Feasibility and Sustainability of an Electric Vehicle Battery Exchange System

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Declaration

I declare that the research and information presented in this document is the product of my own effort, except where acknowledged or referenced.

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Abstract

There is increasing concern over the depletion of fossil fuels and the role transport plays in greenhouse gas emissions. Hybrid vehicles while generally more efficient, still use fossil fuels. A technology with promise is the battery electric vehicle, recharged from the mains or by locally generated renewable energy.

Obstacles to growth in battery electric vehicle sales include higher cost than equivalent internal combustion engine vehicles and shorter driving range. Range is seen as a major difficulty by potential buyers, even though 95% of travel in a typical day is within the reach of current generation electric vehicles.

Among the solutions to increasing the range of electric vehicles is the swappable battery. When the vehicle's battery nears exhaustion, the driver pulls into a roadside battery exchange station. A robotised system removes the battery from underneath the vehicle and replaces it with a charged unit. The process takes a few minutes, approximately the same as a fuel refill.

This paper examines the processes involved in this technology and estimates the feasibility of a network of such stations. The conclusion is that the infrastructure is very expensive to set up, to the point where it can take a decade or more to show a return on investment even under the most optimistic scenarios. Using mains power from the Australian average generation mix, principally derived from coal, means that the use of the system shows little or no reduction in carbon emissions compared with similar fossil fuelled vehicles. The extra cost to the business of using renewable energy for recharging the batteries places financial viability even further out of reach.

With advances in battery efficiency and fast charging methods, a network of fast chargers shows greater promise at lower cost.

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Contents

List of Figures and Tables

Glossary

BEV	Battery electric vehicle. All the energy for driving comes from the battery, which must be recharged at a charge point or swapped when exhausted.
CO_2-e	Carbon dioxide equivalent: a measure of the greenhouse impact of all gases produced normalised to the equivalent of CO_2.
EPA	U.S.A. Environment Protection Agency.
EV	Electric vehicle.
GWP	Global warming potential. An indication of the amount of CO_2 equivalent gases produced during production and/or use of the vehicle.
HEV	Hybrid electric vehicle: one with a combination of battery and internal combustion engine. The ICE is the primary source of power: the battery is recharged by the ICE and by the motor under regenerative braking.
ICE	Internal combustion engine.
ICEV	Internal combustion engine vehicle.
LCV	Light Commercial Vehicle (small delivery vans).
MPPT	Maximum Power Point Tracker. An electronic device which works to make the most efficient use of the output of solar panels.
NEDC	New European Driving Cycle. A driving test to establish the fuel efficiency of a vehicle based on a series of urban and extra-urban speeds.
NPV	Net Present Value: the discounting of future costs to reflect their value today.
PHEV	Plug-in hybrid electric vehicle: one with a combination of battery and internal combustion engine, designed so that the battery can be charged at an external charge point when available.
PV	Photovoltaic: direct conversion of light to electricity.
VISTA	Victorian Integrated Survey of Travel and Activity: a survey of travel habits.

1 Introduction

One of the impediments to the general acceptance of battery electric vehicles (BEVs) is the relatively short range, the distance that can be travelled before the battery is depleted.

The range issue can be addressed in several ways: increasing the range of the vehicle to that of an internal combustion engine vehicle (ICEV) by increasing battery capacity, or by placing recharging stations at regular intervals in cities and along highways. However regardless of the range, once the battery needs charging the vehicle cannot proceed until it has sufficient charge to reach the next charge point. With current technology this takes a minimum of 20-30 minutes for a range of 100-120km using "fast" chargers (Alternative Fuels Data Center 2013).

A quicker alternative is to exchange the exhausted battery for a charged unit, in much the same way as replacing the battery in a torch. The depleted battery can then be recharged and used in another vehicle. The entire process takes two to three minutes, about the same as filling an ICEV with fuel (Forbes 2013). However the infrastructure required is expensive and a large number of battery exchange stations would be needed to serve a population of BEVs.

This document examines the economics and emissions impacts of battery exchange stations and the population size of BEVs needed to make them viable. The alternative of fast chargers is also examined.

2 Objective

The objective of this project is to:

- Determine the conditions necessary for a battery exchange system to be sustainable, financially and environmentally.
- Develop a model of an exchange station and estimate the costs and other parameters to determine the viability.
- Examine the greenhouse gas impact of such a facility.

3 Background

Electric vehicles have been around since the mid-19th century and were the predominant mode of private self-propelled transport until the rise of the internal combustion engine vehicle in the early 1900s (Boyle 2003, 355-356). The main reasons for the ascendancy of the petrol/diesel powered car were the improvements to the internal combustion engine (ICE) and the greater driving range afforded. Once a network of petrol stations was in place there was no stopping the advance of the ICE powered vehicle.

With concerns about depletion of fossil fuels, climate change and energy security there is renewed interest in alternatives to fossil fuelled vehicles. These include ICE vehicles powered by biofuel or hydrogen and hydrogen fuel cells driving electric motors, and battery electric vehicles (BEVs), beginning with hybrids and more recently with plug-in hybrid electric cars. While research continues in all these areas, the BEV is an existing technology and is in commercial production by mainstream car manufacturers. Hybrid vehicles are a partial solution, but still use fossil fuels.

Battery electric vehicles (BEVs) are becoming available for general use. At time of writing there is a limited selection of battery-only vehicles commercially available in Australia The Nissan LEAF and the Mitsubishi i-MiEV both sell in low but gradually increasing numbers (EV-Sales 2012, 2013). US-based Tesla Motors is planning to sell its luxury electric vehicles in Australia in 2014 (Tesla Motors Australia 2013).

Battery electric vehicles have the advantage of quiet and potentially cheap operation without significant compromise in passenger comfort or driving dynamics compared with equivalent ICE passenger cars (O'Kane 2012).

However sales of BEVs are hampered by high initial cost and limited range between charges, typically 80-120km depending on driving patterns (Ingram 2013).

The cost issue will be resolved as with any new technology, as manufacturing processes mature and volumes increase. It has been forecast that the BEV will reach price parity with the ICEV by 2020 (AECOM 2011, 10). At some time before then, a BEV will pay for itself within a short timeframe with reduced running costs, estimated at half that of an equivalent ICEV (Origin Energy 2013).

Advances in efficiency and battery capacity can be expected to increase this, perhaps to as much as 200-300km for the average BEV over the next few years. The Tesla Model S already has a claimed range of 500km (Tesla Motors Australia 2013). Even at a 300km distance potential purchasers of EVs may baulk. A study in the UK found that prior to driving or owning a vehicle, private drivers consider an ideal range for an EV to be about 375km. After 3 months use, this perceived ideal range drops to about 300km (Carroll and Walsh 2013).

No matter what the range is, at some point on a longer trip it will be exceeded. The driver will need to stop and recharge.

One method of removing the range limit is to set up a network of recharging stations. Even ICE powered cars need refuelling, and there are many refuelling stations in every city in developed nations.

There are distinct levels of technology for recharging a vehicle battery. As defined by Standards Australia (Lazar and McKenzie 2009):

1. Level 1 simply uses a 240V 10A or 15A outlet which is available or can be installed cheaply at any premises. The maximum charge rate possible is about 3.5 kWh per hour. A full recharge for a typical 20 to 25 kWh vehicle battery takes eight hours or more. This is considered trickle charging.
2. Level 2, defined as standard charging. This requires special equipment and often wiring upgrades, especially in domestic installations. Charging takes three to four hours.
3. Level 3, fast charging. The charger works with voltages around 400 volts and currents up to 600 amps. A recharge takes less than 30 minutes. Most vehicle and battery manufacturers do not recommend charging beyond about 80% at this level, to minimise heating and reduced life of the battery. The currents required are also beyond the capacity of many residential grid sections.

So at the highest rate recharging a battery takes 20 to 30 minutes for an 80% charge compared with the few minutes required to fully refuel a petrol or diesel car (Alternative Fuels Data Center 2013). Consumers are unlikely to accept a system that requires them to pause for half an hour every hour or so while on a trip. It would be completely unacceptable to people travelling for commercial reasons.

A further possibility is the battery exchange system. A driver would pull into a swap station, park in a specific place and a robotic system would remove the depleted battery from the vehicle and replace it with a freshly charged unit. Battery exchange systems are nothing new: one was developed in 1897 for in-house use by the Electric Carriage and Wagon Company of New York (Kirsch 2000, 37). A working system for the general population was implemented by the Hartford Electric Company in 1912 and survived into the 1920s (Kirsch 2000, 161).

