Working Paper Series
ISSN 1177-777X

# A SIMULATION STUDY OF THE USE OF ELECTRIC VEHICLES AS STORAGE ON THE NEW ZEALAND ELECTRICITY GRID

**Paul Monigatti, Mark Apperley and Bill Rogers**

Working Paper: 02/2012
April 2012


Department of Computer Science
The University of Waikato
Private Bag 3105
Hamilton, New Zealand

# A Simulation Study of the use of Electric Vehicles as Storage on the New Zealand Electricity Grid

Paul Monigatti Mark Apperley Bill Rogers
University of Waikato
Hamilton, New Zealand
paulmoni@waikato.ac.nz m.apperley@cs.waikato.ac.nz coms0108@cs.waikato.ac.nz

***Abstract*— This paper describes a simulation to establish the extent to which reliance on non-dispatchable energy sources, most typically wind generation, could in the future be extended beyond received norms, by utilizing the distributed battery capacity of an electric vehicle fleet. The notion of exploiting the distributed battery capacity of a nation's electric vehicle fleet as grid storage is not new. However, this simulation study specifically examines the potential impact of this idea in the New Zealand context. The simulation makes use of real and projected data in relation to vehicle usage, full potential non-dispatchable generation capacity and availability, taking into account weather variation, and typical daily and seasonal patterns of usage. It differs from previous studies in that it is based on individual vehicles, rather than a bulk battery model. At this stage the analysis is aggregated, and does not take into account local or regional flows. A more detailed analysis of these localized effects will follow in subsequent stages of the simulation.**

***Keywords-electric vehicles, wind energy, smart grids, V2G, simulation***

## I. Introduction

The notion of utilizing the aggregated battery capacity of an electric vehicle fleet as storage on the electricity grid (V2G) is not new. Fifteen years ago Kempton and Letendre [10] reported a detailed analysis of the potential benefits of such a scheme, both in energy and economic terms. The basic concept is that as electrically powered road vehicles become more commonplace, their need to be regularly connected to the electricity grid in order to have their batteries charged can be exploited by regarding them as both a load and a source. By ensuring that vehicles are connected to the grid ("plugged-in") whenever possible (i.e. when not being driven), and by arranging for the immediate future requirements of each car to be specified (next journey time, next journey distance) then surplus electricity can be stored in the batteries, and excess load can be drawn from them, provided that for the individual vehicle, at the stated time for its next journey, sufficient charge remains to complete that journey.

Heightened interest in better integrating renewable and non-dispatchable energy sources (typically wind, but may include other technologies) into electricity grids has provided a strong motivation to explore and develop this concept. It is fundamental to the increased penetration of wind generation systems into electricity grids, that because of non-deterministic fluctuations (intermittency) of output [14], that as this penetration grows to more than ~20% of the total supply, either additional back-up capacity or some form of storage is required [9][12]. The provision of back-up capacity implies inefficiency in overall grid system design [2][3], leading to a focus of interest in range of potential storage technologies [2][4][7][8]. It has been demonstrated that with appropriate and adequate storage, wind energy penetration can effectively be increased to as much as 65% of total generation capacity [8]. The serendipitous match between the need to reduce fossil fuel dependency (and CO2 emissions) in both vehicle fleets and electricity generation, and the consequent growth in both battery capacity and dependency on non-dispatchable renewable energy sources, has not gone unnoticed [12][14][20]. Coupled with the fact that overall vehicle utilization is reckoned to be as low as 4% [12], the notion of exploiting the underutilized electrical storage capacity of a national fleet of electric vehicles to balance the fluctuations inherent in new forms of electricity generation has many attractions.

Earlier research on this topic, generally characterized as vehicle-to-grid, or V2G, technology, has explored economic and business models [2][11][20], as well as vehicle technologies and connection management [12][20], and overall feasibility and system impact [9][13].

This paper describes a simulation model developed to explore the energy balance characteristics of V2G in the New Zealand energy environment. Details of that environment are provided in the next section, but the major generation source is hydro, with little storage capability at present [1], and an increasing development of wind generation capacity. The simulation incorporates accurate wind speed data, and utilizes actual corresponding grid load. It differs from earlier studies in that it incorporates a discrete vehicle model, based on known statistical usage patterns and representative technologies, rather than an aggregated battery.

It is the energy balance capability that is being explored, specifically in seeking means by which non-dispatchable renewables can be more effectively integrated into the grid, and it is acknowledged that there are other important aspects of V2G implementation which are not covered by the present study. These include economic and business models, vehicle and battery technology, and the personal and social implications of large-scale adoption of such a scheme. Specific approaches to battery recharging provision (e.g. plug-and-charge, battery swap, inductive charging) are not addressed here, nor does the model yet take account of the charge cycle impact on battery life. However, the use of a discrete vehicle model does allow any combination of vehicle technologies to be incorporated into the simulation. For example, a mix of straight plug-and-charge (BEV), smart charge (SEV) and energy-storage (V2G) vehicles can be readily included in a simulation run.

## II. Requirements of the Simulation

The simulation attempts to model the potential impact of utilizing the distributed battery capacity of an electric vehicle fleet to allow more efficient and effective integration of intermittent renewable generation capacity, specifically wind, in New Zealand. The main aim of the study is to determine the extent to which load balance can be maintained with an increased proportion of wind generation capacity, and without the need for a corresponding increase in standing and spinning reserves. To provide an effective evaluation of this scenario, the simulation is required to accurately model the present situation in terms of electricity generation and demand, and also the behavior of New Zealand's vehicle fleet; how many trips are made, at what time of day, how long those trips are and average speed of those trips. It must also accurately model wind fluctuations, and in order to incorporate seasonal variation, should be capable of working with a whole year's data. In addition, the specifications of present day electric vehicles are relevant as they dictate the available battery capacity and charging requirements.

