Electrical Vehicle Storage Technologies and Range

Leatham Landon-Lane[1]*, Allan Miller[2], Aaron Marshall[1], Paul Gaynor[3]

[1] Department of Chemical and Process Engineering, University of Canterbury

[2] Electric Power Engineering Centre (EPECentre), University of Canterbury

[3] Department of Electrical and Computer Engineering, University of Canterbury

* Presenting author

EEA Conference & Exhibition 2017, 21 – 23 June, Wellington

Abstract

Information regarding electric vehicles is not always clearly and accurately portrayed to the general public. This paper provides a holistic view of the worldwide vehicle market, focussing on the current and future capabilities of vehicles powered by different fuel sources. The types of vehicles chosen for case studies in this paper are: Internal Combustion Engine (ICE), Hydrogen Fuel Cell (HFC), and Battery Electric Vehicles (BEVs). Factors considered include energy storage density, efficiency, upfront and running costs and scope for improvement in each of the vehicle technologies. The primary purpose of this paper is to inform the reader of the progress made with alternatively fuelled vehicles, what improvements will need to be made in order to make them more like-for-like replacements for ICE vehicles, and the implications an increased market share of each type may have on national and local infrastructure.

The major findings from this paper show that BEVs are a more practicable solution than HFC vehicles for replacing ICE vehicles. BEV sales are increasing rapidly due to falling battery costs, with future sales increases likely to be driven by lower cost and higher energy density batteries. Improvements in battery technology are likely to be limited to Li-ion in the short term, with metal-air batteries offering potentially higher energy densities at a lower cost, but technical difficulties are preventing current use. In order to be equivalent to ICE vehicles, BEVs require increased range and faster charging times, which are both achievable without the need for battery swapping.

1. Introduction

Alternative vehicles, those not powered by internal combustion engines, have become more common in recent times. In 2016, almost 800,000 electric vehicles were sold worldwide, for a market share of 1% [1] [2]. Consumers purchasing alternative vehicles may have a range of motivations including the desire to be environmentally friendly, fear of high petrol prices or a desire to try a different type of driving experience [3]. Sales of electric vehicles are projected to continue increasing, reaching 35% of all sales by 2040 [4]. In New Zealand, the Government has set a target of 64,000 registered electric vehicles on our roads by 2021 [5]. Of the alternative vehicles, sales of Battery Electric Vehicles (BEVs) and plug in Hybrid Electric Vehicles (PHEVs) have increased by a factor of 2-3 year on year in New Zealand, with around twice as many BEVs sold as PHEVs [6, 7]. Hydrogen Fuel Cell (HFC) vehicles are in production, but few are made and are only sold where specific refuelling infrastructure is in place [8, 9].

The purpose of this paper is to compare the utility of petrol powered ICE vehicles with BEVs and HFC vehicles. Electric motor based vehicles were considered because there are production models of both BEVs and HFCs available, whereas combustion style hydrogen vehicles are not. Petrol vehicles considered as models such as the Toyota Corolla and Nissan Sunny are equivalent to the most common BEV, the Nissan leaf. However, it is recognised that diesel ICE vehicles may provide better economics. This paper will aid the reader to understand HFC vehicles, their relative range, and the infrastructure required to enable them. It begins by discussing the relative energy densities of energy storage for each type of vehicle, followed by a discussion on the relative range densities of the vehicles. It then puts this in terms of effective distance each vehicle can travel on a full charge or tank, comparing each vehicle type.

Whilst New Zealand car owners travel on average around 35-52 km a day, long distance travel is required for a few days in the year, such as holidays [10]. BEV owners can currently deal with this by owning both a BEV and an ICE vehicle. However, there is an added cost with this (an extra vehicle and its associated on road costs), which presents a barrier to considering a BEV. To understand whether current BEV vehicles could meet the needs of travellers on their own, assuming substantial charging infrastructure, this paper addresses this from the point of view of stop time required for each vehicle type. This is followed by a discussion on ways in which longer distance travel might be facilitated with BEVs. Finally, the paper addresses infrastructure required for hydrogen powered vehicles.