There have been several recent proposals for battery exchange stations for general use, the best known in Australia probably being from the Better Place company (Business Review Weekly 2013). One of the selling points for this system is that the ownership, and therefore cost, of the battery remains with the battery exchange operator: this reduces the initial cost of the electric vehicle to a point competitive with ICE vehicles. Again, this is nothing new. "Starting in late 1917, purchasers of a redesigned Milburn Light Electric could buy the car for $1,485 without battery (a reduction in cost of approximately two hundred dollars) and sign up for the 'Exchange Power System' for fifteen dollars per month plus one dollar per change of battery." (Kirsch 2000, 158).

As well as the battery exchange infrastructure, BEVs with swappable batteries are needed. The only model available to date from a mainstream manufacturer is a variant of the Renault Fluence (Renault Group 2013). Tesla Motors is also proposing to introduce battery exchange facilities in high-traffic areas for its Model S range as an (expensive) alternative to fast charging (Policymic 2013). However this is specifically only for Tesla cars, and the expectation is that the owner would swap back to the original battery at a later date when it is recharged.

However, to date there has been no successful battery exchange system in commercial operation. This paper examines the reasons behind this.

4 Literature Review

There is not a large body of literature on commercial battery exchange systems, as while the concept is not new there has been little interest or commercial development until recently.

One study (McPherson et al. 2011) looked at the optimal distribution of battery exchange stations to service vehicles undertaking longer trips. The paper assumed that a fully charged BEV had a range of 120 km. Information from studies undertaken in Victoria, NSW and Queensland found that trips longer than this comprised 5% to 9.5% of all weekday trips. It was assumed that a vehicle would normally be charged at home or at the workplace, and the exchange stations would be used to extend the range. However the stations could serve the needs of those without charging facilities. As an example, a set of 27 stations around Melbourne and surrounding areas in Victoria would be sufficient to cover the needs of those driving to locations up to 150km distant. In general, depending on the size and density of the city, up to 20 stations would be needed to satisfy 85% of long trips. The authors considered this to be encouraging. A Yellow Pages search (Sensis 2013) found over 1300 petrol stations in Victoria.

The use of electric vehicles is only worthwhile if, over their full lifecycle, they permit significant savings in fossil fuel use and greenhouse gas production. A recent literature review (Hawkins, Gausen, and Strømman 2012) compared the global warming potential (GWP) in gCO_2-e/km based on typical travel patterns of petrol and diesel ICEVs with hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) and BEVs. The electric vehicles examined in the study were small or light cars, and were compared with a range of ICEVs of differing sizes and fuels. It found that battery electric vehicles and PHEVs had lower global warming potential (GWP) than ICEVs only if the electricity used for recharging came from low greenhouse-gas sources. The GWP from electric vehicle production including its battery was similar to or slightly lower than for ICEVs: the bulk of GWP came from use. It does caution that there is considerable uncertainty in the results, but it is clear that electric vehicles are not an automatic cure for greenhouse gas emissions. The results were sensitive to assumptions made about energy use per km, source of electricity, vehicle lifetime and recycling potential at end of life. One interesting observation in this paper relating to battery swap systems is that they entail the production of excess numbers of batteries to allow for charging off-vehicle (p.1010), thus increasing the GWP per vehicle. However the GWP of a single battery in a battery swap system was found to be about 12gCO_2-e/km compared with 220gCO_2-e/km overall for a BEV powered by typical coal-fired electricity. Using low-GHG electricity for charging would more than offset the impact of doubling the number of batteries in use.

A more detailed lifecycle analysis (Hawkins et al. 2013) compared a full range of environmental impacts from ten contributors such as materials toxicity, minerals depletion and fossil resource depletion as well as GWP. The study compared the Nissan LEAF with the Mercedes Benz A-class ICEV (petrol and diesel variants) as being of similar size, mass and performance. The impacts for the Leaf were further broken down by type of battery used, whether nickel metal hydride, lithium iron phosphate or lithium manganese oxide, and then by the source of electricity: natural gas or coal, or “average European electricity” which includes renewable sources. Such a wide ranging study cannot be easily summarised. However the production phase has more environmental impact for electric vehicles and so the results are sensitive to the relative lifetime assumed for the vehicles and for the batteries, and EVs powered by electricity from coal or lignite (brown coal) simply transfer GWP and air pollution from the road to the mine and power station.

Some work has been done on the use of photovoltaic power to charge EV batteries (Traube et al. 2013). This paper describes a method to mitigate the problems of the variability of solar power when charging batteries as well as delivering power to the electricity grid. The system consists of a MPPT connected to the solar array, a bidirectional inverter connected to the grid and a bidirectional battery charger connected to one or more EV batteries. Under full solar irradiance, the batteries are charged at an optimal rate and the excess power is sent to the grid. If solar irradiance drops due to a passing cloud, battery charging slows or even reverses temporarily to reduce variation in the output to grid. The impact of the transient is minimised by the controller to ensure no significant drop in state of charge and consequent impact on battery life. The focus of the paper is the design of components to maximise efficiency as well as battery life, but it also considers the benefit of using distributed solar arrays to minimize the effect of individual clouds on days of partial cloud cover.

China is actively investigating electric vehicle use, including battery exchange systems. One study (Tang et al. 2012) developed a model of a PV-powered battery exchange station with the goal of maximum profit. In fact several models were used, with differing sizes and arrangements of components. Inputs to the models included the cost of batteries, the cost of various charging system components, depreciation, battery lifetime and discount rate.

The papers reviewed revealed no significant technical or environmental barriers to the introduction of battery electric vehicles or to battery exchange systems. However environmental benefits are highly dependent on the source of electricity used for recharging.

5 Model Development

The physical design of a battery exchange station involves the vehicle driving up to the exchange bay and the driver swiping a membership or credit card. The vehicle enters the bay, something like an automated car-wash bay – in fact a wash may be an optional extra – and is positioned above the exchange robot. The underside of the vehicle is cleaned to remove grime that may interfere with the battery seating or connection then the battery is removed from under the vehicle and replaced with a fully charged unit. The driver then drives out of the bay and continues the journey.

It is expected that the driver will receive a monthly account with the details of battery swaps and the degree of depletion of each battery. The cost is expected to be a combination of a per-swap fee and a recharge fee based on the amount of charge each battery needed. The owner is also leasing a battery, the one that is in his vehicle at any given time. This is a cost to the vehicle owner, but it is not relevant to the operation of the exchange station. The lease fee may be paid to the vehicle manufacturer, to a battery manufacturer or to the battery swap franchise. The owner of the vehicle might elect never to visit an exchange facility.

The exchange station will probably not be a standalone operation. It is more likely to be attached to a petrol station or similar service centre, and sharing the forecourt and other facilities. It is assumed that the station would also have fast-charge facilities for BEVs that have a fixed battery.

The model developed here considers the operation of an exchange service station: the annualized fixed costs of the real estate and battery handling hardware, the cost of batteries, and the cost of charging and transporting. This will be balanced by the income from battery swap services.

A battery swap station comprises:

1. Service station premises, with forecourt, office, battery storage area and waiting area for customers in the event that there is a queue for the service. In practice this is most likely to be an adjunct to an existing petrol or service station for ICEVs, much as current service stations may have an attached car wash or fast food outlet.
2. One or more battery exchange bays with drive-through area and exchange robot, similar to automatic car wash bays. The automated system requires access to the underside of the vehicle. When a vehicle parks over the robot, with the driver having activated the process by swiping a card, the unit makes any minor adjustments necessary to locate the battery attachment screws. It then washes the area around the battery with a high pressure water spray before undoing the connectors, removing the battery and placing the depleted battery on a conveyor for transfer to storage. Meanwhile a fresh battery has been brought from storage by the conveyor and is screwed into place. The process is normally fully automatic and no intervention is needed. The driver remains in the vehicle.
3. A stock of charged and depleted batteries.
4. If the location is suitable, a battery charging system drawing power from the grid or from a nearby PV or wind farm.

Some service stations will not be able to recharge batteries on the premises. Especially stations located in city or inner suburban areas might not have the area for a PV array (or shadowing could be an issue), and the grid in the vicinity may not be robust enough to support fast charging of multiple batteries. In this case a dedicated charging plant will be needed elsewhere, with transport for charged and depleted batteries to and from the exchange stations.

For the purpose of initial investigation it is assumed that there is only one type and size of battery. One battery exchange robot will be able to service a given number of vehicles per hour. Some estimation of allowable queue lengths and daily operating hours will be needed. As the vehicle population grows, the operation will become more profitable, up to the point where another robot must be installed.

In the commercial context, a battery exchange station may be set up in several ways, for example:

- As a franchise. A central operator develops the equipment and processes, and sells franchises to individual operators. This is the model used by some fuel companies (Caltex 2013). Depending on the type of franchise, the initial startup effort and cost can vary considerably, as can the ongoing franchise fee.
- A corporation such as a vehicle manufacturer or electricity utility sets up a network of stations using its own resources and staff.
- Individual entrepreneurs set up stations using their own funds. These individuals may form buying groups to reduce costs and development effort, for example in using common billing software. The vehicle owner should not be limited as to which stations around the country they can attend. A single membership/credit card should work at all locations.

