Chemistry Innovations in Sustainable Development

'Learning-by-Notes' Package for Senior School

Lesson 12: Green Chemistry

Making Better Batteries

Teaching Sustainability in High Schools: Subject Supplement

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The Natural Edge Project

The Natural Edge Project (TNEP) is an independent non-profit Sustainability Think-Tank based in Australia. TNEP operates as a partnership for education, research and policy development on innovation for sustainable development. TNEP's mission is to contribute to, and succinctly communicate, leading research, case studies, tools, policies and strategies for achieving sustainable development across government, business and civil society. Driven by a team of early career Australians, the Project receives mentoring and support from a range of experts and leading organisations in Australia and internationally, through a generational exchange model. TNEP's initiatives are not-for-profit. Our main activities involve research, creating training and education material and producing publications. These projects are supported by grants, sponsorship (both in-kind and financial) and donations. Other activities involve delivering short courses, workshops, and working with our consulting associates as we seek to test and improve the material and to supplement the funds required to run the project. All support and revenue raised is invested directly into existing project work and the development of future initiatives.

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Lesson 12: Green Chemistry

Making Better Batteries

Persistent organic pollutants and other obsolete pesticides and heavy metals, such as nickel or cadmium from batteries, may contaminate soil and water systems. During an extreme weather event such as a hurricane, the contamination can be massive in scale and costly to remediate.

Basel Convention[1]

Educational Aim

This lesson aims to introduce students to the issues and possible opportunities within the field of batteries, as well as the role batteries will play in enabling sustainable development. In particular, this lesson highlights the opportunities in hybrid-electric and electric vehicle applications, biodegradable batteries, and batteries that can support reliable renewable energy supply.

Key Words for Searching Online

Electrochemical cell, oxidation-reduction, redox, types of batteries, closed loop thermochemical energy storage, hybrid-electric vehicle.

Key Learning Points

1. A sustainable energy future is likely to require the widespread use of renewable energy technologies, such as solar photovoltaics, wind power, geothermal, tidal power and wave power. One of the richest renewable energy sources in Australia is solar energy, however, in the past a major barrier to renewable energy use has been the variable supply of energy (i.e. during the day only, or during windy weather), as battery technology was not advanced enough to store energy for use when the sun was not shining, or the wind was not blowing.
2. Batteries have a very important role in a creating a sustainable energy future by providing a reliable source of stored chemical energy. In effect batteries can provide society with a consistent supply – or 'base load' – of energy that is generated from renewable sources. However, batteries in use around the world today still contain a number of heavy metals which can include Aluminium, Cadmium, Mercury, Nickel, Lead, Iron, Zinc, Calcium, Magnesium, and Lithium, which can be highly toxic for humans, animals and plants, and pollute the soil and groundwater. According to Colin Butfield, Head of Campaigns at the World Wildlife Fund (WWF) in the UK, *'In the UK, 660 million batteries are bought each year.*

[1] UNEP (2008) *Our Sustainable Future: The Role of the Basel Convention,* A brochure by the United Nations Environment Program about the 'Basel Convention: The World Environmental Agreement on Wastes', p2. Available at http://www.basel.int/pub/broch090508.pdf. Accessed 19 November 2008.

95 percent of these are disposable - cumulatively that's an enormous amount of batteries heading straight to landfill, releasing damaging chemicals into the environment.'[2]

3. If batteries are going to form part of a future 'sustainable society', a key question to ask about battery design and use is, what materials and processes are used to make them? It is important for designers to ask questions, such as, 'how can we use safe materials that are plentiful (or renewable) to make batteries? How can we ensure that the battery components can be easily recycled into new batteries? How can we develop a 'low energy' process to make batteries? How do we ensure the battery has a long life?'

4. A 'battery' is essentially any device that generates electricity as 'direct current' (DC) via an *electrochemical process*. The device can comprise one or more electrochemical *cells.* Chemical energy is stored in molecules in each electrochemical cell (i.e. a 'cell') and is released as electrical energy, or electricity, when a particular chemical reaction takes place. Each cell is comprised of: an *anode* (negative electrode), a *cathode* (positive electrode), an *electrolyte* and an *external electric circuit*.[3] The *electrochemical process* in a cell is called an *oxidation-reduction*, or *redox*, *reaction*. An oxidation-reduction reaction involves two *half-reactions*, including an oxidation half-reaction at the anode, where electrons are released, and a reduction half-reaction at the cathode, where electrons are accepted.

5. The full reaction can be completed only when there is an external electric circuit connected to the electrodes. The specific half-reactions, voltage produced (called the *characteristic voltage*) and rechargeability, depend on the materials from which the anode, cathode and electrolyte are made. Batteries are often used in devices that require more voltage or current than a single battery can provide. In these devices, multiple batteries are arranged 'in series' (serial, where the voltages add up and the current stays the same) or 'in parallel' (where the currents add up and the voltage stays the same) to meet the requirements.[4]

6. Two common batteries available for use today are 'alkaline batteries' which are non-rechargeable, and lead-acid batteries which are one of the earliest rechargeable types, but quite toxic to the environment (see Brief Background Information for how these batteries work). There is significant research being undertaken to find safer, more environmentally benign options for rechargeable batteries, with alternatives such as 'nickel metal hydride' batteries becoming quite popular for mobile applications such as radios, shavers etc. UNIROSS is an example of a global corporation that just produces rechargeable batteries, partnering with the World Wildlife Fund (WWF) to research battery design and production.[5]

7. A new type of battery called the 'lithium-ion' battery has a high energy capacity for its low mass, which makes it very suitable for mobile devices such as laptop computers and mobile phones (see Brief Background Information for how these batteries work). This innovation has also allowed vehicle makers to greatly extend their vehicles range without excessive mass, [6] as lithium-ion batteries produce much more energy for their mass (150 Watt hours per kilogram (i.e. energy density – 'Wh/kg')), compared with 100 Wh/kg for nickel metal hydride

[2] Dabek, B. (2008) '5 Reasons To Use Rechargeable Batteries', *AboutMyPlanet,* 10 January 2008. Available at http://www.aboutmyplanet.com/science-technology/green-household-batteries/. Accessed 19 November 2008.
[3] See Encyclopedia Britannica Online – *Electrolytic Cell: Basic Components*, *Online Art* at http://www.britannica.com/eb/art-1405. Accessed 16 May 2008.
[4] Brain, M. and Bryant, C.W. (2008) 'How Batteries Work', *Howstuffworks*. Available at http://electronics.howstuffworks.com/battery.htm. Accessed 15 May 2008.
[5] See UNIROSS Website at http://www.uniross.com/consumer_html/enviroment.php. Accessed 20 November 2008.
[6] Voelcker, J. (2007) 'Lithium Batteries for Hybrid Cars', *IEEE Spectrum Online*, January 2007. Available at http://www.spectrum.ieee.org/jan07/4848. Accessed 16 May 2008.

