# Work Package 5

# Smart Grid Solutions

E-Mobility NSR WP5

London, 10th April 2014

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# WP5: Smart Grid Solutions

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**Aims (Northumbria Contribution)**

- Study the impact of Smart Grid solutions, such as V2G, and demand management.
- Model EV battery behaviour and test EV batteries to quantify the implications of using the EV battery for Grid support including smoothing demand, meeting grid regulations and optimise the use of renewable energy.
- Quantify the economic and engineering implications of V2G which would make the acquisition of an EV a more attractive investment for the owner, the manufacturer and the grid operator.
- Define requirements to allow for economic V2G and develop a business case.

# Progress so far

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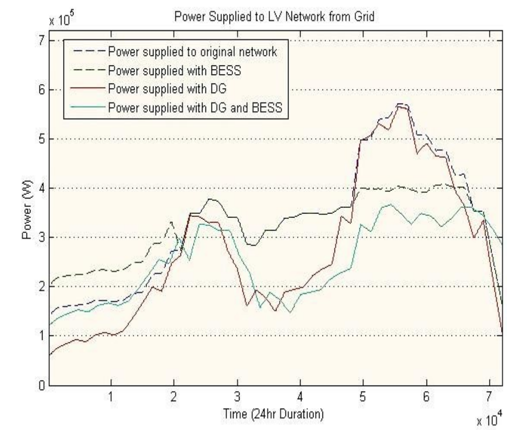
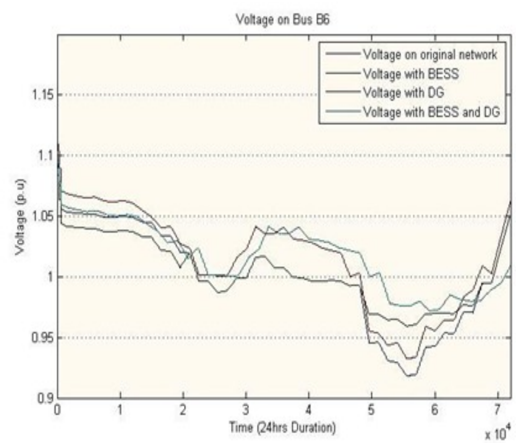
## System modelling, analysis and development

- Impact of EV charging and generation from renewables on the grid.
- Controlled EV charging (G2V) to support the grid.
- Implementation of V2G for existing and future power distribution networks (Smart Grids).
- Use of second life EV batteries for storage and grid support (BESS).
- Grid-code, network specifications and requirements relevant to V2G. Battery requirements based on smart grid use.
- A computer model of a typical low voltage (LV) network, including EVs, RES, BESS in the presence of low carbon technologies (e.g. heat pumps) has been developed.
- A laboratory experimental model of a smart battery charger is under development.



# Progress so far

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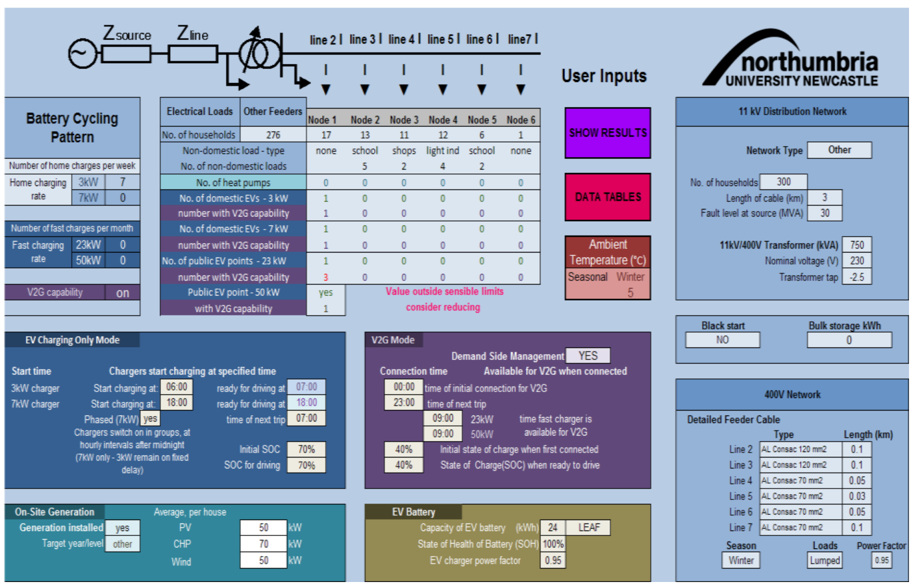
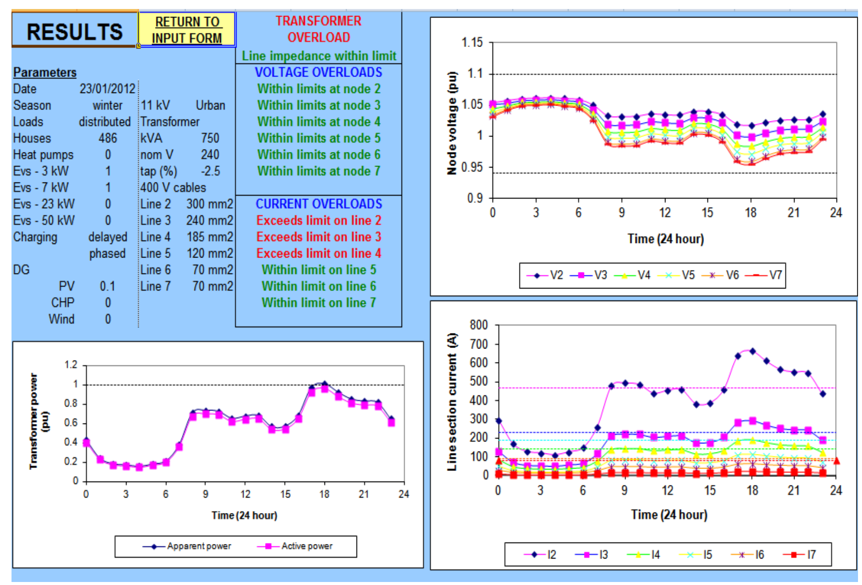
## System modelling and analysis

A computer model is used to simulate a typical LV network and show how the power flow and voltage vary though a 24 hour period with and without EVs, renewable energy sources, battery energy storage systems, etc.

The model allows evaluation of the impacts of EV charging posts and analysis of smart grids solutions, G2V, V2G, smart charging and the impact of battery cycling on the battery state of health.




The modelling tool was developed as part of a project funded by Charge Your Car North (Electric Vehicle Infrastructure – Smart Grids and EV Infrastructure Regional Impact).

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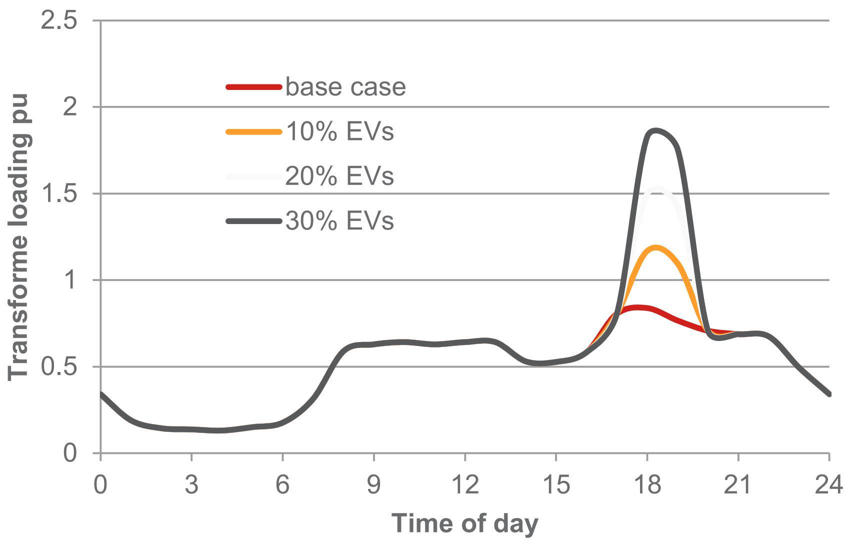
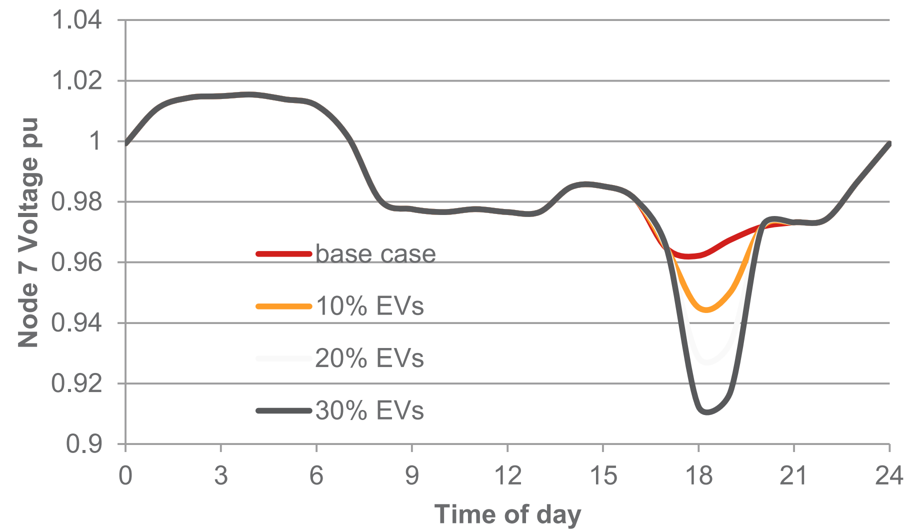
# EV charging on arrival in Winter