### A. *Electricity in New Zealand*

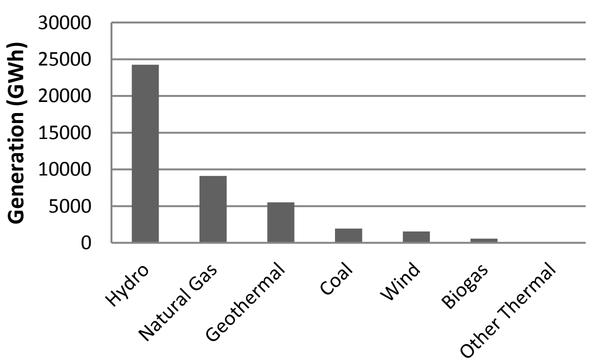


Figure 1. New Zealand Generation by source [15].

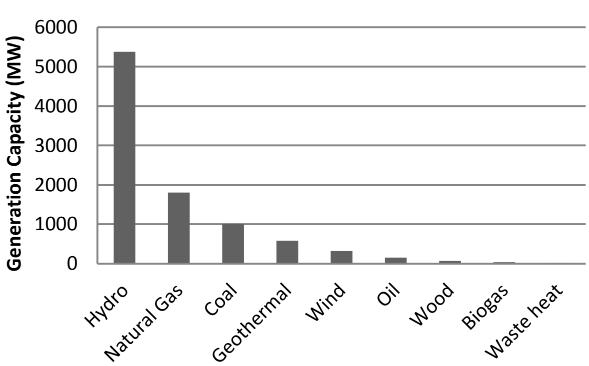


Figure 2. New Zealand Generation by installed capacity [15].

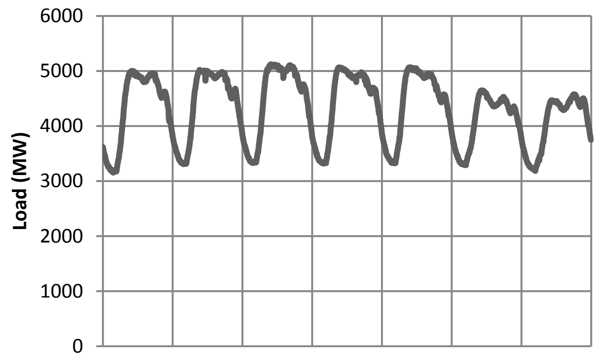


Figure 3. New Zealand weekly electricity demand [22].

New Zealand's electricity network has 9.4 GW of generation capacity, as shown in Fig. 2, generating 43 TWh annually [15], shown in Fig. 1. In 2010, 74% of this energy was generated from renewable sources; a figure that the government wishes to improve to 90% by 2025 as long as security of supply can be maintained [16].

Wind generation has become of increasing interest, as New Zealand's average capacity factor for wind farms is 40%, versus a global average of only 22% [19].

The intermittent output from wind farms can be somewhat offset by the storage offered by hydro lakes, but this does not address transmission and distribution constraints. Because of the high dependency on hydro-electric generation, New Zealand suffers electricity shortages during dry years. Long-term pumped hydro has been proposed to help mitigate the effects [1]. Bull [5] has shown a correlation between low hydro inflows and low wind speed, implying that dry years may also be calm years, and recommends reducing the assumed contribution of wind generation by 10%.

### B. *Vehicle Fleet in New Zealand*

New Zealand is a small country with a population of approximately 4.4 million [21], and in December 2010, had 2,599,568 light passenger vehicles [17]. These light passenger vehicles make up 78% of the nationwide fleet of road vehicles, and will serve as the basis of this simulation.

A household travel survey conducted between 2007 to 2010 shows that personal vehicles are in use an average of 3.3% of the time over a year (consistent with Kempton and Tomic's [12] figure of 4%), and that the average distance driven per day is 28 km spread over three trips [18]. Given typical present-day electric vehicles with a range of 150-160 km and battery capacity of 16-24 kWh (Mitisubishi MiEV, Nissan Leaf), up to 350 km and 56 kWh (Tesla Roadster), there is significant potential for grid storage. For example, with a fleet of 1 million electric vehicles (40% of the current fleet), each with a 50 kWh battery, and assuming that only 3.3% on average are in use at any time, 48 GWh of storage would be available. In New Zealand, this is sufficient to fully cover peak load for three hours. Of course, such a simplistic analysis ignores the effects of vehicles arriving at and departing from the grid during this period, effects which will be well observed by the simulation proposed.

During 2010, 150,000 light passenger vehicles entered the fleet, while 110,000 were retired. At this rate, it would take about 17 years to replace the entire fleet, however the Ministry of Transport notes that the replacement rate over the last three years has dropped significantly from previous years, which is likely to result in a higher replacement rate over the next five years because of vehicles reaching the end of their useful lives [17]. Partly because of the relatively high cost of new vehicles, the average private light vehicle age in New Zealand, 12.8 years, and terminal odometer reading of 195,000 km, are higher than many other developed countries.

Present adoption rates for electric vehicles in New Zealand (largely plug-in hybrid, PHEV) are low, but one recent study, which was concerned with the impact of electric vehicle charging on electricity requirements, suggests take-up rates of between 50% and 80% of new private light vehicles entering the fleet by 2040 [6]. At this estimate, and assuming linear growth in the proportion of electric vehicles from 0% in 2010 to 50% in 2040, we might suggest a total proportion of electric vehicles in the fleet of 1 million by 2040, or 1.6 million with an 80% proportion, from a total fleet size of 4 million.