2. Energy Storage

To understand some of the reasons for these market phenomena, it is useful to consider the stored energy density that supplies each vehicle type considered, depicted in Figure 1.

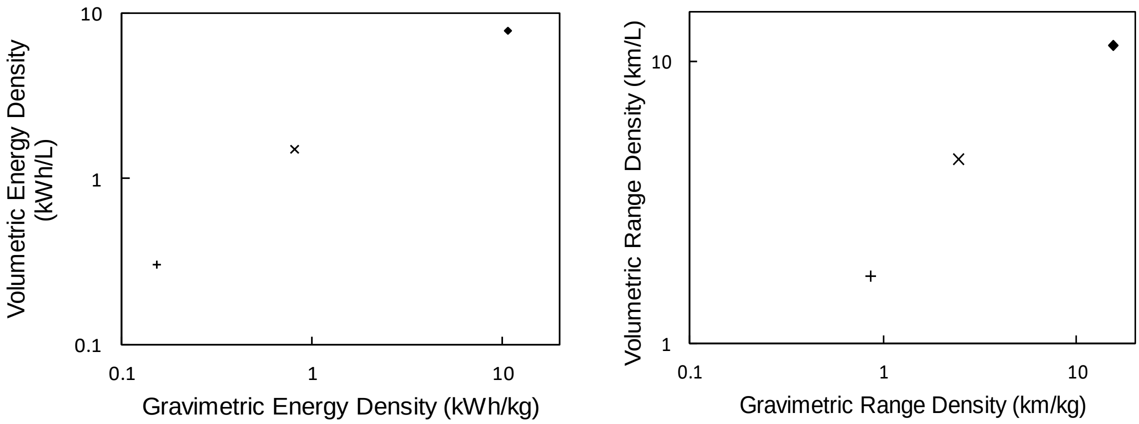

Figure 1: Energy density of different fuels: a) Estimated density of energy stored in Li-ion batteries + [11], Compressed hydrogen at 700 bar × [12] and petrol ♦ [13]. b) Estimated distance travelled in vehicles relative to the size of energy storage system, Li-ion batteries +, Compressed hydrogen × and petrol ♦. Log scale on all axes.

The energy density of petrol is clearly greater than that of both compressed hydrogen and Li-ion batteries. The energy density of Li-ion batteries varies based on a number of factors, thus the value in Figure 1 is considered indicative and includes the battery cells and battery pack materials which are needed for safety and cooling [14] [11]. In the case of the hydrogen this energy density refers to 5.6 kg of hydrogen, compressed at 700 bar, stored in pressure cylinders [12]. The volumetric and gravimetric energy density of petrol was calculated assuming a fuel tank mass of 10 kg and is much greater than that of Li-ion batteries, by factors of 26 and 72 respectively. By contrast, hydrogen stored at 700 bar has a five times higher volumetric and gravimetric energy density than Li-ion batteries.

Higher stored energy density enables cars to have longer range without increasing the mass or size of the cars. This is the primary advantage ICE vehicles have over the alternative options; the high energy density provides them with the ability to travel long distances without stopping, for instance a 2017 Toyota Corolla CVT L can travel 676 km with a tank volume of 50 L [2]. While energy density contributes significantly to the range of a vehicle and hence how appealing it is to the customer, other factors must be considered, in particular energy efficiency.

In a BEV with a DC permanent magnet motor, 89% of the energy drawn from the battery will be converted into useful energy by the motor and transmission [15]. For a hydrogen vehicle, the electricity to power the motor must first be produced by reacting the stored hydrogen with oxygen, which is provided through an air inlet, this process has an efficiency of around 50% [16].[1] Other factors such as regenerative braking and different vehicle designs influence the overall efficiency of the vehicle [17].

[1] When hydrogen is converted in a fuel cell, water is produced but no CO_2 formed, the oxidation of the hydrogen produces electrons that travel through an external circuit and are used to power an electric motor.