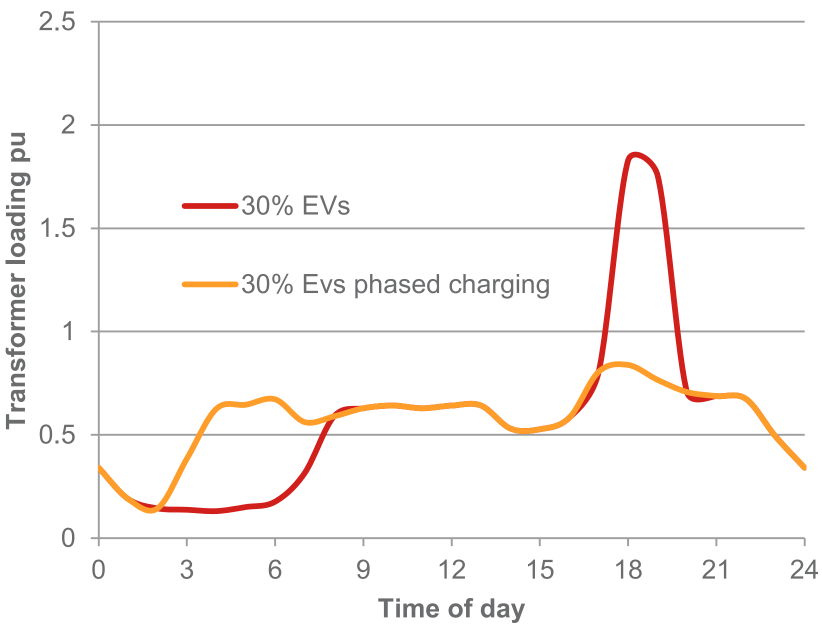



Transformer Loading




End of line voltages

# 30% EVs with phased charging to avoid overload and excessive voltage drops

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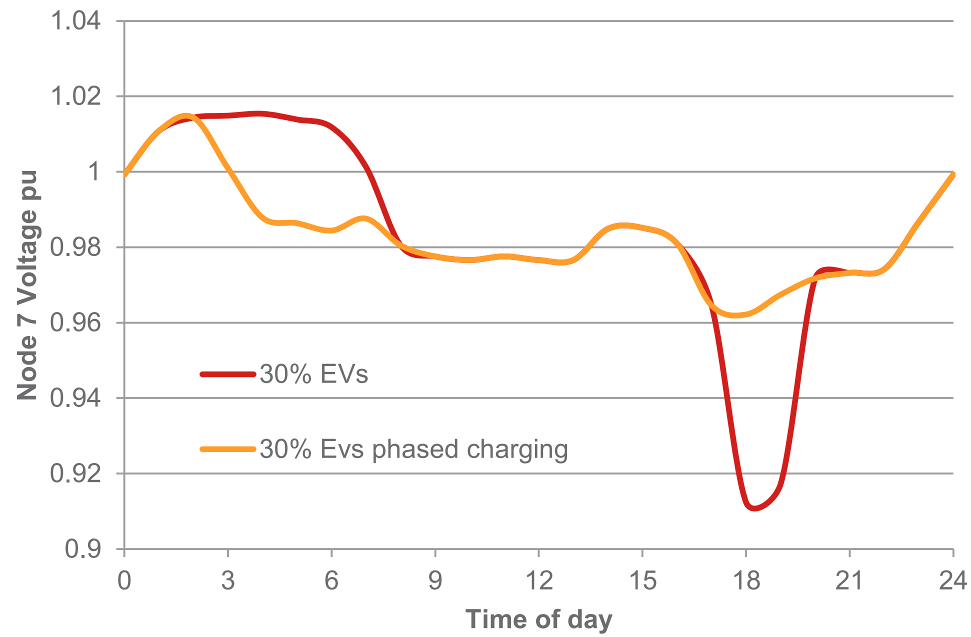
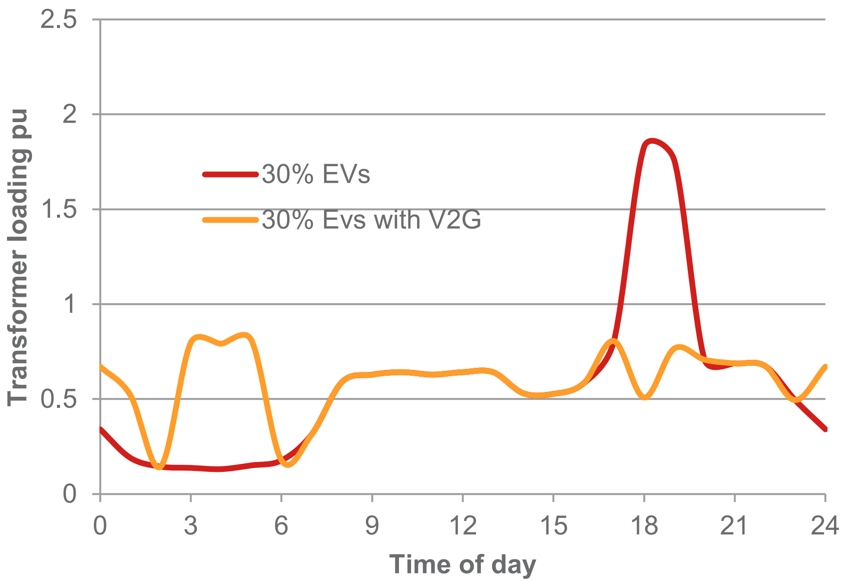



End of line voltages

# 30% EVs with V2G to avoid overload and excessive voltage drops

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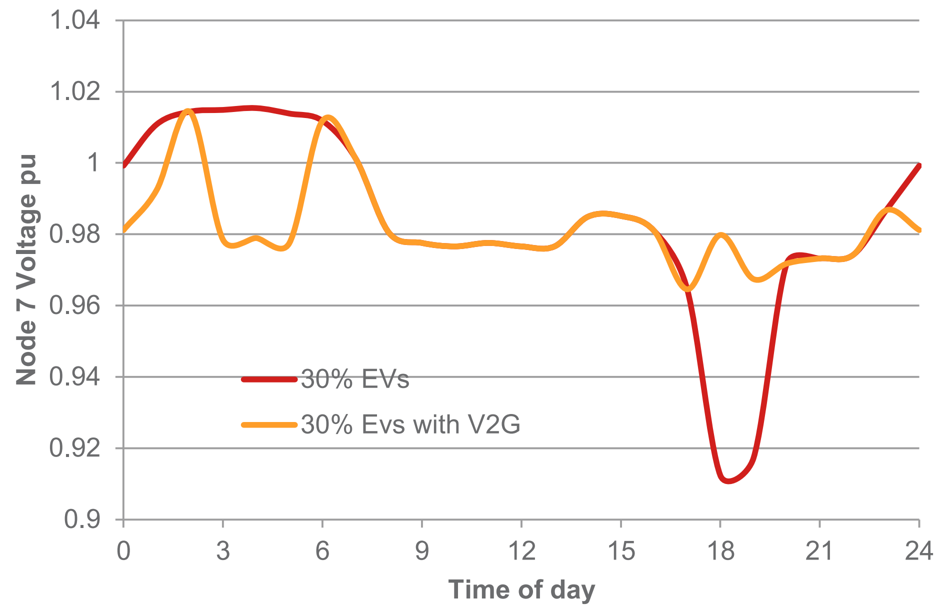
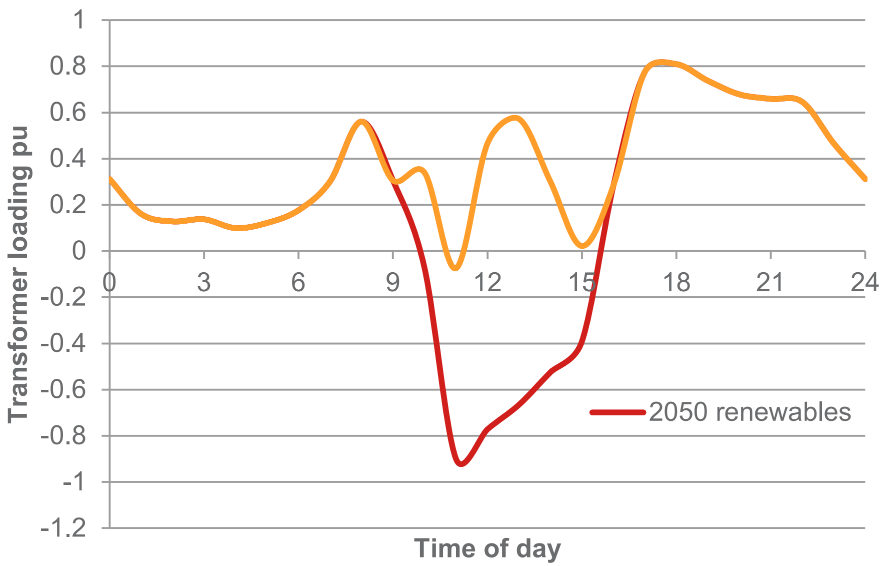
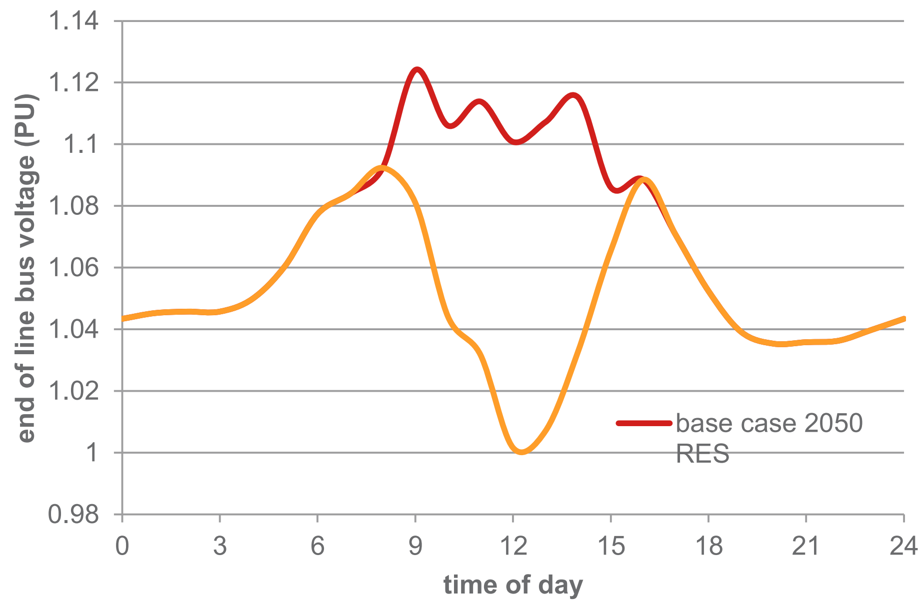