For the purpose of this model it is assumed that the owner is an individual entrepreneur. They may be the owner of an existing vehicle related business, expanding into electric vehicle sales or service. The type of owner is not expected to have a significant effect on the model. A large corporation may be able to trim costs slightly through economy of scale, and a franchisee may pay a little extra for the support of the franchise.

5.1 Vehicle Processing

In later sections we will attempt to estimate the relationship between electric vehicle population, distribution and number of visits to a given exchange station. In this section we will look at a particular station and model the operation, and the effect of increasing visits.

We will assume a 24 hour operation with a distribution of visits over a 24 hour period with lower probability of arrival at night. Arrivals within a short interval (say 5 minutes) will follow a Poisson distribution. This is a reasonable assumption if we accept a relatively large exchangeable-battery BEV population, a relatively low proportion of the population using the service in a given period and drivers with diverse driving patterns and destinations.

We will also assume a fixed service time of 3 minutes. The proponents of the robotised battery swap system claim 2 minutes for a swap, but there will be extra dead time required while the freshly recharged vehicle is removed and the next vehicle driven into position.

Queues will form once the rate of visits increases to a certain point. The length of a queue would normally determine how many customers abandon the queue and go somewhere else, but in this case the customers are essentially captive and are unlikely to have sufficient charge in the battery to reach another station except in large cities where there are multiple stations in a small area. The maximum queue wait is arbitrarily set at 15 minutes, to be exceeded less than 5% of the time. The size of queues and the number of vehicles that can be accommodated per day is discussed in detail in Section 5.2.

5.2 Vehicle Arrivals and Queuing

We need to estimate how many vehicles per day can be serviced by a single robot station. If A_d vehicles arrive at the service centre each day, how many stations are needed?

An exchange robot will be able to change a battery in approximately 90 seconds (Tesla Motors 2013). This does not include the initial underside wash required to remove grit and grime from the vehicle and battery connection area. Initially we will assume three minutes for the whole process from driving up to the robot station to departure with a fresh battery. The robot can therefore process a fixed 20 vehicles per hour.

The rate of arrival of vehicles for battery exchange will vary during the day. We have assumed that vehicles will leave home or the workplace with a battery that has been fully charged, and will visit the exchange station during the day as the battery is depleted. Based on a transportation study in Sydney in 2002 (Transfigures 2005) the temporal distribution of vehicle movements for private vehicles and light commercial vehicles during the week is as in Table 1. Light commercial vehicles (LCVs) have been included as electric LCVs are possibly even more likely to be adopted in numbers than private vehicles.

Table 1: Distribution of Trips by Time Period, Weekdays

Time of Day	Time Distribution			
	Private Vehicle		Light Commercial (LCV)	
	Per Period	Hourly	Per Period	Hourly
7am-9am	17%	9%	17%	9%
9am-3pm	36%	6%	48%	8%
3pm-6pm	25%	8%	21%	7%
6pm-7am	22%	2%	15%	1%

For the purpose of calculating the capacity of the exchange station to service vehicles we consider only the peak arrival rate. If the peak period demand is satisfied there should be no problem satisfying demand off-peak. The maximum hourly peak arrival rate from Table 1 is 9% of the total daily rate. To be conservative we can assume 10% in the peak hour of the peak period. From this we can use a relationship of peak-time arrival rate $A_p = A_d/10$ vehicles per hour.

Waiting in a queue is a tedious experience for most people. The amount of time a driver will tolerate in a queue for a fresh battery is subjective. It will possibly vary according to the type of driver (a courier will have less patience than a holidaymaker) and the location (if you could leave your car and visit a shop, a toilet or a food outlet while waiting you would be less likely to fret). However as an initial estimate we will assume that a wait time, including the time actually in the exchange station, of 15 minutes or less 95% of the time will be acceptable in all cases. In most cases the driver will have no choice but to wait. However if the service is poor the users are likely to find ways to avoid that service centre in future.

For the analysis we assume that the rate of arrival follows a Poisson distribution. The expected rate of arrival in peak period $\lambda_p = 0.1A_d$ vehicles per hour. We know the service rate is a fixed $\mu = 20$ per hour per robot. For a waiting line queuing model M/D/c (Poisson distribution of arrival rate, fixed service time, c servers) the steady-state expression for waiting time is given by the Franx equation (Franx 2001):

$$P\{W \leq x\} = e^{-\lambda(kD-x)} \sum_{j=0}^{kc-1} Q_{kc-j-1} \frac{\lambda^j (kD-x)^j}{j!}$$

$$\text{for } (k-1)D \leq x < kD$$

Where P is the probability of waiting time W being less than or equal to x.

D is the service time

λ is the Poisson arrival rate

c is the number of servers

Q_x is the cumulative probability of x customers in the system.

The parameter ρ in a queuing model is the ratio of arrival rate and service rate $\frac{\lambda}{\mu}$. If ρ is equal to or greater than 1, the queue length will continue to grow. For a steady-state condition to be satisfied, $\lambda < \mu$, i.e. $\rho < 1$. The model also assumes that the population is large compared with queue size, and the queue is not limited in size.

Using a program based on the Franx equation, MCQueue (Tijms 2013), Table 2 below shows the effect on $\rho = \frac{\lambda_p}{\mu c}$ in maintaining P {W ≤ 15 minutes} to 95% of a varying number of servers (c = 1, 2, 3, ... 10). The total number of vehicles per hour that can be serviced by the given number of servers is ρ * μc = λ c and the number of vehicles per day is simply ten times the peak hourly figure based on the assumption above. The expected waiting time in the queue remains relatively constant at about 3.5 minutes, and Pwait is the probability that an arriving vehicle will have to wait in the queue. Note that the expected time in the system will be the waiting time plus the service time, about 6.5 minutes.

Table 2: Capacity of Exchange Bays, Maximum 15 Minute Wait.

Number of Servers (Bays)	**Value of ρ for ≤15 minutes time in system**	**Total Vehicles per Hour**	**Total Vehicles per Day**	**Expected Waiting time in Queue Minutes**	**Expected Length of Queue**	**Pwait**
1	0.70	14	140	3.3	0.79	0.70
2	0.84	33	334	3.5	1.95	0.75
3	0.89	53	534	3.7	3.27	0.79
4	0.92	73	732	3.7	4.46	0.80
5	0.93	93	930	3.6	5.59	0.82
6	0.94	113	1128	3.5	6.66	0.83
7	0.95	133	1327	3.6	8.01	0.84
8	0.96	153	1530	3.7	9.46	0.85
9	0.96	173	1728	3.6	10.5	0.86
10	0.97	193	1930	3.8	12.2	0.86

From this we can see that a single bay can service 140 vehicles per day, the second will add an incremental 194 vehicles per day, and so on.

If it is decided that the motorist should spend a maximum of only 10 minutes in the system, the capacity of bays is reduced accordingly as in Table 3. The average waiting time is also halved, and the probability of arriving to find a queue is reduced to a little over 50%. This is closer to the experience of the motorist filling up with petrol.

Table 3: Capacity of Bays with 10 Minute Waiting.

Number of Servers (Bays)	**Value of ρ for ≤10 minutes time in system**	**Total Vehicles per Hour**	**Total Vehicles per Day**	**Expected Waiting time in Queue Minutes**	**Expected Length of Queue**	**Pwait**
1	0.50	10	100	1.5	0.25	0.50
2	0.70	28	280	1.5	0.69	0.56
3	0.80	48	480	1.6	1.3	0.63
4	0.85	68	680	1.7	2.0	0.67
5	0.88	88	880	1.8	2.7	0.70

5.3 Costs

The costs associated with an operation of this type are:

1. Fixed cost C_f, consisting of the annualised cost of owning or leasing real estate, buildings etc. Since a battery exchange facility is most likely to be part of a general service setup of fuel station, car wash or truck stop, the cost is not simple to establish. As an initial estimate we will use \$100,000 per year which would cover items such as real estate set aside, insurance and computer systems for financial tracking etc. By comparison, a fuel station startup cost is typically \$150,000 to \$800,000 (Caltex 2013). If the startup cost was for an exchange station was in the middle of that range at about \$500,000, the annualized cost would be \$100,000 per year for the first five years based on the repayments for a commercial loan (Westpac 2013).
2. Running costs C_r including utilities (not including battery charging), wages, etc. For the purpose of this model it is assumed that C_r is a cost that is fixed for a certain volume of exchanges per day (one staff member can handle up to X exchanges per day, but above X a second person is needed). The exchange robots are automated and self-service, but staff is presumably needed to load and unload banks of charged and depleted batteries at the ends of the day. For the purpose of the model the costs are assumed to be \$90,000 p.a. for staff to handle up to two exchange bays based on the typical cost of employing low-skilled operators for up to ten shifts per week (ACTU 2013) plus overheads and on-costs (VCEC 2007). It assumes that an operator is not needed 24 hours per day, only during busy periods and battery charge/transfer shifts.
3. Operating cost C_o which is the annualised cost of owning and operating the battery exchange bay. In a commercial development this will usually be a lease, but it could be an amortised cost of purchase. One exchange bay can handle up to 140 exchanges

per day, as determined by the queuing model. A bay with associated battery handling equipment costs approximately USD$500,000 (Tesla Motors 2013), which corresponds with the Better Place estimate of AUD500,000 (AECOM 2011, 32). However this does not cover the cost of handling equipment to move the batteries into and out of storage and to charging facilities. The total cost is expected to be in the vicinity of $750,000. A lease arrangement for this amount would cost approximately $150,000 per year over five years with 25% balloon payment (Westpac 2013). The equipment should have a lifetime of at least 10 years.

