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CSIRO UltraBattery & Renewable Energy Storage

Melbourne ATA meeting – 16 September 2009

Chris Phyland
CSIRO Energy Transformed Flagship

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Thank you for the opportunity to speak at your meeting. In this presentation I would like to tell you about three different research programs that I'm currently involved in…

Presentation Outline

CSIRO UltraBattery

UltraBattery in Wind Energy applications

Domestic Energy Storage (Vehicle to Grid – V2G)

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The three research programs are:

The CSIRO developed "UltraBattery": What it is; Why it was developed; and some test results.

A research program underway to use the UltraBattery in wind energy applications; and

A recently started program to investigate strategies to use PHEVs as an energy storage device in a domestic house.

The UltraBattery

It combines a lead acid battery and an asymmetric supercapacitor in one unit cell, without extra electronic control.

It has longer life and low cost. It can be made in a conventional battery factory

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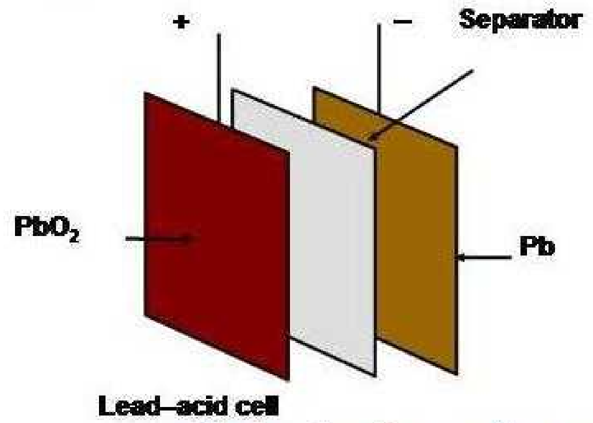
The UltraBattery combines a lead acid battery and a supercapacitor.

Let's have a closer look at what it is…

Lead acid batteries

Discharging the positive lead oxide plate:

$PbO_2 + 3H^+ + HSO_4^- + 2e^- \Rightarrow Pb^{2+} + SO_4^{2-} + 2H_2O$



Discharging the negative sponge lead plate:

$Pb + 3H^+ + HSO_4^- - 2e^- \Rightarrow Pb^{2+} + SO_4^{2-} + 4H^+$

The first component, is the conventional lead acid battery.

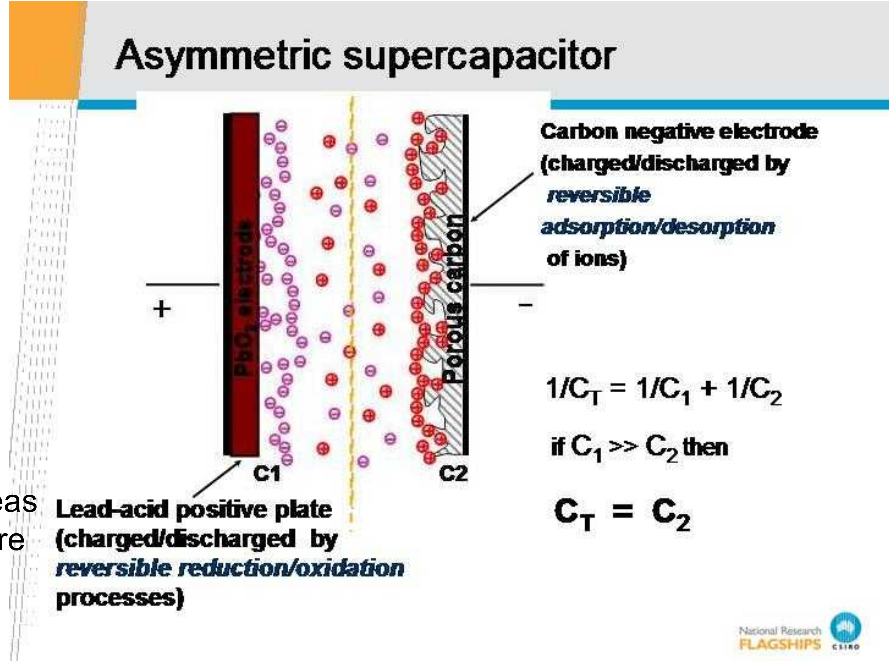
Here is a simplified diagram of a lead-acid battery. It consists of two plates – positive and negative. Between these plates with have a "separator" who's job it is to keep the positive and negatives plates from shorting out, but at the same time allowing ions to be exchanged between the two plate. In an AGM battery, the separator is also a sponge that holds the acid.

[EXTRA]

The positive plate is made of lead-dioxide while the negative plate is made of sponge lead. The separator is impregnated with sulphuric acid.

As the battery discharges to provide electrical energy, the lead oxide plate converts to lead sulphate. The sponge lead also converts to lead sulphate.

During charging of the battery, the lead sulphate in the positive plate is converted back to lead oxide and in the negative plate, converts into sponge lead.



The second component of the UltraBattery is a supercapacitor. Whereas batteries store energy through chemical reactions, supercapacitors store energy electrostatically.

The UltraBattery actually uses a special class of supercapacitor called an asymmetric supercapacitor – it is half battery and half supercapacitor. In this case the positive plate is a battery plate and the negative plate is a capacitor.

[Extra]

Onto the second component of the UltraBattery: the asymmetric supercapacitor side.

In a supercapacitor there are **2 capacitors (C1 and C2)** are in series so that, as the equation shows, the **inverse of the total capacity is equal to the sum of the inverse of C1 and C2**.

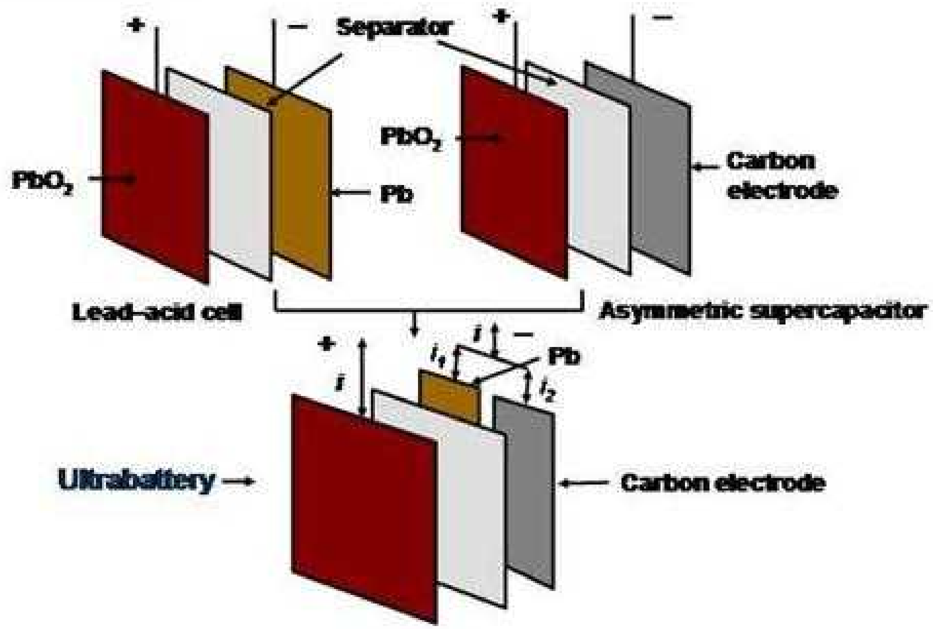
In an asymmetric supercapacitor, the electrodes are of different materials. In the case of the UltraBattery, the positive electrode is lead oxide, while the negative electrode is porous carbon.

The capacity of the negative carbon electrode is a lot greater than the lead oxide electrode, so in effect, the total capacity is equal to the capacity on the carbon electrode.

The benefit of the supercapacitor is the ability to accept high rates of charge and discharge.

Schematic of the Ultrabattery

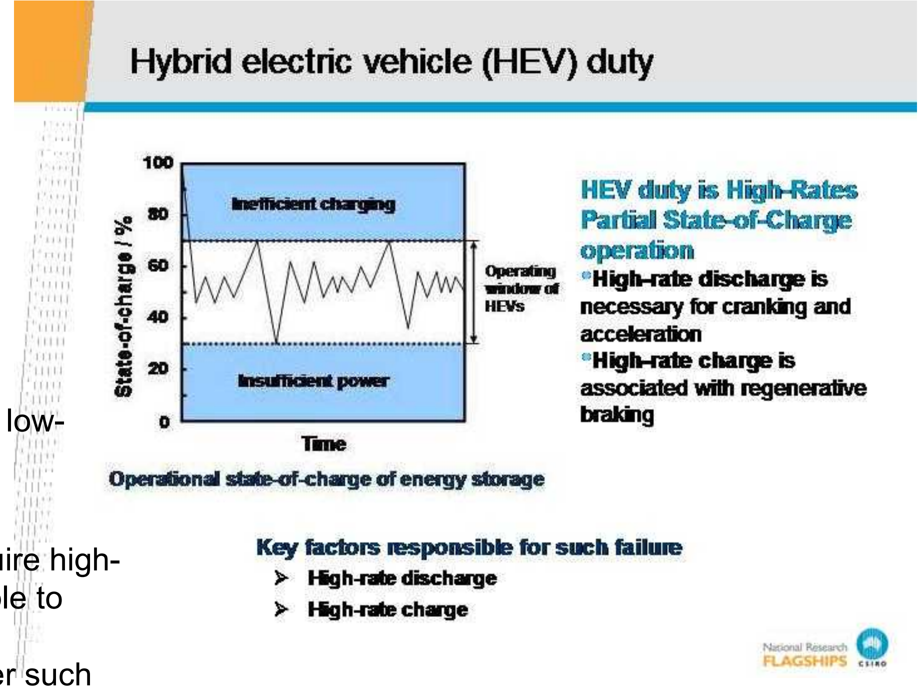
- Ultrabattery is a hybrid energy-storage device, which combines an asymmetric capacitor and a lead-acid battery in one unit cell, without extra electronic control



The UltraBattery is a combination of a conventional lead-acid battery – which are good a storing and delivering ENERGY;

With an asymmetrical supercapacitor – which are good at storing and delivering POWER.

By combining these two, we get an UltraBattery which has the benefit of the battery's ENERGY DENSITY and the capacitor's POWER DENSITY.



Why was the UltraBattery developed? Simply, it was designed as an low-cost battery for hybrid electric vehicles (HEV).

HEVs place significant demands upon their battery banks. They require high-rate energy delivery to accelerate the vehicle; and they need to be able to accept high-rate charge during regenerative braking. The low-cost conventional lead-acid battery isn't able to provide adequate life under such duty.

[Extra]

When a **conventional battery is used in HEV applications, problems arise**.

This graph shows the typical **cycling of a battery in a hybrid electric vehicle**.

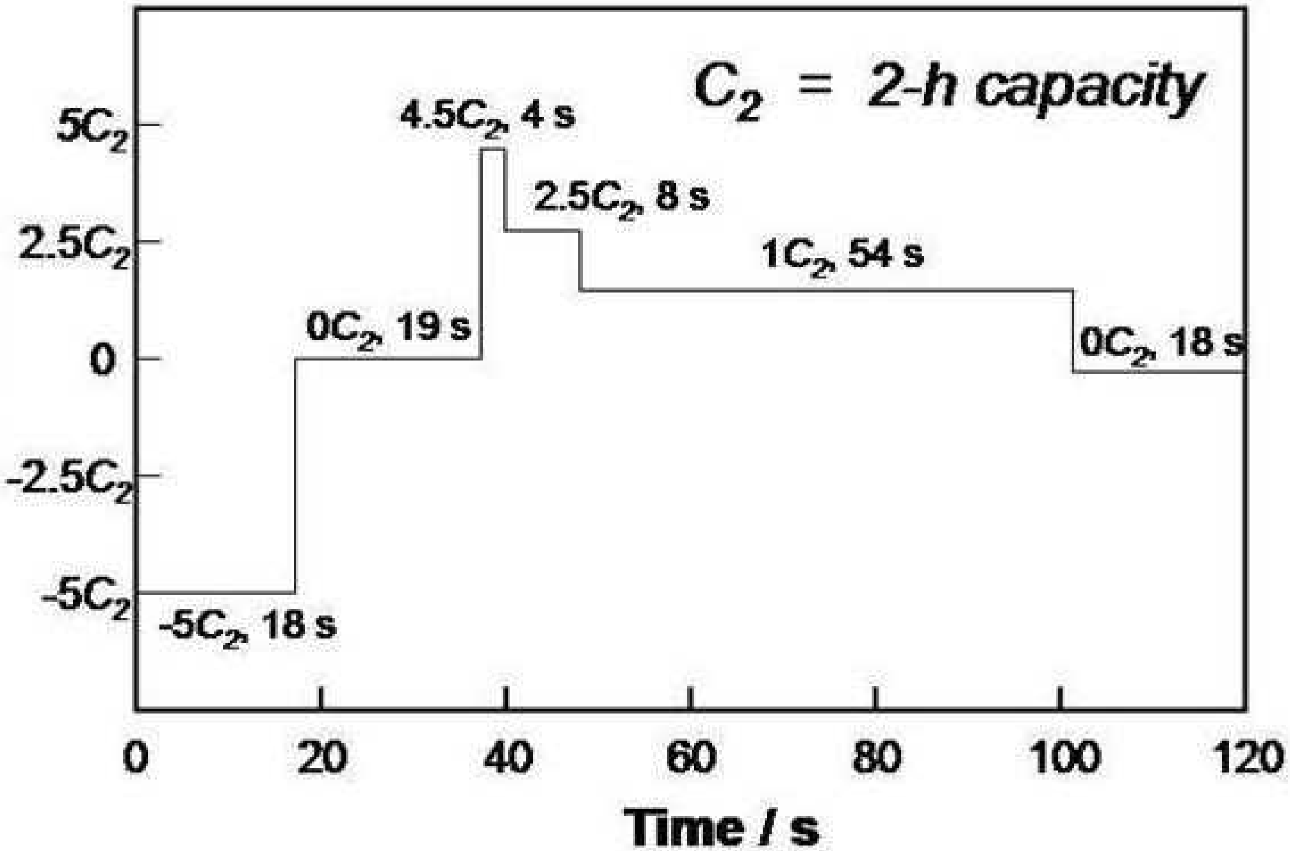
The battery needs to **cycle between 30 and 70% partial state of charge**, however it also needs be able to

provide a high rate of discharge to provide power to the electric motor during cranking and acceleration, and

accept a high rate of charge during regenerative braking.