End of line voltages

# 2050 level of renewables in Winter and Summer




Transformer Loading
50% EVs in winter with phased charging to avoid reverse power flow




End of line voltages
90% EVs in summer with G2V to avoid over-voltages

# Transformer loading with 2050 level of renewables in Summer with 500 kWh bulk storage to avoid reverse power flow

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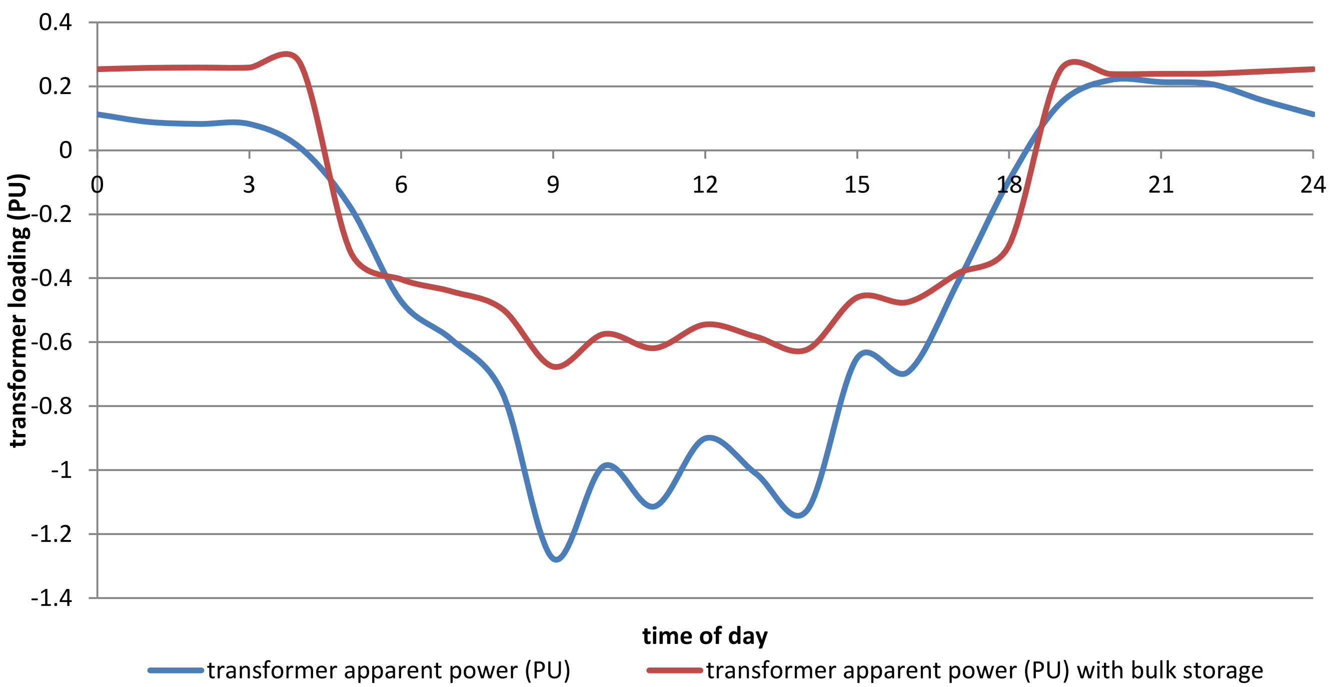


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# Progress so far

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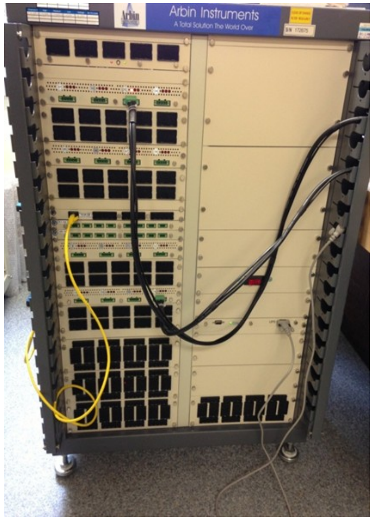
## Battery testing




- Dedicated equipment to analyse the state of health (SOH) of rechargeable batteries. Up to 16 cells can be simultaneously cycled (charge/discharge) in a controlled way (independently) and controlled environment (temperature and humidity).
- Analyse battery degradation and define factors affecting the ageing process
- Model battery degradation and develop a battery aging model

## Collaboration with Ghent University

- Data from actual EV driving trials collected by Ghent University is being analysed to validate lab results and develop battery SOH model

## Publications

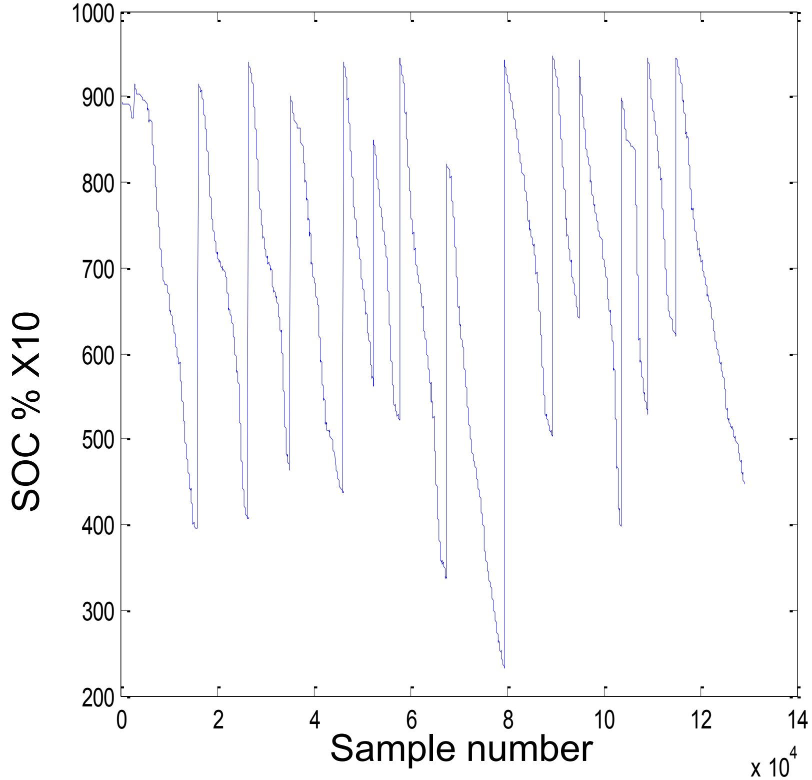
- 3 conferences, 3 invited talks, 2 journal papers

# Progress so far

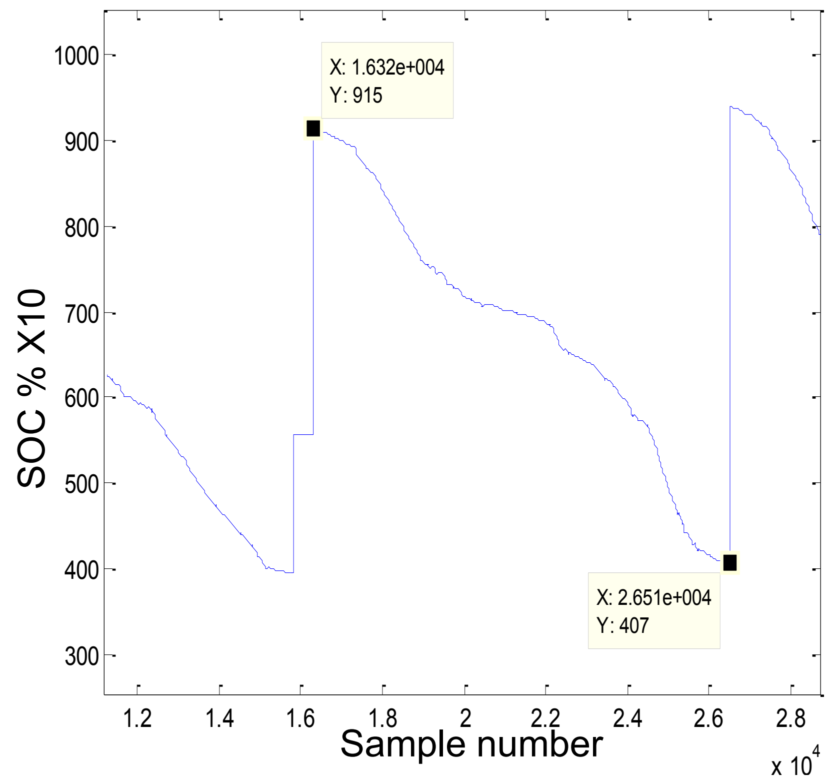
## Collaboration with Ghent University

- Experimental data collected by Ghent University from actual EV driving trials.
- Initial work is conducted to establish the degree of degradation in battery SOH.
- It is necessary to know the energy input to the battery (during charging) to obtain a given increase in battery state of charge; the energy input will decrease as the battery SOH falls. Therefore, the variation in SOH can be derived.
- With appropriate data, a correlation between the degradation in SOH and charge/discharge cycles may be defined.
- The results of data analysis will then be compared lab testing results and with those predicted by existing theoretical and simulation work, and adjustment made to  the parameters in the latter so that the model developed reflects reality.