Using the Environmental Protection Agency (EPA) range estimates for typical vehicles [18], allows for the vehicle range to be related to storage system size, shown in Figure 1b. This is essentially scaling the results shown in Figure 1a, by each vehicle's respective efficiency. It can be seen that BEVs have lower range density than both HFC and ICE vehicles, however the difference is significantly less than on a total energy stored basis (Figure 1a) due to the higher efficiency of BEVs. After taking vehicle efficiencies into account, the range density of an ICE is approximately seven times greater on a volumetric basis and 18 times on a gravimetric basis. For HFC vehicles the range density is almost three times greater than for BEVs.

2.1 Possible Future Battery Development

In order to improve the competitiveness of electric vehicles for long distance travel, the energy and range density of BEVs will need to increase significantly. For a battery to have the equivalent range density as petrol, it must store 2,500 Wh/kg. This will require the development new battery types, as the maximum theoretical energy density of Li-ion batteries is below 400 Wh/kg [19]. Substituting the graphite anodes with silicon increases the theoretical energy density by approximately 50%, however the volume occupied by silicon anode changes with charge state, presenting a challenge that must be solved in order to develop a useful battery [20]. Beyond Li-ion batteries, promising technologies include Li-Sulfur and metal-air batteries, as they have higher theoretical energy density. The biggest challenge facing the development of metal-air batteries is the difficulty of cycling and recharging [21]. If these problems can be overcome the rewards will be great as evidenced by the significantly higher energy densities achievable, shown in Figure 2.

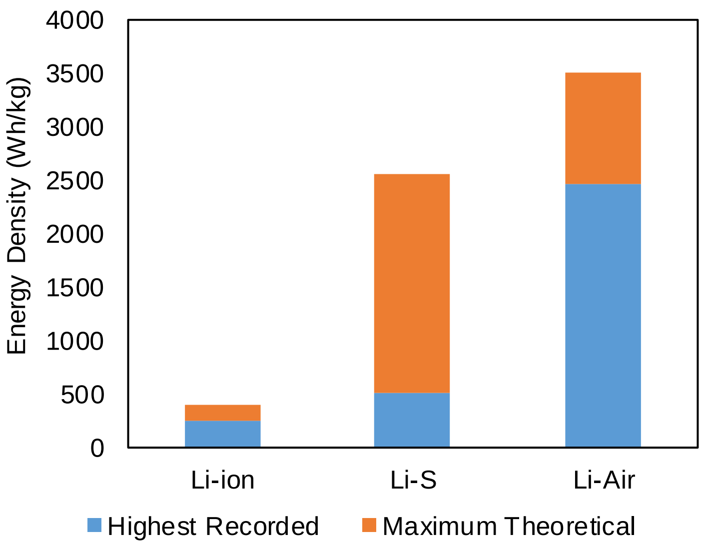

Figure 2: The highest recorded values may not be scalable due to practical challenges of manufacturing on a large scale. Values obtained from [19, 22-24].

The information shown in Figure 2 is significant, as it shows that Li-Air batteries can have far higher energy densities than commercially available Li-ion batteries today. Hence it could be concluded that these hold promise for the future of BEVs to meet the long trip requirements, but not necessarily the charge time requirements [21]. Batteries with an energy density of 2500 Wh/kg, deemed practically achievable for Li-Air, have the equivalent range density of petrol.

3. Comparison of Vehicles by Powertrain Type

As BEVs are sold in greater numbers than HFC vehicles, it is clear that the density of stored energy and the efficiency of the vehicle are not the sole determining factors of car sales. Pricing, availability, access to refuelling/recharging (including whether infrastructure already exists for this, as it does in the case of electricity) and running costs all play a part in the purchasing decisions of consumers and distributors of the vehicle technology [3]. Comparing key technical details for cars of each type of power supply is useful to understand the relative advantages and disadvantages, indicating why the popularity of each type varies. Table 1 compares three roughly equivalent vehicles. In Table 1 a Toyota Corolla is chosen to represent ICE vehicles, the Toyota Mirai to represent the HFC vehicles and the Nissan Leaf to represent BEVs.