## III. Simulation Overview

Although the simulation provides for individual vehicle representation in its present form, it deals only with system wide aspects of the interactions between the vehicles and the electricity network. It is intended that as this work progresses, the simulation will be expanded to include localized effects such as transmission and distribution flows, since a real-world system needs to take into account transmission line and transformer constraints.

A general overview of the simulation is provided in Fig. 4. On the left are generation sources which only feed power into the grid, while the bulk load on the right only consumes power. The vehicle fleet allows energy flows in both directions.

Each of the components of this model, and the data on which they are based, are described in the following sections.

The generation output does not attempt to follow changes in load. The responsibility for maintaining balance between generation and load is primarily assigned to the EV fleet, and peak generation is only called upon when absolutely necessary.

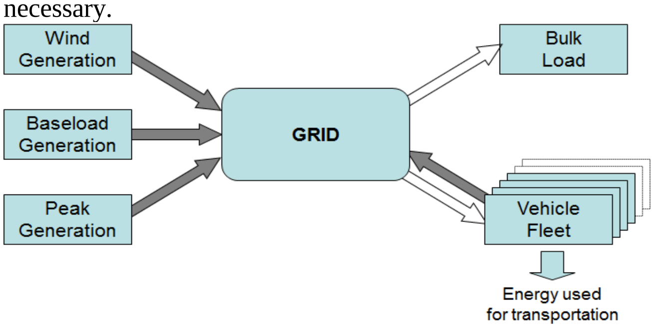


Figure 4. NZ Generation by source [15].

### A. *Base Generation*

For the purposes of this simulation, base generation is assumed to have a constant output such that average annual wind generation, plus base generation, is approximately equal to the average load, including the additional requirements of the electric vehicle fleet (i.e. energy used for transportation). In reality, there is a variety of base generation such as hydro, geothermal and thermal, each with different characteristics in terms of responsiveness to changes in load and of energy storage, but for this initial evaluative stage of the simulation such complexities have been ignored. Also ignored are seasonal variations in base generation to match demand. The ratio of wind capacity to base generation is set to test different levels of wind penetration.

### B. *Wind Generation*

To accurately model the combined output of current and proposed New Zealand wind farms, the simulation uses a synthetic wind speed data set described by Turner et al. [23]. This consists of time series wind speed data for 15 current and potential wind farm locations at 10-minute intervals over a year. However, for commercial reasons, the wind speeds for each site are disguised by either normalizing, or not revealing mast height or co-ordinates. This does not cause a problem for our simulation, since we are more interested in the variation in wind speed than we are in an absolute value. According to Bull [5], the relationship between wind speed and power output is approximately linear once factors such as turbine characteristics and farm layout are taken into account.

To use this dataset in the model, all 15 sites are first averaged for each 10-minute interval to create one large wind farm, using only data for the year 2007, since this is the most recent complete year in the dataset. In order to map wind speed to a power output, the wind speed at which the wind farm produces its full output must first be calculated. According to the New Zealand Wind Energy Association [19], New Zealand wind farms have an average capacity factor of 40%. Since the average synthetic wind speed for 2007 was 9.44 $ms^{-1}$, the nameplate power output will be achieved at wind speeds of 23 $ms^{-1}$. It is important to note that wind turbines can continue to generate maximum power above this speed. The formula to map wind speed to power output is therefore:

$$W_t = \min\left(\frac{wind\ speed[t]}{optimal\ speed}, 1.0\right) \times nameplatecapacity \quad (1)$$

### C. *Peak Generation*

Peak generation is used to fill in the shortfall between base generation and bulk load. These generators are highly responsive and dispatchable, but commonly burn fossil fuels and are less efficient than base generators [3]. For this reason, one of the simulation goals is to minimize their use by smoothing out fluctuations in both wind generation and electricity consumption, using the EV fleet. The peak generation requirement is therefore an output from the simulation rather than a model within it.

### D. Bulk Load

It is essential to model electricity consumption in order to see the interactions between "normal" electricity consumption and that introduced by an electric vehicle fleet that supports bi-directional power flows. This is achieved by "playing back" zone load data for the year 2011, provided by Transpower, New Zealand's transmission network operator [22].

The data contains both real and reactive power for the main load centers in New Zealand at five minute intervals; initially the simulation utilizes only the aggregate real power for the whole country.

### E. Simulation of the vehicle fleet

There are two main aspects to the vehicle model in the simulation; (i) the electrical model, which makes charging/discharging decisions when a vehicle is connected to the grid, and (ii), the vehicle behavior model that determines the timing and energy use of trips made by individual vehicles.

These models utilize, and contribute to, the basic parameters which are held for each vehicle during the simulation. Static parameters, which remain fixed during the simulation, are outlined in table 1, while dynamic parameters, which maintain the state of the vehicle throughout the simulation, are outlined in table 2. For the purposes of simulation, battery capacity is 50 kWh, minimum state of charge is 1 kWh, maximum charge and discharge rates are 5 kW, and a battery-to-wheel efficiency of 110 Wh / km.