(previously used for hybrid-electric vehicles) and 25 Wh/kg for lead-acid batteries (used for diesel/ petrol/ LPG powered vehicles).[7]

8. With regard to environmental performance, while other types of batteries include toxic metals such as cadmium, the metals in lithium-ion batteries (cobalt, copper, nickel and iron) are considered safe for landfills or incinerators. However, there is still an issue with billions of these batteries being thrown away to landfills around the world, rather than being recycled. This situation is improving, with for example, the European Union passing a battery recycling law in 2006 that requires vendors in member states to reclaim for recycling a minimum of 25 per cent of the batteries they manufacture and sell by 2012, and 45 per cent by 2016 (including lithium-ion batteries).[8]

9. As research progresses with better battery design, there are opportunities to improve the performance of some types of batteries in the interim, by combining them with other technologies. An example of a combined battery technology is the *UltraBattery* developed by CSIRO in Australia. The UltraBattery combines a lead-acid battery and a 'super-capacitor' in a single cell that delivers high total energy, high burst energy, fast charge and discharge, and long life at about 70 per cent lower cost than current hybrid-electric car battery systems.

10. Chemists are also researching ways to create a totally different type of battery using advanced green nano-chemistry. Rather than 'building' a new battery, researchers in America have developed a virus which can latch onto and coat itself with inorganic materials including gold and cobalt, turning each virus strand into a tiny length of wire. Lined up, these nano-wires form compact and powerful battery components. As the viral battery essentially grows itself (using water as a solvent), there is practically no waste and it is biodegradable. According to the research team, by weight the virus-based batteries are roughly twice as powerful as traditional chemical batteries (see Brief Background Information).[9]

11. In addition to mobile and vehicle applications, perhaps the ultimate design challenge for battery technology is to find environmentally friendly processes and resources to make reliable, efficient and effective batteries that can generate electricity from renewable energy! Recent innovations in batteries have meant that renewable energy technologies can now be used to provide a constant supply of electricity, storing excess energy for later use. For example, UltraBateries' long life reliability makes them suitable for use with renewable energy technologies that face the challenges of an intermittent energy source, such as solar energy technologies and wind turbines.

12. In Australia there is particular interest in using batteries to provide a constant flow of electricity from solar energy, as Australia receives a large amount of solar energy on its surface (called insolation).[10] Researchers are developing innovations for 'solar photovoltaic technologies' (discussed in Lesson 5) that work with battery storage. In addition, 'solar thermal' technologies are also presenting interesting opportunities for renewable energy supply, where a different type of 'thermochemical energy storage' can be used to store the sun's energy in gases, for later use in a chemical reaction (see Brief Background Information

[7] See Everything2 – *Energy Density* at http://everything2.com/index.pl?node=energy%20density. Accessed 16 May 2008.
[8] See European Commission - *Batteries* at http://ec.europa.eu/environment/waste/batteries/index.htm. Accessed 19 November 2008.
[9] Bland, E. (2008) 'Viruses to power batteries of the future', *ABC Science: News in Science,* 1 September 2008. Available at http://www.abc.net.au/science/articles/2008/09/01/2352015.htm. Accessed 3 November 2008.
[10] Lovegrove, K. (2007) 'Maintaining Australia as an Energy Exporter', ANZSES Solar Congress, October 2007.

for how this process works). This process is a ‘closed loop’, where the gases are in a sealed circuit and so never need to be replaced.

Brief Background Information

The Role of Batteries in a Sustainable Energy Future

Batteries provide a source of stored chemical energy, which is used to power many conveniences in our 21st Century lifestyle - from clocks and watches, mobile phones and laptop computers, electric toothbrushes, shavers, heart monitors, hearing aids, cars, trucks and boats. Chemical energy is stored in molecules and is released as electrical energy (electricity) when particular chemical reactions take place.

In addition to such conveniences, batteries also have an important role in creating a sustainable energy future, particularly when considering how renewable energy might be used to power mobile devices (i.e. any device that can be moved around) and freight-carrying vehicles:

- The future is likely to include the widespread use of *mobile devices*, from laptop computers and mobile phones, to *freight-carrying vehicles*, which are one of the world's largest consumers of non-renewable energy sources. Most mobile devices have not been able to take advantage of renewable energy technologies in the past because they could not physically access renewable energy sources, and could not carry the technology on board. In this lesson we consider how batteries can help to overcome these issues.
- The future is likely to require the widespread use of *renewable energy technologies*, such as solar photovoltaics, wind power (see Lesson 5), geothermal (see Lesson 6), tidal power and wave power (see Lesson 8). Many renewable energy technologies have the drawbacks that their energy source is not always available (for example solar and wind energy), or not available everywhere (wind, geothermal, tidal, and wave energy). One of the richest renewable energy sources in Australia is solar energy, and in this lesson we discuss how batteries can help to overcome the day-night variability in solar energy supply.

However, in considering the potential for batteries to capture renewable energy, and power our energy intensive lifestyles, we need to be mindful of the environmental consequences of producing batteries to do this. After all, a battery that requires toxic materials and a lot of energy to produce is potentially not a sustainable option! With this in mind, it is important for designers to ask such questions as:

- How can we use safe materials that are plentiful (or renewable) to make a battery that meets our needs?
- How can we develop a 'low energy' process to make the battery?
- How can we ensure that the battery components can be easily recycled into new batteries?
- How do we ensure the battery has a long life, either through slow release energy or improving rechargeability?

With regard to recharging, an independent study commissioned in 2008 by rechargeable battery manufacturer UNIROSS and endorsed by the World Wildlife Federation has found that, when compared with disposable batteries, rechargeable batteries have significant advantages because fewer are required and they are less toxic.[11] According to the report there are also savings in waste packaging, since one pack of rechargeable batteries is needed to obtain 1kWh

[11] See Greener Loudoun - *Are rechargables better than disposable batteries*? at http://greenerloudoun.wordpress.com/2008/01/10/are-rechargables-better-than-disposable-batteries/ Accessed 15 December 2008

of energy compared with 93 packs of disposable batteries. Perhaps the ultimate design challenge is to find environmentally friendly processes and resources to make reliable, efficient and effective batteries that can be indefinitely recycled!