4. C_i the inventory cost of keeping a stock of spare batteries. The number of batteries required will depend on the number of daily exchanges. The cost of batteries is examined in section 5.5.
5. Battery charging unit cost C_b. In the situation where the batteries are charged from the grid or from a dedicated off-site plant it is assumed that this is a constant value: where a charging plant is attached to the station there may be a reducing incremental cost associated with the plant setup.

5.4 Income

The income from battery exchange will be a fixed charge I_e per exchange plus a variable charge I_r based on the amount of charging needed for the depleted battery.

A constraint on the income is that a battery swap should not cost more per kilometre travelled than the running cost of an ICEV, and preferably less. If not, there is little incentive for the ordinary motorist to use an electric vehicle. The top selling passenger vehicles in Australia currently are the Toyota Corolla and the Mazda 3 (FCAI 2013). These are small cars, about the size to be expected of electric vehicles. The Corolla has fuel economy of 7.1 l/100km (Toyota Australia 2013) and the Mazda 7.9 l/100km (Mazda Australia 2013). They sell in similar numbers, so we assume a simple average consumption of 7.5 l/100km. The current price of standard unleaded petrol in regional areas of Victoria is around $1.40 to $1.60 per litre. If we assume $1.50 per litre and fuel efficiency of a light car at 7.5 l/100km the fuel cost per kilometre is 11.25 cents.

If we assume a range of 185km on a full 22kWh battery as provided by the battery electric Renault Fluence (Renault Group 2013) based on the NEDC (New European Driving Cycle) then the exchange of a fresh battery for a completely exhausted one should cost no more than $20.80 to match the cost per kilometre of an ICEV: perhaps $5.00 per exchange and $15.00 for 26kWh of charge, corresponding to 85% charging efficiency of the battery. For comparison, Tesla propose charging USD50 for a swap of the 60kWh battery in its Model S (Policymic 2013), and the official EPA range of the Model S is 335km (Green Car Reports 2013). Allowing for currency conversions and considering it is only a proposed fee, this is about 15c/km.

The foregoing assumes that the vehicle has travelled in a mix of city and long-distance driving equivalent to the NEDC, the combined cycle in Australian terms. If the driving had been principally at highway speeds the range would be reduced and the cost per kilometre increased accordingly. City driving is at lower speeds with lower friction and wind resistance losses, and there is opportunity for energy recovery in regenerative braking (using the motor as a battery charger to decelerate). The NEDC figure is based on a carefully executed series of accelerations, decelerations and steady speeds. The actual range will depend on driver behaviour: hard acceleration will use much more energy than can be recovered in regenerative braking.

The driver who recharged his electric Renault Fluence at home overnight using off-peak power would have paid about 19c/kWh, or 38c/kWh at peak rates (Power Direct 2012) or 2.7 to 5.4c/km. However this would have taken 8 to 10 hours using a level 1 charger (using standard house wiring), compared with the few minutes for an exchange. The extra cost of a battery exchange is the price of convenience.

5.5 Cost of Batteries

There are several components to the cost of batteries.

Inventory cost: the current cost of EV batteries is around USD700 per kWh (IEA 2013). Ignoring price disparities between U.S.A and Australia, this translates to approximately AUD770 per kWh, or $19,250 for a 25kWh battery. The IEA report expects this to drop by half by 2020. We have not determined a time when the battery exchange stations will be built, but if we assume they will be in operation in 2015, we can further assume a price per battery of around $18,000.

Batteries have a limited life. In normal usage they last between five and 20 years (American Chemical Society 2013). Lifetime depends upon storage and operating temperatures as well as number of charge/discharge cycles. In a battery exchange program we must assume that any given battery will be recharged daily and its lifetime will be at the shorter end of the scale. A battery that is no longer suitable for use in vehicles can be used for other purposes such as temporary storage for charging facilities. Completely exhausted batteries can be recycled. For the purpose of modelling we will assume a life of five years and residual value of 50%. Ignoring discounting, inflation or the declining cost of battery technology, each battery will cost $9000 over 5 years or a little under $5 per day.

In the worst case for stock level we can assume that depleted batteries are not recharged immediately, but are charged overnight using off-peak electricity rates or are delivered overnight from an off-site charging station. So if 100 battery exchanges were made during the day, 100 freshly charged batteries will be required at the start of the day. Inventory stock and cost will therefore depend upon the rate of visits. In practice it may be cheaper to reduce stock and recharge at least some of the batteries during the day as they are removed from the vehicle. The differential cost as calculated below for charging at peak rates is about $3.50, compared with the cost of stocking an extra battery at $5 per day. The actual gain will depend on the number of times per day the batteries are discharged and the impact on lifetime.

Vehicles arriving at the station are unlikely to have a fully depleted battery. If we assume as close to worst case an 80% depth of discharge and 80% efficiency in the recharge process including charger efficiency, a 22kWh battery for the electric Renault Fluence will require 22kWh of electricity to recharge.

For a business with high energy use it makes sense to use a time-of-use tariff with off-peak rates. Typically these are around 31c/kWh peak (7am – 11pm) and 15c/kWh off-peak for a business customer on a 7-day time of use tariff (RedEnergy 2014). At this off-peak rate the electricity cost per recharge will be approximately $3.30. At peak tariff the average cost per recharge will be $6.80.

5.6 Recharging and CO_2

Recharging of batteries can be performed using power from various sources: standard grid power, “green” grid power or locally produced from renewable energy devices.

5.6.1 Standard grid power

The CO_2-e emissions from electricity generation in Australia vary from state to state, from 1.1kg/kWh in Victoria to near zero in Tasmania (AEMO 2013). For the NEM (Eastern States) as a whole, the average is approximately 0.9kg/kWh.

Based on the 185km range of the 22kWh Renault Fluence battery, and assuming an 80% overall charging efficiency the battery will require 27.5kWh to recharge, producing 23.3kg CO_2 equivalent at the NEM average: 134g CO_2 per km travelled. If the charging had been performed in Victoria, this would become 161g/km. By comparison, a similar sized 1.8L petrol automatic Toyota Corolla produces 152g/km (Toyota Australia 2013). An electric vehicle driver in Victoria will not be reducing his or her carbon footprint under this regime.

5.6.2 Green power from the grid

Homes and businesses may elect to pay a little extra for power sourced from low-emissions generators such as wind, biogas or hydro. Typically there is a range to choose from, from 25% to 100% “green”. Selecting 100% green power typically adds up to 8c/kWh to the cost (GreenPower 2013): recharging cost at our facility increases from $3.30 at the off-peak rate to approximately $4.80. Recharging at peak rate would now cost around $8.60. CO_2 emissions will be zero.

5.6.3 Locally generated power

With optimum conditions as shown in Section 5.7 below, the business can be profitable with 70 exchanges per day depending upon the cost of electricity. With batteries requiring 22kWh of charge on average (Section 5.5), the total load each day is at least 1.5MWh.

The actual form of renewable power used will depend upon the location and the land area available. For example, at Bendigo in regional Victoria the long-term mean wind speed at 9 am is 9 km/h in June and 16.1 km/h in December, and the minimum solar exposure on a horizontal surface in June is 6.7 MJ/m^2/day (1.9 kWh/m^2/day), up to 27.4 MJ/m^2/day (7.6 kWh/m^2/day) in December (Bureau of Meterology 2013). If a photovoltaic solar system was sized for 1.5 MWh/day in the worst month, a 800 kW system would be required.

A typical large-scale PV system costs about $2.85/Wp (Mills et al. 2011, 9), although this is a conservative estimate as panel prices are still reducing. An 800kW system would therefore cost approximately $2.25 million for panels, mounting and power conditioning. However some form of storage would be needed for dull days: often, retired electric vehicle batteries are used for this purpose. The complete system would cost approximately $3.5 million. The levelised cost of electricity (LCOE) from this system given a 20-year lifespan would be approximately 20c/kWh (Mills et al. 2011, 10) so charging would cost $4.40 per battery. This is more than off-peak grid power, but less than peak power. Some cost may be saved by constructing for a higher solar insolation or omitting the storage, and topping up with grid power when necessary.