# Battery SOC from driving data

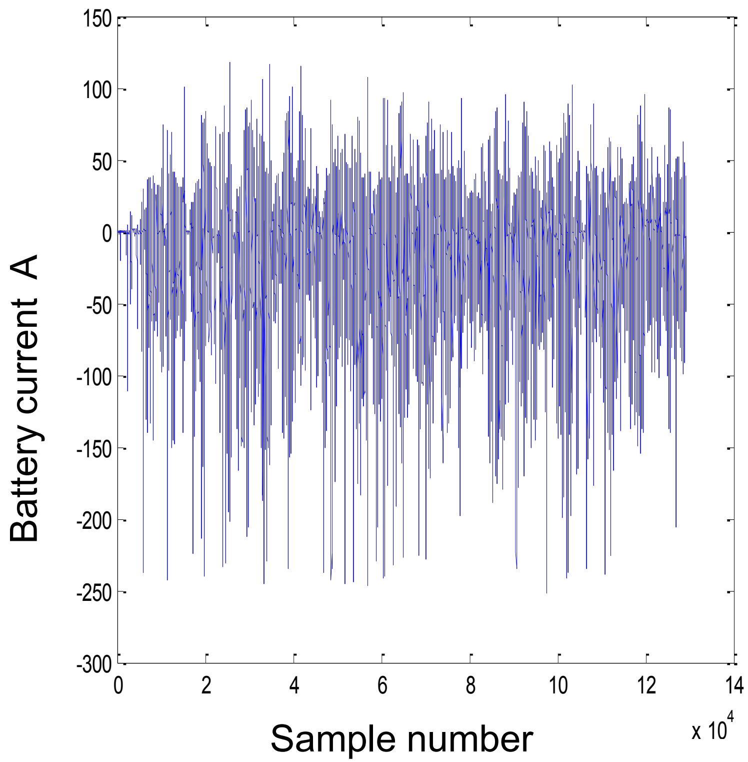


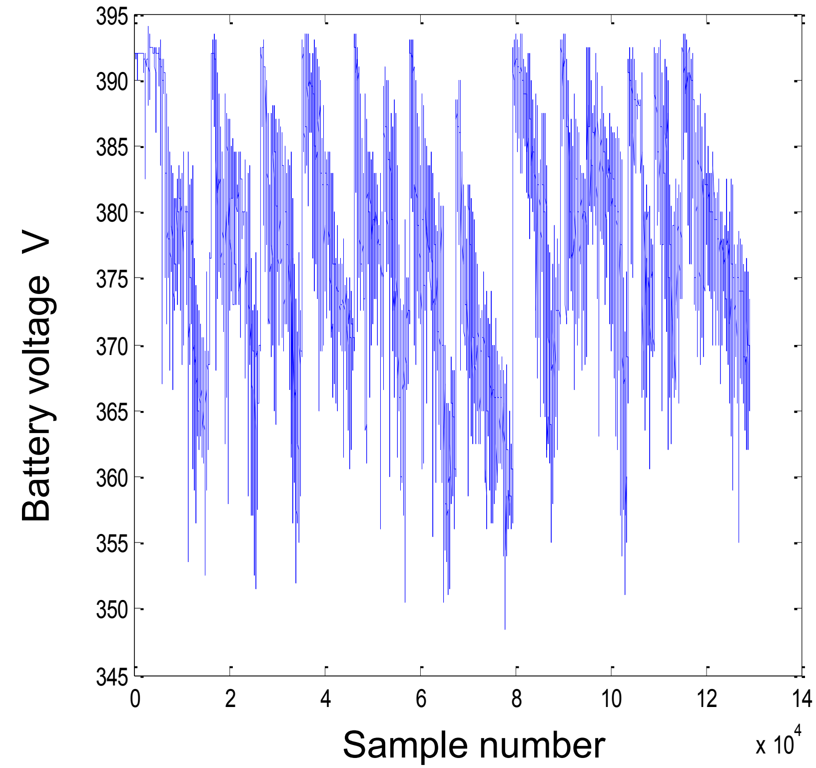

*SOC vs sample number from driving data containing a number of discharge cycles*




Close up of 2nd discharge cycle showing sample numbers for start and finish of the cycle, with corresponding SOC.
SOC fell from 91.5% to 40.7%

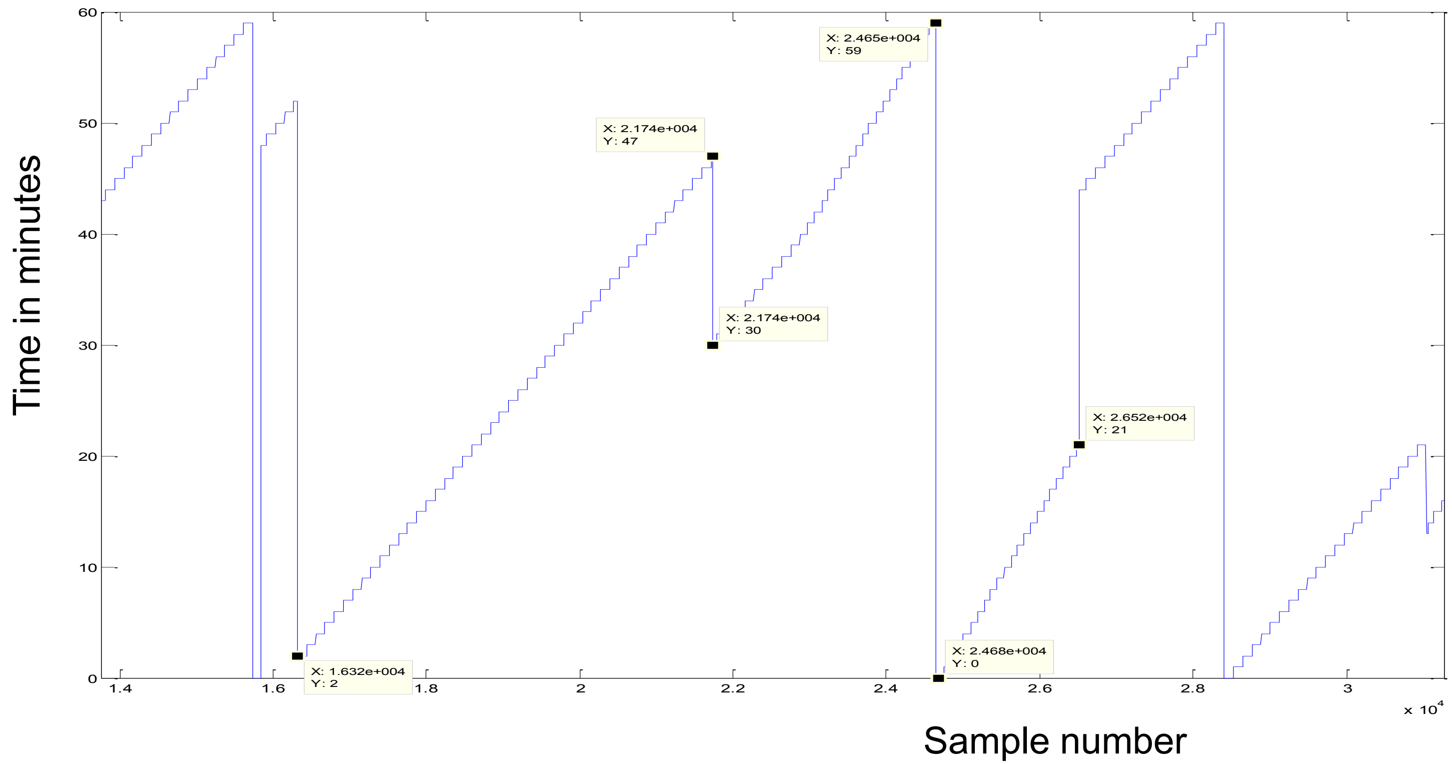
# Battery I, V from driving data




Battery current and voltage versus sample number

# Driving time *during 2nd discharge cycle*




Plot of time in minutes versus sample number showing a total duration of 95 minutes for 2nd discharge cycle.
In 45 minutes there are 5420 samples, giving sampling rate of 2Hz.

# Battery power for $2^{nd}$ discharge cycle

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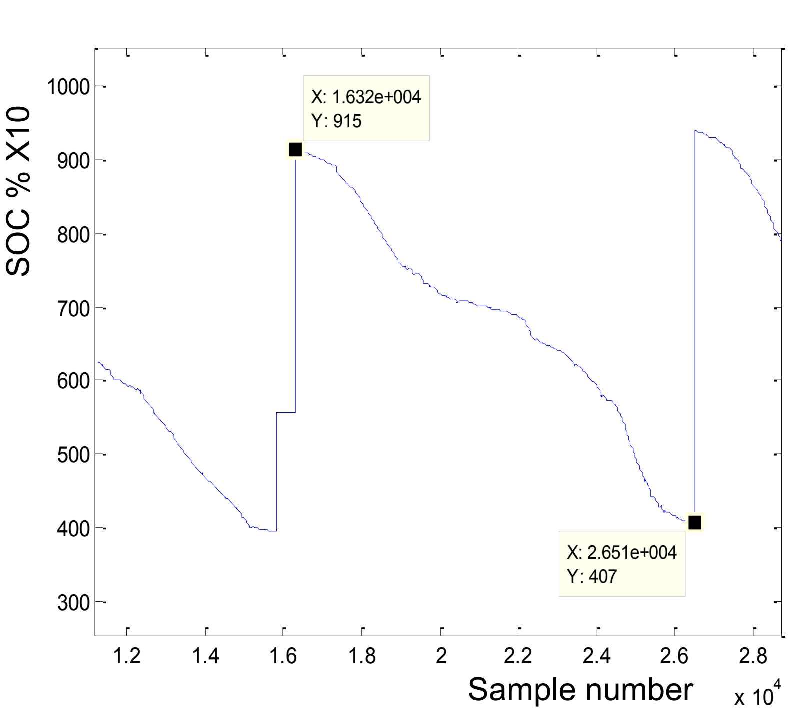
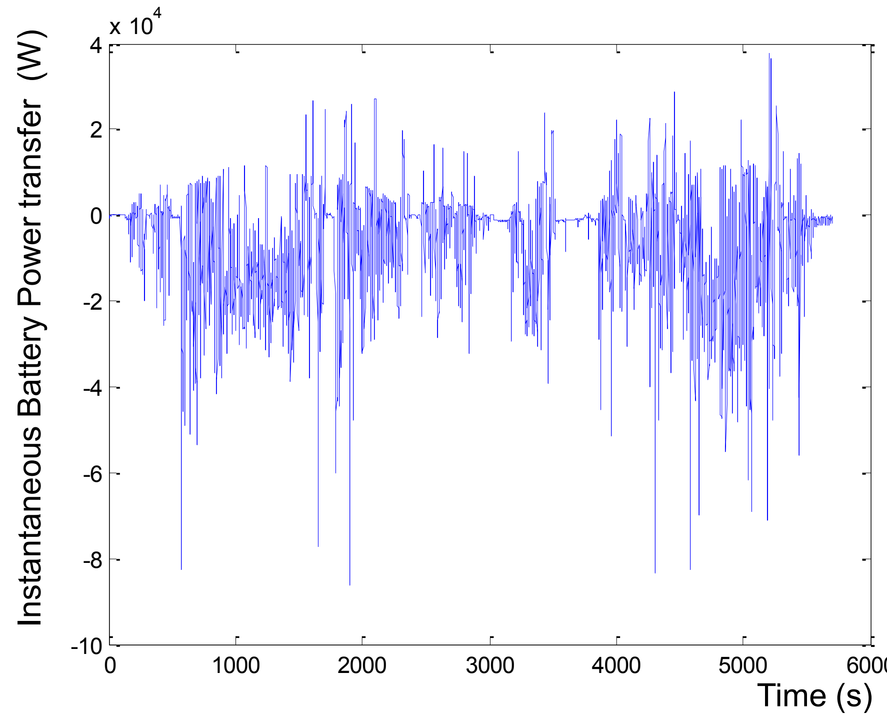