A Brief Look at How Batteries Work

Batteries are made up of one or more *electrochemical cells*, which are devices that generate electricity as direct current (DC) via an *electrochemical process*.

Each electrochemical cell, or simply *cell*, is comprised of the following, as shown in Figure 12.1:

- An *anode* (negative electrode): a solid that gives up electrons, usually a highly-reactive metal.
- A *cathode* (positive electrode): a solid that accepts electrons, usually a moderately reactive metal or a compound of this metal.
- An *electrolyte*: a solid or solution that facilitates the flow of *cations* (positive ions) or *anions* (negative ions) from one electrode to the other, usually an acid or a base.
- An *external electric circuit* (technically not part of the cell): a metal wire and *load* (i.e. the device to be powered) that carries electrons from the anode terminal to the cathode terminal.

Fundamentals

Electricity, or *electric current*, is the flow of electrical charge. Electrons carry electrical charge. Thus, the flow of many electrons creates an electrical current.

Fundamentals

Ions are atoms or molecules that are either positively-charged due to losing an electron; or negatively-charged due to gaining an electron.

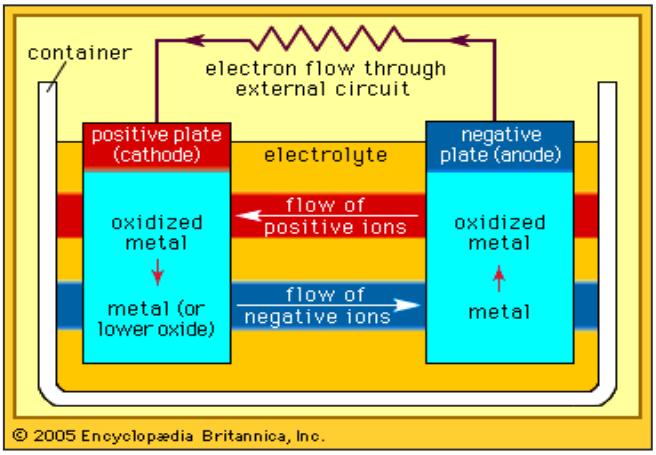

Figure 12.1. An electrochemical cell

Source: Encyclopedia Britannica, Inc.[12]

The *electrochemical process* in a cell is called an *oxidation-reduction*, or *redox*, *reaction*. An oxidation-reduction reaction involves two *half-reactions*:

[12] See Encyclopedia Britannica Online – *Electrolytic Cell: Basic Components*, Online Art at http://www.britannica.com/eb/art-1405. Accessed 16 May 2008.

- An oxidation half-reaction at the anode, which releases electrons; and
- A reduction half-reaction at the cathode, which accepts electrons.

The full reaction can be completed only when there is an external electric circuit connected to the electrodes, which is why batteries can retain their charge when they are not in use. The specific half-reactions, voltage produced (called the *characteristic voltage*) and 'rechargeability' of the battery depends on what materials are used to make the anode, cathode and electrolyte.

Multiple batteries are often used in devices that require more voltage or current than a single battery can provide, as shown in Figure 12.2:

– *Parallel*: batteries are arranged next to each other, with the external electric circuit connecting to every battery's anode and cathode terminal. The currents add up and the voltage stays the same. The parallel arrangement of the four AA batteries (1.5 V, 3 mAh) provides 1.5 V and 12 mAh.

– *Series* (serial): batteries are arranged end-to-end, with the external electric circuit connecting to the first battery's anode and last battery's cathode. The voltages add up and the current stays the same. The serial arrangement of the four AA batteries (1.5 V, 3 mAh) provides 6 V and 3 mAh.

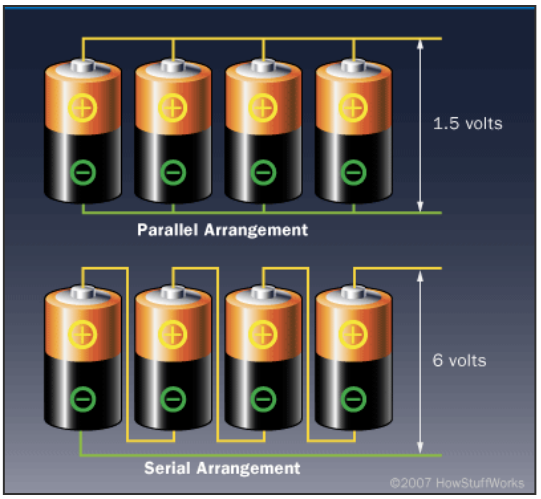

Figure 12.2. Batteries in series (serial) and parallel arrangement

Source: Brain, M. and Bryant, C.W. (2008)[13]

[13] Brain, M. and Bryant, C.W. (2008) 'How Batteries Work', *Howstuffworks*. Available at http://electronics.howstuffworks.com/battery.htm. Accessed 15 May 2008.

A Brief Look at Two Common Types of Batteries

There are many types of batteries and readers are encouraged to view websites by *PowerStream,*[14] *Brain and Bryant,*[15] and *Goebel*[16] to learn more about how different types of batteries work.

Generally speaking, there are two groups of batteries:

1. Batteries used once and then thrown away, also called 'disposable' or 'primary' batteries (for example alkaline, lithium, saline etc).
2. Batteries that can be recharged, commonly known as 'rechargeable' batteries (for example lead-acid, lithium-ion, and nickel metal hydride).

We will now discuss two common 'conventional' types of batteries on the market: 1) alkaline batteries (non-rechargeable); and 2) lead-acid batteries (rechargeable), to provide examples of how different batteries operate and subsequent differences in environmental impacts.

1. Alkaline Batteries

These *non-rechargeable* or 'disposable' batteries come in well-recognised sizes such as 'triple-A' (AAA), 'double-A' (AA), C and D, and are used for a wide variety of applications, for virtually any piece of equipment that needs a small to moderate power source. The component materials and reactions of Alkaline batteries are presented in Table 12.1.