TABLE I. STATIC PARAMETERS IN THE VEHICLE MODEL

| **Parameter** | **Unit** |
|---|---|
| *Battery capacity* | *kWh* |
| *Minimum state of charge* | *kWh* |
| *Maximum charge rate* | *kW* |
| *Maximum discharge rate* | *kW* |
| *Battery-to-wheel efficiency* | *kWh / km* |

TABLE II. DYNAMIC VARIABLES IN THE VEHICLE MODEL

| **Parameter** | **Unit** |
|---|---|
| *Present state of charge* | *kWh* |
| *Next trip departure* | *Timestamp* |
| *Next trip distance* | *km* |
| *Next trip average speed* | *km / hour* |

#### 1) Electrical Model

When connected to the grid, each EV must decide whether it should be charging, discharging (supplying energy to the grid), or neither. Each vehicle makes this decision by itself at each tick of the simulation. Naive solutions could simply charge at the maximum rate until the battery is full, or charge at the minimum rate necessary to meet the requirements of the next trip, but these would not realize the potential benefits of V2G. Worse, the charging behavior of all EVs is likely to be synchronized, not only with other EVs, but also traditional electricity demand, and therefore amplify peaks in overall electricity demand.

The proposed model makes a smarter decision based on internal information, such as state of charge, battery capacity and the requirements of the next trip, and external information including the current surplus/deficit of generation on the grid, and aggregate battery state of other grid-connected EVs.

In a real system, knowing the state of charge and battery capacity is relatively straight-forward, while Kempton and Tomic mention possible ways of specifying or learning patterns of use to estimate the requirements of the next trip [12]. External information could be collected using existing communication networks, or it may be possible to infer by analyzing the changes grid frequency that are caused by the imbalance between generation and load.

To calculate an appropriate charge rate, firstly the required external information needs to be known; current surplus generation (2), the energy required to fully charge all connected EVs (3) and the current level of energy in the connected EVs that is available for grid management purposes (4).

These values are calculated on each simulation tick, but are not available to vehicles until the following tick. This is consistent with reality, as it is not possible to know the state of the grid at the time it is measured, but shortly afterwards. This is especially true when grid state is inferred using changes in grid frequency.

TABLE III. SYMBOLS USED IN THE VEHICLE CHARGING STATE MACHINE

| | |
|---|---|
| *P* | *The vehicle is able to supply energy to the grid* |
| *F* | *The vehicle is fully charged* |
| *N* | *The grid has a shortage of generation* |

| | |
|---|---|
| *State A* | Idle, when: $\overline{P}.F + F.\overline{N}$ |
| *State B* | Flexible charging, when: $P.\overline{F}.\overline{N}$ |
| *State C* | Imperative charging, when: $\overline{P}.\overline{F}$ |
| *State D* | Flexible discharging, when: $P.N$ |

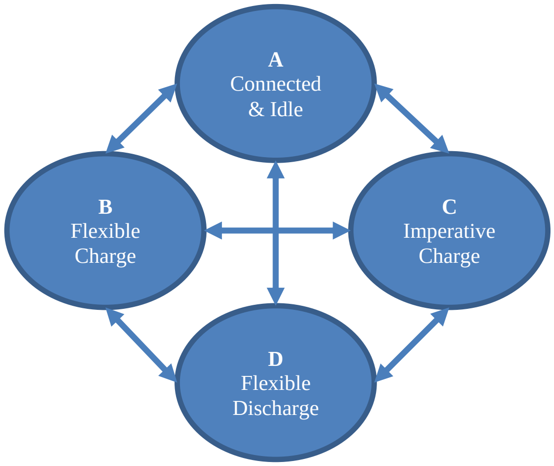


Figure 5. Finite state machine to execute EV charging decisions.

TABLE IV. SYMBOLS USED TO CALCULATE EV CHARGE POWER

| | |
|---|---|
| *S* | *Surplus generation (W)* |
| *t* | *Simulation tick number* |
| *B* | *Base generation (W)* |
| *W* | *Wind generation (W)* |
| *L* | *Bulk load (W)* |
| *Lev* | *Imperative EV charging load (W)* |
| *Er* | *Energy required to fully charge the EV fleet(J)* |
| *Qmax* | *Maximum battery capacity of an EV (J)* |
| *q* | *Current battery charge of an EV (J)* |
| *Eav* | *Energy available in the EV fleet (J)* |
| *qmin* | *Minimum allowable EV battery charge (J)* |
| *Q1* | *Battery charge required by time T1 (J)* |
| *Rin* | *Maximum charge power to an EV (W)* |
| *T1* | *Time of next departure of an EV (W)* |
| *st* | *Current simulate date and time* |

$$S_t = B_t + W_t - (L_t + Lev_t) \quad (2)$$

$$Er_t = \sum_{i=1}^{n} Qmax_i - q_i \quad (3)$$

$$Eav_t = \sum_{i=1}^{n} q_i - \max(qmin_i, Q1_i - Rin_i \times (T1_i - st)) \quad (4)$$

In state A, charge power is zero, while in state C, charge power is simply the maximum rate possible for the vehicle. Charge power for states B and D require further calculation.

For state B, vehicles that are near their full capacity are charged at a lower rate than those which are near empty, according to (5).

$$Pin = S_{t-1} \times \frac{Qmax - q}{Er_{t-1}} \quad (5)$$

For state D, vehicles that are near their full capacity are discharged at a higher rate than those which are near empty, according to (6).

$$Pout = S_{t-1} \times \frac{q - \max(qmin, Q1 - Rin \times (T1 - st))}{Eav_{t-1}} \quad (6)$$

The desired effect of these equations is to balance the charge between each EV, while attempting to maintain the balance between generation and load at all times.

