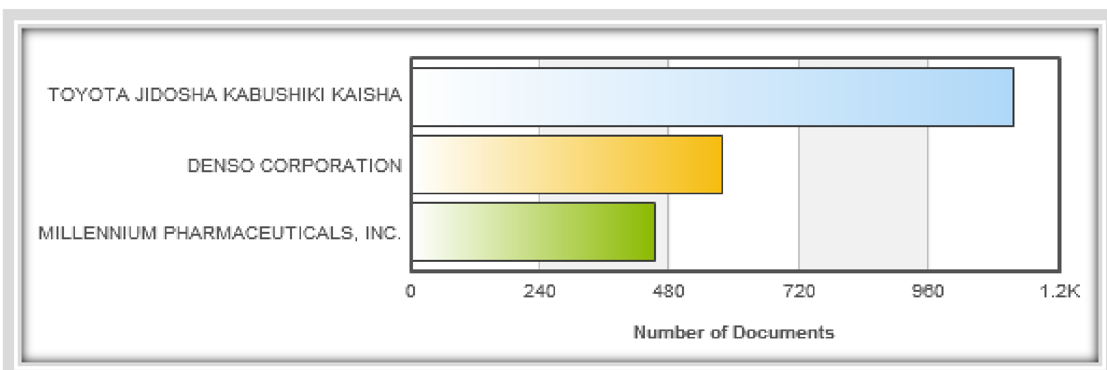


Figure 11: Worldwide Patent Granted Per Year - Solid State Vehicle Battery - Top Three Assignees

Lithium-Ion Solid State Vehicle Battery – Patents (5,678 documents as of 06/28/2011)

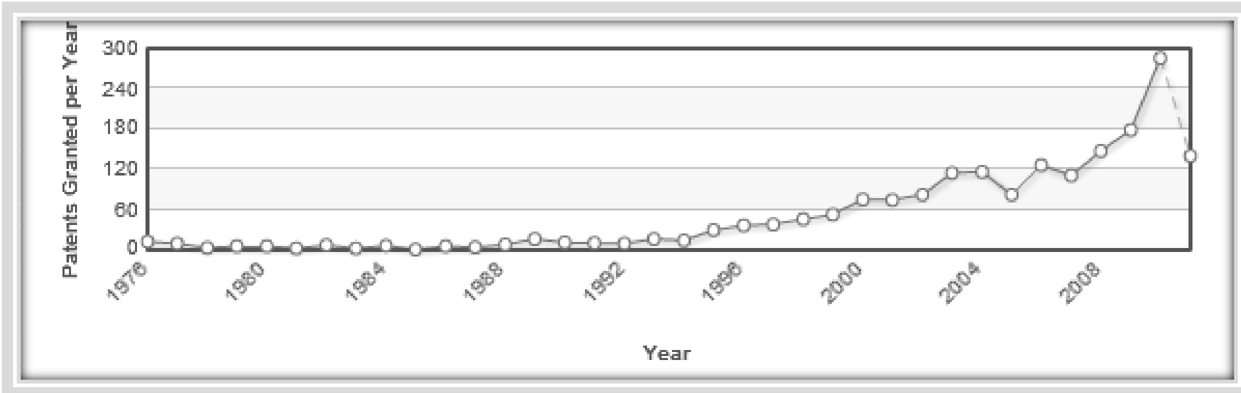


Figure 12: Worldwide Patent Granted Per Year - Lithium-Ion Solid State Vehicle Battery

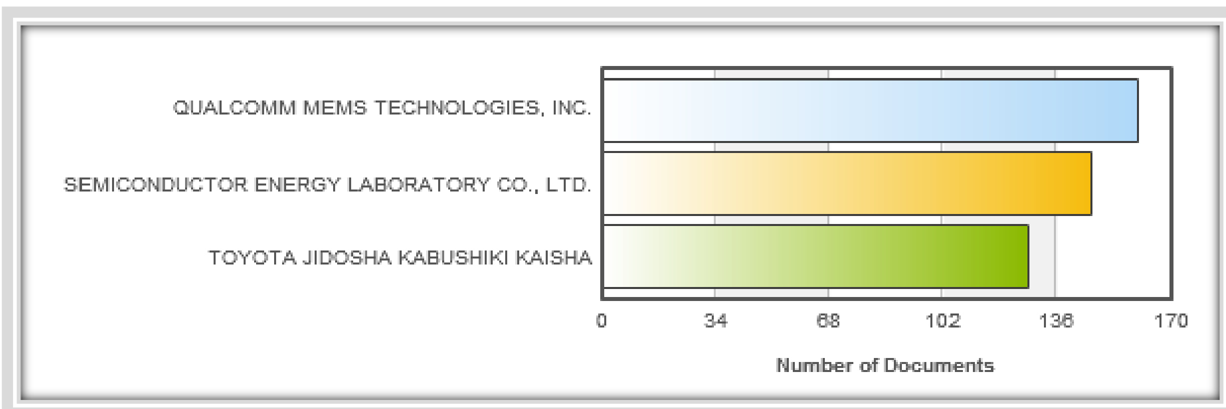


Figure 13: Worldwide Patent Granted Per Year - Lithium-Ion Solid State Vehicle Battery - Top Three Assignees

Electric Vehicle and Battery Manufacturers

Batteries are an important part of EVs and PHEVs. Hence, most vehicle manufacturers have developed alliances with battery suppliers. BYD Auto was originally a battery manufacturer and has expanded into automotive manufacturing. According their production output plans, 0.9 million units per year are projected by 2015 and 1.4 million units per year by 2020.