The above does not include the cost of land required to support a system this size. Based on typical requirements, a 1.2MW system using fixed panels would require approximately 3.7ha of land at 3.1ha/MW (Ong et al. 2013, 10). The cost and availability of this area of land with appropriate flatness and/or slope will vary greatly from inner Sydney or Melbourne to the outskirts of a regional town, or beside a country highway: it is not possible to quantify its effect on the cost of electricity generated.

A wind turbine might require less land area, but in many cases the wind will not be sufficiently reliable, and local bylaws may prohibit construction of a turbine in the vicinity. Similarly generators based on biofuels are likely to fall foul of local regulations in developed areas in many cases.

5.7 Application of the Model

We wish to find the maximum of the annual profit. That is, the maximum of

$$P = n(I_e + I_r) - (C_f + b\,C_o + f(C_r) + n(C_i + C_b))$$

where

n is the number of battery exchanges per year.

I_e is the fixed charge per exchange.

I_r is the fee to recharge the depleted battery: assume 80% depth of discharge.

C_f is the fixed cost of owning the operation.

b is the number of exchange bays installed.

C_o is the annualized cost of an exchange bay.

$C_r = f(b)$ is the running cost of one or two exchange bays.

C_b is the cost of recharging a battery.

C_i is the inventory cost of battery stock.

Certain costs are assumed to be fixed: the cost of business operation and the cost per exchange bay. Similarly the charges per exchange and for battery charge are assumed fixed. All other variables are dependent on the number of exchanges performed per day. As a result the only independent variable is n. The number of bays b is determined by the values in Table 2, and is also dependent on n. For example if the business services 500 vehicles per day, three bays will be needed.

6 Results from the Model

In the initial scenario (base case) we have:

$I_e = 5$

$I_r = 15$

$C_f = 100,000$

$C_o = 150,000$

$C_r = \{90,000, 90,000, 180,000, 180,000, ... \mid b = 1, 2, 3, 4, ...\}$

$C_i = 5$

$C_b = 1.5$

All cost and income values are in Australian Dollars.

With these values the profit curve appears as in Figure 1. While it will make a loss at volumes below about 80 vehicles per day, it is potentially profitable.

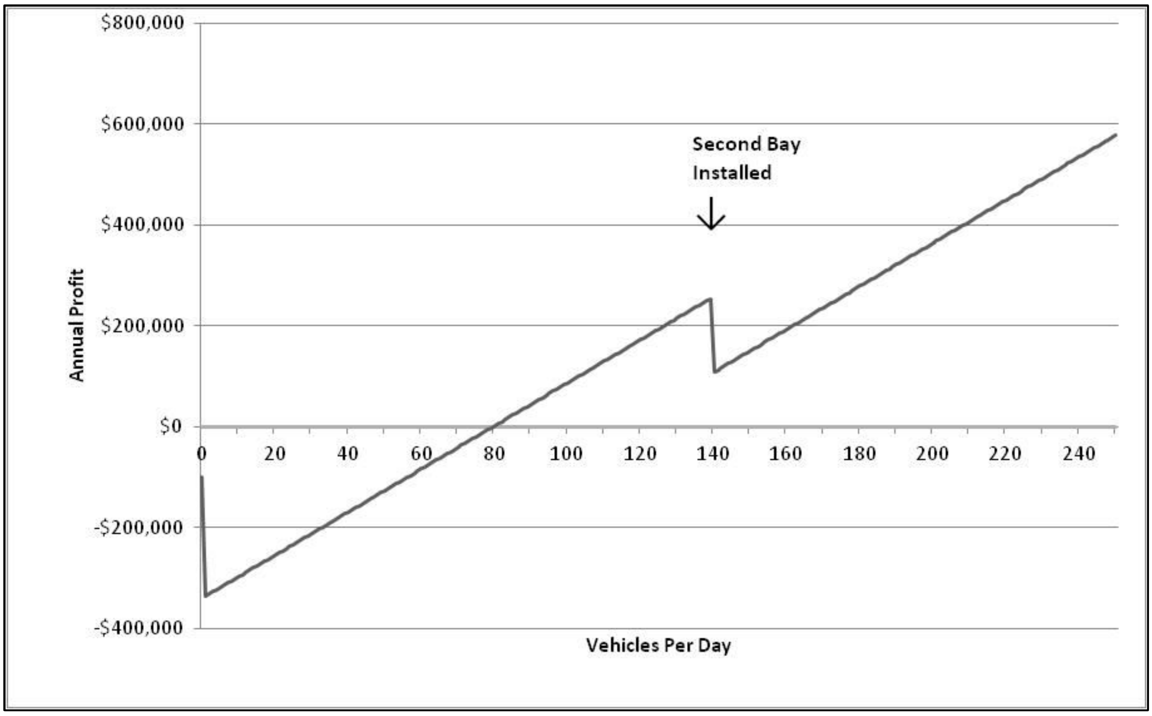

Figure 1: Annual Profit vs Exchanges Per Day

6.1 Sensitivity Analysis

The result in Figure 1 is based on optimum values: lowest costs, highest income per battery exchanged.

If we increase the cost of charging from $3.30 to the peak tariff rate of $6.80 per battery, the profitability becomes questionable: there is no significant profit until the arrival rate exceeds 110 vehicles per day (Figure 2), and there is a disincentive to installing a second bay when volumes rise past 140 vehicles per day.

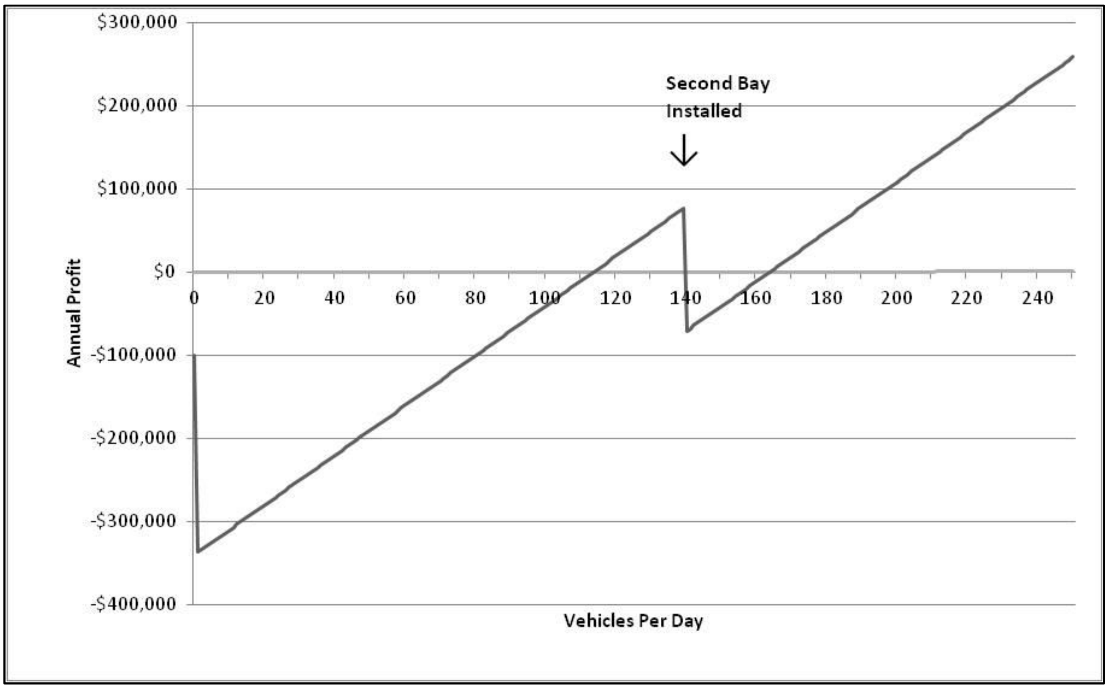

Figure 2: Profitability with Recharging at Peak Tariff $6.80.

If the maximum waiting time (95%) is reduced to 10 minutes for a better experience for the motorist, the maximum capacity of the first bay is about 100 vehicles per day. At the off-peak charging cost of $3.3, the result is shown in Figure 3. The station is profitable above 80 vehicles per day as before, but the operator soon has to install a second bay, returning to a loss again until business builds to 115 swaps per day.