$2^{nd}$ discharge cycle with corresponding SOC versus sample number




Plot of V*I (W) versus time (s), regenerative positive going data weighted at 85% to allow for losses

*Total net energy supplied by battery =* $\int V{*}I \, dt$

Using trapezoidal numerical integration gives total energy supplied by the battery during the $2^{nd}$ discharge cycle = 4.0364e+007 Ws = 1.1212e+004 Wh = 11.212 kWh

# Battery SOH from driving data

- The 2nd discharge cycle lasted for 95 minutes, during which the battery has provided 11.212 kWh.
- A Nissan Leaf was used for the trial, which has a battery capacity of 24 kWh at 100% SOH. If battery initial SOC = 91.5% (0.915), such a power drawdown would correspond to a change in SOC of $11.212 / (24 \times 0.915) = 51.06\%$ with a battery having 100% SOH.
- The measured change in SOC for the discharge cycle was: $(0.915 – 0.407) / 0.915 = 56\%$
- Therefore SOH for this battery during the 2nd cycle was: $(51.06 / 56) \times 100 = 91.16\%$

# Battery Testing

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- Samples of Li Ion cells and packs are being tested
- Cycling has been programmed to investigate the factors that determine the battery state of health (SOH):
  – Cell temperature
  – Charge/Discharge rate
  – Average state of charge (SOC)
  – Depth of Discharge (DOD)
  – Number of charge/discharge cycles
- Data measured at 1 minute intervals and stored in excel files for analysis

# Recommendations for prolonging the life of the battery

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- Keep battery temp between 20 and 35°C
  - Ensure BMS keeps cells temperature within range
  - Avoid fast charging/discharging, especially when ambient temp is high
- Keep average SOC low
  - Minimise charging as much as practically possible. Charge before next use (smart charging).
  - V2G can be used to minimise SOC!
- Keep DOD low
  - Allow low charge/discharge several times rather than full recharging/discharging
- Keep charging rate low
  - Charge at the lowest convenient current rate whenever possible

# Publications

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**Invited talks**
1. "Integration of Low Carbon Technologies in Power Networks Impacts, Challenges and Opportunities" EFEA 2012 June 2012, Newcastle upon Tyne, UK.
2. "Smart Grids: Energising Future Power Networks", keynote speech, ICEEP III conference, October 2013, Hebron, Palestine.
3. "Smart Charging of Electric Vehicles", EPSRC Workshop on Smart Management of Electric Vehicles, Cardiff University, March 2014.

**Journal papers**
1. "Smart Grids: Energising the Future", International Journal of Environmental Studies, Vol. 70, No. 5, October 2013, pp 691-701.
2. "Development of a Decentralized Smart Charge Controller for Electric Vehicles", accepted for publication in the Elsevier International Journal of Electrical Power & Energy Systems, April 2014.

**Conference papers**
1. "Modelling the Use of Second Life Electric Vehicle Batteries for Storage and Grid Support", IEEE EUROCON2013, (Zagreb), July 2013.
2. "The Effect of Cycling on the State of Health of the Electric Vehicle Battery", UPEC2013 Conference Proceeding, Dublin, Ireland, Sept. 2013.
3. "A Modelling Tool to Investigate the Effect of Electric Vehicle Charging on Low Voltage Networks", EVS27 conference Barcelona, Spain, November 17-20, 2013.

**Prepared for publication**
1. "Energy Efficiency in Electric and Plug-in Hybrid Electric Vehicles and its Impact on Total Cost of Ownership", accepted in "E-Mobility Business Models" published by IEA IA-HEV, April 2014.
2. "The implications for the degradation of Electric Vehicle batteries of Smart Grid behaviour", prepared for publication.

# Battery Testing

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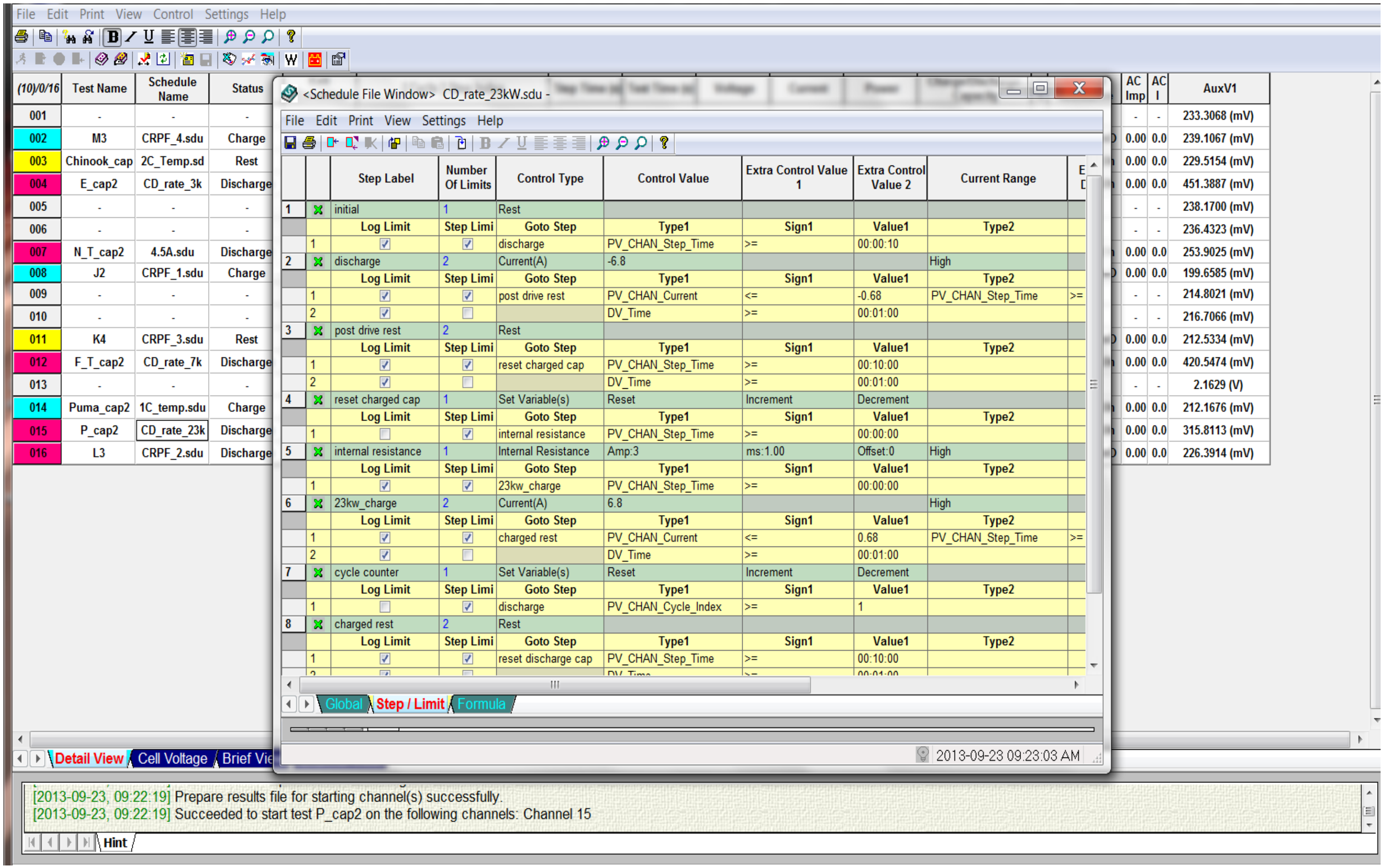


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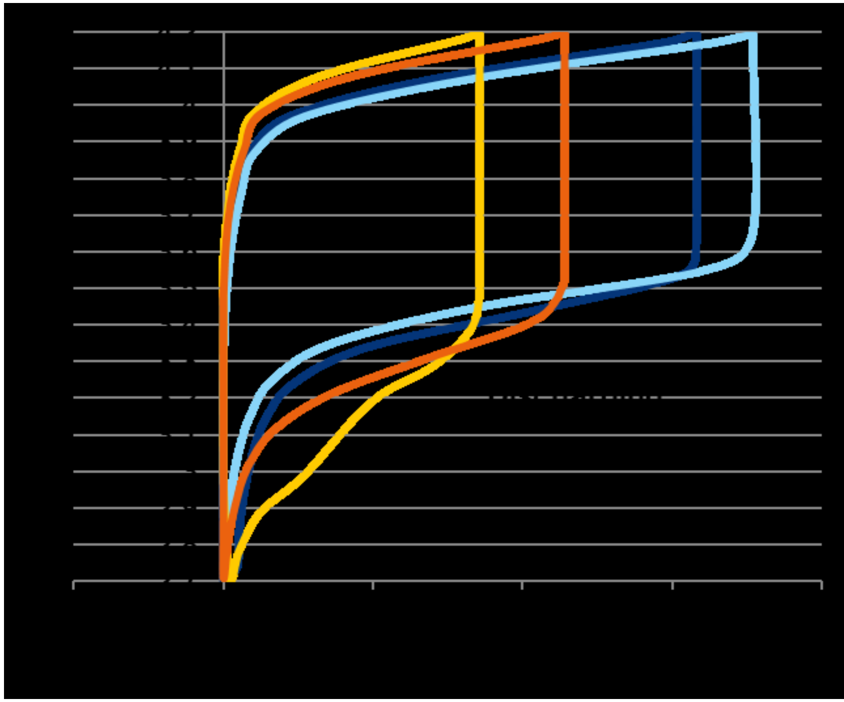
# Factors affecting battery degradation