		Full Range (km)	Energy Input in 5 min (kWh)	Range Added in 5 min (km)	Efficiency (km/kWh)	Fuel Cost ($NZD/year)	Price ($ USD)
	**Toyota Corolla (ICE)**	676	470	676	1.4	2,100	18,500
	**Toyota Mirai (HFC)**	502	167	502	3.0	800	57,500
	**Nissan Leaf (BEV)**	172	4	23	5.7	500	30,680

Table 1: Important metrics of commercially available vehicles, comparing the performance based on the powertrain type.[2]

It is clear that the Toyota Corolla has the greatest range, due to the high energy density of petrol, despite the poor efficiency of an ICE vehicle. The Toyota Corolla is also the cheapest vehicle due to the absence of a large Li-ion battery or expensive fuel cell, and economies of scale in production. The Nissan Leaf is more competitively priced and cheaper to run than the Toyota Mirai, however the shorter range and significantly higher time required to recharge may not be suitable to many potential buyers, as range and charge time are the biggest barriers to EV adoption after purchase price [3].

The Toyota Mirai has a competitive range and can be refilled quickly, but is the most expensive vehicle, due to the early stages of its development and the use of platinum in the fuel cell [25]. The BEV with the greatest total range currently available is the Tesla 100D, capable of travelling 539 km (EPA estimate). While this range is comparable to the range of ICE vehicles, the Tesla 100D is targeted at a more premium market, and therefore has a higher upfront cost starting at 95,000 USD.

---

[2] Toyota Corolla refilled using a standard petrol pump, Toyota Mirai refilled at currently unavailable hydrogen refilling station by transfer of pressurised hydrogen and Nissan Leaf recharged at a 50 kW DC fast charger. The cost of petrol was estimated at $2/L, hydrogen at $6/kg and electricity at $0.2/kWh for 14,000km/year of driving. Both the Toyota Mirai and Nissan Leaf running costs exclude fuel excise charges as is the current law. However, both would still have a lower fuel cost than the Toyota Corolla if the excise costs of $700 are levied in the future. The fuel costs are subject to variation, but show that in general significant running cost reductions are possible.

4. Long Distance Travel

For a BEV to be recharged at the same energy transfer rates as an ICE vehicle, the charger would need to deliver 5.7 MW, which is 40 times faster than the 145 kW Tesla "Superchargers" (the fastest car chargers currently available [6]). However, the more logical metric to consider is how quickly range can be added to a BEV, since BEVs are more efficient. For this metric to match an ICE vehicle, the charger would need to produce 1.5 MW, which is still 10 times faster than anything available today. Increasing the rate at which Li-ion car batteries can be charged presents significant engineering challenges in equipment design and distribution network capacity. Safe use of the chargers must also be considered, as they will be operated by untrained users. Rate of transfer of energy to BEVs therefore remains an impediment to them being a complete replacement for ICE vehicles.

BEVs being a functional replacement is attractive from a market acceptance point of view, especially given that BEVs are currently more expensive. However, to achieve a transition away from fossil fuels may require some trade-offs, and higher carbon price in the future may bring the total cost of ownership of ICE vehicles and BEVs close. To deal with longer charge/refill times may require a shift in mind set of travellers and more infrastructure, such as sharing of driving, regular rest stops equipped with rapid chargers, and rapid chargers at restaurants and accommodation. However, it is also important to note that BEVs have the advantage of being able to be charged without the driver present. Hence while charging the driver if free to undertake other tasks (shopping, resting, working, and importantly, sleeping.)

Whilst ICE vehicles are a useful performance benchmark, it is worth considering whether electric vehicles need to match the energy storage and refilling metrics of ICE vehicles. While a Toyota Corolla can be driven for 676 km and refilled within 5 minutes, it is unlikely and potentially unsafe to do so. For instance, professional drivers in New Zealand must stop for 30 minutes at least every 5.5 hours, for the purpose of safe driving practices as described in the New Zealand Transport Agency's *Your Safe Driving Policy* [26]. To demonstrate how each of the previously discussed vehicles copes with long range driving, a case study was performed and is summarised in Table 2.

Table 2: Minimum required stopping time in selected vehicles when driving from Wellington to Auckland, a 643 km journey at an average speed of 80 km/h.[3]

	Minimum stop time required to refuel (minutes)	Minimum stop time following safe driving practices (minutes)
Toyota Corolla	0	30
Toyota Mirai	5	30
Nissan Leaf	100	100
Tesla Model S P100	12	30

[3] Nissan Leaf recharged at a 50 kW DC fast charger and Tesla Model S at a 145 kW Supercharger.