*2) Vehicle Behaviour Model*

An important part of the simulation is to accurately model the times of day vehicles are used, how far they travel and the amount of time they spend on the road, in order to track both their energy requirements, and their availability for grid management purposes. The New Zealand Household Travel Survey [18] invites people from 4600 households each year to record all of their travel over a two day period. The results are used to generate trips in the simulation.

Each vehicle in the simulation knows its next trip, which consists of a time of departure, distance, and average speed. When a vehicle returns from a trip, its next trip is generated, and the vehicle stays connected to the grid until departure.

To generate the next trip's time of departure, the cumulative distribution function of Fig. 6 is sampled 22 times, such that these trips are more likely to occur at the most common times of day. The sample that is immediately after the current simulation time will be the time of next departure, wrapping back to the start of the next week where necessary. The distribution is sampled 22 times, since this is, on average, the number of trips made each week [18].

Once the departure time is calculated, an average distance is taken from the distribution shown in Fig. 7. Next, a random sample is taken from the distribution shown in Fig. 8, which is the distribution of trip distance per day, normalized to have a mean of 1. The average trip distance from Fig. 7 is then multiplied by this value and becomes the distance of the next trip.

Finally, the average speed of the trip is simply chosen to be 36 km/h, a figure indicated by [18].

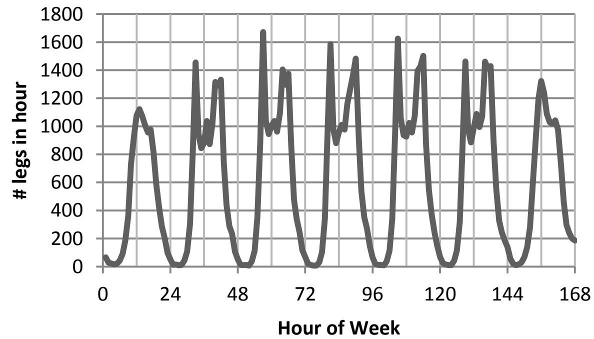


Figure 6. Trip legs by hour of week [18].

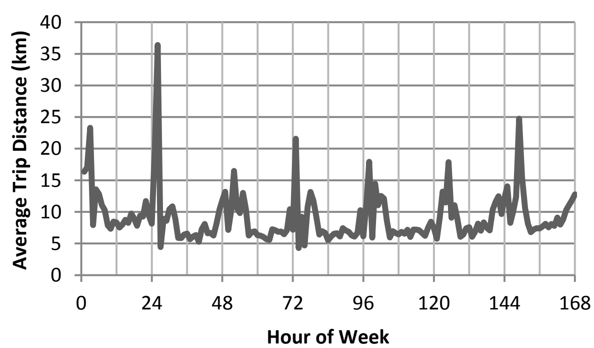


Figure 7. Trip distance by hour of week [18].

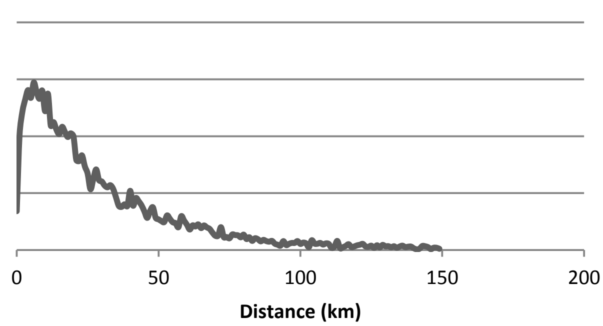


Figure 8. Distribution of daily travel distance per vehicle [18].

Immediately after generating the next trip, a check is done to see if that trip is possible. It may not be, either because the distance is further than the range of the vehicle, or it is scheduled to depart before the vehicle can be bought up to a sufficient charge. In either case, the failure is recorded and a new trip generated to replace it.

## IV. Running the Simulation

The simulation works on a tick-by-tick basis. At the beginning of the simulation, the state is often unsettled - the entire EV fleet having an empty battery, for example. This is addressed by running the simulation for a day before the intended start time, allowing state to settle down.

The duration of a single tick can be changed dynamically. Smaller tick duration means greater output resolution and accuracy, at the expense of slower execution.

A five minute tick interval has been chosen, as our finest-resolution dataset is of this duration. Not all models are derived from data sources with this resolution; in this case, linear interpolation between data points is used.

The process that is executed for each tick can be described as follows:

1. For each vehicle that has departed since the last tick, disconnect from the grid.
2. For each vehicle that has returned from a trip since last tick, update battery state, reconnect to the grid and generate the next trip.
3. Look up values for wind generation, base generation, and bulk load from their respective models.
4. For each connected EV, make the charging decision described previously.
5. Add the power input/output of all entities connected to the grid to calculate overall power imbalance.
6. Record the current state of the network, including generation breakdown, spinning reserve needed to maintain balance between generation and load, and the state of the EV fleet.
7. Calculate values for (2), (3) and (4) for use at the next tick, as described in the previous section.

In a real electricity network, generation must match load at all times, and an output of the simulation is the amount of additional generation required to keep this balance. This could well be negative, implying that some energy must be spilled, for example by turning wind turbines out of the wind flow, or spilling water at a hydroelectric dam.

## V. Results

The results presented here were generated by running the simulation for a one-year period, with wind penetrations of 10%, 20%, 30%, 40% and 50% with 1 million EVs. The generation model consists of only wind and a fixed base generation level, which were both set to the average demand over the year (4.6 GW average loads, plus an additional 130 MW average to meet the demands of the EV fleet). The proportion of wind to base generation is set according to the wind penetration being tested. With this configuration, a simulation run requires about 1 hour on a modern PC.