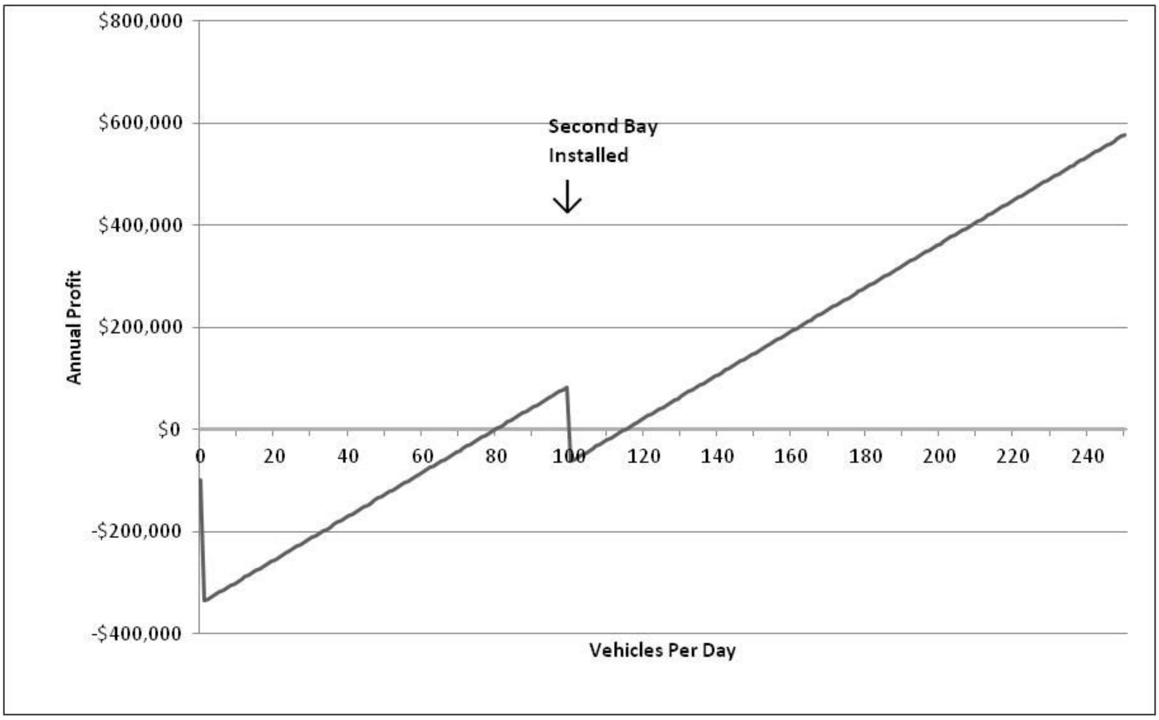

Figure 3: Profitability with Maximum 10 Minute Wait

If competition or other factors are such that the operator cannot charge $20 for a battery exchange ($5 per battery and $15 for recharge) the income will be reduced. If for example the recharge fee is reduced to $10 the result is shown in Figure 4, where all other factors are kept the same: $3.30 charge cost, 15 minute waiting time. The operation does not show a profit below 200 exchanges per day..

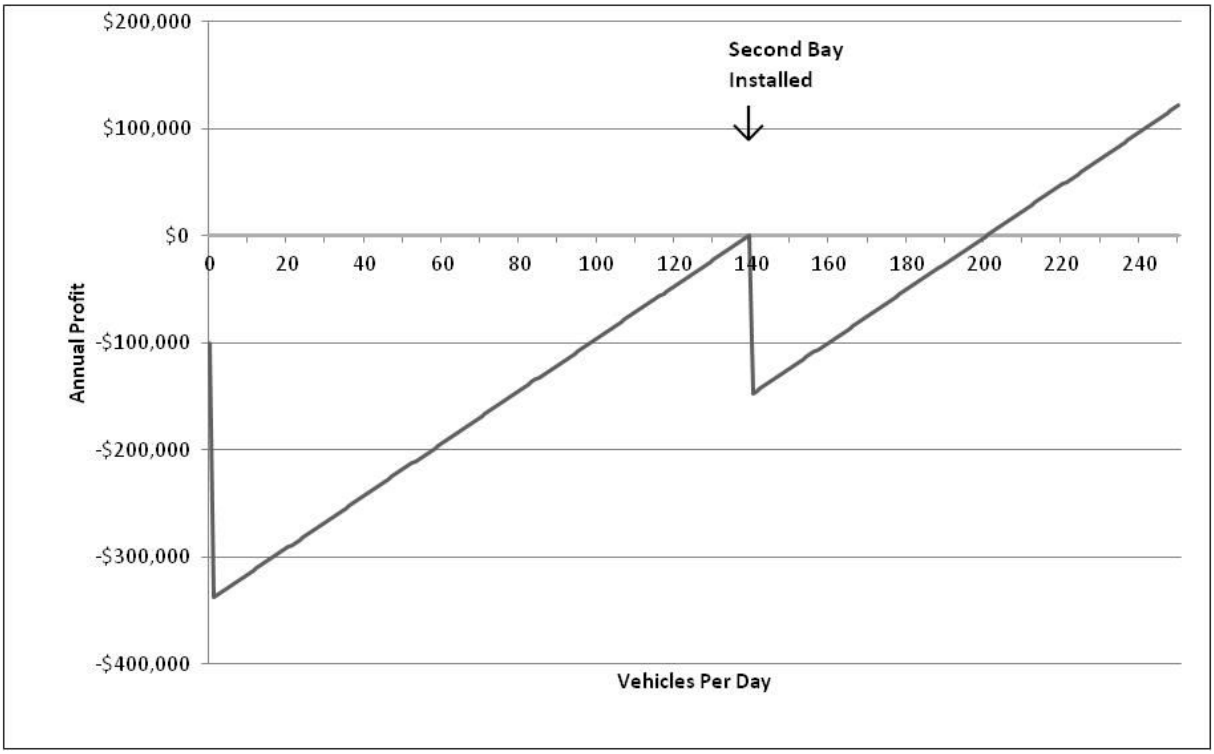

Figure 4: Profitability for Reduced ($15) Battery Swap Fee

6.2 Summary of Results

Figure 1 represents a best-case scenario for profitability: above 80 vehicles per day at a battery exchange station the operation can be successful. However this is sensitive to a number of factors:

- If the batteries are recharged at peak tariff rates the minimum viable turnover is 160 vehicles per day.
- If the operator has to charge customers at a lower per-kilometre rate than current fossil fuel prices, e.g. $20 per average swap, 200 vehicles per day must be serviced to break even if the rate was only reduced to $15.
- If customers baulk at waiting times up to 15 minutes, reducing queue length to 10 minutes or less 95% of the time increases the arrival rate required increases to about 115 vehicles per day.

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7 Case Study: Holbrook Battery Exchange Station

In order to estimate whether an exchange station will receive the required level of business we need to determine the level of passing traffic and the proportion of that which is BEV.

Within population centres, it is difficult to estimate how many BEV drivers will need an exchange. While ICE drivers need to attend a petrol station to top up, a BEV can be recharged at home, and if the day's trip is less than 120km or so, an exchange will not be required. Where BEV drivers have no choice is on long trips between towns.

In Victoria, the VISTA 2007 results show that the median daily travel distance by car varies from 1.6km in inner Melbourne to 11.9km in the outer suburbs: in regional centres it is 10.3km. Ninety per cent of daily travel is under 80km in all areas (Loader 2011). In fact only 5.4% are greater than 120km (McPherson et al. 2011, 6). So for the great majority of electric vehicle owners, travel on a given day is within the range of the battery and recharging can be performed at home or at the business premises overnight.

While the remaining 5.4% of longer trips may be undertaken in electric vehicles, it is expected that for a considerable time in the future households and businesses will still have an ICE or hybrid vehicle at their disposal for longer journeys. So the proportion of BEVs in that last five percent is likely to be very low, considerably less than the representation in the national fleet. Also for the foreseeable future, not all will have exchangeable batteries, so they will use recharge stations. Of the BEVs currently commercially available in Australia, principally the Nissan Leaf and Mitsubishi i-MiEV, none have a quick exchange capability. The Renault Fluence BEV was withdrawn from sale in early 2013 when it became apparent there would be no battery exchange infrastructure for the foreseeable future. By 2020, under the AECOM optimistic scenario, perhaps 20% of the BEVs sold in Australia will have exchange capability.

Finally, on any given day up to 24% of the population do not travel at all (Loader 2011). There is thus a quite limited candidate population for battery exchange within cities. In a regional centre of 50,000 to 80,000 people there may be need for only one exchange station: in a large centre such as Melbourne it was found that 15 stations were sufficient to cater for the greater metropolitan area (McPherson et al. 2011). However that study considered only the requirement for sufficient stations to satisfy the needs of the motorists, and not whether there would be sufficient patronage of each station to be financially viable.