Table 12.1: Component materials and reactions in alkaline batteries

Component materials	
Anode:	zinc (Zn) powder
Cathode:	manganese (IV) dioxide (MnO_2) powder
Electrolyte:	potassium hydroxide (KOH) aqueous solution
Reactions	
Anode (half):	$Zn + 2OH^- \rightarrow ZnO + H_2O + 2e^-$
Cathode (half):	$2MnO_2 + H_2O + 2e^- \rightarrow Mn_2O_3 + 2OH^-$
Overall:	$Zn + 2MnO_2 \rightarrow ZnO + Mn_2O_3$

Source: *PowerStream*[17]

In the battery cell, the potassium hydroxide electrolyte separates into potassium ions (K^+) and hydroxide ions (OH^-) and the following reaction occurs when the external electric circuit is complete:

– In the anode half-reaction, zinc reacts with hydroxide ions in the electrolyte to produce zinc oxide (ZnO), water (H_2O) and electrons (e^-). The water moves to the cathode through the electrolyte and the electrons move to the cathode through the external electric circuit.

[14] See PowerStream website – *PowerStream Battery Chemistry FAQ* at http://www.powerstream.com/BatteryFAQ.html. Accessed 16 May 2008.
[15] Brain, M. and Bryant, C.W. (2008) 'How Batteries Work', *Howstuffworks*. Available at http://electronics.howstuffworks.com/battery.htm. Accessed 15 May 2008.
[16] Goebel, G. (2007) *Elementary Chemistry*, Chapter 12: Batteries & Fuel Cells. Available at http://www.vectorsite.net/tpchem.html. Accessed 16 May 2008.
[17] See PowerStream website – *PowerStream Battery Chemistry FAQ* at http://www.powerstream.com/BatteryFAQ.html. Accessed 16 May 2008.

– In the cathode half-reaction, manganese (IV) dioxide reacts with water and electrons (both created at the anode) to produce manganese (III) oxide (Mn_2O_3) and hydroxide ions. The hydroxide ions move to the anode through the electrolyte.

The flow of electrons caused by these half-reactions produce a characteristic voltage of 1.5 Volts (V).[18] As long as the external electric circuit is connected, these half-reactions continue until all the zinc and manganese (IV) dioxide is converted into zinc oxide and manganese (III) oxide, after which the battery is flat and cannot be recharged.

Unfortunately, alkaline batteries can contain a number of heavy metals including Aluminium, Cadmium, Mercury, Nickel, Lead, Iron, Zinc, Calcium, Magnesium, and Lithium, which can be highly toxic for humans, animals and plants, polluting soil and groundwater. According to Colin Butfield, Head of Campaigns at the World Wildlife Fund (WWF) in the UK, *'In the UK, 660 million batteries are bought each year. 95 percent of these are disposable - cumulatively that's an enormous amount of batteries heading straight to landfill, releasing damaging chemicals into the environment.'*[19]

2. Lead-Acid Batteries

The oldest type of *rechargeable* battery, the lead-acid battery is perhaps most recognisable in the form of car batteries, although they are also used extensively as a back-up supply in power stations and other power-reliant industries. There are two types – starting batteries which deliver a short burst of high power, and deep-cycle batteries which deliver a lower, steady level of power for a much longer time. Lead-acid batteries have component materials and reactions as seen in Table 12.2.

Table 12.2: Component materials and reactions in lead-acid batteries

Component materials	
Anode:	metallic lead (Pb) sponge
Cathode:	lead dioxide (PbO_2) powder
Electrolyte:	sulfuric acid (H_2SO_4) aqueous solution
Reactions	
Anode (half):	$Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$
Cathode (half):	$PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$
Overall:	$Pb + PbO_2 + 2SO_4^{2-} + 4H^+ \rightarrow 2PbSO_4 + 2H_2O$

Source: *PowerStream*[20]

In the cell, the sulfuric acid electrolyte separates into hydrogen ions ($2H^+$) and sulfate ions (SO_4^{2-}) and the following reaction occurs when the external electric circuit is complete:

[18] Goebel, G. (2007) *Elementary Chemistry*, Chapter 12: Batteries & Fuel Cells. Available at http://www.vectorsite.net/tpchem.html. Accessed 16 May 2008.
[19] Dabek, B. (2008) '5 Reasons To Use Rechargeable Batteries'. *AboutMyPlanet*., 10 January 2008. Available at http://www.aboutmyplanet.com/science-technology/green-household-batteries/. Accessed 19 November 2008.
[20] See PowerStream website – *PowerStream Battery Chemistry FAQ* at http://www.powerstream.com/BatteryFAQ.html. Accessed 16 May 2008.

- In the anode half-reaction, lead reacts with sulfate ions in the electrolyte to produce lead sulfate ($PbSO_4$) and electrons (e^-). The electrons move to the cathode through the external electric circuit.
- In the cathode half-reaction, lead dioxide reacts with sulfate ions and hydrogen ion in the electrolyte, and electrons (created at the anode) to produce lead sulfate and water.

The flow of electrons caused by these half-reactions produce a characteristic voltage of 2.39 V.[21] As long as the external electric circuit is connected, these half-reactions continue until all the lead and lead dioxide is converted into lead sulfate and water, after which the battery is flat. However, the lead-acid battery can be recharged by applying the characteristic voltage to the opposite terminals, which reverses the reactions and hence causes the lead and lead dioxide to reform.

With regard to environmental impact, the process used to create the lead for the batteries (i.e. lead smelting operations) is quite toxic and energy intensive, and continuous improvement in battery recycling plants and furnace designs is required to keep pace with emission standards for lead smelters. Lead acid batteries pose a potential threat to human health and the environment if improperly discarded, as the two main components of these batteries are sulfuric acid and lead which can contaminate soil and ground water. Fortunately lead-acid battery recycling is one of the most successful recycling programs in the world – for example, in the United States 97 per cent of all battery lead was recycled between 1997 and 2001.[22] The typical new lead-acid battery contains 60 to 80 per cent recycled lead and plastic. [23]

Low Impact Battery Innovations

There is significant research underway around the world to find more environmentally friendly solutions to battery design, where manufacture and disposal impacts on the environment are minimised and possibly avoided altogether. We will now consider a number of innovations including:

- Hybrid-Electric and Electric Vehicles – Lithium-Ion Battery Innovation
- Combined Battery Technologies
- 'Virus' Battery Technology
- Solar-Thermal Battery-Style Technology

[21] See PowerStream website – *PowerStream Battery Chemistry FAQ* at http://www.powerstream.com/BatteryFAQ.html. Accessed 16 May 2008.
[22] See Battery Council International website at http://www.batterycouncil.org/LeadAcidBatteries/BatteryRecycling/tabid/71/Default.aspx. Accessed 3 December 2008.
[23] Ibid.