## Permanent loss in Capacity (kWh) or performance (kW)

- Due to a change in chemical and physical construction of the battery, which results in an increased internal resistance in the battery and/or a reduced upper and lower voltage.
- The chemical changes affect the ohmic, charge transfer or diffusion resistance.
- The physical changes affect how much ion transfer, and thus capacity is possible before the battery reaches its maximum SOC.
- The behaviour of a particular EV user will change these parameters, and so the battery in the EV will age at a different rate to others



**Hysteresis curves for cells of different ages**

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# Factors affecting battery degradation

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**State of Charge**

Higher average SOC degrades batteries faster than a low average.

**Temperature**

Higher temperatures degrade batteries faster than lower temperatures

**Current**

Faster charging current rates degrade batteries faster than slower rates

**Depth of Discharge**

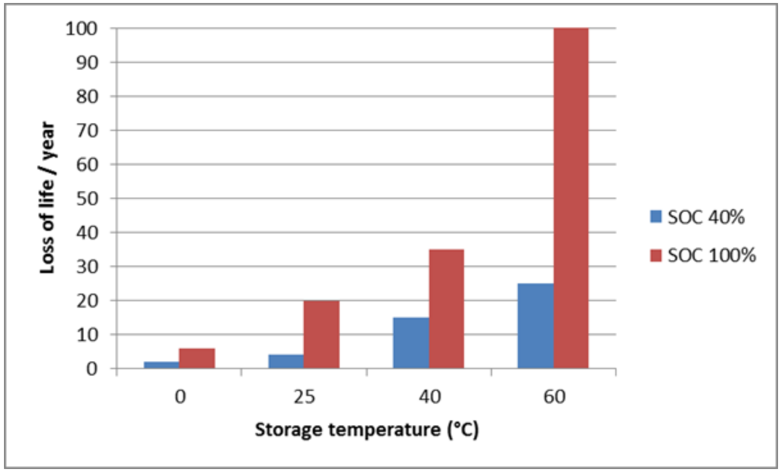
The deeper the DOD, the faster the battery will degrade

**Number of Cycles**

Charging and discharging a battery causes it to age faster than time alone

# Battery Temperature

- EV batteries are designed to operate at an ambient temperature between -10°C and 40°C
- The literature shows ageing as temperature increases, which has been reflected in the model
- Testing is underway to cycle batteries at different temperatures from 0°C to 40°C. Test results will allow the model to reflect the battery's behaviour more precisely .

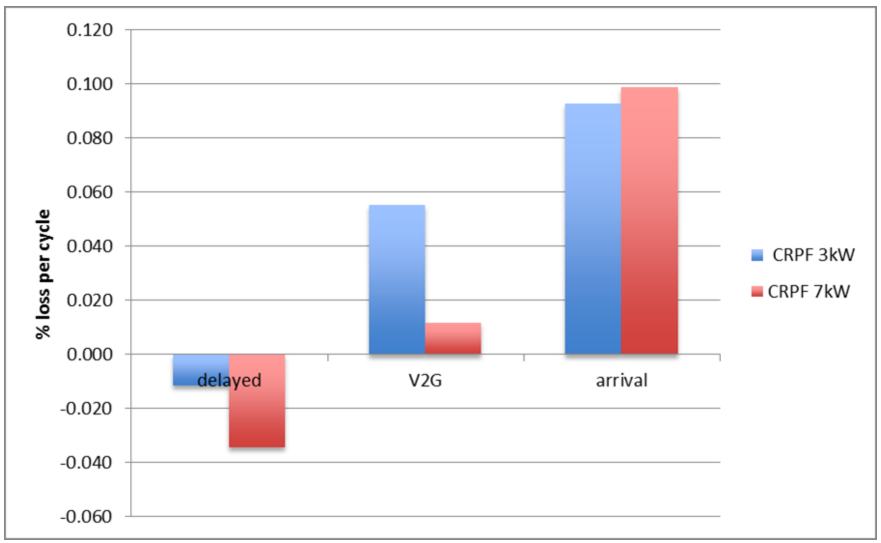



http://batteryuniversity.com/learn/article/how_to_prolong_lithium_based_batteries

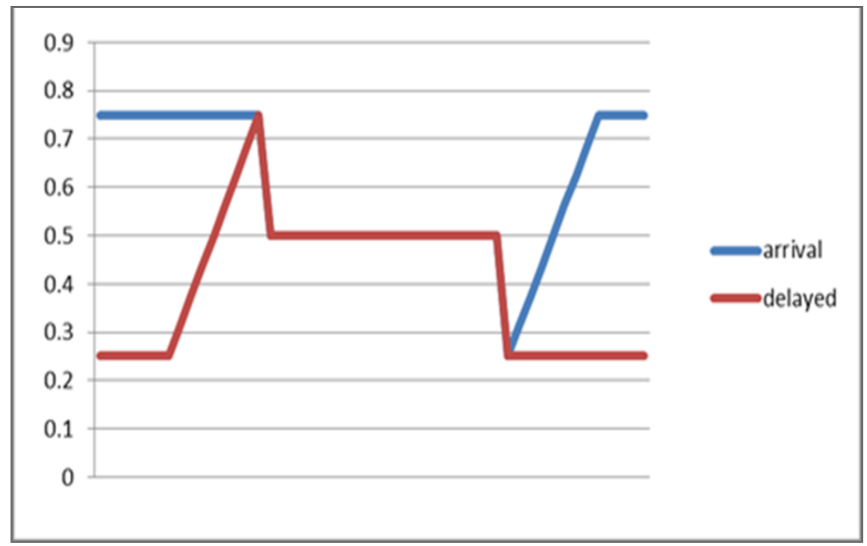
# Average State of Charge

Test results verify the literature, that low average SOC  reduces capacity loss and thus increases battery life

This can be achieved by delaying charging until required for next use




Based on 4 ‘Enix’ Li-ion cells, capacity 6.8Ah cycled on a daily basis between 25 and 75% SOC for 100 cycles.




Smart charging can lower average SOC

# Charge / Discharge Rate

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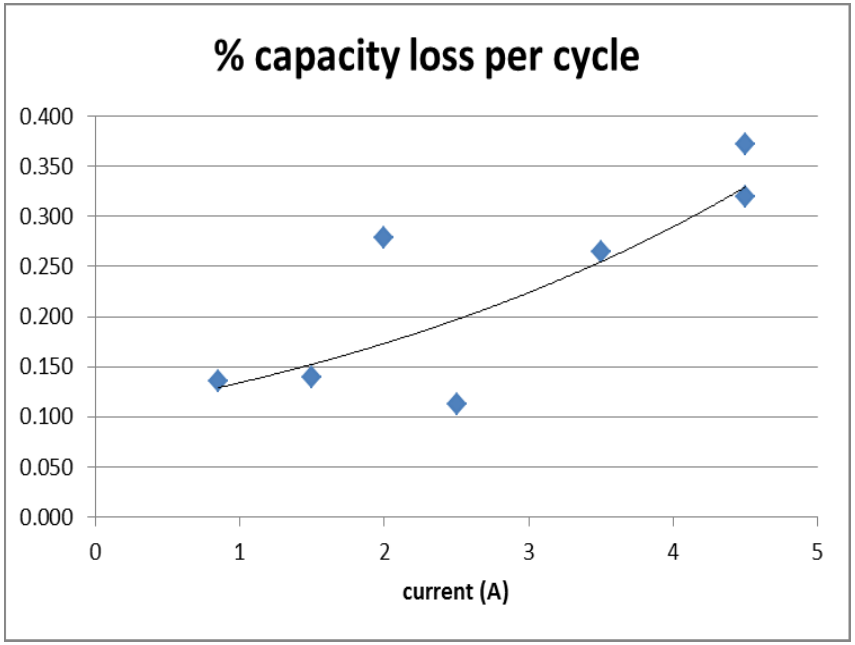
Tests at different charge rate show some variation but the trend is clear




Cycling tests are currently underway, mimicking 3 kW, 7 kW, 23 kW and 50 kW charging

| kW equivalent charging rate | % capacity loss / cycle |
|---|---|
| 3 | 0.013 |
| 7 | 0.028 |
| 23 | 0.3200 |

These cells are not designed to run at 1C so results for 23kW is not typical.

| | Change in internal resistance (over 100 cycles) | Change in capacity (over 100 cycles) |
|---|---|---|
| 1 C cycling | 4.5% | 1.4% |
| 2 C cycling | 4.4% | 2.6% |