The Hume Highway between Melbourne and Sydney is one of the busiest in Australia. Close to Melbourne and Sydney, more than 60,000 vehicles a day pass along it. But in the middle, near Holbrook, only 4900 vehicles per day pass through (NSW Roads and Maritime Services 2006, 14). Those 4900 vehicles can be taken to represent the long-distance traffic between Melbourne and Sydney, although even then some may be travelling between adjacent towns. Sixty percent or about 3000 vehicles per day were passenger cars and light commercial vehicles. Traffic has been growing at a consistent three to four percent for several years (NSW Roads and Maritime Services 2006, 14). At this rate, by 2020 we could expect around 5000 passenger and light commercial vehicles per day.

Holbrook is 60km from Albury and 120km from Gundagai. Albury to Gundagai at 180km represents a distance greater than is achievable with existing BEV technology at sustained high speed. If a battery exchange station was located 20km north of Holbrook and if it was appropriately spaced from others along the highway, all BEVs with exchangeable batteries will stop for a swap.

In 2011, the Victorian Department of Transport issued a forecast for the uptake of electric vehicles in Victoria (AECOM 2011). It predicts relative sales of ICE, HEV, PHEV and pure electric vehicles (BEV) through to 2040 under four different scenarios. The scenarios were:

- Base case. Only ICE and hybrid vehicles, no plug-in hybrids or pure electric vehicles.
- Scenario 1. Level 1 household charging only. In this scenario, vehicles are generally bought only by enthusiasts willing to put up with the inconvenience of long recharge times.
- Scenario 2. Level 1 and 2 charging at home, and Level 2 public charging in city areas.
- Scenario 3, all the above plus public level 3 charging and battery swap facilities.

Scenario 3 has the most favourable conditions for BEV. With ready availability of BEV. However there is no distinction between those BEVs with fixed or with swappable batteries. This is a very optimistic forecast. In the first half of 2013 actual sales of BEVs totalled 107 (EV-Sales 2013). However this will be the basis for subsequent calculations.

Victoria has 25% and NSW 29% of the national fleet of 17 million vehicles (ABS 2013), or about 8.5 million passenger cars and LCVs between the two states. If we extrapolate the sales for Victoria to include NSW, by 2020 about 300,000 BEVs will have been sold. Assuming these EVs replace existing ICE vehicles and allowing for 2.3% annual growth in the total vehicle population (ABS 2013) by 2020, the 300,000 BEVs will represent 3% of the car fleet: perhaps 3% of the 5000 vehicles passing through Holbrook on the Hume Highway represents 150 vehicles per day. In practice, it is to be expected that the proportion of electric vehicles undertaking interstate trips will be considerably less than their representation in the national fleet: for the foreseeable future there will be ICE and hybrid vehicles for the long trips.

However, even if all EV owners are comfortable using their cars on long trips, if less than 60% have exchangeable batteries, we are back at the financial break-even point for the Holbrook station.

Let us assume there is an existing petrol and service station at a good location near Holbrook, and the owners decide to invest in a battery exchange operation. From our optimistic assessment of BEV sales, we can estimate the proportion and therefore the number of BEVs passing the premises over the next ten years.

Let us further assume that:

- The total number of passenger and light commercial vehicles in Victoria and NSW in 2013 is 8,500,000 (ABS 2013).
- Annual growth of the Victorian/NSW vehicle fleet is 2.3% (ABS 2013).
- Light traffic counts on the Hume Highway at Holbrook in 2013 is 3,800 per day and the annual growth is 3.5% (NSW Roads and Maritime Services 2006).
- Sales of BEVs in Victoria and NSW follow the pattern from the AECOM document.
- The base count of BEVs before 2013 is zero. This is certainly true for exchangeable battery BEVs.
- 50% of all BEVs will have exchangeable batteries (this may be optimistic).
- New BEVs sold replace old ICE vehicles except for total growth: within the period to 2025 EVs will not replace old EVs.

- Income and expenses for the station are as in the original scenario in Section **Error! Reference source not found.**.
- For financial considerations we will use Net Present Value (NPV) of profit and loss with a discount rate of 8%. Given the risk involved, this is possibly conservative.
- Inflationary effects are not considered. The impact of inflation is less likely to be significant than the rate of increase in the costs of electricity and ICEV fuels (the latter would allow the operator to increase swap fees to match) and the probable reduction in cost of replacement batteries.

The results are shown in Table 4 and Figure 5. By 2025 the station still has a cumulative loss of around one million dollars. It is clear that this is not a profitable exercise, and it will not be any time soon: the bank will lose patience long before the exchange station shows a return on investment.

Table 4: Projected Profit/Loss for Holbrook Battery Exchange Station

Year	Accum. Sales of BEV	Proportion of VIC/NSW Fleet	Daily Traffic Past Holbrook	Exchangeable Battery EVs per Day	Annual Profit $,000 Discounted	Cumulative Profit/Loss $,000 Discounted
2013	10800	0.1%	3800	2	-330	-330
2014	32400	0.4%	3933	7	-286	-616
2015	54000	0.6%	4071	12	-246	-862
2016	86400	0.9%	4213	20	-202	-1064
2017	129600	1.4%	4361	30	-155	-1219
2018	172800	1.8%	4513	41	-113	-1332
2019	226800	2.3%	4671	54	-69	-1401
2020	280800	2.8%	4835	68	-30	-1431
2021	345600	3.4%	5004	84	10	-1420
2022	432000	4.1%	5179	106	57	-1363
2023	529200	4.9%	5360	132	33	-1330
2024	648000	5.9%	5548	163	134	-1196
2025	777600	6.9%	5742	198	192	-1004

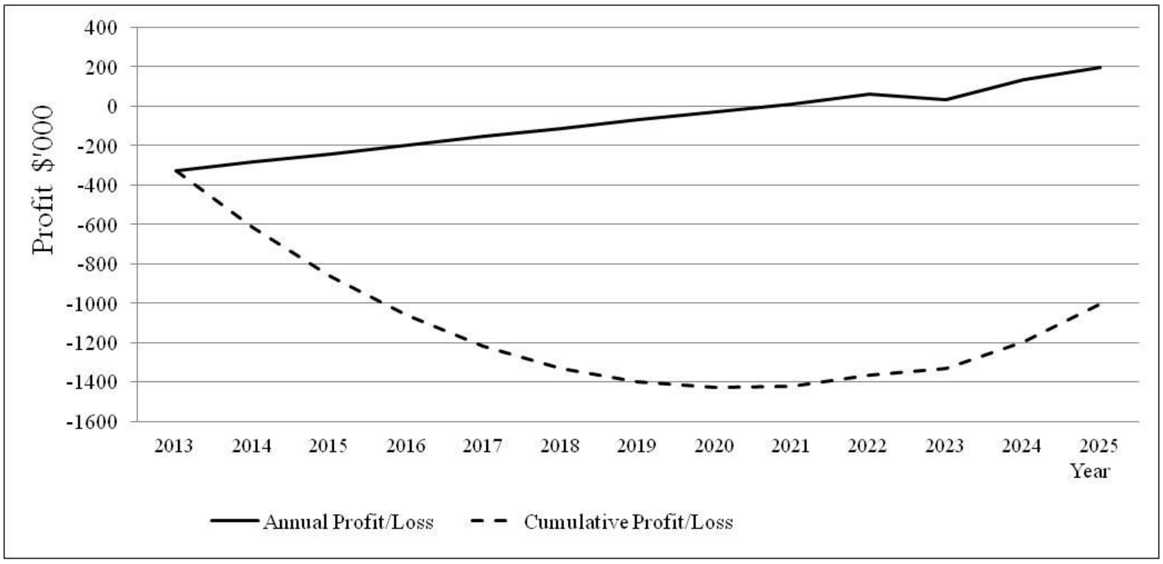

Figure 5: Annual Profit and Loss for Holbrook Station Using NPV

Even if we assume 100% of all BEVs sold have exchangeable batteries, it would be 2023 before there is a return (Figure 6).