To evaluate the charging strategy described in this paper (henceforth called co-op), several other charging strategies have been simulated:

- Greedy: once connected, an EV will charge at its maximum rate until fully charged. This is most similar to uncontrolled charging.
- Lazy: a "just in time" charging method. No charging will be done until the last minute (i.e. as close as possible to the time of departure); at that point, the EV will charge at its maximum rate.
- Lazy+: similar to *Lazy*, but will charge in the interim if there is excess generation.
- Slow: once connected, an EV will charge constantly at the minimum rate required to meet the energy needs of the next trip.

### A. *Reserve Generation and Spillage*

For the purposes of discussion, "reserve generation" refers to the generation needed to maintain balance between generation and demand at all times, in addition to wind generation, base generation and the V2G output of the EV fleet. Reserve generation is only used when the EV fleet can't supply the necessary power. Similarly, "spillage" refers to electricity that would be generated, but must necessarily be wasted because there's neither demand nor storage available to absorb it.

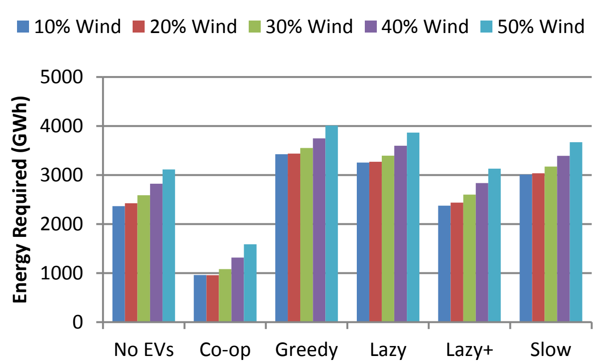


Figure 9. Annual reserve generation required

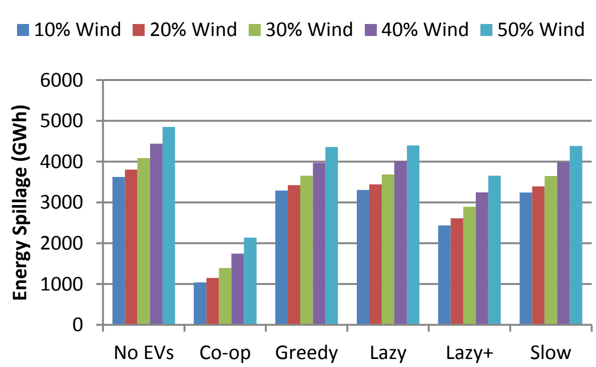


Figure 10. Annual energy spillage

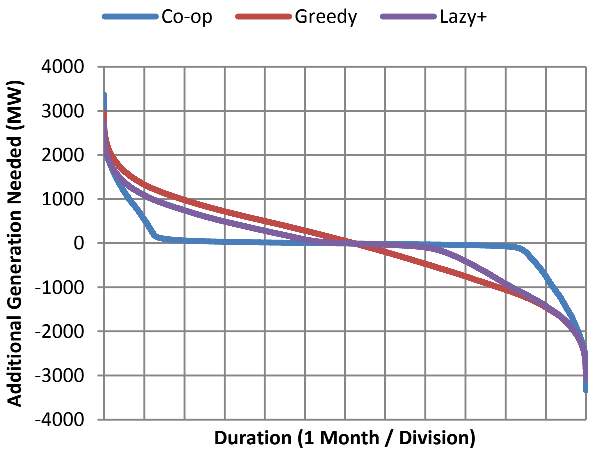


Figure 11. Annual reserve generation load-duration curve, 30% wind

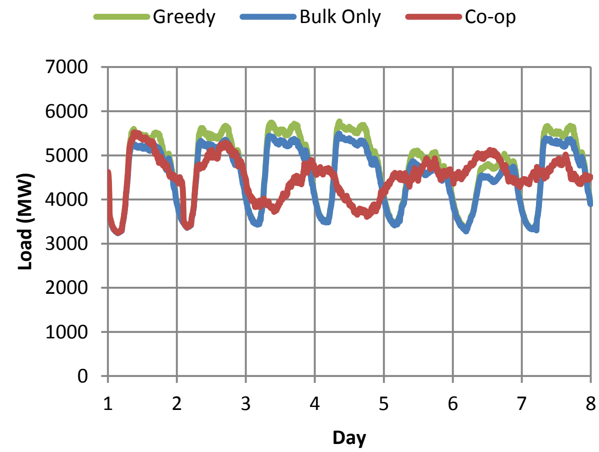


Figure 13. Electricity Load during the first week of February 2011

By using a fleet of 1 million EVs to cover generation shortages, it is possible to substantially decrease the energy required from reserve generation sources. Fig. 9 shows that the co-op charging strategy performs much better than all others, including the case where no EVs are present. As expected, a similar situation exists for energy spillage, shown in Fig. 10. Surplus generation is absorbed by batteries in the EV fleet, for use at a later time.

The load-duration curve for the reserve generation required over the year (Fig. 11) shows that co-op maintains balance between generation and demand for about 75% of the year, a significant improvement over greedy and lazy+.

Unfortunately, the peak power requirement for co-op was the highest of all charging strategies. These large peaks occur during periods of high bulk demand and low wind generation, where V2G makes up a high proportion of input to the grid. The EV fleet is eventually drained of energy, requiring a sudden input of reserve generation to cover not only the bulk demand, but also the transport requirements of the EV fleet. It should be possible to predict these peaks hours, if not days, before they occur. It may then be possible to increase reserve input long before it is needed, and spread the load over a longer time period.