You will find that a **conventional lead acid battery will fail quite quickly** under this mode of operation.

Life Testing – EUCAR Test



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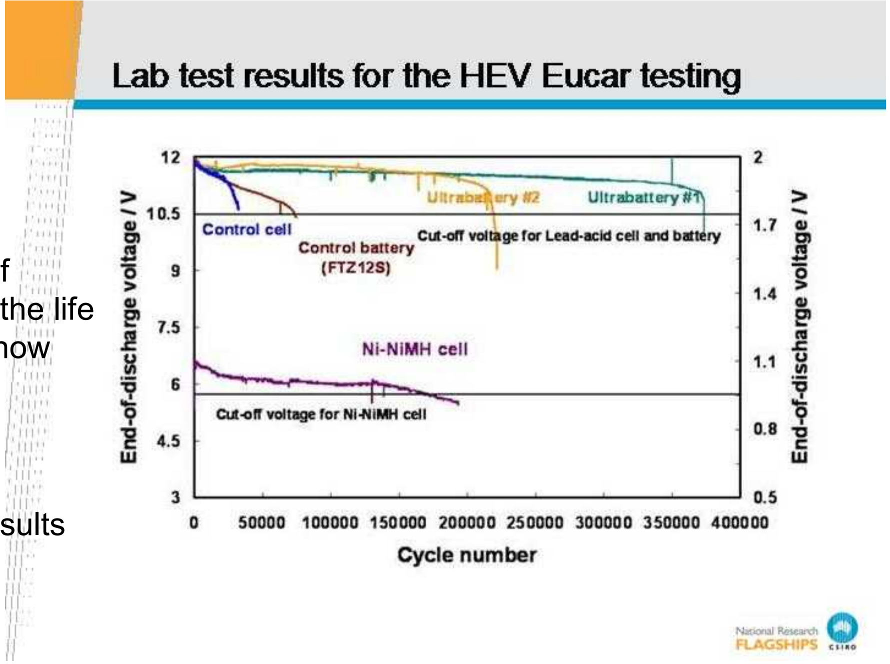
So how does the UltraBattery last compare to standard batteries? One way of comparing the life of batteries is to subject them to simulated testing.



So how good as an UltraBattery? Here are some CSIRO test results of batteries under simulated HEV duty. The blue line and red line shows the life of a typical standard lead-acid battery; the yellow and light blue lines show the life of two UltraBatteries.

The results show that the UltraBattery has a significantly longer than conventional lead-acid batteries – about 5 times longer. Also, these results show the life of an UltraBattery is comparable to that of a nickel-metal-hydride battery.

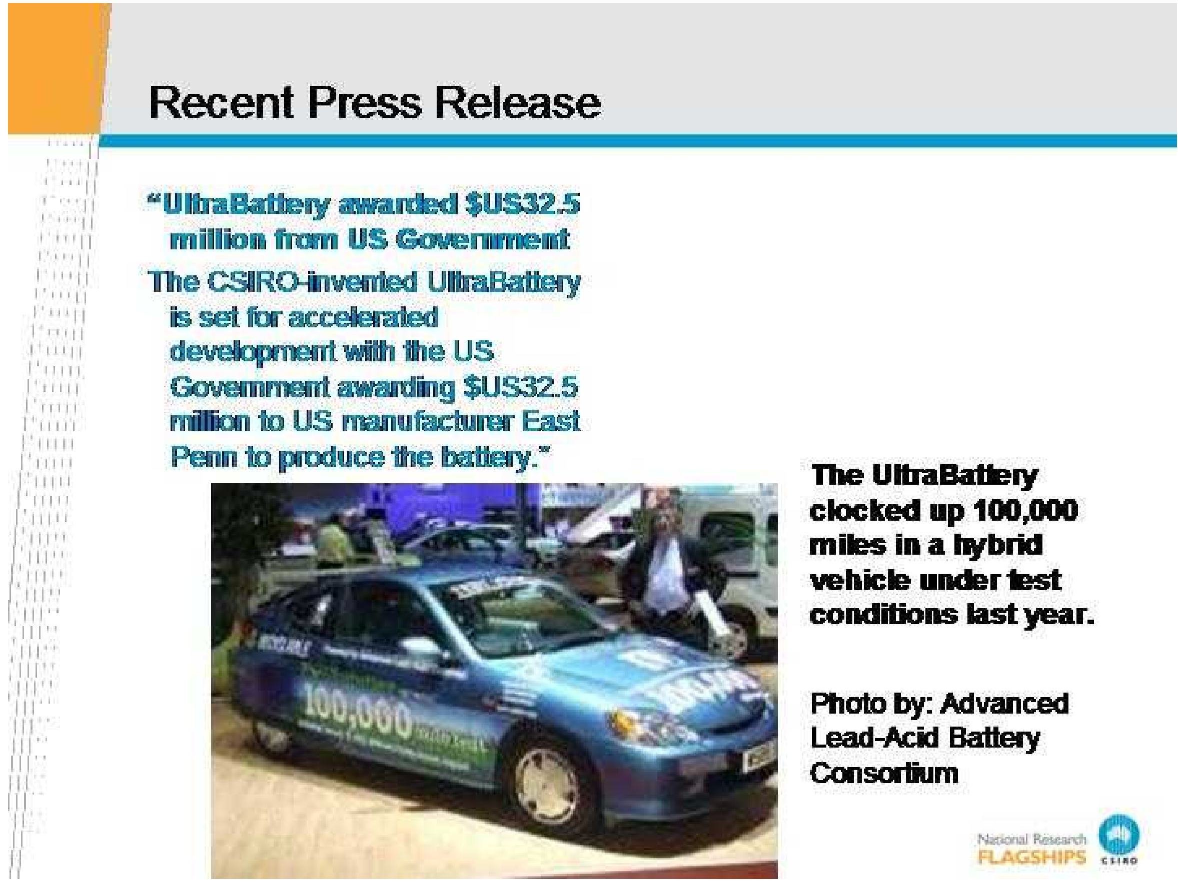
[EXTRA]

Laboratory tests have been conducted on conventional lead acid battery cells (see control), Ni-Metal Hydride cells (the existing batteries used in cars such as the Honda Insight), and the ultrabattery.

We have many different testing profiles to simulate the different types of HEV duty conditions

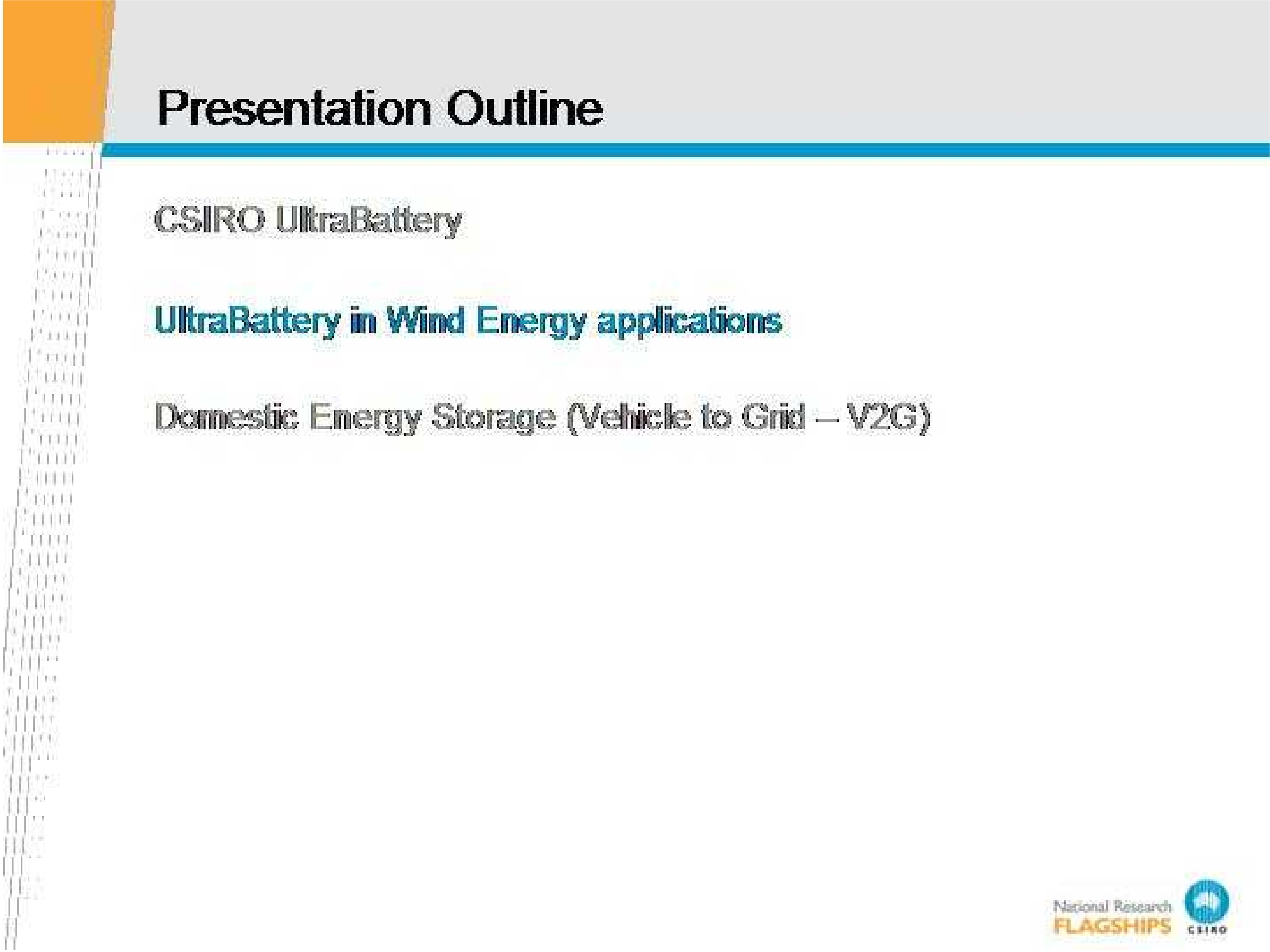
In this particular example, the batteries were subjected to a charge and discharge cycle until they reached a pre-set cut-off voltage.

The control cells are the conventional lead acid batteries – as you can see, they lasted for approximately 80 000 cycles. The Ni-MH cell was double the number of cycles. But more exciting are the number of cycles achieved by the UltraBattery – it matches and exceeds that of the Nickel metal hydride batteries.



Independent (non-CSIRO) real-life tests have also shown the longevity of the UltraBattery in HEV duty. For example, the ALABC modified a Honda Insight to use the UltraBatteries. This vehicle was tested in the UK by driving it over 100k miles (160,000 km). This represents about 10 years of driving for the average motorist. At the end of the testing the batteries are still in good condition.

These batteries were operated in PSoC (partial state of charge) mode. The batteries were continually operated "part full" and at no stage during the testing was any maintenance nor equalisation of the batteries carried out. A pleasing result of this test is that all of the individual cells within the battery bank remained balanced. It seems that the UltraBattery has a feature that makes it particularly good in battery packs.



Now that we have covered the what and why of the UltraBattery, let’s move on to the second part of my presentation and have a look at another application that the CSIRO is investigating for the UltraBattery: Energy Storage for wind farms…