In a typical ICE vehicle, the driver would not have to stop for fuel, however 8 hours of continuous driving is potentially dangerous, according to the New Zealand Transport Agency's "Your Safe Driving Policy" [15]. If the driver followed these safe driving practices, they would stop for a 30-minute rest after no more than 5.5 hours of driving. Recharging times may present an inconvenience when multiple drivers are willing to swap responsibilities without stopping for a break. Under this scenario only the driver of the Nissan Leaf would be forced to stop longer than what is considered safe, in order to transfer energy into their vehicle. Both the Toyota Mirai and Tesla Model S can refill/recharge in a short period of time that is of little significance, assuming a recharging or refuelling station was available at a suitable location.

4.1 Battery Swapping

Another way to reduce stoppage time for long distance travelling with BEVs is to swap partially or fully discharged batteries for fully charged equivalents. Even though the total range of the BEV is still below that added of an ICE and HFC, the time to 'recharge' a BEV can be reduced to under 5 minutes. Battery swapping has been developed and is currently available to a select number of Tesla drivers in California. This service has not proven popular, likely due to the free DC fast charging stations being so fast most customers would prefer not to spend money for the battery swap [27]. Beyond the low demand for battery swapping, technical challenges will also likely impede the wide-scale use of battery swapping. This includes interoperability issues between batteries and vehicles from different vehicle manufacturers and models.

4.2 DC Fast Charging

DC fast charging stations, typically capable of delivering up to 50 kW charging rates, have been installed in New Zealand with the network continuing to expand in the coming years [28]. In the near future the DC fast chargers are likely to increase in power output, with a joint venture between Ford, BMW, Audi, Porsche and Daimler targeting the installation of 350 kW stations [29]. Chargers capable of delivering 350 kW charging will bring down the stop time needed to drive for 5.5 hours to under 15 minutes. Whether 350 kW charging becomes commonplace is yet to be seen, as a number of issues must be overcome such as distribution system sizing to enable such a large connection, or connections if multiple super chargers are located at one place. Very high charging rates will put pressure on both the energy delivery system, namely transformers, charging cable and possibly the grid as a whole. From a vehicle perspective, significant improvements in battery pack design will be required to allow batteries to charge at this rate safely, both on the short and long term. High speed charging can cause degradation by lithium plating, leading to irreversible capacity loss [30].

5. Electric Vehicles and Battery Costs

As BEVs are cheaper to run, can be charged at home, and do not emit harmful gases [2], they can be sold at a premium over ICE vehicles. Currently the price of BEVs is significantly greater than that of ICE vehicles, limiting uptake [31]. In order to increase the number of people willing to purchase electric vehicles, the upfront cost must be reduced. The component with the largest scope for price reductions is the battery, with improvements in the short term most likely to come from achieving mass production, with newer higher energy density batteries yielding further improvements in the future. The sales of BEVs are increasing year on year as the price of batteries decreases, and is expected to continue with large factories planned by automakers and battery manufacturers alike [32].

6. Hydrogen Refuelling Infrastructure

Currently 80-85% of hydrogen is produced by Steam Methane Reforming (SMR) of Natural gas [33], with a thermal efficiency of 67% and emissions of 13.7 kg of CO_2 per kg of hydrogen, thus it is not a renewable source of hydrogen. If hydrogen produced from SMR was used to power a Toyota Mirai, the car would be responsible for 153 gCO_2/km of emissions, slightly higher than the 152 gCO_2/km of emissions from a 1.8 L ICE Toyota Corolla [34]. For HFC to reduce the emissions of Greenhouse Gases, the Hydrogen must be made in a more sustainable way. In New Zealand over 80% of our electricity is produced from renewable sources, thus electrolysis may be used to produce hydrogen sustainably.