## B. *Electricity Demand*

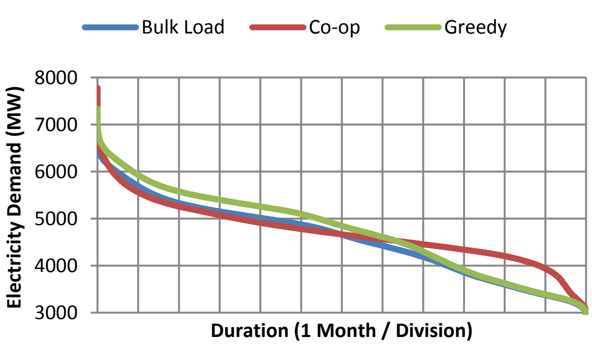


Figure 12. Annual demand load-durtion curve, 30% wind

In terms of overall electricity demand, the introduction of an EV fleet using the greedy charging strategy increases load during higher demand periods, while utilizing very little off-peak capacity (Fig. 12). Using the co-op charging strategy increases the electricity load primarily during off-peak times, while contributing energy back to the grid during higher demand (Fig. 12). This behavior is a desired side-effect of the strategy in terms of infrastructure requirements; however the primary aim is to match supply and demand.

Fig. 13 shows the demand curve during the first week of February, with the weekend occurring on the 5$^{th}$ and 6$^{th}$. This figure again shows how the greedy strategy contributes to peaks, and does not effectively utilize off-peak capacity.

The co-op strategy almost completely decouples the daily load variation, and instead follows the variable output from the wind generation model.

There are two cases of energy spillage appearing in Fig. 13 using the co-op strategy, occurring during the early hours of the 1$^{st}$ and 2$^{nd}$. Overall load drops to the original bulk demand level when the EV fleet becomes fully charged, and resumes following wind generation once demand rises later in the day.

## C. *Aggregate Battery Charge*

An EV fleet of one million vehicles, each with a battery capacity of 50 kWh, has a potential storage capacity of 50 GWh. Over the course of the year, the storage capacity connected to the grid averages 48 GWh with a minimum of 46 GWh. The actual charge level averages approximately 25 GWh over the year, of which 24 GWh is available for grid management purposes (after allowing a 1 kWh minimum charge for each vehicle). 24 GWh is sufficient to completely provide New Zealand's average electricity demand for five hours in the unlikely event of a total generation blackout. Of course, real values will be lower, since the simulation currently works on the assumption that a vehicle is connected at all times that it is not being driven.

Figure 14 shows the aggregate energy stored in the EV fleet's batteries over the month of February.

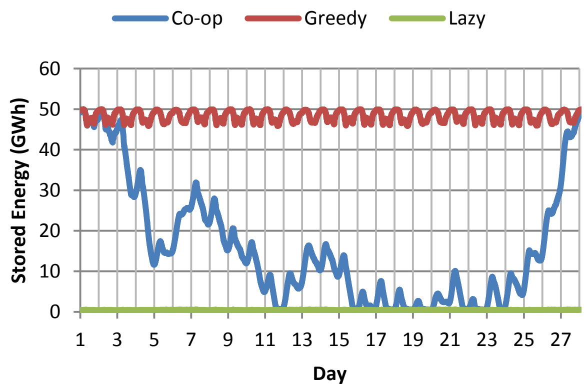


Figure 14. Aggregate EV battery state-of-charge during February 2011

Not surprisingly, the greedy strategy maintains batteries near full capacity. The daily variation shown is primarily a result of vehicles being connected and disconnected from the grid. The lazy charging strategy tends to maintain batteries near empty, since they will be charged as late as possible before departing on the next trip.

The difference in charge between these two strategies is available for grid management purposes, with the maximum charge bounded by the levels shown under the greedy strategy, and the minimum bounded by the lazy strategy.

The co-op strategy most commonly charges overnight, which is evident in Fig. 14, but may charge at any time when generation exceeds load. When the EV fleet's charge reaches the maximum, any excess generation is spilt. Conversely, when EV charge is at a minimum, further input is required from reserve generation to maintain balance.

The problem that the co-op charging strategy has regarding high peak demands could potentially be addressed by setting a threshold when reserve generation is brought online, for example when EV capacity drops below 10 GWh, rather than only taking action once the fleet is empty. Energy shortages would therefore be spread over a longer time period, reducing demands on both generation and transmission infrastructure.

### D. *Unchargable Trips*

A top priority of any EV charging strategy should be to ensure that all trips can be made when required. Several of the strategies have the drawback of only providing for the next trip. In particular, the lazy and slow strategies only attempt to provide the minimum energy necessary for the next trip. If, for example, a 10-minute trip was followed shortly afterwards by a 2-hour trip, it would not be possible to charge the vehicle between trips due to time and power constraints.

During the simulation run, 5% of all trips using the lazy strategy could not be charged on time. Co-op also exhibits this problem, with approximately 1% of all trips failing to charge on time. Since the greedy strategy maintains batteries near full capacity, it does not suffer from this issue.

## VI. Conclusion

This paper describes a simulation framework that can be used to model how an electricity network might behave following the introduction of an electric vehicle fleet and high wind penetration, and understand how the distributed battery capacity of an EV fleet can be utilized to allow greater proportions of intermittent renewable generation in an electricity grid without compromising security of supply.

Models for various parts of New Zealand's electricity network have been developed, including bulk load, wind generation and vehicle use, using real and projected data.

A co-operative vehicle charging strategy has been described, where each vehicle makes charging decisions independently, while taking into account external factors such as the current surplus/deficit of generation, charge state of other vehicles, as well as internal factors such as charge state and the details of the next trip.