Energy Storage for Wind

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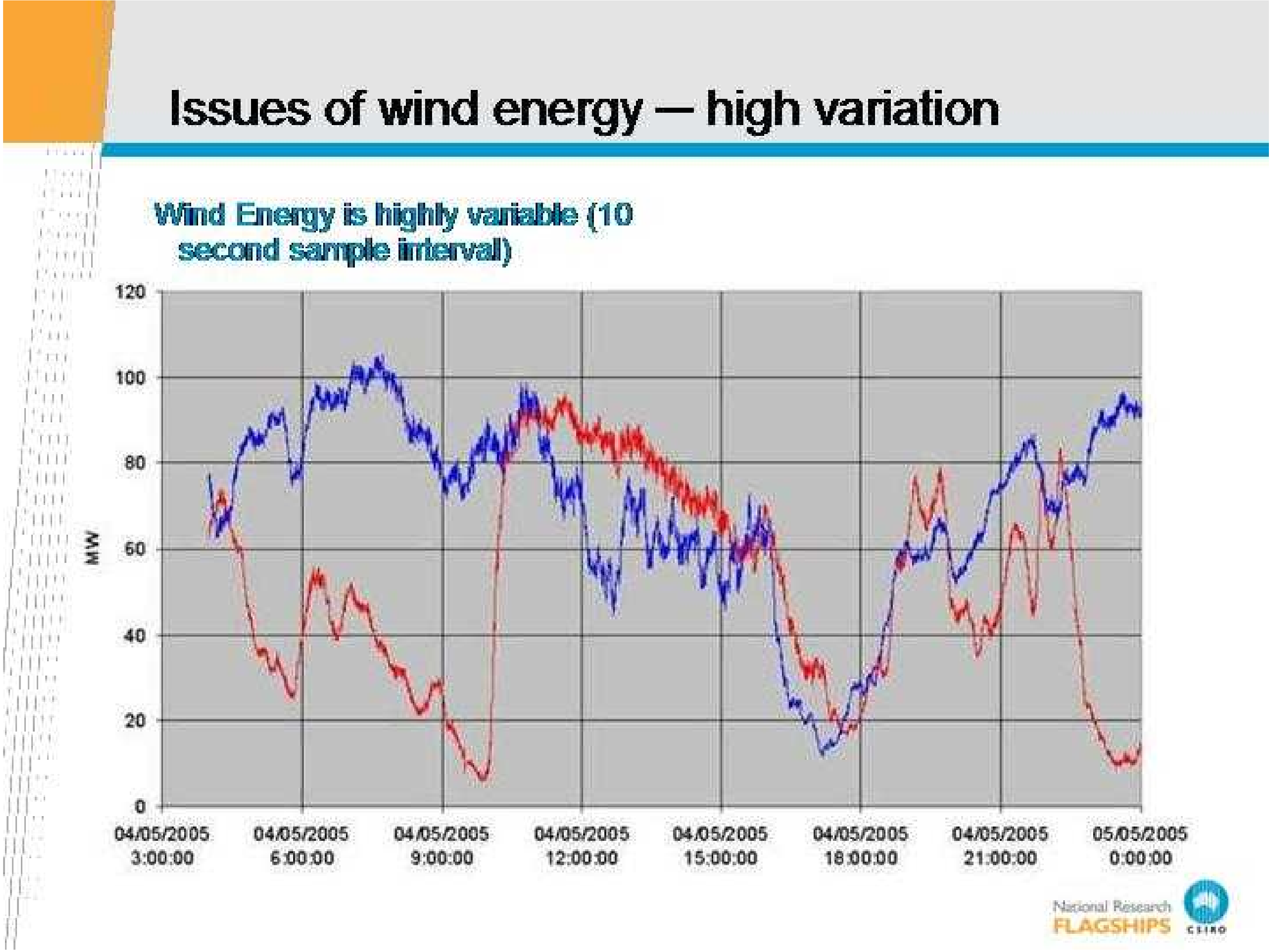
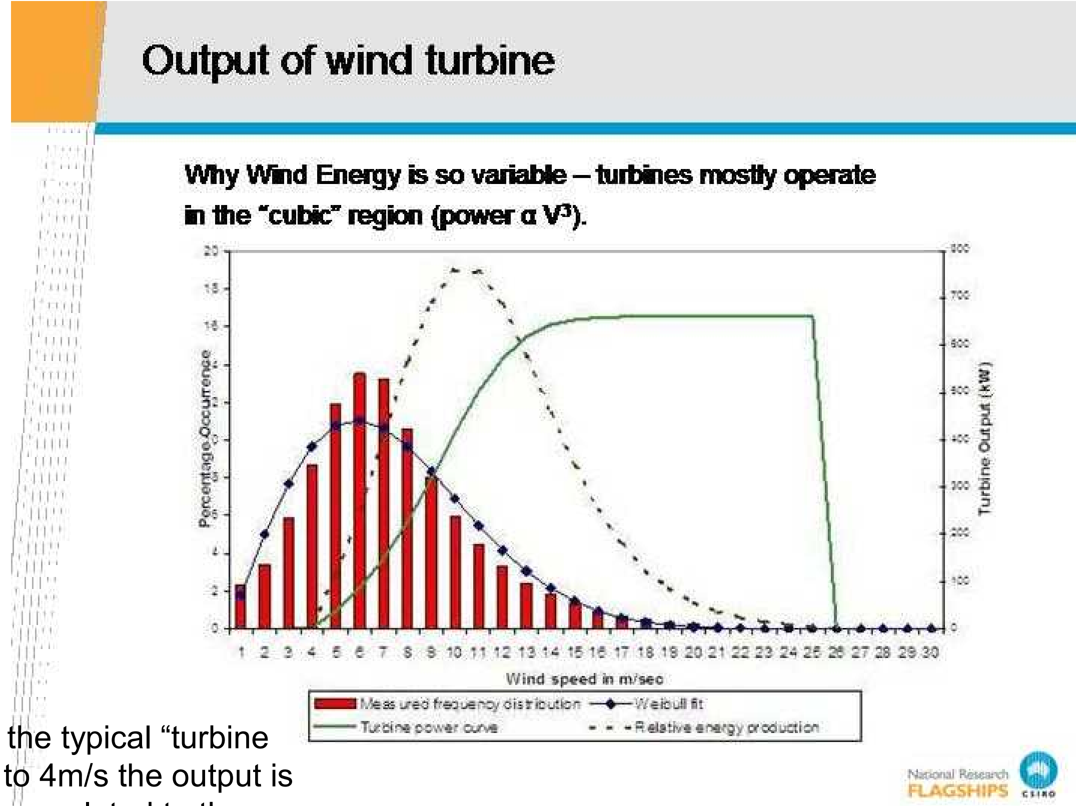


First, a bit of background on wind energy. Wind turbines produce a highly variable energy output. This graph shows the typical power output from two different wind farms. This variability in energy delivery is referred to as "intermittency".



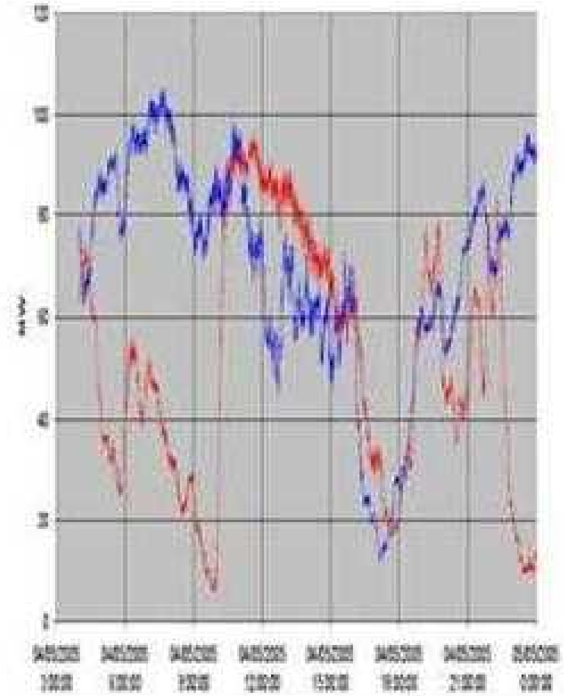
Why is wind power so variable? The green graph shows the typical "turbine output curve" (in this case a 660kW turbine). Between 0 to 4m/s the output is zero (or close to zero). Above about 16 m/s, the output is regulated to the maximum rated power. However, between 4m/s and 16m/s, the power output grows at a rate proportional to the cube of wind speed. i.e. a 10% variation in wind speed will produce a 33% variation in power.

The red bar graph shows a histogram of typical wind speeds. You can notice that wind speeds of 6~7m/s are the most common. The blue curve is a "best fit" of the histogram. Multiplying the wind speed by the turbine output curve gives the energy production curve. You will notice that the peaks of wind speed and energy production are in the "cubic" region of the turbine curve. Therefore the power output is most likely to vary with the cube of the wind speed. This is why relatively small changes in wind produce large changes in power.

This is also the misquoted 30% efficiency.

Network stability & “Ramp Rate”

- The electricity grid needs to be balanced for stability
  - Energy In = Energy Out
- Wind energy has variations in power generation
  - To maintain balance another generator has to be adjusted to “compensate” for the variations
  - Supply regulator doesn't want generators to vary at a rate of more than 6MW per 5 minute interval – this is maximum allowable “Ramp Rate”



- Wind farm often exceed Ramp Rate limits and cause network INSTABILITY
- “RAMP RATE” = rate of change of power generation (MW/5min)

This is the issue limiting the uptake of wind energy

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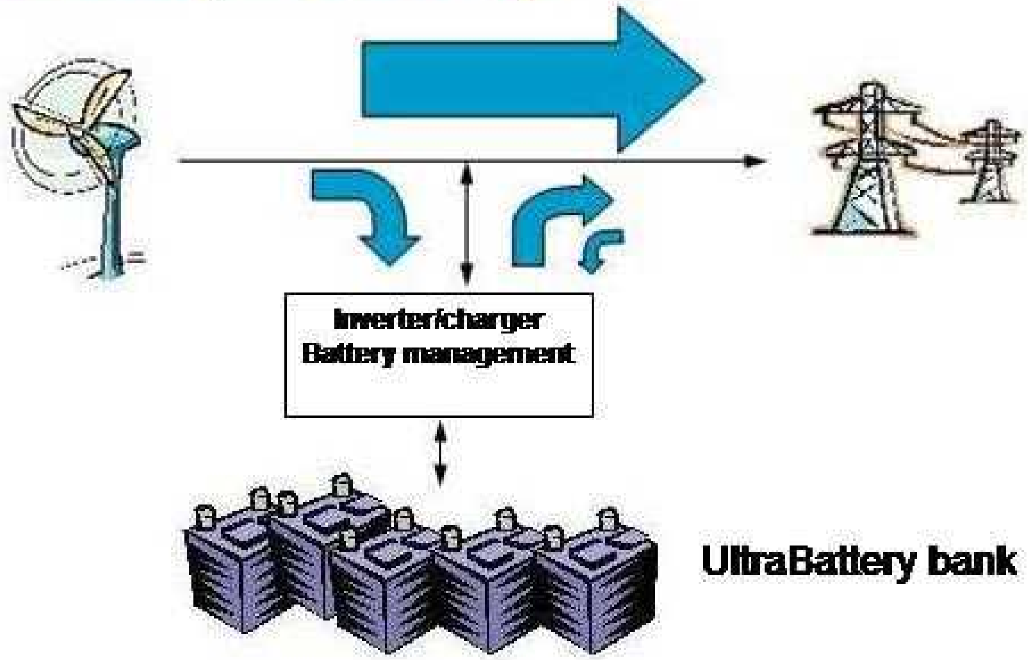
So why is this a problem? The electricity grid consists of a large number of interconnected individual generators. The total power that is generated must match the total load to ensure that the grid remains balanced – that is, the energy in must equal the energy out.

Energy storage for wind

- A solution is Energy Storage at the wind generator to smooth the power delivery



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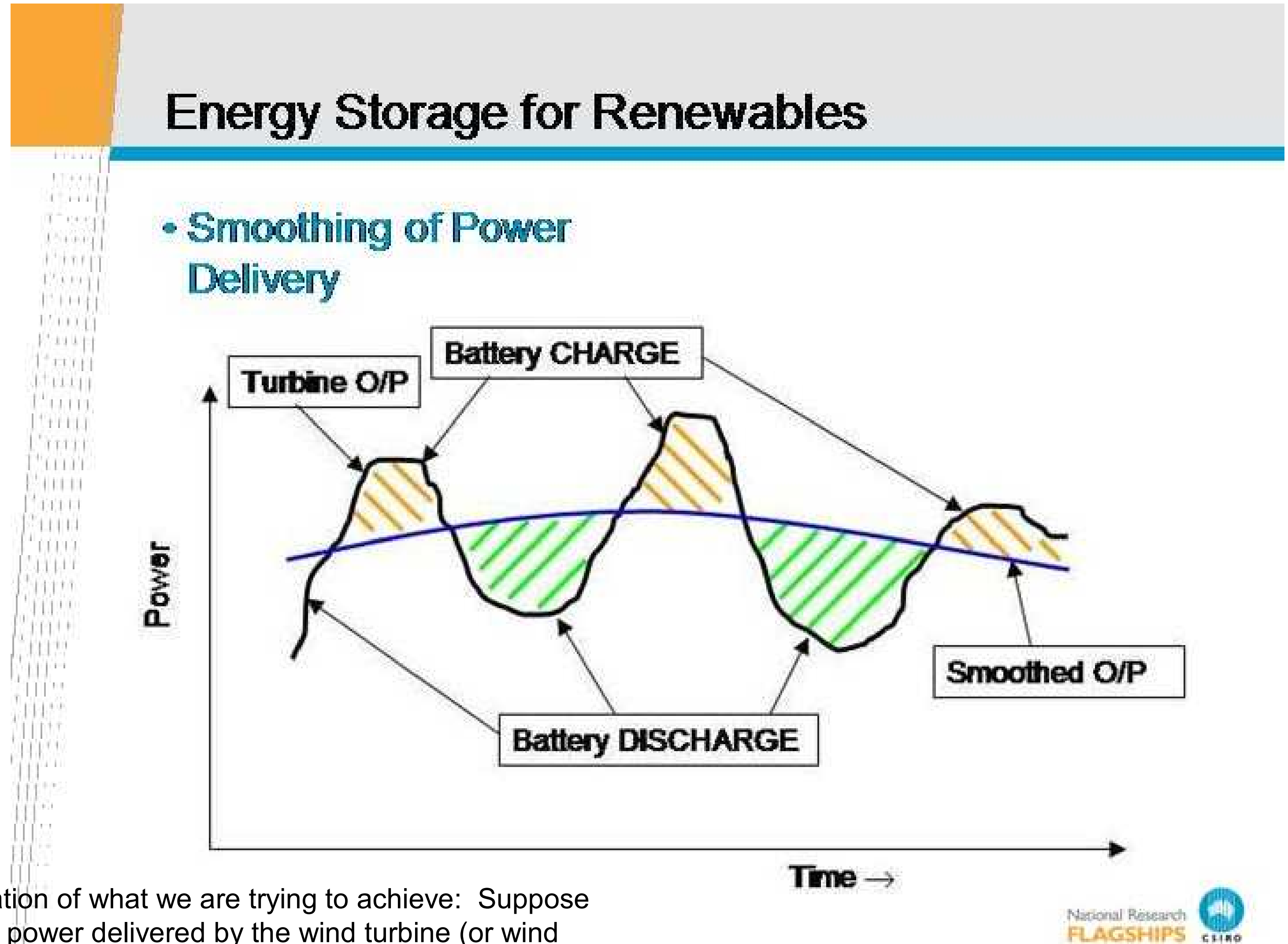
An energy storage system placed near the wind turbines can be used to smooth the delivery of power to the electricity grid.

The bulk of the energy travels straight from the turbine to the grid. The inverter/charger is used to add or subtract some of the power from the turbine to produce an "anti-noise" to cancel out the fluctuations in the energy produced by the wind turbine.