Different cells with 2C capability show increased ageing with rapid charging

# Depth of Discharge or Change in SOC

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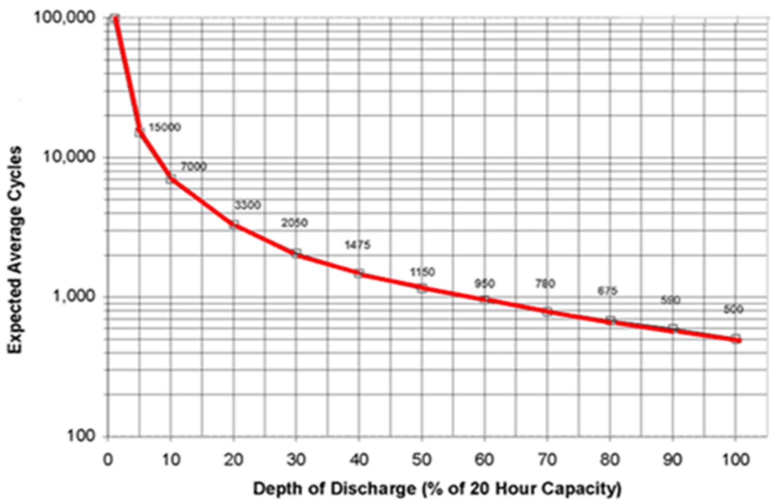
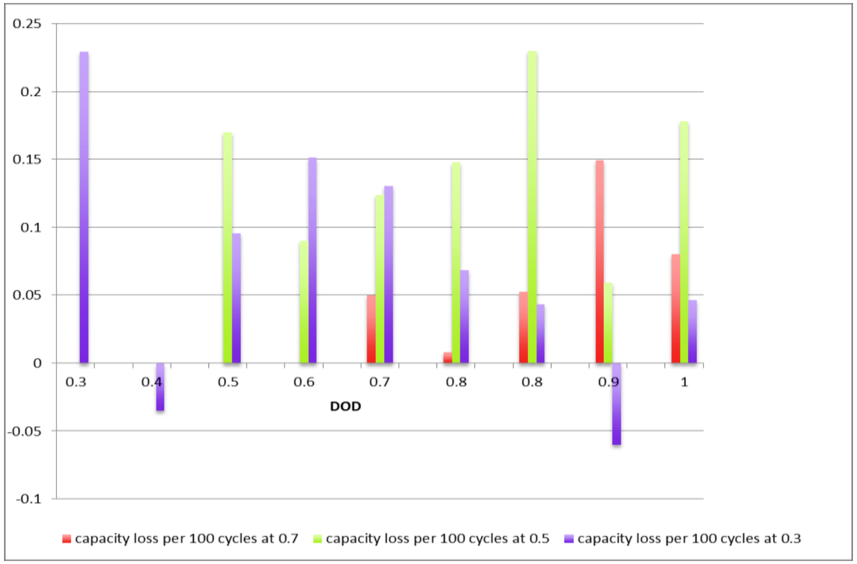
Capacity decreases with depth of discharge




The graph was constructed for a Lead acid battery, but with different scaling factors, it is typical for all cell chemistries including Lithium-ion. This is because battery life depends on the **total energy throughput** that the active chemicals can tolerate. Ignoring other ageing effects, the total energy throughput is fixed so that one cycle of 100% DOD is roughly equivalent to 2 cycles at 50% DOD and 10 cycles at 10% DOD and 100 cycles at 1% DOD.

Results appear to show that the effect of DOD or ΔSOC on capacity loss is not statistically significant




It is unclear whether DOD is the same as change in SOC as published results always use 100% SOC as the max value

# Scenarios Considered in Lab testing (realistic values)

- Four cells are stored to provide data for calendar ageing at two different SOCs and temperatures.
- Cells are charged at C-rate to match existing charge points, controlling SOC and discharge rate.
  - Three cells charging at C/8 (slow), C/3 (medium ) and 1C (fast)
  - Two cells cycling at 1C (fast) rate and 2C (rapid) rate
- Four cells are cycled with two different charge rates
  - Charging immediately after driving,
  - Immediately before driving,

# Scenarios Considered in Lab testing (range of values)

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- Three cells are cycled at different currents, maintaining that value for constant C/D rate
- Cells are cycled at different DOD, each with a constant ΔSOC
- Two cells are cycled at different temperatures

# Summary of Results Obtained so far

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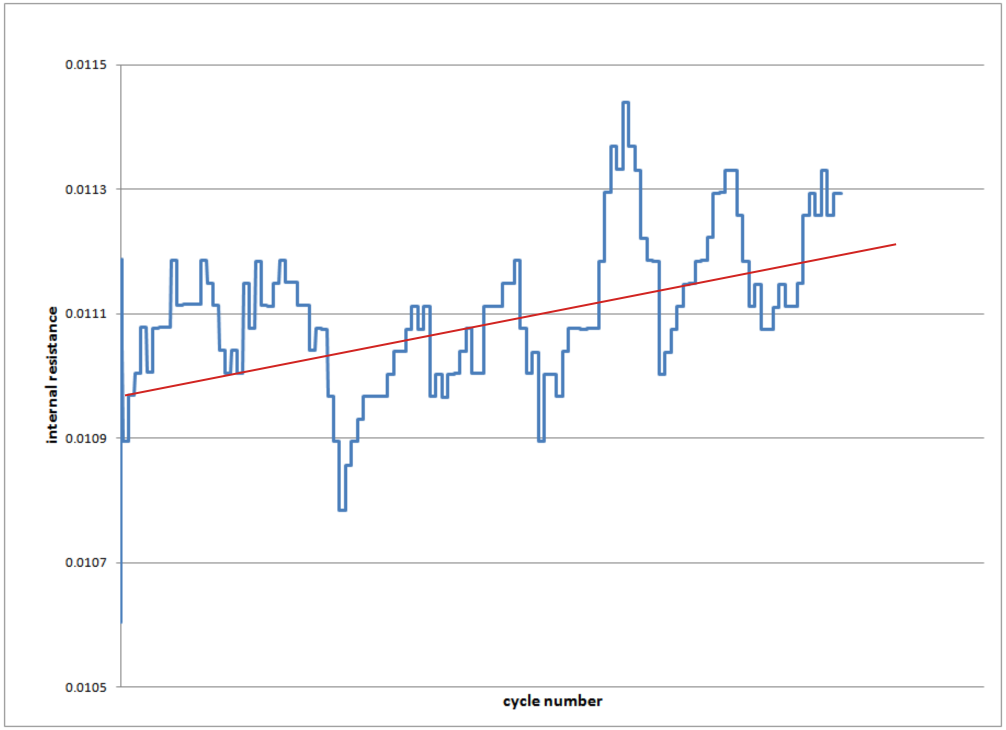
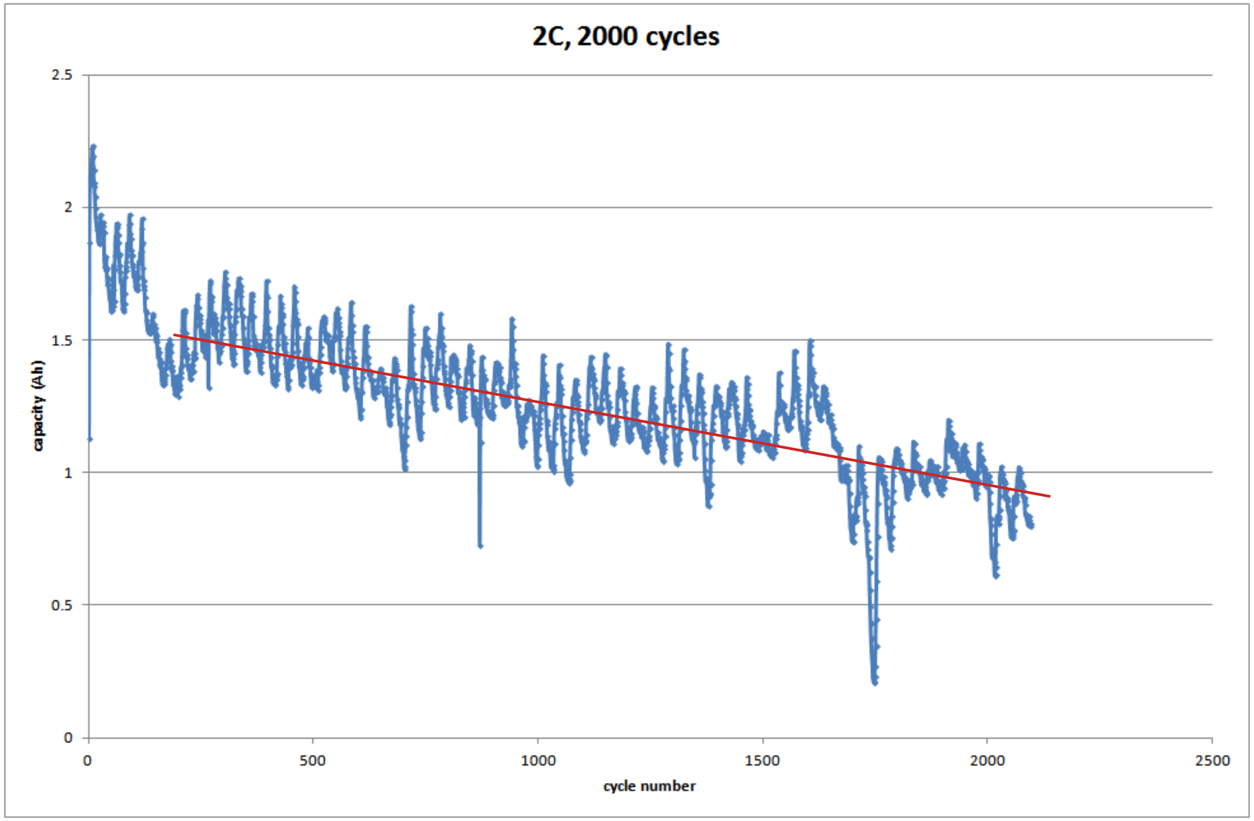
- Internal resistance of the cell appears to increase with cycle number, which agrees with published results