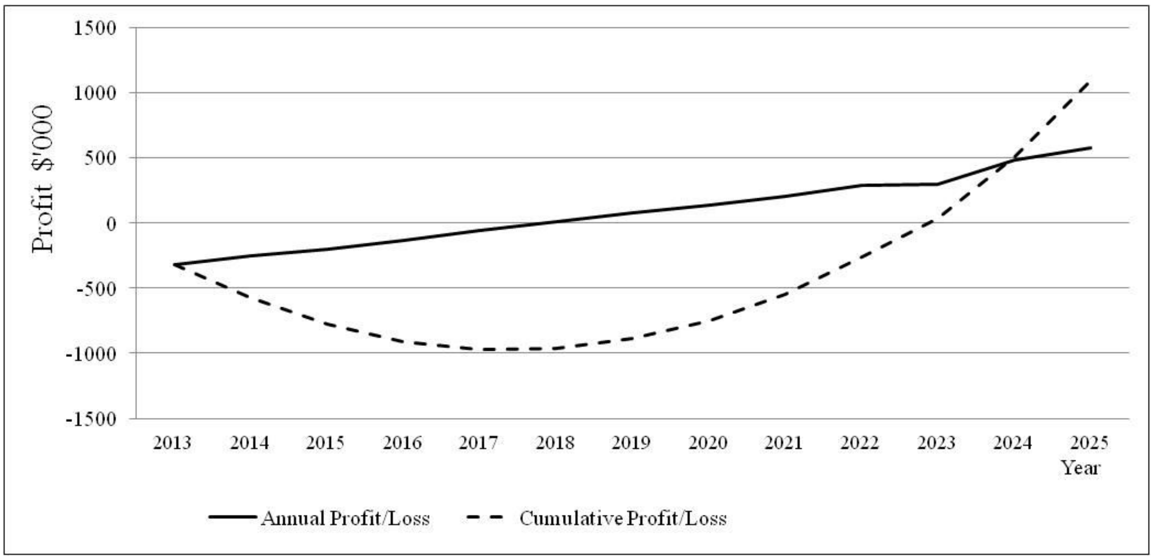

Figure 6: Profit and Loss for Holbrook Station, 100% Exchangeable Battery BEV

The situation for a city-based battery exchange station is expected to be similar. The cause of the problem is the high up-front investment in plant, for a decade-long negative return until customer numbers build up.

The scenario above examined a busy road in the two most densely populated states. The situation in a larger state such as Western Australia with very long distances between relatively small population centres is such that there will never be enough traffic on the highways to justify an exchange station outside Perth and some of the larger cities in the south.

It is a chicken-and-egg situation: until the exchange infrastructure is in place, there will be no sales of vehicles that use the technology. With no vehicles on the roads, there is no income. There is one advantage: the exchange station owns the batteries, so the cost to the consumer of the vehicle is reduced by the cost of the battery. However this is unlikely to sway the buyer if that infrastructure is not in place.

8 The Alternative: Fast Chargers

As a comparison with exchange stations, we can compare the numbers for providing a fast-charge service as an adjunct to a small business, perhaps a 24-hour roadside cafe near Holbrook. Fast-charge stations currently cost around $13,000 plus installation expenses (GoAuto Australia 2011). If we assume:

- The cafe spends $18,000 buying and installing a fast charger;
- Electricity cost at peak tariff for a business is 31c/kWh ex GST (RedEnergy 2014);
- The cafe elects to use 100% green power for an extra 6c/kWh, bringing the total cost to 37c/kWh;
- A Nissan LEAF has a 24kWh battery and has a real-world freeway driving range of 80 miles or 128km (Ingram 2013), equal to 5.3km/kWh;
- Fast recharging the battery will take 20 minutes, restore 80% of the range and use 25kWh, reducing the "fuel" economy to 4km/kWh. This assumes that fast recharging is a little less efficient than normal at 75%;
- The year is 2014: the number of BEVs passing the cafe near Holbrook is 15/day;
- The majority of these vehicles will accept Level 3 charging;
- The location is such that all BEVs will need to drop in to be sure of reaching the destination.

If we use the same queuing model as in Section 5.2, and assume customers will tolerate a wait of up to 10 minutes before being able to plug in (total time in system 30 minutes, about the time it takes to buy and drink a coffee), the value of ρ is 0.5: it can service a vehicle every 40 minutes, or 1.33 per hour, 13 per day. This is conveniently close to the expected number of BEVs passing the door in 2014.

The 25kWh of green power will cost the business owner \$9.25 excluding GST. If they charge \$12 including GST per recharge they will make \$1.65 profit per charge. At 13 vehicles per day and 365 days per year this results in \$7,830 profit in the first year of operation: the recharger will pay for itself in a little over two years. In addition, they have presumably increased their turnover of coffee and cakes as customers will choose to stop there preferentially and are on the premises a little longer.

The motorist has spent \$12 for a 100km top-up, or 12c/km with emissions of 0g CO_2/km. This compares with 11.25c/km and 152g CO_2/km for a typical light car as calculated above in Section 0.

The above relatively simplistic calculation shows that a network of fast chargers can be financially and environmentally sustainable.

Such a network of chargers also distributes the load on the electricity grid: utility companies will be better able to develop the grid to cope with large numbers of EV recharges around the nation than if the recharging was concentrated in large exchange stations.

9 Conclusion

This document examined the conditions under which a battery exchange station would be financially viable. Under the most favourable conditions, the station would need to handle 70 or more vehicles per day. These conditions include:

- Charging an exchange fee equivalent to the cost of refuelling an ICE for the same kilometres driven, providing no financial incentive for owning an EV.
- Recharging depleted batteries at off-peak electricity grid prices: this means that all batteries must be recharged within an eight-hour window at night. If 100 exchanges are made during the day, the plant will need to draw 250kW from the grid for eight hours, which may exceed the capacity of the grid in some areas.
- Recharging depleted batteries using standard grid power, providing little or no reduction in carbon emissions over an ICE.

If any of the above conditions is not met, the required number of battery exchanges per day balloons out to unsustainable proportions.

It also examined the potential client population for a network of battery exchange stations. Within population centres a large majority of travel in a day will be short enough that the owner can recharge overnight at home. On even the busiest main highways the actual core of long-distance travellers is relatively small. Even on the Hume Highway between Melbourne and Sydney, the most optimistic scenario results in approximately 200 exchangeable-battery EVs travelling per day by 2025.

Driver attitude and behaviour is also important. If the exchange infrastructure is not in place in sufficient quantity, motorists will not buy vehicles that use the technology in the first place. Within large centres, if the driver has to make too large a detour from the journey to get to an exchange station, the technology will be seen as a failure. A century ago private motorists were innovators and pioneers, willing to sacrifice some convenience or expense to travel in their cars. Now there are too many other well established options whether ICE or hybrid, with fossil fuel readily available wherever needed. Motorists have come to expect convenience.

Vehicle manufacturers will not produce cars with exchangeable batteries unless there is demand. Customers will not demand these cars while the infrastructure is no in place to support them. The infrastructure is too expensive to put in place in the hope that it will become profitable in perhaps ten or fifteen years. The only way the technology could be introduced is for it to be supported by government (who would have no reason to do so) or by vehicle manufacturers until the market matures. It is unlikely that the manufacturers will wish to take that gamble when much cheaper alternatives – fast charging stations – exist. It is just possible that some fleet owners such as taxi or courier companies will find the technology useful for in-house use and can justify the expense of the exchange equipment, at the same time providing the instant market for the infrastructure. Tesla Motors might also persist with the technology as a loss-making service to its well-heeled customers.

For those motorists who embrace battery electric vehicles, there are still other options. They can recharge at home overnight, using standard or “green” electricity: and for longer journeys they can use fast recharging stations and tolerate the 20- to 30-minute wait. Or they may use other means of transport altogether: the other, fossil fuelled car in the garage, or even public transport.

Over the next decade there is likely to be gradual growth in BEV production and sales. As production increases, the pricing disparity between ICEV and BEV will diminish to the point where a BEV will pay for itself within a few years with lower running cost. Improvements in battery capacity will extend the range of BEVs to cover most requirements. Fast charging technology will also improve and perhaps be able to deliver 200km of highway travel in about 20 minutes without impact on the life of the vehicle battery. This will align with road safety messages about taking a break every two hours on long trips (TAC Victoria 2013).

Fast recharge stations are relatively inexpensive and the cost is likely to continue to drop as with most technology. This places the units within reach of entrepreneurial business owners, even small businesses such as coffee shops, to install them as drawcards for customers. Petrol station owners will be able to offer several fast chargers as an adjunct to fuel sales without a huge financial risk. With appropriate adaptors, the chargers can be used on all BEVs, not just those with exchangeable batteries. Once a network of fast chargers is in place around the country in similar numbers to petrol stations, range anxiety fades away. Section 8 examines the advantages of fast chargers even now and how they can be economically and environmentally sustainable.

In summary, battery exchange technology is a victim of its cost: initial installation of the infrastructure is likely to be too large a hurdle when there are much cheaper alternatives available. The service it can offer will not save customers money in day-to-day running and the service provider would not be able to afford to use low-emissions energy in recharging. Alternatives such as a distributed network of fast chargers can offer a slightly slower service at much lower cost.

This project examined the conditions under which a battery exchange system could be viable. This was achieved by focusing on a single exchange station and determining whether it could be profitable, and under what circumstances. It was found that while it is possible to make a profit, the growth in population of exchangeable-battery electric vehicles would not be sufficient for the station to become profitable in less than a decade. Even under the most favourable conditions a station, and therefore the whole system, is deemed unviable.

A battery exchange system has no inherent advantages in terms of reducing greenhouse gas emissions of electric vehicles. In fact, attempting to use low-emissions power for recharging the batteries places financial viability even further out of reach.

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