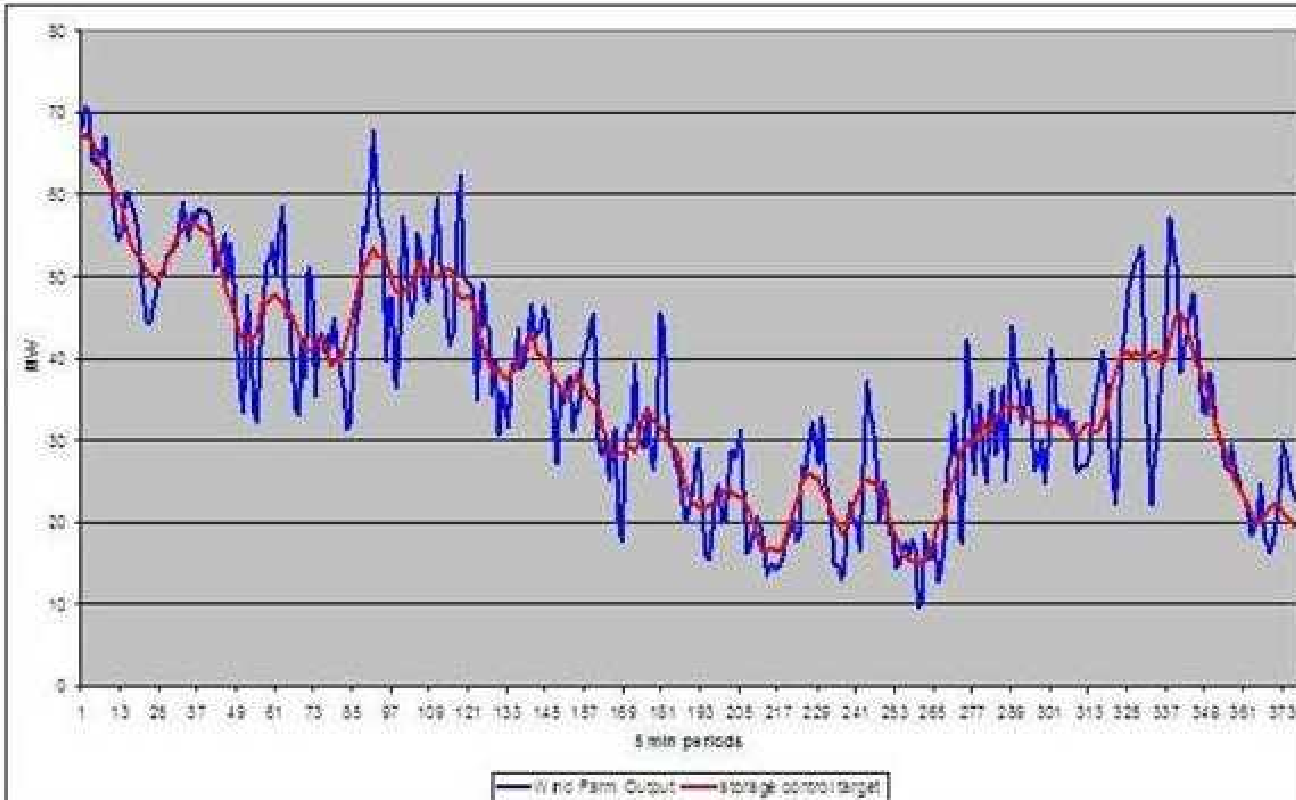


Here is a simplified representation of what we are trying to achieve: Suppose the black line is the fluctuating power delivered by the wind turbine (or wind farm); suppose the blue line is the smoothed power delivery we which to achieve instead; what we can do is store the energy that exceeds the blue line (orange area) to the battery bank – and use it later to supplement the power delivery when the output from the turbine is below the blue line (green areas).

There are two aspects to the energy management. Firstly, when to charge and discharge the energy store. This is also the problem of trying to determine what the smoothed output should be (blue line).

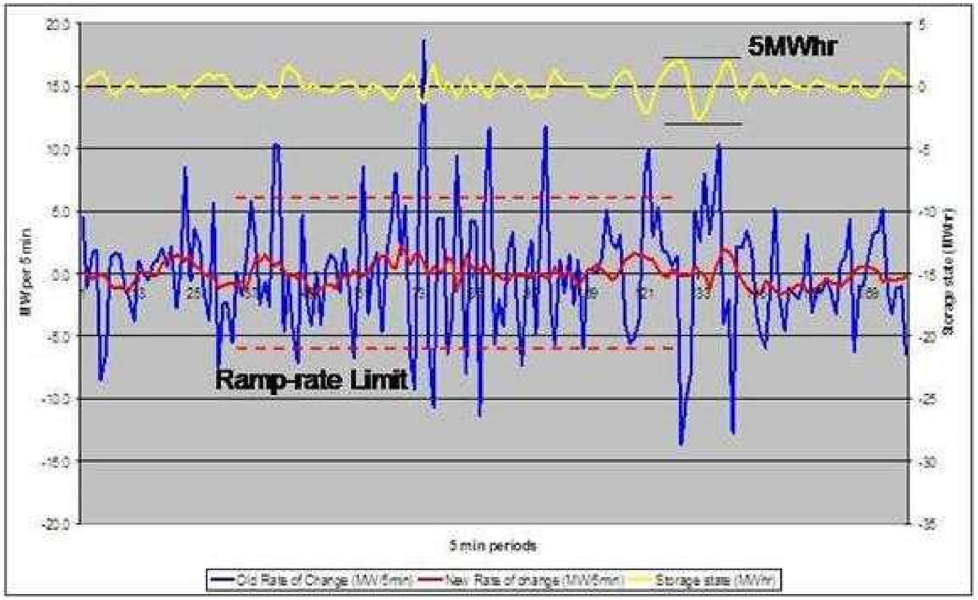
Filtered wind farm output simulation

30min centered running mean



Here is the same idea shown on real wind farm data. In this case we have just ran a simple running average to the output.

Battery effect on ramp rate and capacity required

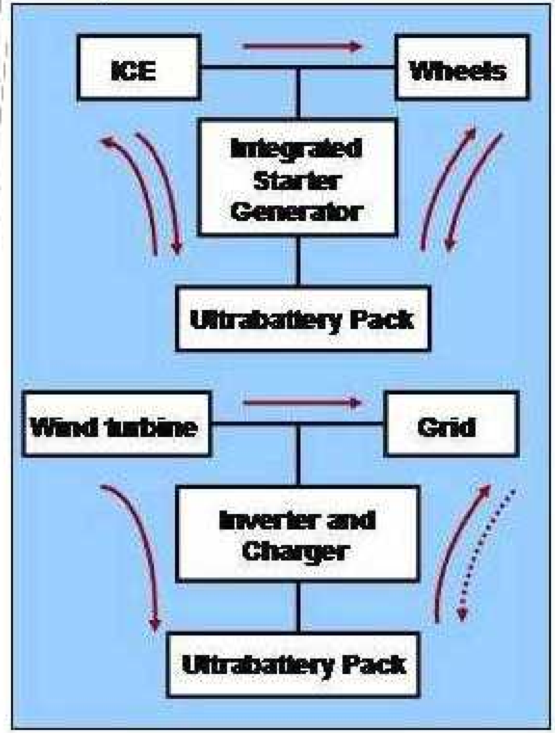


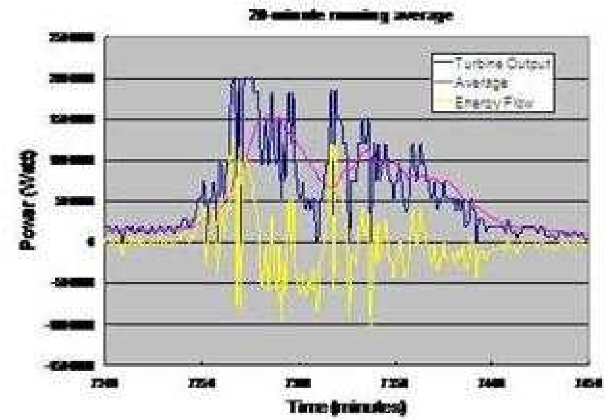
So how much difference can an energy storage system make to smoothing the power delivery from a wind farm? The blue line in this graph is not the power delivered by the wind farm as shown in the last slide, but rather it is the differential of the power delivered – i.e. it is a graph of how rapidly the power changes. The vertical scale is "MW per 5 min" - and if you recall, the "ramp rate limit" is 6 MW per 5 min – the red dashed lines show the 6 MW per 5 min limits. You can see that the wind farm frequently exceeds the network ramp rate limit – and this is no of the major issues that is limiting the growth of wind energy in Australia.

The red line shows a simulated filtered output from this wind farm and you can see that the ramp rate has been reduced to well under the 6 MW per 5 min limit. At the same time, the yellow line shows the amount of energy storage used during this smoothing. This graph shows that a 5MWh battery bank should be able to filter an 80MWh wind farm.

Battery Development HEV to renewable energy

Similarity between HEV and wind turbine systems





Our research in HEV batteries provides a good starting point for development of the Wind UltraBattery.

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Why use an UltraBattery? There are similarities between how a battery pack is used in a HEV and a wind energy system.

In a HEV, the ICE is used to deliver a relatively steady power delivery; the wheels have a fluctuating load. The battery pack supplies the difference in power.

In the wind system, the turbine generates fluctuating power, but we want the power to be smoothly delivered to the grid. The battery bank is used to supply the difference.

CSIRO Energy Centre Newcastle

The research program will be setting up energy storage demonstrations on three different scales. At the CSIRO Energy Centre in Newcastle NSW, we have set up a small "proof of concert" system.

Newcastle Energy Centre Demonstration

Westwind 20kW
3 on site

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This system is used to smooth the power delivery from the three Westwind turbines on that site.

UltraBattery and conventional VRLA Modules installed at Newcastle Energy Centre

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Here is a picture of the energy storage systems. There are actually eight separate systems: the blue systems on the right use conventional VRLA lead-acid batteries and are used as experimental control systems to form a baseline reference. The green systems are electrically identical (but physically different) but use UltraBatteries.

UltraBattery Modules installed at Newcastle Energy Centre

This picture provides a better idea of the systems. These systems are about man height.

UltraBattery Storage Module

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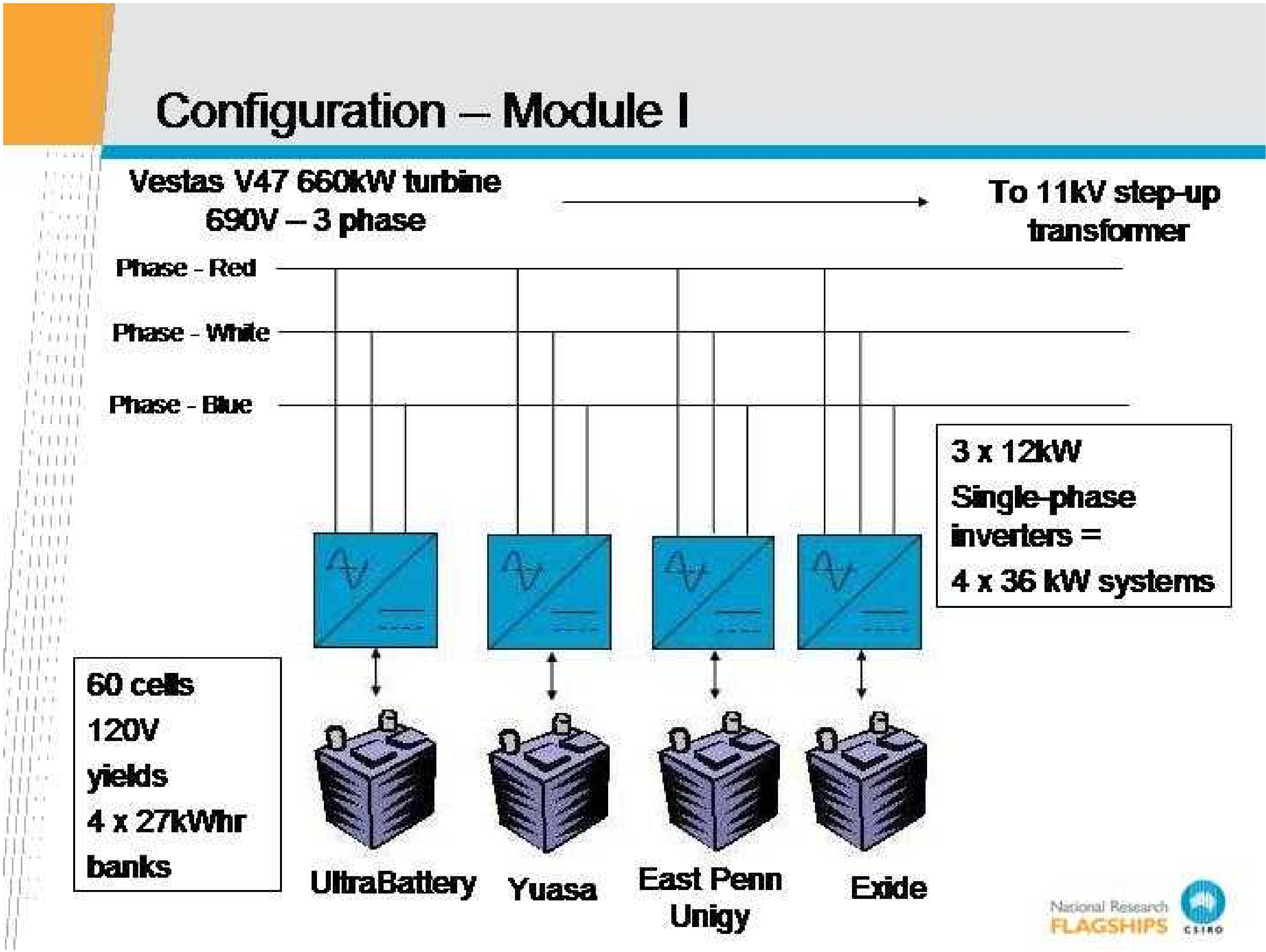
Inside, you can see the UltraBatteries in the bottom section; the bidirectional power inverter in the upper left; and the data logging in the upper-right. The control of this system is done using a separate PC – not shown here.

AEST - Grid Connected Trial

Hampton Wind Park
2 Vestas V47-660kW

The next step in the demonstration program is a field demonstration system that uses a real world sized wind turbine. In this instance, we are going to install an energy storage system on to a 660 kW wind turbine.



The field demonstration system is essentially the same as the proof of concept system, but it is much larger. We are also using three different control batteries in this setup as well as the UltraBattery.

Storage containers under construction

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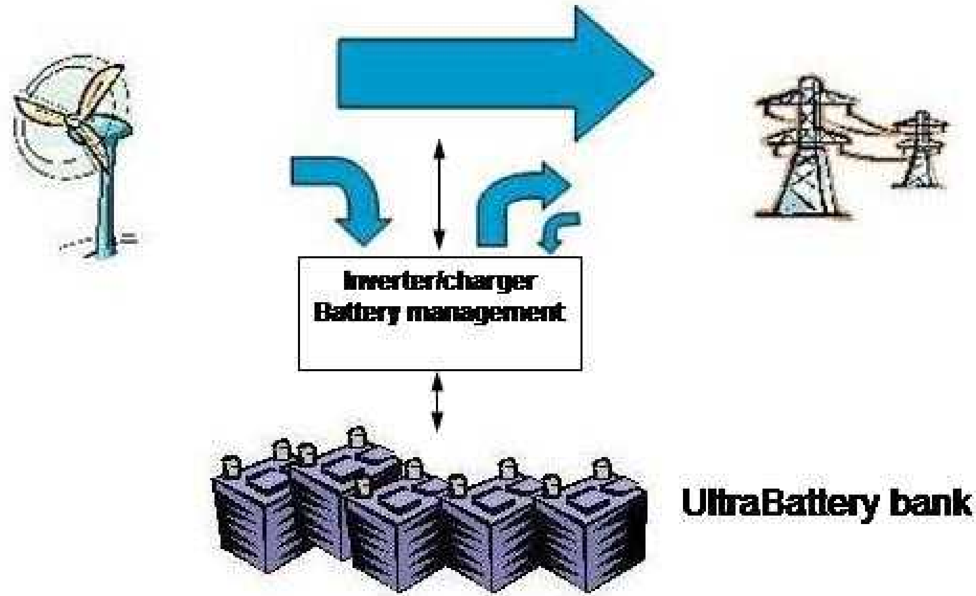
How big are these systems – think shipping containers.