Table 2: Manufacturers of EVs/PHEVs and Partnering Battery Manufacturers, With Production Targets Where Available (IEA, 2011)

Car Manufacturer	Announced/Reported Production/Sales Targets	Battery Manufactures (May Contains Development Partners and Former Partnership)
Daimler	10 000 in 2013 (5)	Johnson Controls-Saft (JCS), Sanyo, SK Innovation, Li-Tec Battery
Fisker	50 000 in 2013 (1)85 000 in 2014	A123 Systems

Ford	18 000 in 201221 000 in 2013	LGChem, JCS, MAGNA E-Car Systems, Toshiba, Sanyo
General Motors	120 000 in 2012 (1)	LG Chem, JCS
Mitsubishi	40 000 in 2012 (2)5% in 2015 20% in 2020	GS Yuasa Corporation,Lithium Energy Japan, Toshiba
Nissan	50 000 in 2010 in Japan150 000 in 2012 in United States 50 000 in 2013 in United Kingdom	AESC
PSA	40 000 in 2014 (4)	Lithium Energy Japan, GS Yuasa, JCS
Renault	250 000 in 2013	AESC, LG Chem, SB Limotive (SBL)
Tesla	10 000 in 2013 (1) 20 000 in 2014	Panasonic Energy Company
Th!nk	10 000 in 2013 (1) 20 000 in 2014	A123 Systems, Enerdel, FZ Sonick
Volkswagen	3% in 2018 (3)	Sanyo, Toshiba, SBL,Varta Microbattery
BMW	SBL, E-One Moli Energy	BMW
Volkswagen	3% in 2018 (3)	Sanyo, Toshiba, SBL,Varta Microbattery
BYD Auto		BYD Group
Chrysler-Fiat		SBL, LG Chem
Coda Automotive		Coda Battery Systems
Hyundai		LG Chem, SBL, HL Green Power, SK Innovation
SAIC		JCS
Magna		GS Yuasa Corporation
Subaru		AESC
Suzuki		Sanyo
Tata		Electrovaya,EIG
Toyota		Primearth EV Energy, Sanyo
Volvo		EnerDel, LG Chem

(1) www.energy.gov/media/1_Million_Electric_Vehicle_Report_Final.pdf.
(2)www.mitsubishi-motors.com/publish/pressrelease_en/corporate/2011/news/detail0771.html.
(3) www.treehugger.com/files/2010/03/volkswagen-plans-sell-300000-electric-cars-year-2018.php.
(4) www.ft.com/cms/s/0/3a4324f4-4353-11e0-aef2-00144feabdc0.html#axzz1FLb87CdI.
(5) www.bloomberg.com/apps/news?pid=20601100&sid=aT_u.QS7Y4tg.

(6) http://gm-volt.com/2011/04/15/lg-chem-opens-ochong-battery-plant-expects-major-market-share/.

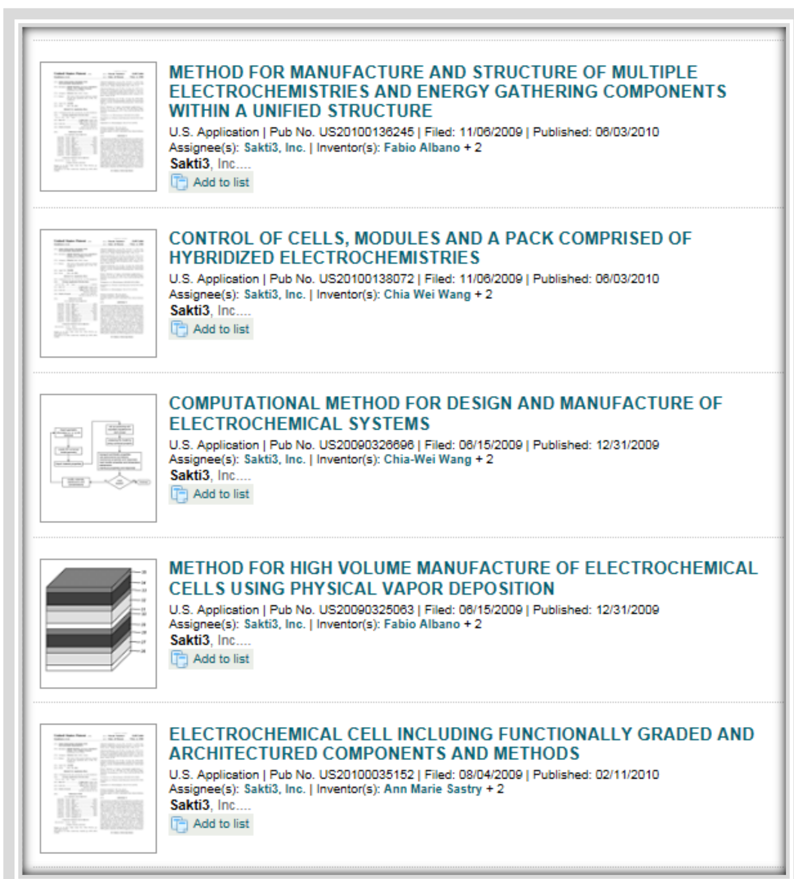
Sources: Various, updated by IEA May 2010.