Hybrid-Electric and Electric Vehicles – Lithium-Ion Battery Innovation

Batteries are used in hybrid-electric vehicles to provide energy to the electric motor. Until recently, in hybrid-electric vehicles, the battery's relatively low energy and high mass were somewhat limiting factors to the distance a vehicle can travel (called the range) on battery alone and the vehicle's acceleration. However, recent innovation in the form of a *lithium-ion* battery, has allowed vehicle makers to greatly extend their vehicles range without excessive mass:

> *The first production car to use lithium-ion batteries was the Toyota Vitz CVT 4, a small car sold only in Japan. It used a four-cell, 12 ampere-hour lithium-ion battery pack to power its electric accessories and restart the engine after idle stop. More recently, Tesla Motors, in San Carlos, Calif., has offered the Tesla Roadster, an all-electric sports car that uses 6831 lithium-ion cells, each roughly the size of a double-A battery. They give the car up to 400 km (250 miles) of range, as well as the breathtaking acceleration of 0 to 100 kilometers per hour (0 to 60 miles per hour) in less than 4 seconds.*[24]

Lithium-ion batteries are a promising technology for highly efficient, all-electric vehicles because they produce a lot of energy for their mass – 150 Wh/kg, compared with 100 Wh/kg for nickel metal hydride (the previous battery technology for hybrid-electric vehicles) and 25 Wh/kg for lead-acid batteries.[25] However, before lithium-ion batteries are ready for wide-spread use in vehicles, there are a few improvements to be made:

> *To make lithium-ion batteries practical for mass-produced electric-drive vehicles, new technologies must increase the energy the batteries store and the speed with which they can discharge it. They must also lengthen cycle life to 15 years or 241 000 km (150 000 miles) - the average life of a vehicle. Finally, they must keep the cost as low as possible.*[26]

Lithium-ion batteries' high energy capacity for their low mass also makes them suitable in mobile devices such as laptop computers and mobile phones. Lithium-ion batteries' components materials and reactions are summarised in Table 12.3.

Table 12.3: Component materials and reactions in lithium-ion batteries

Component materials	
Anode:	lithium graphite (LiC_6)
Cathode:	lithium cobalt oxide ($LiCoO_2$)
Electrolyte:	lithium hexafluorophosphate ($LiPF_6$) aqueous organic solution
Reactions	
Anode (half):	$LiC_6 \rightarrow C_6 + Li^+ + e^-$
Cathode (half):	$CoO_2 + Li^+ + e^- \rightarrow LiCoO_2$
Overall:	$LiC_6 + CoO_2 \rightarrow C_6 + LiCoO_2$

Source: Bergveld, H.J., Kruijt W.S. and Notten P.H.L. (2002);[27] Dhameja, S. (2001)[28]

[24] Voelcker, J. (2007) 'Lithium Batteries for Hybrid Cars', *IEEE Spectrum Online*. Available at http://www.spectrum.ieee.org/jan07/4848. Accessed 16 May 2008.
[25] See Everything2 – *Energy Density* at http://everything2.com/index.pl?node=energy%20density. Accessed 16 May 2008.
[26] Voelcker, J. (2007) 'Lithium Batteries for Hybrid Cars', *IEEE Spectrum Online*. Available at http://www.spectrum.ieee.org/jan07/4848. Accessed 16 May 2008.
[27] Bergveld, H.J., Kruijt W.S. and Notten P.H.L. (2002) *Battery Management Systems: Design by Modelling*, Springer, pp107-108,113.
[28] Dhameja, S. (2001) *Electric* Vehicle *Battery Systems*, Newnes, p12.

In the cell, the lithium hexafluorophosphate electrolyte separates into lithium ions (Li^+) and hexafluorophosphate ions (PF_6^-) and the following reaction occurs when the external electric circuit is complete:

- In the anode half-reaction, lithium graphite separates into graphite (C_6), lithium ions (Li^+) and electrons (e^-). The lithium ions move to the cathode through the electrolyte and the electrons move to the cathode through the external electric circuit.
- In the cathode half-reaction, cobalt oxide (CoO_2), lithium ions (Li^+) and electrons (e^-) combine into lithium cobalt oxide.

The flow of electrons caused by these half-reactions produce a characteristic voltage of up to 4 V.[29] As long as the external electric circuit is connected, these half-reactions continue until all the lithium graphite and cobalt oxide is converted into graphite and lithium cobalt oxide, after which the battery is flat. The battery can be then be recharged by applying the characteristic voltage to the opposite terminals, which reverses the reactions and hence causes the lithium graphite and cobalt oxide to reform.

The reactions in lithium-ion batteries differ from the reactions in alkaline and lead-acid batteries in that they *don't* involve the electrolyte (although the electrolyte does play an important role that is not discussed in this lesson). The reactions in lithium-ion batteries represent a simple exchange of lithium ions and electrons between the graphite anode and the cobalt oxide cathode, seen in Figure 12.3.

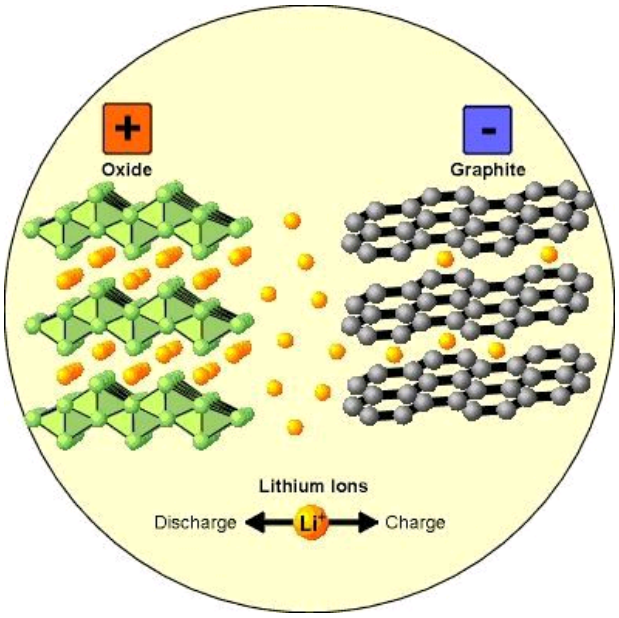

Figure 12.3. Exchange of lithium ions in between the anode and cathode of a lithium-ion electrochemical cell

Source: Paul Scherrer Insitut[30]

Lithium-ion batteries incorporate a computer-controlled electronic circuit that ensures the battery's safety and longevity. The circuit's tasks include:[31]

[29] Brain, M. (n.d.) 'How Lithium-Ion Batteries Work', *Howstuffworks*. Available at http://electronics.howstuffworks.com/lithium-ion-battery.htm. Accessed 15 May 2008; See Harding Energy, Inc.– *Lithium Ion* at http://www.hardingenergy.com/pdfs/LiIon.pdf. Accessed 16 May 2008; See Paul Scherrer Insitut - *Batteries* at http://ecl.web.psi.ch/lithium/. Accessed 16 May 2008.
[30] See Paul Scherrer Insitut - *Batteries* at http://ecl.web.psi.ch/lithium/. Accessed 16 May 2008.