Finally, the results from an initial simulation run of the grid over a one-year period have been presented that demonstrate the potential benefits of using V2G technology, and some of the capabilities of the simulation itself.

The initial trial shows that with a relatively simple charging strategy and access to information about the current state of the grid, the proportion of wind generation can be increased beyond received norms. Although the charging model doesn't perform well in terms of peak load, it should be restated that the generation model uses only a fixed base generation and variable wind generation; no generation attempts to follow load.

## VII. Future Work

The work presented in this paper opens up the possibility of investigating many scenarios. These may include:

- local and regional effects regarding transmission and distribution networks
- more complete generation models, for example, solar, tidal and hydroelectric generators
- other forms of storage such as hydro, pumped hydro and battery banks
- evaluation of a mixture of vehicle technologies, such as hybrid or fuel cell vehicles with different capabilities
- detailed vehicle models that includes battery life considerations
- other charging and dispatch strategies to improve upon the co-op strategy
- economic factors influencing the likely uptake

## References


[1] Bardsley, W.E. (2005): Note on the pumped storage potential of the Onslow-Manorburn depression, New Zealand. Journal of Hydrology (NZ), 44(2): 131-135.

[2] Bathurst, G.N. and Strbac, G. (2003): Value of combining energy storage and wind in short-term energy and balancing markets. Electric Power Systems Research, 67(1): 1-8.

[3] Black, M. and Strbac, G. (2006): Value of storage in providing balancing services for electricity generation systems with high wind penetration. J of Power Sources, 162(2): 949-953.

[4] Blarke, M.B. and Lund, H. (2008): The effectiveness of storage and relocation options in renewable energy systems. Renewable Energy, 33: 1499-1507.

[5] Bull, B. (2010): Correlation between wind generation output and hydro inflows. Report prepared for the Electricity Commission. Retrieved 27 January, 2012 from http://www.ea.govt.nz

[6] CAENZ (2010): Electric Vehicles - Impacts on New Zealand's Electricity System, Technical Report, retrieved 27 January 2012 from http://www.caenz.com/images/stories/Books/pdfs/ElecVehWeb.pdf

[7] Connolly, D. (2010): The Integration of Fluctuating Renewable Energy Using Energy Storage. PhD thesis, University of Limerick.

[8] Connolly, D. (2010): A Review of Energy Storage Technologies (version4). Research Report, University of Limerick.

[9] Franco, A, and Salza, P. (2011): Strategies for optimal penetration of intermittent renewables in complex energy systems based on techno-operational objectives. Renewable Energy, 36: 743-753.

[10] Kempton, Willet, and Letendre, Stephen E, (1997): Electric vehicles as a new power source for electric utilities. Transportation Research Part D: Transport and Environment, 2(3): 157-175.

[11] Kempton, Willet, and Tomic, Jasna (2005): Vehicle-to-grid power fundamentals: Calculating capacity and net revenue, Journal of Power Sources 144: 268-279

[12] Kempton, W. and Tomic, J. (2005): Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy, Journal of Power Sources, 144:280-294.

[13] Lund, H. and Kempton, W. (2008): Integration of renewable energy into the transport and electricity sectors through V2G. Energy Policy, 36: 3578-3587.

[14] McKay, David J.C. (2009): Sustainable Energy - without the hot air. UIT, Cambridge, UK.

[15] Ministry of Economic Development (2011): New Zealand Energy Data File, Report, ISSN 1177-6684, http://www.med.govt.nz/sectors-industries/energy/pdf-docs-library/energy-data-and-modelling/energydatafile-2011.pdf

[16] Ministry of Economic Development (2011): New Zealand Energy Strategy - Developing our energy potential, ISBN 978-0-478-35894-0, Retrieved 27 January 2012 from http://www.med.govt.nz/sectors-industries/energy/pdf-docs-library/nz-energy-strategy-lr.pdf

[17] Ministry of Transport (2011): The New Zealand Vehicle Fleet. Statistical Report, ISBN 978-0-478-07228-0. Retrieved 27 January 2012 from http://www.transport.govt.nz/research/Documents/NZ-Vehicle-Fleet-2010-annual-statistics-Aug-2011.pdf

[18] Ministry of Transport (2011): New Zealand Household Travel Survey 2007 - 2010: Driver Travel. Fact Sheet, retrieved 27 January 2012 from http://www.transport.govt.nz/research/Documents/Driver-travel-household-travel-survey-Sept-11.pdf

[19] New Zealand Wind Energy Association (2011): Wind Turbine Technology, Factsheet, retrieved 27 January 2012 from http://windenergy.org.nz/documents/factsheets/technology.pdf

[20] Short, W. and Denholm, P. (2006): Preliminary assessment of plug-in hybrid electric vehicles on wind energy markets. NREL Report no.TP-620-39729.

[21] Statistics New Zealand (2011): National Population Estimates: September 2011 quarter. Website, retrieved 27 January 2012 from http://www.stats.govt.nz/browse_for_stats/population/estimates_and_projections/NationalPopulationEstimates_HOTPSep11qtr.aspx

[22] Transpower (n.d.): Zone Load Graphs, website, http://systemoperator.co.nz/n1944,download=true.html

[23] Turner, R., Zheng, X., Gordon, N., Uddstrom, M., Tait, A., Pearson, G., De Vos, R., Sterk, M., Carey-Smith, T. and Moore, S. (2009): Multi-year ten-minute synthetic wind speed time-series for 15 actual or proposed New Zealand wind farms. Client Report , NIWA.