UltraBatteries, Inverters

Each shipping container holds two 120V battery strings, and 6 inverters. There will be two shipping containers of batteries in this system. The first of these containers has been delivered to the site and is presently being installed.

Energy storage for wind



Returning to the outline of the energy storage system, these physical demonstration systems are in fact testing and proving facilities for not only the batteries, but just as importantly, they are used to test and develop the control methodologies used to smooth the power delivery. The key question we are trying to answer are: “how bigger battery do we need? and how big does the inverter need to be? We are also trying to determine how long the batteries will last.

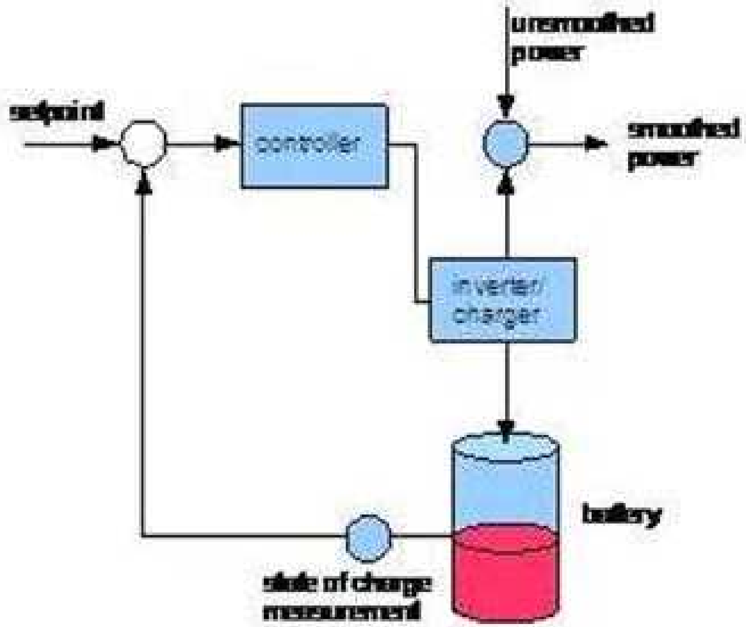
We have our mathematicians hard at work developing and refining control systems to maximise the performance of the system; and to minimise the size – and cost – of the battery bank.

Algorithm deployment

Proportional Integral Controller

From level control algorithm for surge tanks

- smooth the flow rate while simultaneously manipulating the tank level
- tank level is controlled towards 50%.



Let's have a look at a typical control system. For example, if we used a typical Proportional – Integral control system, we would find that the battery tends to be maintained at about half-full – half the battery is ready to absorb energy and the other half is ready to deliver energy.

Algorithm deployment

Low Battery Algorithm Controller

- Keep the battery at a level appropriate to state of input
  - relatively low while wind is low – with capacity ready to absorb peaks as required
  - relatively high while wind is high – with capacity ready discharge to fill lulls as required
  - maintain output rate-of-change below set ramp rate limit.

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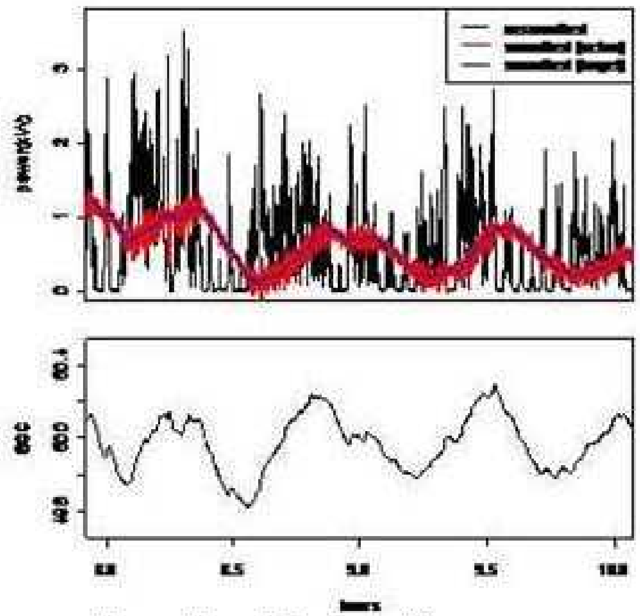
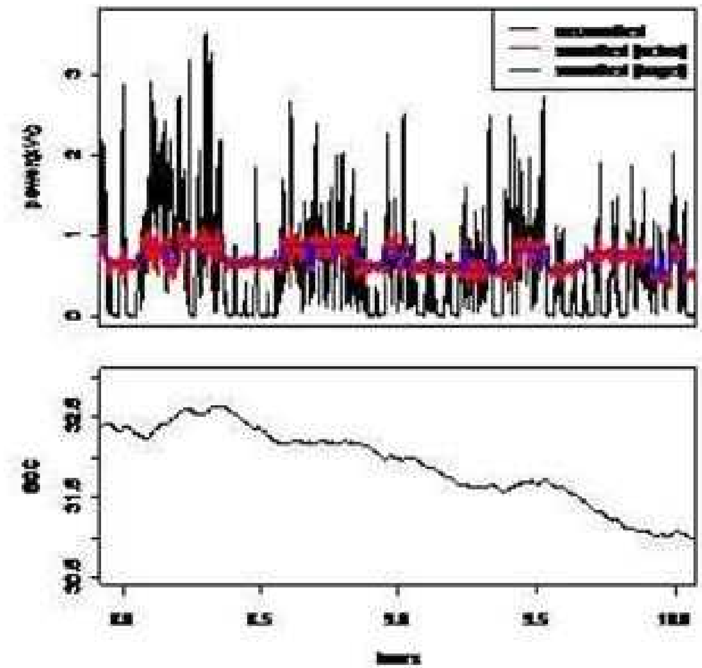
Our mathematicians have developing and evaluating many different control algorithms. One of these new algorithms is called "low battery". It sets the battery state-of-charge at different levels under different operating conditions: (read slide)

Comparison of smoothing algorithms



Baseline PI algorithm

"Low battery" algorithm



Here is a comparison of the two control algorithms using the Newcastle proof of concept systems:

The top graphs show the wind energy from the turbine (black line); the blue lines shows the output the control system is trying to achieve; and the red lines shows the actual output achieved.

The bottom graphs show the corresponding state-of-charge of the battery bank. Not only has the "low battery" algorithm produced a smoother result, it has actually cycled the battery bank less therefore it should yield a better battery life.

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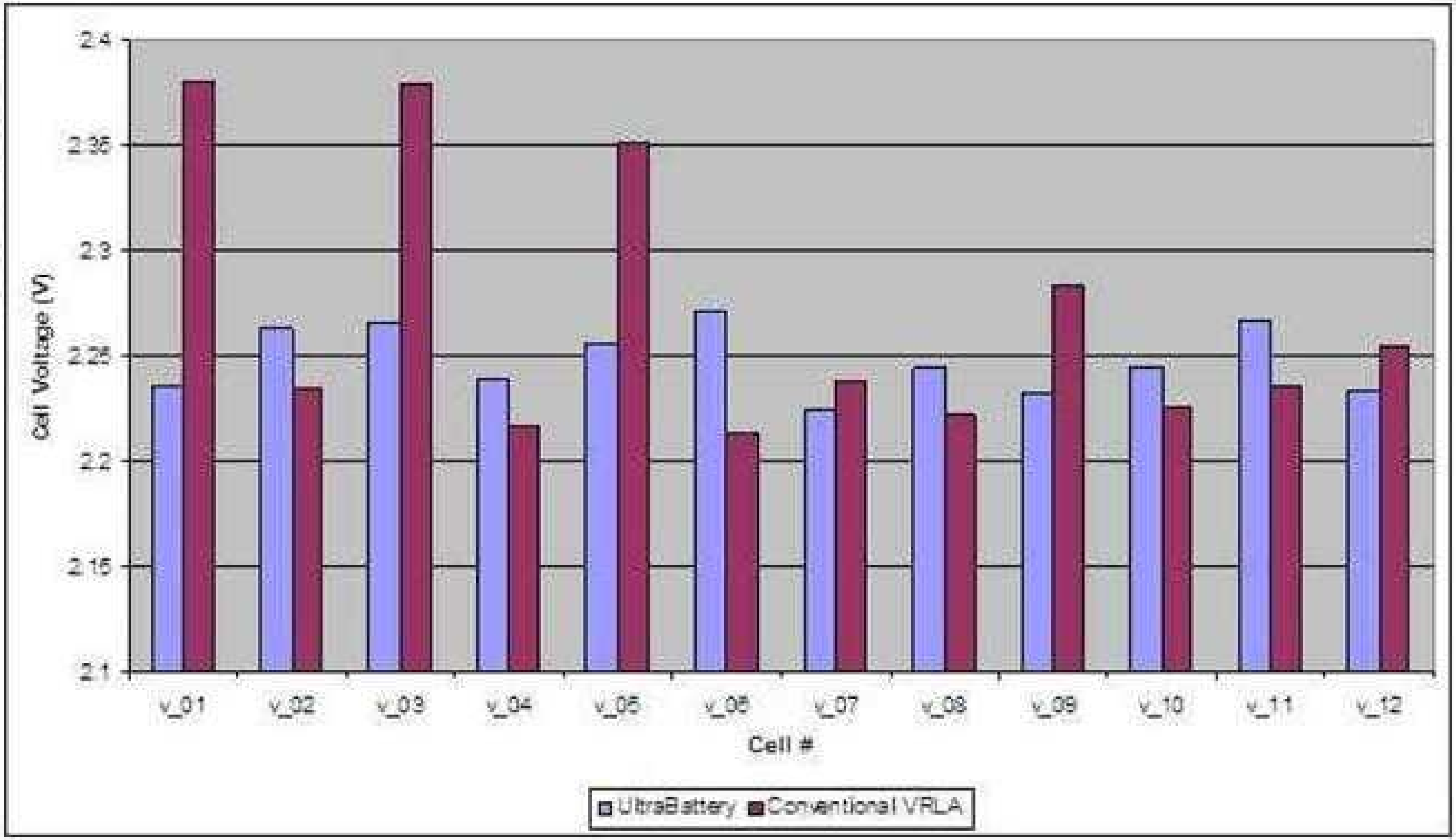
String Cell Voltages after 5 months of intermittent trials



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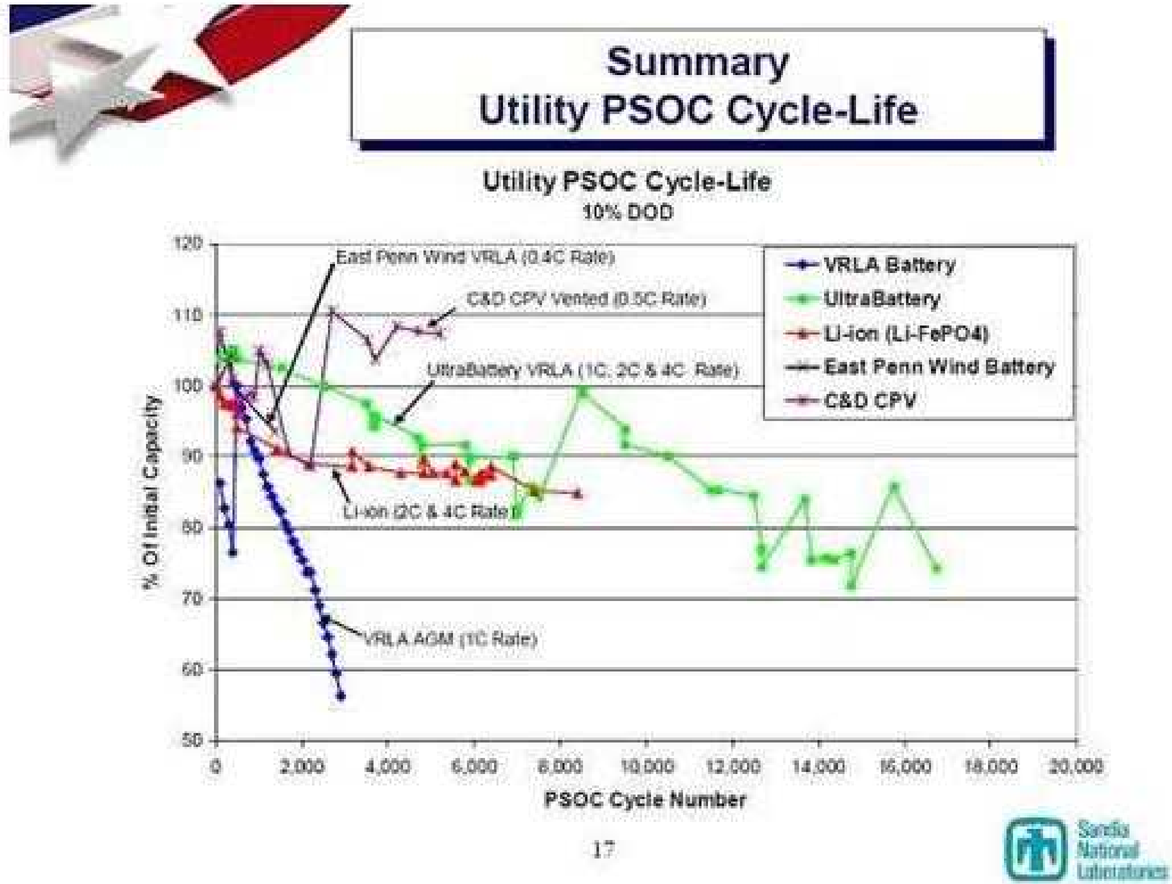
You may recall earlier when we were talking about Hybrid Vehicles, that we noticed that UltraBatteries seem to have a property that helps them stay balanced under partial-state-of-charge cycling. We have also found this to be the case in the wind demonstration systems. This graph shows the voltage of the individual cells in the wind energy battery banks. Note that the UltraBattery voltages show significantly less variation than the VRLA batteries.