- maintaining safe operating temperatures and turning off the battery when the temperature is dangerously high;
- maintaining safe and appropriate voltage and current output (during discharge) and input (during charge);
- preventing the voltage from exceeding 4.5 V or falling below 3 V, which would degrade the battery; and
- managing the charging process to minimise recharge time.

Although lithium-ion batteries contain an ionic form of lithium they contain no lithium metal and are classified by the US federal government as non-hazardous waste and are safe for disposal in the normal municipal waste stream. [32] While other types of batteries include toxic metals such as cadmium, the metals in lithium-ion batteries (cobalt, copper, nickel and iron) are considered safe for landfills or incinerators. However, a bigger issue is the throwing away of more than 2 billion batteries a year, when this material that could be recovered through recycling. For example, each lithium-ion battery contains between 10 to 13 per cent cobalt by weight and it is estimated that between 8,000 and 9,000 tons of cobalt is used in the manufacture of lithium-ion batteries each year.[33] While the market does not factor in the social cost of disposal, or the lower economic and environmental cost of recycling rather than mining raw materials such as cobalt, these batteries are still being thrown away by the millions. The European Union passed a battery recycling law in 2006 that requires vendors in member states to reclaim for recycling a minimum of 25 per cent of the batteries they manufacture and sell by 2012, and 45 per cent by 2016, including lithium-ion batteries.[34]

Combined Battery Technologies

As the research progresses on better and more environmentally benign batteries, the disadvantages of some types of batteries can be overcome by combining them with other technologies. An example of a combined battery technology is the *UltraBattery*,[35] developed by CSIRO in Australia. The UltraBattery combines a lead-acid battery and a *supercapacitor* in a single cell that delivers high total energy, high burst energy, fast charge and discharge, and long life at about 70 per cent lower cost than current hybrid-electric car battery systems. Consider the following:

- Like most batteries, lead-acid batteries can store a large amount of energy but charge and discharge

Fundamentals

Static electricity is the accumulation of electric *charge* on an object.

An object becomes charged when there is an imbalance between the number of electrons (negative charges) and the number of protons (positive charges).

When a charged object is connected to a *closed electric circuit*, electrons flow to parts of the circuit that best balance all the charges in the circuit. This flow of electrons is *electricity*.

[31] Brain, M. (n.d.) 'How Lithium-Ion Batteries Work', *Howstuffworks*. Available at http://electronics.howstuffworks.com/lithium-ion-battery.htm. Accessed 15 May 2008; See Corrosion Doctors – *Lithium-Ion Batteries: Liquid Electrolyte* at http://www.corrosion-doctors.org/Secondaries/li-ion.htm. Accessed 16 May 2008.

[32] Mitchell, R. (2006) 'Lithium ion batteries: High-tech's latest mountain of waste', *Computer World*, a website blog, August 22, 2006. Available at http://blogs.computerworld.com/node/3285. Accessed 19 November 2008.
[33] Ibid.
[34] See European Commission - *Batteries* at http://ec.europa.eu/environment/waste/batteries/index.htm. Accessed 19 November 2008.
[35] See CSIRO – *UltraBattery: No Ordinary Battery* at http://www.csiro.au/science/UltraBattery.html. Accessed 23 May 2008.

slowly. Their capacity deteriorates after about 1000 recharge cycles.[36]

- *Capacitors*, on the other hand, are energy storage devices that can store relatively little energy but can charge and discharge quickly, delivering high energy for a short period of time. Their capacity deteriorates after about 500,000 recharge cycles.[37] Capacitors store energy as *static electricity*, rather than as an electrochemical process like in a battery.
- *Supercapacitors* are a type of capacitor technology that can store a large amount of energy (thousands of times more charge than regular capacitors) and still charge and discharge quickly, providing an energy burst 50 per cent larger than lead-acid batteries. Supercapacitors can deliver an energy burst large enough for applications such as accelerating a car.
- The *UltraBattery* combines lead-acid batteries and supercapacitors to extend the life of the battery to four times longer than a lead-acid battery operating alone. Since the supercapacitor can accommodate far more recharge cycles, it buffers the smaller bursts of electricity input and output so that the lead-acid battery only experiences relatively steady charges and discharges. Consequently, the lead-acid battery in the UltraBattery undergoes fewer and larger recharge cycles (for which it is more suited) than a lead-acid battery operating alone. The UltraBattery's long life reliability makes it suitable for use with renewable energy technologies that face the challenges of an intermittent energy source, such as solar energy technologies and wind turbines. As it extends the life of the battery, it improves the battery's environmental impact, but does not address the toxicity issues associated with the battery's manufacture and disposal.

'Virus' Battery Technology

Chemists are researching ways to potentially create a new generation of batteries. Angela Belcher - a materials scientist and bioengineer at the US Massachusetts Institute of Technology (MIT) is trying to create a totally different type of battery using advanced green nano-chemistry. Rather than 'building' a new battery, she is growing it. Working with several MIT colleagues, Belcher has engineered a virus known as an *M13 bacteriophage* that latches onto and coats itself with bits of inorganic materials, including gold and cobalt. This process (see Figure 12.4) turns each virus strand into what amounts to a minuscule length of wire.

The key steps include:

1. A polymer electrolyte is dipped into a solution of genetically engineered viruses. These viruses form a uniform coating on the electrolyte.
2. The coated polymer is then dipped into a solution of battery materials. The viruses coat themselves with the battery material, transforming into nano-wires with a regular crystal structure.