Cell cycled at 2C

# Summary of Results Obtained so far

- Charging capacity decreases with cycle number at fast charging rate



# Temperature effects

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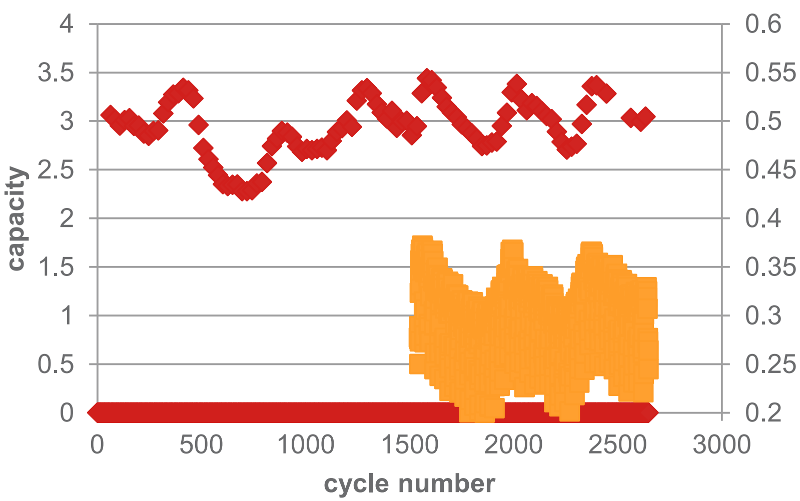
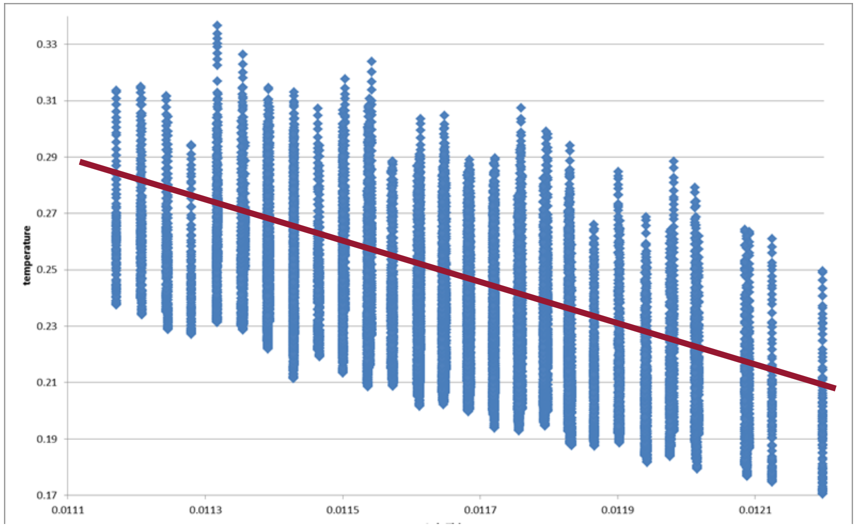
## Capacity is affected most strongly by temperature

Ongoing results will allow us to screen out this factor. Existing comparative results are undertaken at the same time and place, to eliminate this bias




## Internal resistance decreases with temperature, masking the ageing effects.

Since this factor appears to be linear, a correction factor can be placed in the results.





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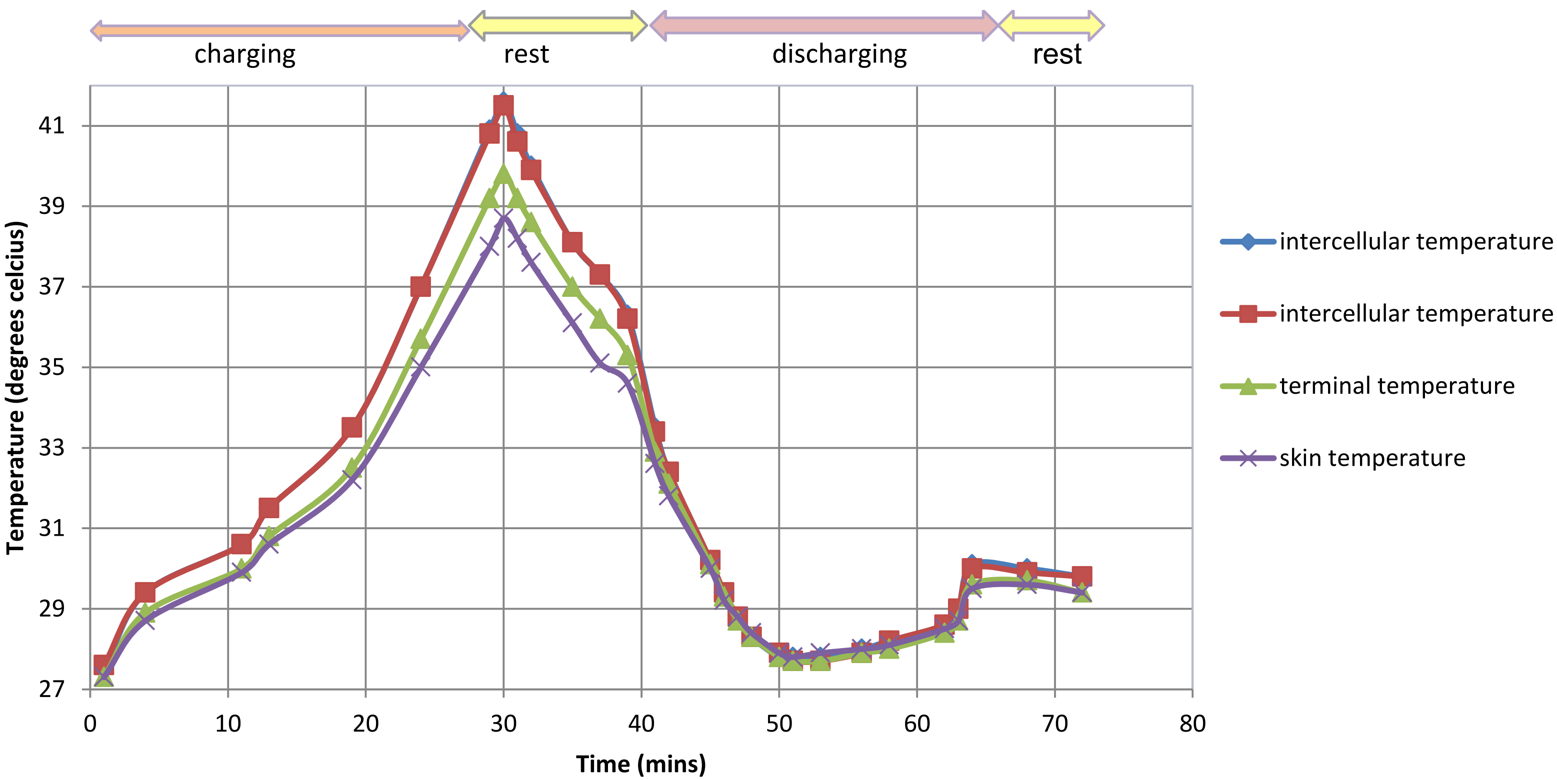
# Further Analysis - Temperature

- Temperature of cells rises during charging and decreases at the start of discharge before leveling off and rising



# Method for establishing SOH for battery

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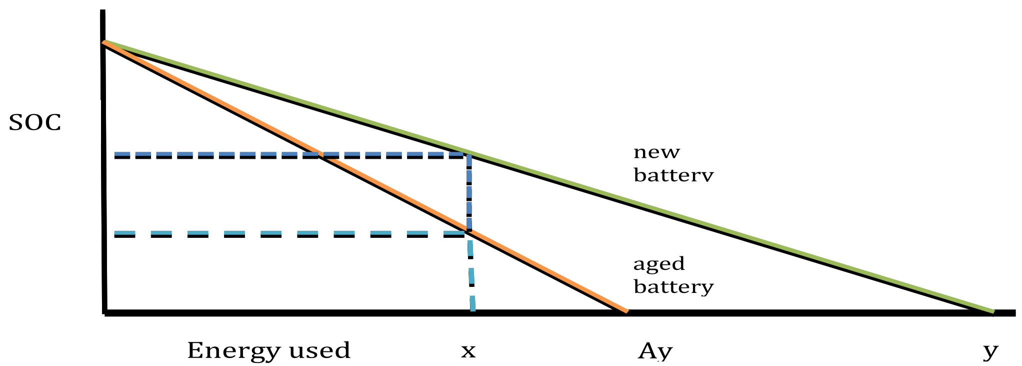


If a battery, of original capacity $y$ kWh, has aged so its SOH is $A$, then its actual capacity (100% SOC) is $Ay$.

Thus a fixed loss in energy ($x$) will result in a larger loss in SOC as $A$ decreases.

$$SOC_{aged} = \frac{Ay - x}{Ay} . 100\%$$

# Method for establishing SOH for battery

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If a battery loses $x$ kWh of charge, where the rated capacity is $y$ kWh, then

the SOC is $$SOC_{new} = \frac{y-x}{y}.100\%$$

However, the SOC is measured from the actual battery data and thus the aged SOC ( $SOC_{aged}$ ) is the displayed value.

Thus, for any value of capacity $$SOH = \frac{SOC_{aged}}{SOC_{new}}.100\%$$

And $$SOH = \frac{SOC_{aged}}{\frac{y-x}{y}}.100\%$$

For example, a 16kWh nominal capacity battery loses 8kWh of energy. The display reads 40% SOC remaining.

And the battery is at the end of its useful life. $$SOH = \frac{0.40}{\frac{16-8}{16}} = 80\%$$

# Conclusions so far

- Charging of EVs can cause problems for power networks if not appropriately controlled.
- Smart charging not only reduces the impact of EVs on the grid but also provide opportunities to use the EV to support to the grid via G2V. With appropriate smart controllers and V2G, EVs can provide ancillary services such as supply/demand matching and voltage/frequency control.
- Use of second life EV batteries can provide a valuable support for the grid and therefore reduce the EV total cost of ownership.
- More work is needed to verify interim results regarding battery degradation and SOH. More cycling whilst controlling temperature will help to verify understanding of ageing mechanisms.
- Analysis of data provided by Ghent University and experimental results will allow the battery ageing model to be verified.
- Defining the battery degradation factors will enable optimum charging/discharging control strategies to prevent or minimize the damage to the battery whilst providing V2G service.

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# Further work

The ultimate aim is to establish a charging regime for EV batteries which will permit economical V2G and smart charging suitable for smart grids:

1. Use temperature chamber for more testing to analyse the effect of battery temperature
2. Develop model for battery degradation and check against lab results and data from real EV trials from Ghent University
3. Using the model, establish conditions for minimizing battery degradation and verify in the lab
4. Use economic models to establish a business case for V2G