Sandia results



Source: Hund, et al. "Testing and Evaluation of Energy Storage Devices", DoE Energy Storage Systems Program review, Washington, Sept 2008

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There has been some independent testing done on UltraBatteries under wind farm duty. The Sandia National Laboratories have been testing the UltraBattery and other batteries. Their results are very encouraging.

Sandia results

Summary

Utility PSOC Cycle-Life

- The Sandia utility PSOC cycle-life testing has identified a number of battery technologies with good Utility PSOC cycle-life, such as:
  - UltraBattery (carbon enhanced VRLA with supercap) - up to 4C? rate
  - East Penn (carbon enhanced large format VRLA) – up to 1C rate
  - Li-ion (Li-$FePO_4$) – up to 4C? rate
  - C&D CPV (Sb+Selenium large format vented) – up to 0.5C rate
- The new carbon enhanced negative electrodes in VRLA batteries have dramatically improved utility PSOC cycle-life up to a factor of 10.
- The new Li-ion (Li-$FePO_4$) battery technology proposed for hybrid electric vehicles is comparable in utility PSOC cycle-life to the new carbon enhanced VRLA batteries.
- Future work will include completion of testing and may include an energy storage system implementation - such as the wind system at Condon BPA wind farm and/or other demonstrations.

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Sandia National Laboratories

Source: Hund, et al. "Testing and Evaluation of Energy Storage Devices", DoE Energy Storage Systems Program review, Washington, Sept. 2008

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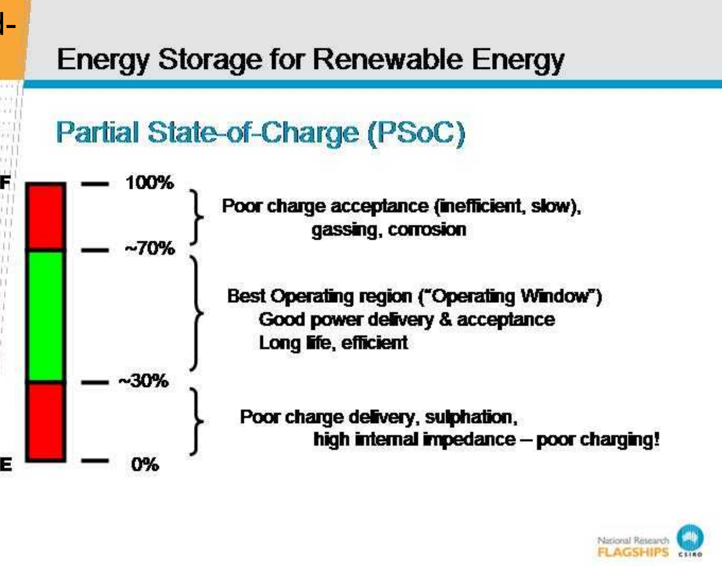
This is the summary of the Sandia presentation: The UltraBattery was reported to have lasted 13 times longer than a conventional lead-acid battery in simulated wind farm duty.

Just to summarise a couple of points: The UltraBattery, while based upon an lead-acid battery, is best used in different duties to a conventional lead-acid battery. The UltraBattery particularly shines in PSoC duty (rather than deep cycle) and is better at "high-rate" cycling than a conventional lead-acid battery. It thrives on the hard work.



[EXTRA]

The other aspect is to maintain the batteries SoC in the correct operation region. The battery will perform best and give greatest life if the SoC "window" is carefully controlled.

Basically I see the need for 2 levels of energy storage:

Firstly, there is short-term storage for power quality. This storage covers the milliseconds to minutes time frame. This storage would be used to provide coverage of lulls in wind and short-term cloud cover in PV. This storage would be used to smooth out noise and as such it would be best located near the generator.

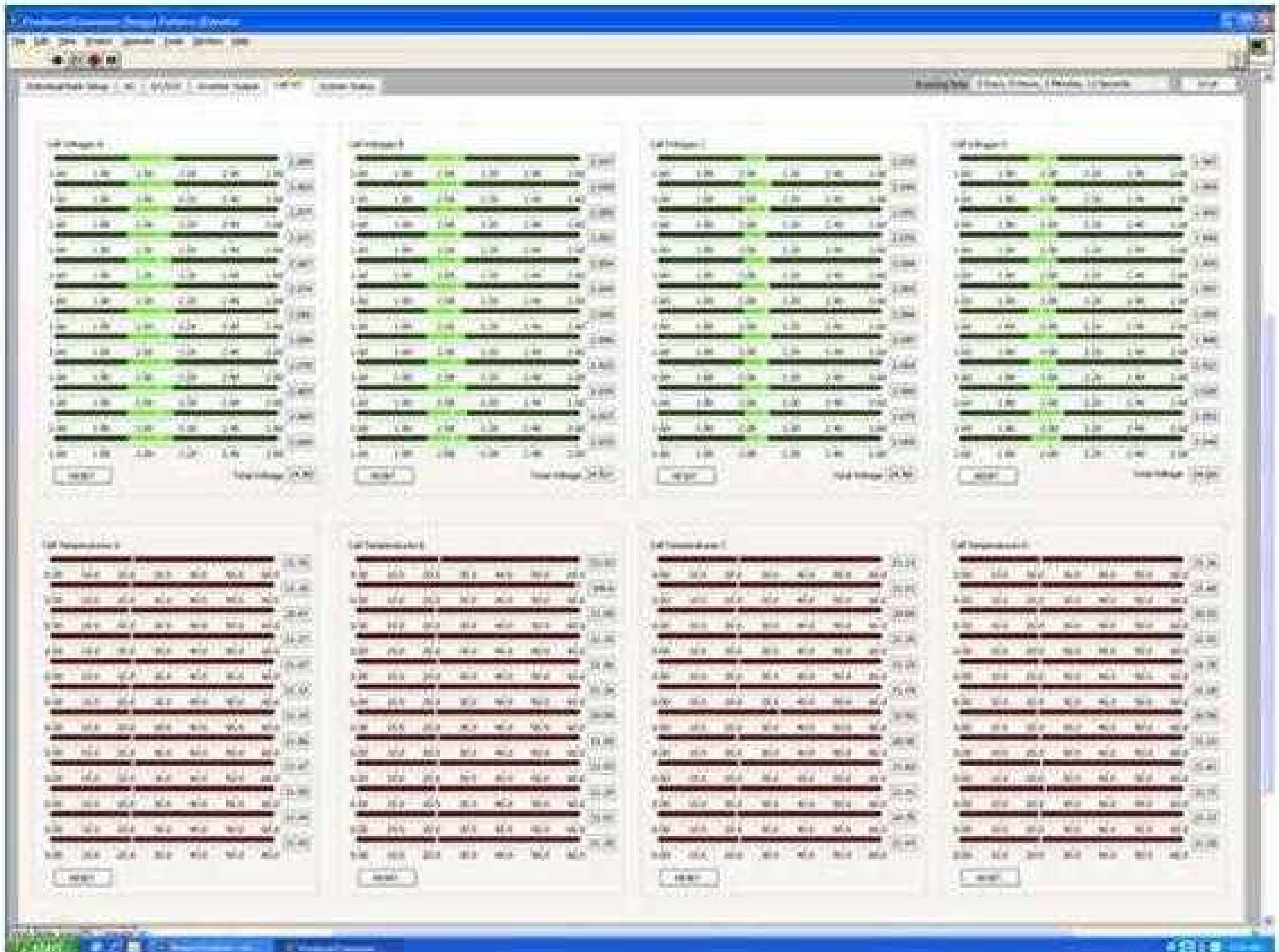
Secondly, there is the need for bulk energy storage. This would be used to time-shift energy. E.g. night to day for wind, and day to night for PV. This energy store doesn't need to be located near the renewable generators – it can be a network entity in its own right.

Cost is a major hurdle but I don't think there is any energy storage technology that is truly economical – especially at the current low-cost of energy. Environmental concerns are likely to be the main driver, but cost will come into it somewhere down the track. There will be a push to minimise the cost.

Ideally, the bigger the energy store the better. But energy storage is extremely costly (1MWh = $40, storage system $M's). One of the big questions is the "storage size to benefit" relationship. What is the optimum size for the energy storage system?

If we can minimise the size, we should minimise the cost?

Battery Pack Monitoring



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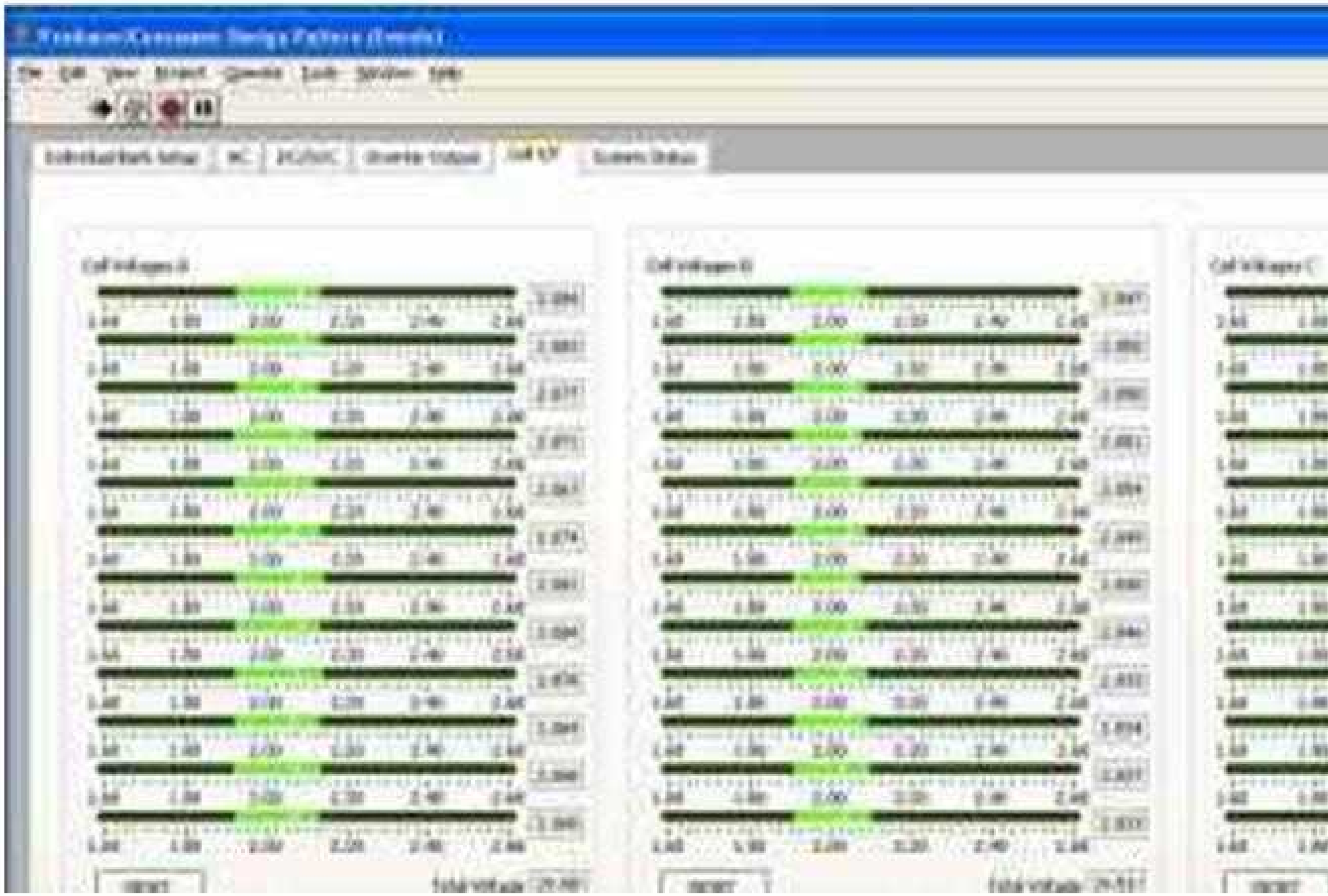
Battery Pack Monitoring



Presentation Outline

CSIRO UltraBattery

UltraBattery in Wind Energy applications

Domestic Energy Storage (Vehicle to Grid – V2G)

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On to my third and final topic – using HEVs as a domestic battery bank. This is not an UltraBattery system!

PHEVs as domestic energy stores

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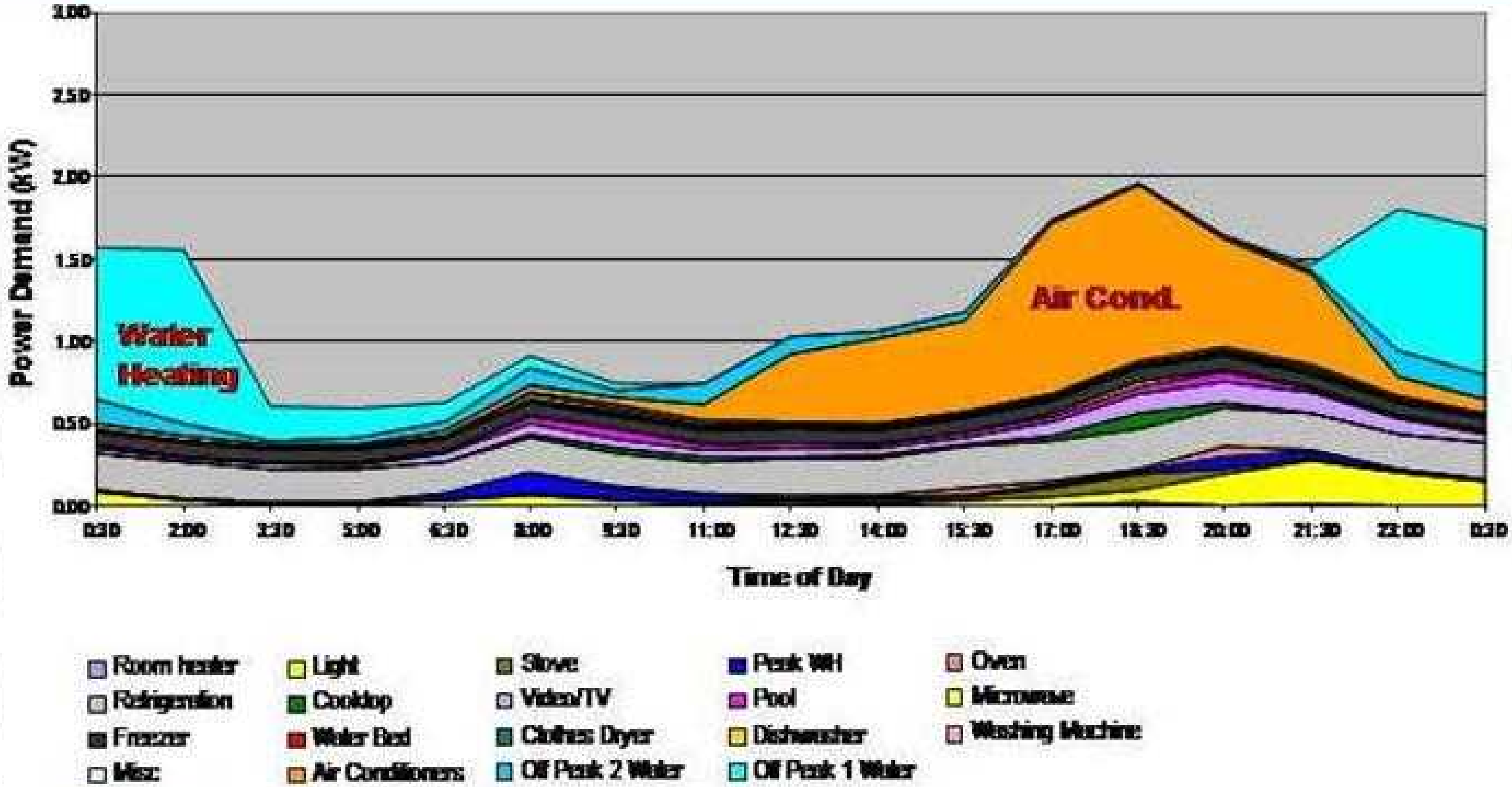
This is a program that has recently started in the CSIRO. Why use EVs…?