If these nano-wires can be lined up, they form compact and powerful battery components. Instead of a conventional battery which generates a lot of waste during manufacture and which is difficult to dispose of due to component heavy metals and acids, a viral battery essentially grows itself (using water as a solvent) so there is practically no waste. According to the research

[36] See CSIRO – *Supercapacitors: Powerful Mobile Energy Storage Devices* at http://www.csiro.au/science/Supercapacitors.html. Accessed 23 May 2008.
[37] See CSIRO – *Supercapacitors: Powerful Mobile Energy Storage Devices* at http://www.csiro.au/science/Supercapacitors.html. Accessed 23 May 2008.

team, by weight the virus-based batteries are roughly twice as powerful as traditional chemical batteries, and it takes about an hour for an M13 battery to form. As most of the components of a viral battery are organic, the battery is also biodegradable. Belcher was voted the 2006 best scientific researcher by Scientific American for the advances she and her team made over the last ten years in this area.[38]

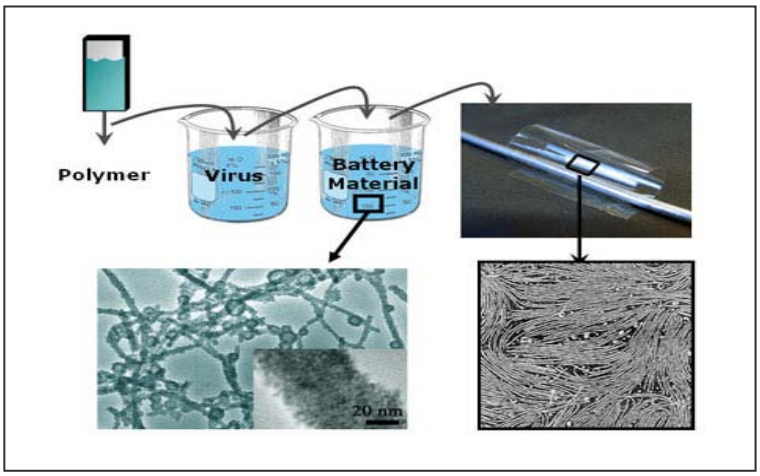

Figure 12.4: A diagram of the process for making a virus-battery

Source: Images courtesy of Angela Belcher in *MIT Technology Review* (2006)[39]

Solar-Thermal Battery-Style Technology

Recent innovations in battery technologies has meant that batteries can now be readily used with renewable energy technologies to provide continuous electricity (i.e. 24 hours/day), rather than just during daylight hours (for solar energy) or during windy periods (for wind energy). As Australia receives a lot of solar energy on its surface (called *insolation*) every day as shown in Figure 12.5, researchers are particularly interested in harnessing this energy effectively. Indeed some researchers have calculated that all of Australia's electricity needs could be met with solar thermal power stations (a type of solar energy technology) covering 20 per cent of a 138 km by 138 km piece of land as shown in Figure 12.6.[40]

[38] Bland, E. (2008) 'Viruses to power batteries of the future', *ABC Science: News in Science,* 1 September 2008. Available at http://www.abc.net.au/science/articles/2008/09/01/2352015.htm. Accessed 3 November 2008.
[39] Bullis, K. (2006) 'Virus-Assembled Batteries - A biological template ramps up electrode performance and scales down size', *MIT Technology Review*, 7 April 2006. Available at http://www.technologyreview.com/read_article.aspx?id=16673&ch=biztech&sc=&pg=1. Accessed 3 November 2008.
[40] Lovegrove, K. (2007) 'Maintaining Australia as an Energy Exporter', ANZSES Solar Congress October 2007.

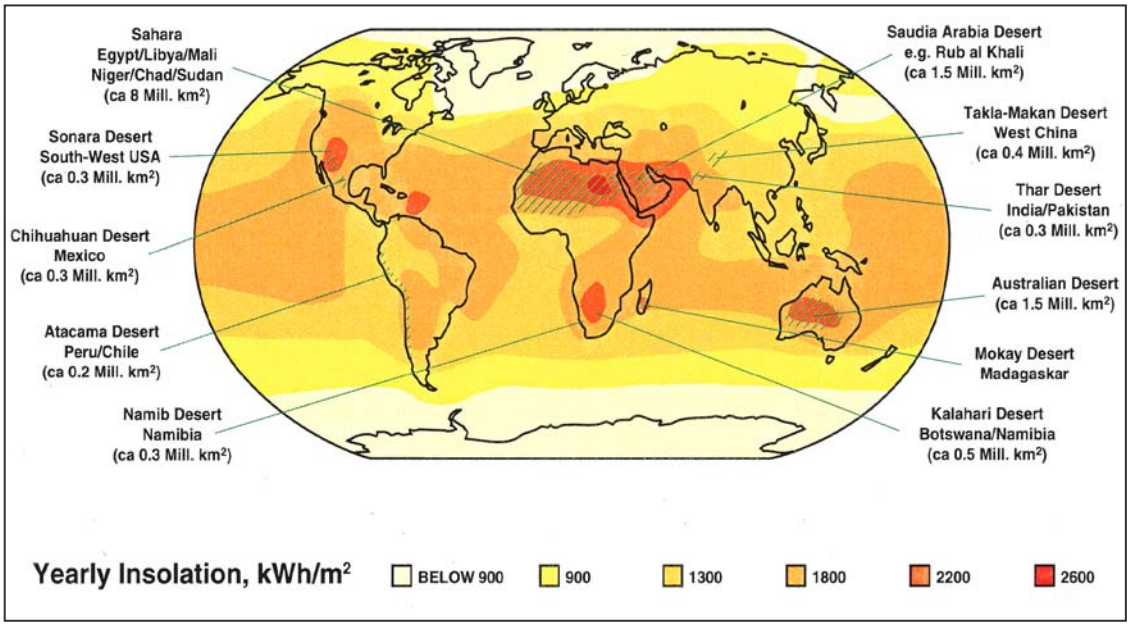

Figure 12.5: Global map of solar resources (KWh/m^2)

Source: Lovegrove, K. (2007)[41]