Sakti3

Sakti3 is Michigan startup which has gained a high-profile and is developing a solid-state lithium ion battery with funding from General Motors and a premier venture capital firm, Khosla Ventures. Sakti3 has been declared as a top ten emerging technology for 2011 by MIT's Technology Review magazine (Bullis, 2011). Sakti3's CEO, Dr. Sastry holds Ph.D. and M.S. degrees from Cornell University, and a B.S. from the University of Delaware, all in mechanical engineering. In her academic life, Sastry is the Arthur F. Thurnau Professor of mechanical, biomedical and materials science at the University of Michigan.

Sakti3's solid-state batteries replace the liquid electrolyte with a thin layer of inflammable material thus increasing the energy density two or three-fold and yet able to withstand high-temperatures. Sakti3 has proprietary simulation software to identify optimum combinations of materials and structures for compact and reliable devices. Sakti3 is also developing manufacturing processes for volume production.

Sakti3 has been granted 5 patents for "electrochemical cells"—design and manufacturing (Figure 14). Their exact stage of development and commercialization of the technology is not clear.



METHOD FOR MANUFACTURE AND STRUCTURE OF MULTIPLE ELECTROCHEMISTRIES AND ENERGY GATHERING COMPONENTS WITHIN A UNIFIED STRUCTURE

U.S. Application | Pub No. US20100136245 | Filed: 11/06/2009 | Published: 06/03/2010
Assignee(s): Sakti3, Inc. | Inventor(s): Fabio Albano + 2
Sakti3, Inc....
Add to list

CONTROL OF CELLS, MODULES AND A PACK COMPRISED OF HYBRIDIZED ELECTROCHEMISTRIES

U.S. Application | Pub No. US20100138072 | Filed: 11/06/2009 | Published: 06/03/2010
Assignee(s): Sakti3, Inc. | Inventor(s): Chia Wei Wang + 2
Sakti3, Inc....
Add to list

COMPUTATIONAL METHOD FOR DESIGN AND MANUFACTURE OF ELECTROCHEMICAL SYSTEMS

U.S. Application | Pub No. US20090326696 | Filed: 06/15/2009 | Published: 12/31/2009
Assignee(s): Sakti3, Inc. | Inventor(s): Chia-Wei Wang + 2
Sakti3, Inc....
Add to list

METHOD FOR HIGH VOLUME MANUFACTURE OF ELECTROCHEMICAL CELLS USING PHYSICAL VAPOR DEPOSITION

U.S. Application | Pub No. US20090325063 | Filed: 06/15/2009 | Published: 12/31/2009
Assignee(s): Sakti3, Inc. | Inventor(s): Fabio Albano + 2
Sakti3, Inc....
Add to list

ELECTROCHEMICAL CELL INCLUDING FUNCTIONALLY GRADED AND ARCHITECTURED COMPONENTS AND METHODS

U.S. Application | Pub No. US20100035152 | Filed: 08/04/2009 | Published: 02/11/2010
Assignee(s): Sakti3, Inc. | Inventor(s): Ann Marie Sastry + 2
Sakti3, Inc....
Add to list

Figure 14: Patents Granted to Sakti3 (as of 6/28/2011)

Seeo, a U.S. startup competitor solid-state polymer lithium battery has 18 patents (using technology from Lawrence Berkeley National Laboratory). Researchers in University of Bologna, Italy have also developed a solid-state polymer lithium metal battery having a LiFePO4/C composite cathode and a poly(ethylene oxide) PEO-based solid polymer electrolyte (Damen, Hassoun, Mastragostino, & B. Scrosati, 2010). They tested this against standards set by USABC-DOE (United States Advanced Battery Consortium (USABC), Electric Vehicle Battery Test Procedure Manual, 1996) with favorable results.

Sakti3 may have some competitive advantage of their technology but this is not clear from the current literature. For the technology to be successful the manufacturing and integration processes are equally important and for these Sakti3 appears to be at a less mature level.

Conclusion

This is an initial conclusion on new battery technologies for electric vehicles and the role of Sakti3 as player in this market. A top-down review of the electric vehicle market, use of the Li-ion battery as the main battery type with its diverse configurations and variations including the solid-state battery, and the market players was conducted to get an overview of the market and Sakti3's potential to succeed on a "technology basis". The patent survey revealed that Li-ion solid state batteries are a very competitive state and the top assignees have significant patents in this space. Sakti3 may have a role as a provider of low-cost IP (intellectual property) to General Motors (one of its investors), its 5 patents may have blocking value, or its simulation software may be marketable.

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