Example Residential Power Demand (Summer Peak- NSW)



Source: UTS Sustainable Futures

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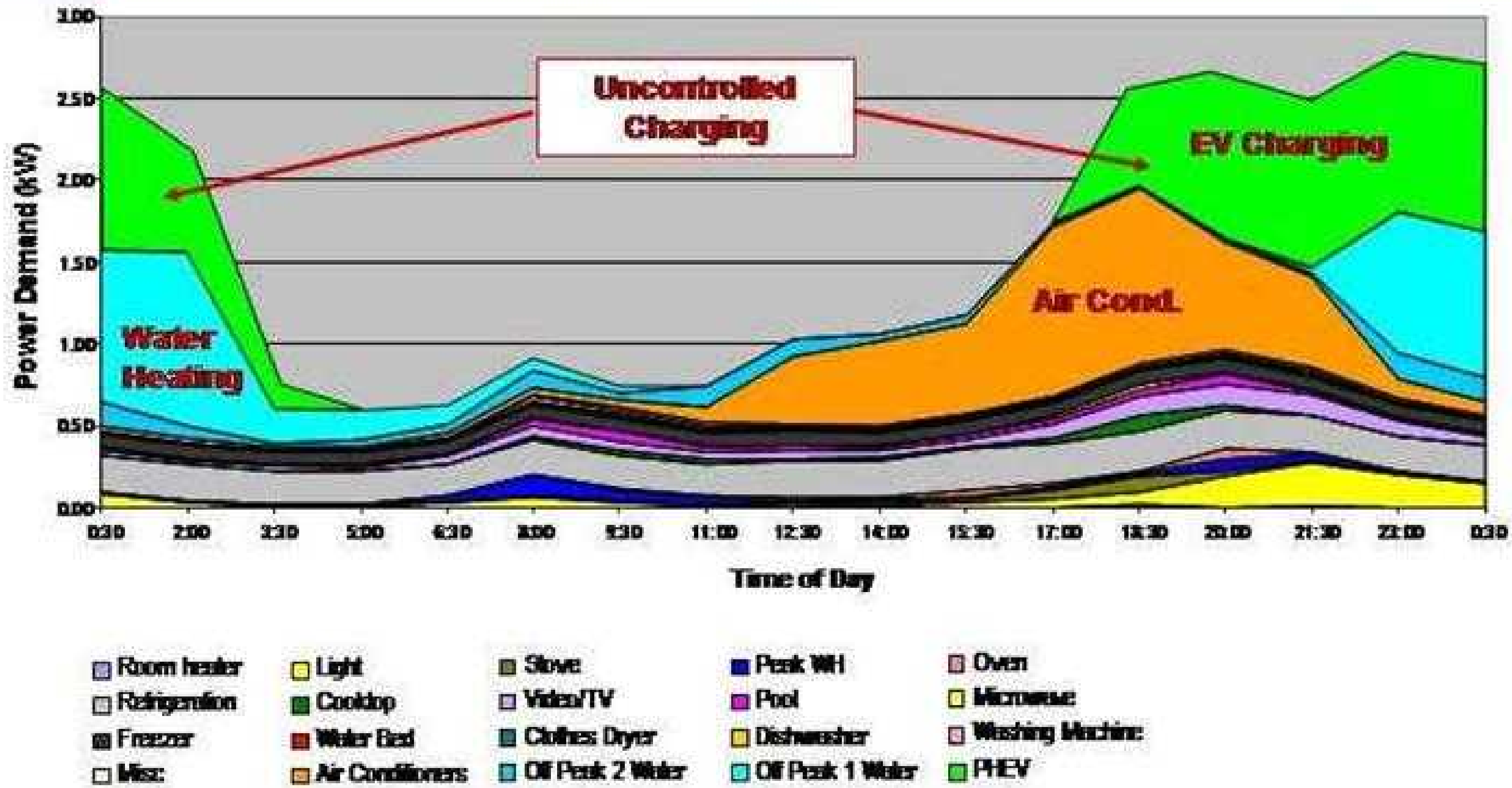
Example Uncontrolled Charging (Summer Peak- NSW)



Source: UTS Sustainable Futures

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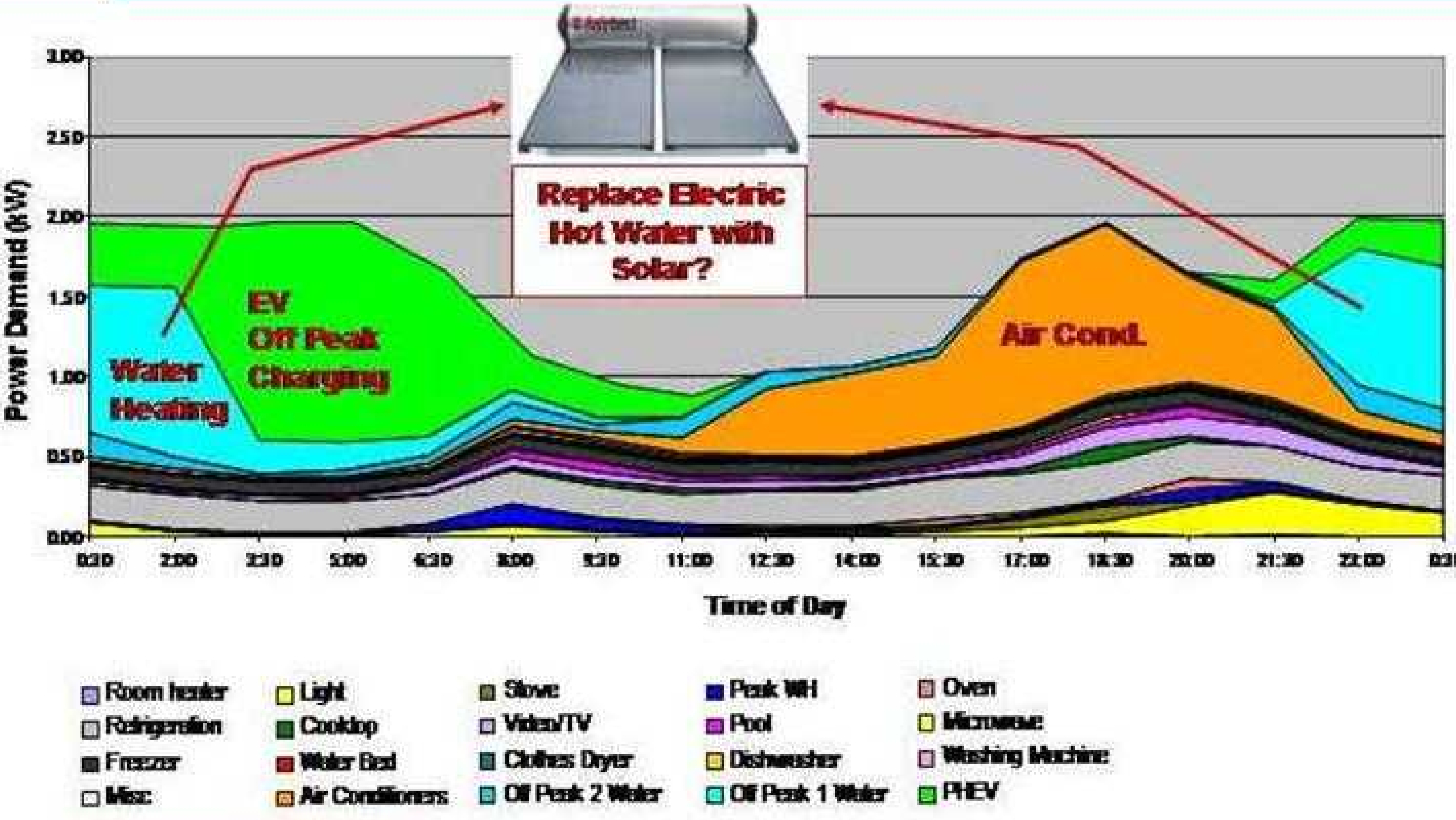
Example Off-Peak Charging (Summer Peak- NSW)



Source: UTS Sustainable Futures

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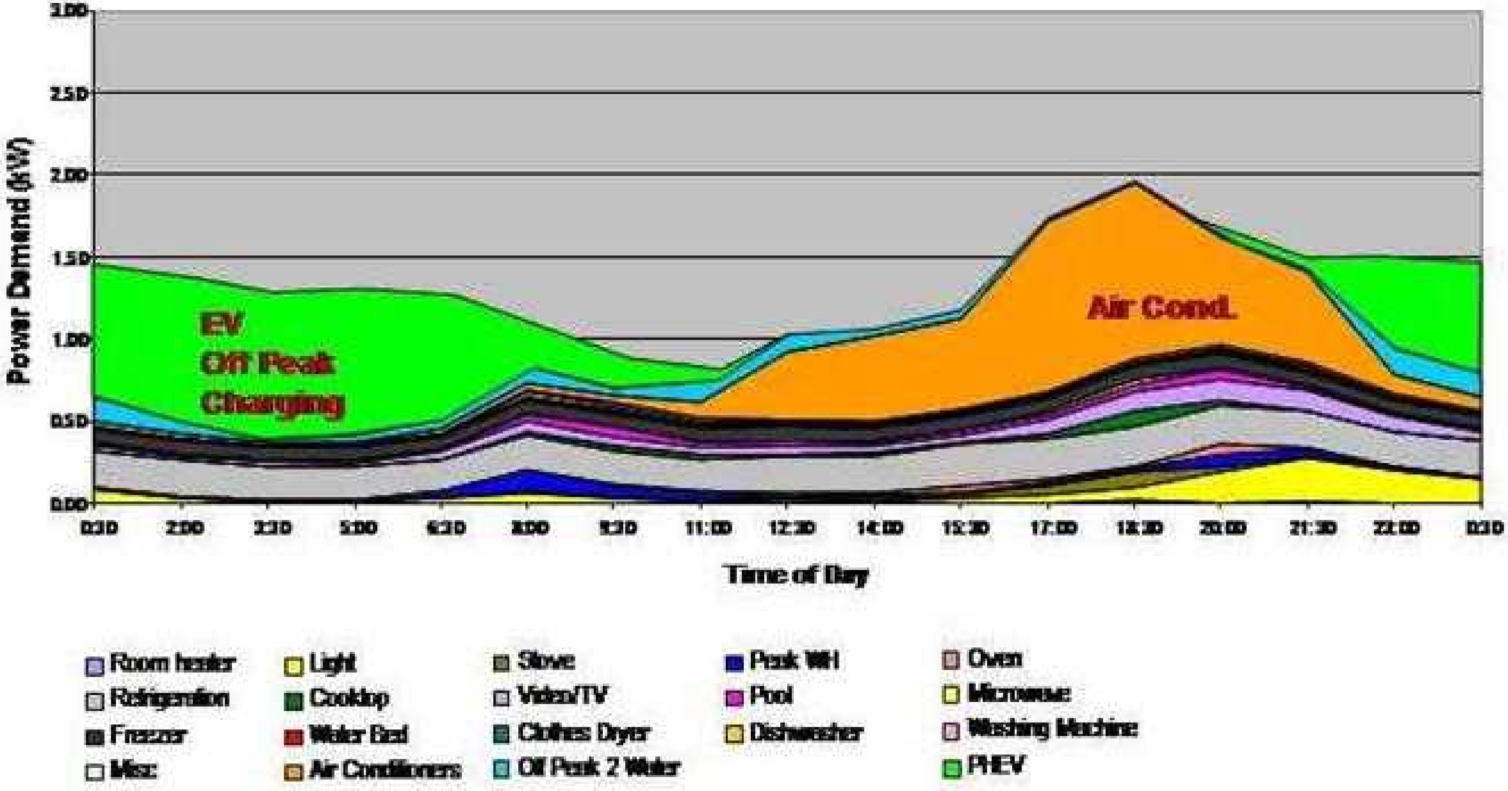
Controlled Charging + Solar Water (Summer Peak- NSW)