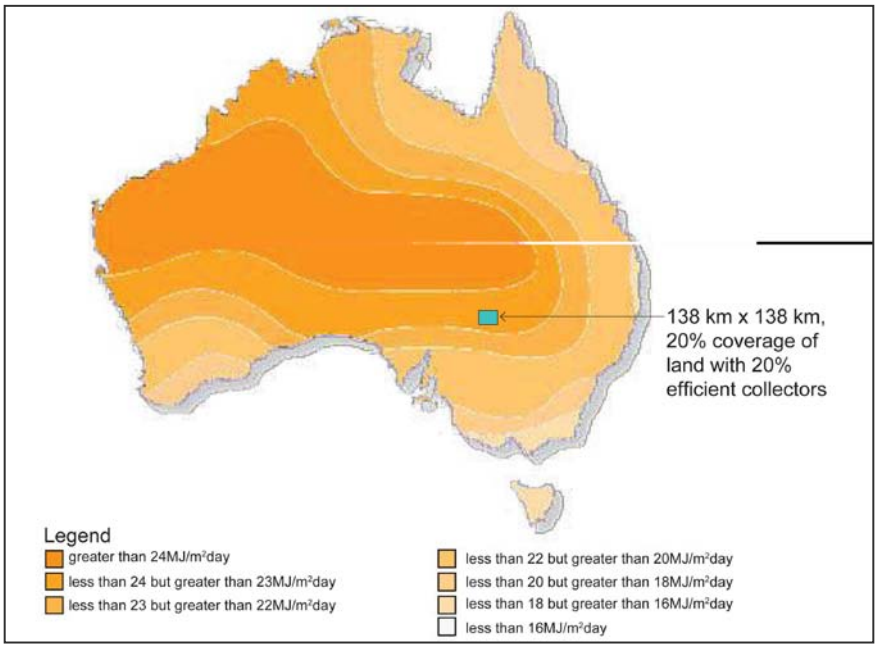

Figure 12.6: Size of solar thermal power stations to meet Australia's electricity needs

Source: Lovegrove, K. (2007)[42]

[41] Lovegrove, K. (2007) 'Maintaining Australia as an Energy Exporter', ANZSES Solar Congress October 2007.
[42] Ibid.

Australian researchers are developing innovations for solar photovoltaic technologies, which are discussed in Lesson 5. In addition, 'solar thermal' technologies are also presenting interesting opportunities for renewable energy supply. As discussed in Lesson 6, the majority of the world's non-renewable electricity is produced using steam turbines and electric generators. The steam is usually produced by burning coal in a boiler or by atomic fission in a nuclear reactor. Alternative technologies for producing steam are now emerging, in the form of 'solar thermal technologies' as shown in Figure 12.7.[43] These technologies use mirrors to capture the heat in the sun's radiation and concentrate it onto 'receivers'. To increase the amount of radiation captured the mirrors also rotate to follow the sun. The heat is then transferred from the receivers to the water, producing steam.

Figure 12.7: The Luz project, the world's largest solar thermal-electric plant, in California's Mojave Desert, USA (peak capacity: 350 MW)

Source: The Open University[44]

But how can the heat be efficiently taken from the receivers, and its energy 'stored' for conversion to electricity later? Storage in the form of hot or 'superheated' water is one option, requiring a very well insulated container. Another process uses a chemical battery-style reaction, called 'closed loop thermochemical energy storage'. This very efficient technology stores the sun's energy in *gases*, for later use in a chemical reaction, as summarised in Figure 12.8.

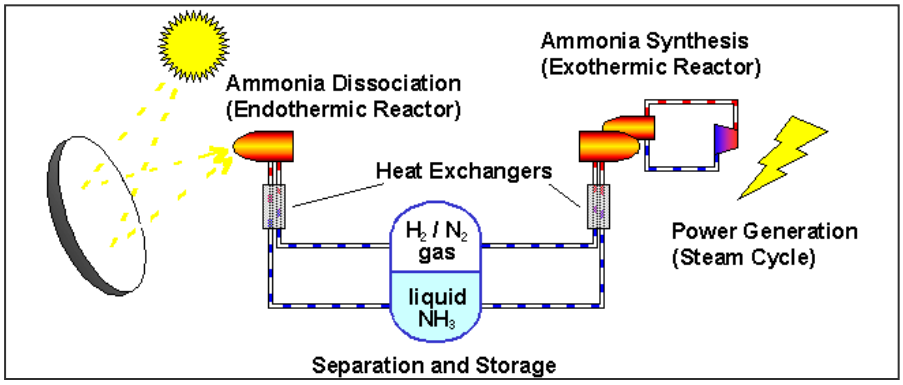

Figure 12.8: Diagram of closed loop thermochemical energy storage using ammonia

Source: Solar Thermal Energy Research[45]

[43] Lovegrove, K. and Dennis, M. (2006) 'Solar thermal energy systems in Australia', *International Journal of Environmental Studies*, Vol 63, No. 6. Available at http://engnet.anu.edu.au/DEresearch/solarthermal/pages/pubs/IJES06.pdf. Accessed 2 June 2007.
[44] See The Open University - *Why Sustainable Energy Matters: 4.2 Solar Energy* at http://openlearn.open.ac.uk/course/view.php?id=1697. Accessed 16 May 2008.

This process is initially an 'endothermic' reaction (i.e. it uses heat), where the sun's heat captured at the receiver is used to separate ammonia (NH_3) into two gases: nitrogen gas (N_2) and hydrogen gas (H_2), according to the following equation:

$$2NH_3 + \text{heat} \rightarrow N_2 + H_2$$

These two gases can then be stored in gas cylinders or tanks indefinitely. When electricity is needed, the nitrogen and hydrogen gases can be brought together and will recombine in an 'exothermic reaction' to produce ammonia as follows:

$$N_2 + H_2 \rightarrow 2NH_3 + \text{heat}$$

The Sun's energy has now been converted back to heat, which can be used to produce the steam needed to create electricity (see Lesson 6 for details about this process).

Thermochemical energy storage is called a 'closed loop' process because the ammonia, nitrogen gas and hydrogen gas are in a sealed circuit and so never need to be replaced. Therefore, there are minimal material requirements over the life of the system (apart from maintenance of the cylinders and panels), and minimal disposal requirements as most of the component materials can be recycled.

[45] See The Australian National University: Solar Thermal Energy Research - *Closed Loop Thermochemical Energy Storage System Using Ammonia* at http://engnet.anu.edu.au/DEresearch/solarthermal/high_temp/thermochem/index.php. Accessed 16 May 2008.

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3. Goebel, G. (2007) *In the Public Domain: Elementary Chemistry*, Chapter 12: Batteries & Fuel Cells. Available at http://www.vectorsite.net/tpchem.html. Accessed 16 May 2008.
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5. See PowerStream – *PowerStream Battery Chemistry FAQ* at http://www.powerstream.com/BatteryFAQ.html. Accessed 16 May 2008.
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