Source: UTS Sustainable Futures

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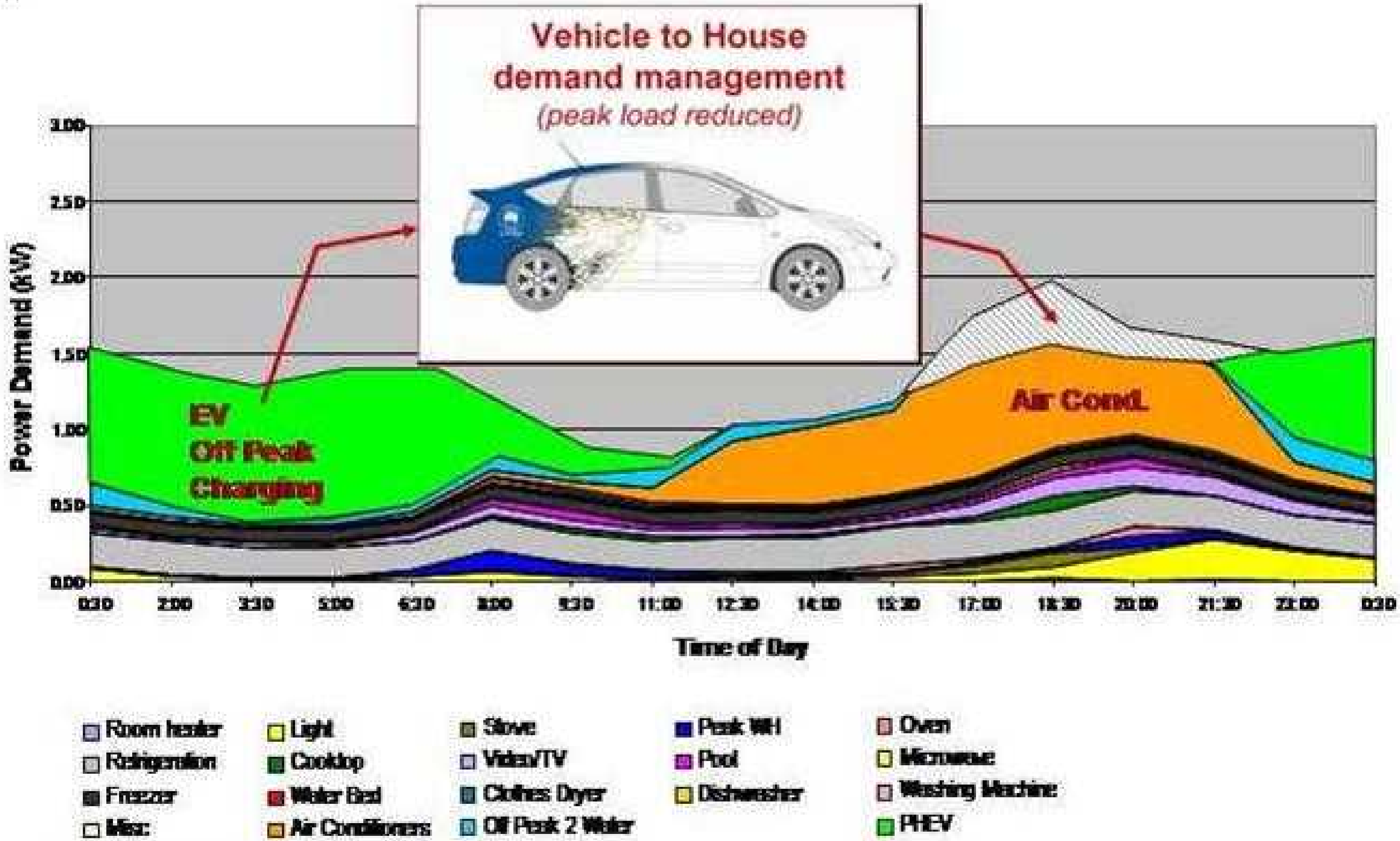
Vehicle to House Load Management
(Summer Peak- NSW)



Source: UTS Sustainable Futures

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Current Status

- **Conversion of three Toyota Prius**
  - **Plug-in charge & discharge**
  - **Extra battery capacity**
  - **Advanced monitoring & control of energy flow**

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Acknowledgements:

• Dr Lan Lam	UltraBattery material
• Dr Peter Coppin	Wind Energy Storage material
• Dr Phillip Paevere	PHEV to Grid material

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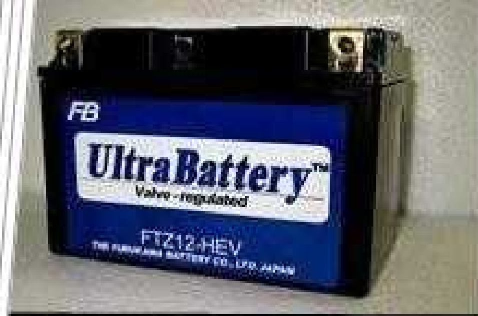

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Thank You

Chris Phyland
Principal Electronics Engineer
Chris.Phyland@csiro.au
CSIRO Energy Transformed Flagship

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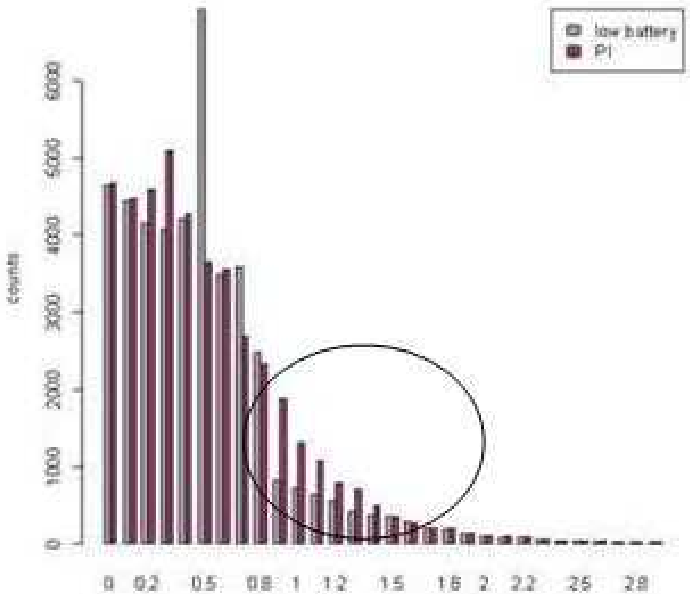
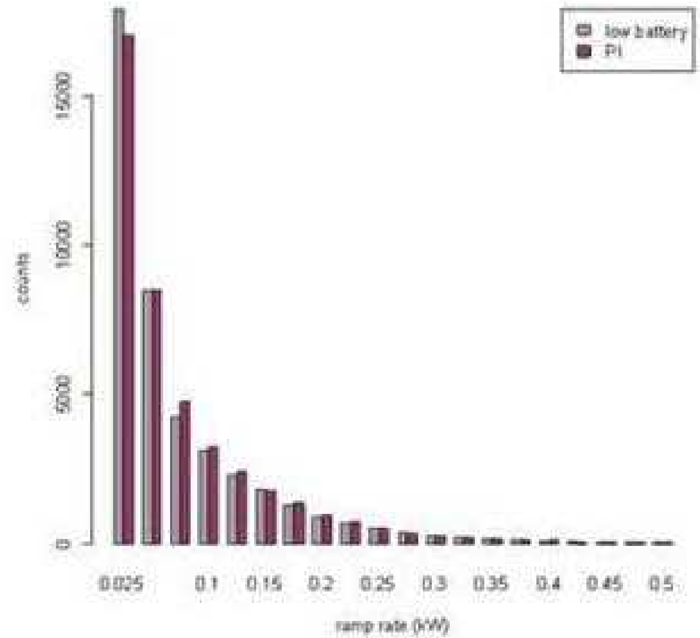
UltraBattery pack

Testing Stationary version

Power flow stats



Inverter power



Output signal ramp rate
(rate of change)

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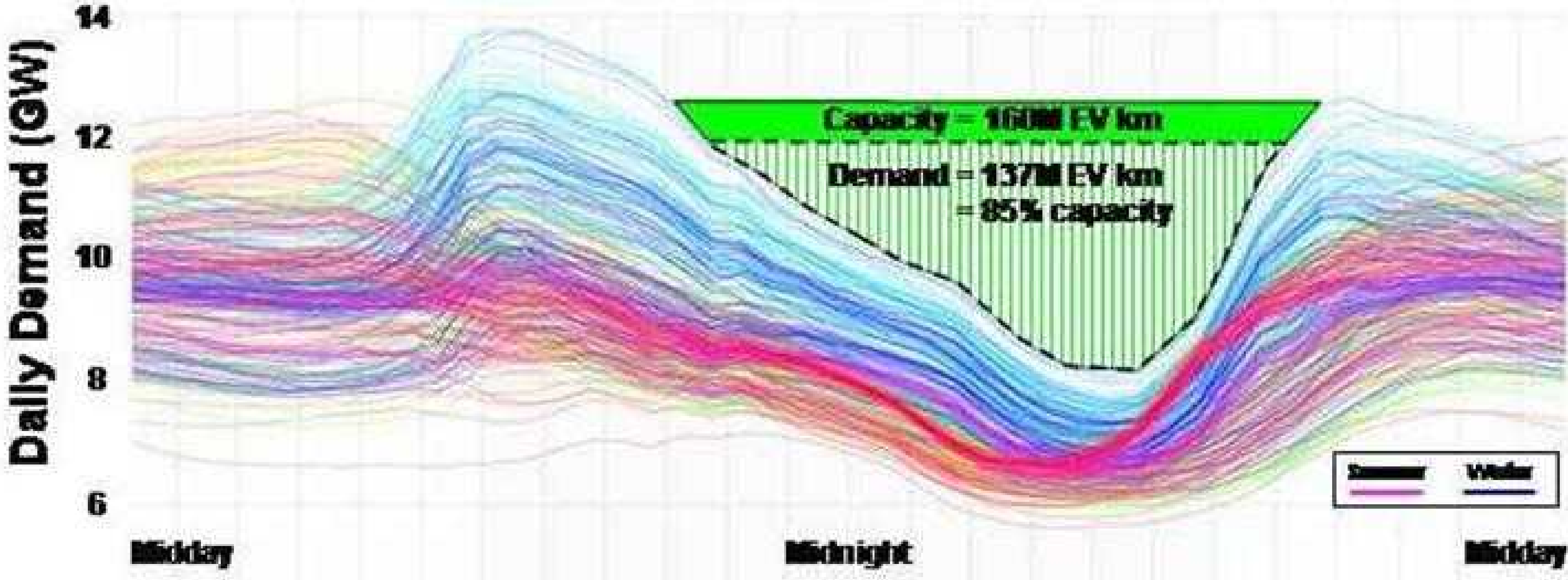
Daily Electricity Demand - NSW



Source: NEMMCO 2007; ABS 2007

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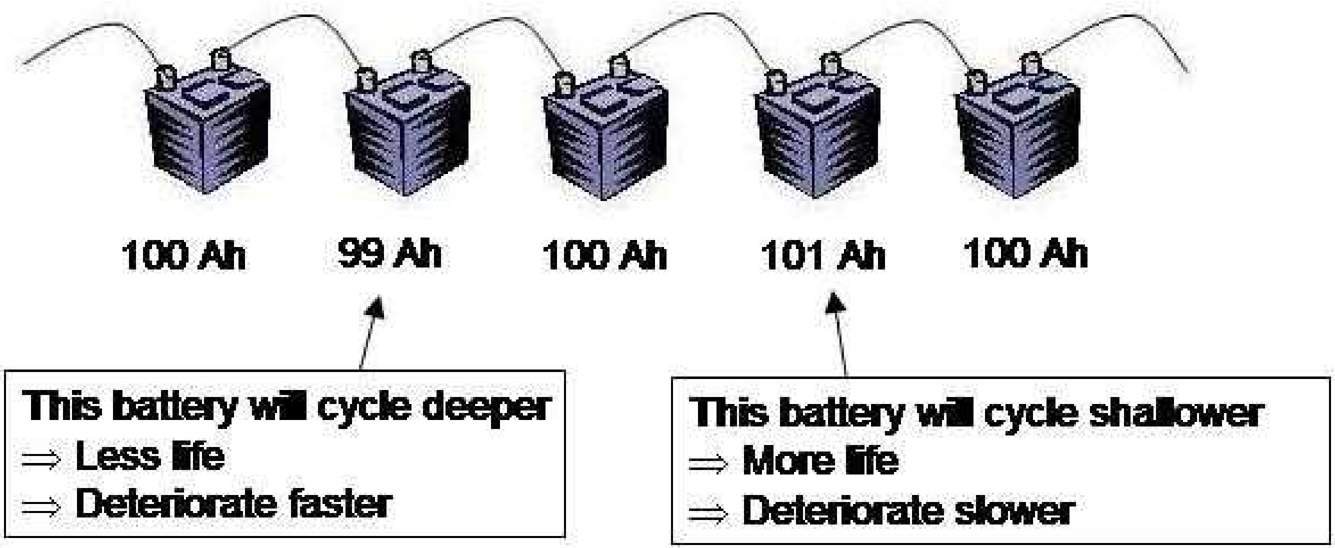
Energy Storage for Renewable Energy

How Battery Packs Fail



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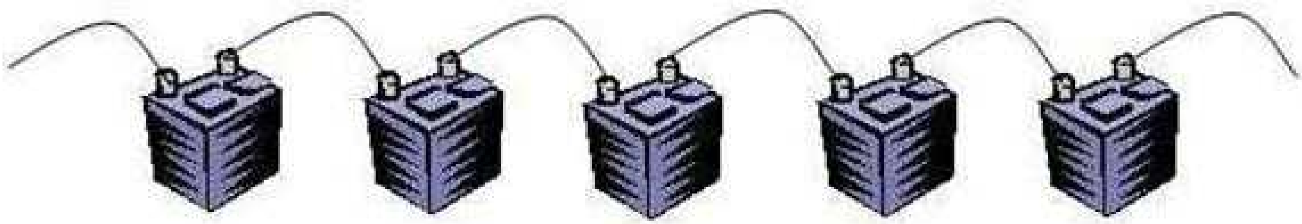
As an aside, it is useful to understand something about battery banks and how they fail. Usually there is some variation in the individual modules or cells – some will be a little better than others. When we cycle a battery pack (i.e. discharge and charge it), the weaker batteries actually relatively cycle slightly deeper than the others and wear out a little faster than the others. What tends to happen is that the slightly weaker cells deteriorate fastest.

Energy Storage for Renewable Energy

Battery Packs Become Unbalanced



To restore battery pack balance, the pack needs an "equalisation charge"

Another thing that can happen in battery packs is that the relative charge between each cell can drift, if not controlled, some cells can be over discharged or over charged, weakening the cell and causing the cell to rapidly fail.

My advice, for maximum battery pack life it is important to monitor all the voltages of the individual cells within the pack.