Electrolysis of water refers to the splitting of water (H_2O), into hydrogen gas (H_2) and oxygen gas (O_2) through the use of electricity. The electrolysis process is essentially the reverse of the reaction that occurs in a fuel cell in a HFC, where hydrogen is converted in the presence of oxygen to produce water and electricity. Common commercial electrolysers have an average efficiency of 73%, with electrolyte quality, temperature, pressure and other factors influencing the overall efficiency [35]. Once this hydrogen is produced it must be compressed to 800 bar so that it can be subsequently used to refill the 700 bar storage tanks in HFC. With current technology compression will consume approximately 20% of the energy stored within the hydrogen, due to the high adiabatic coefficient and initial specific volume of hydrogen [36]. This hydrogen must then be converted into electricity at the previously stated efficiency of around 50%. Consequently, if 1 MWh of electricity was used to produce hydrogen for an HFC vehicle, only 0.29 MWh would be converted into usable electricity, Figure 3 represents this.

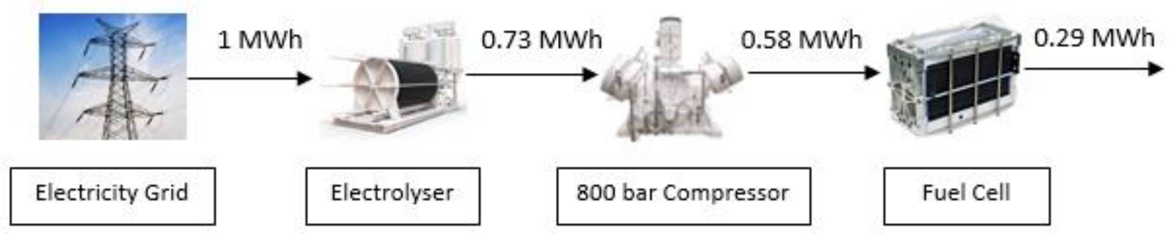

Figure 3: Energy losses at key steps of powering vehicles through the production and storage of hydrogen.

In the case of electric vehicles, electricity from the grid is used to charge a battery which is then discharged to power an electric motor. When compared to hydrogen, the round trip efficiency of a battery is significantly greater at up to 90% [37], thus three times less energy would need to be drawn from the grid to attain the same energy supply to the electric motors.

In addition to the loss of energy that would be present when producing hydrogen for use in vehicles, the capital cost associated with producing the infrastructure necessary to service the vehicles would be significant, given that there is currently no infrastructure. Where the hydrogen is produced has a significant bearing on what future infrastructure would be required. In order to produce hydrogen from electricity cheaply, large centralised production plants would be required [38]. The downside to this is that the hydrogen produced must then be transported to refuelling stations.

Transportation of the hydrogen would through pipelines in the same manner natural gas is distributed currently presents challenges. Hydrogen gas is an explosion hazard and due to its smaller atomic size it diffuses through and causes embrittlement of steel, requiring more expensive piping or frequent maintenance and higher energy losses due to compression. This further reduces the system level efficiency and increases costs [39].

The lifetime GHG emissions of BEV's in Europe is significantly below that of ICE vehicles. BEV's release more GHG emissions during manufacturing due to the large batteries, however lower emissions during use are more significant, despite electricity grid emissions of 500 gCO2/kWh [40]. In New Zealand, the emissions saved would be significantly higher due to a larger market share for renewables [41]. HFC's emit more GHG over a life cycle than BEV's if the hydrogen is sourced from natural gas reforming, the same is true for electrolysis due to the lower system efficiency outlined in Figure 3 [42].

7. Discussion and Conclusions

The market for vehicles powered by alternative energy sources is growing world-wide, likely due to increased environmental awareness, Government subsidies (see [43] for a discussion of Government subsidies), reduced costs (albeit still higher than ICE equivalents) and wider availability of products world-wide. While a vehicle can be powered in many ways, only two alternative fuel sources have made it to production: BEV and HFC vehicles. BEVs have lower stored energy density than both HFC and ICE vehicles and although they are more efficient, the range and refilling rates are significantly lower. Despite these downsides, BEV sales are increasing, primarily due to Government subsidies and a burgeoning second-hand market, but also due to the lower running costs [43].

The adoption of BEVs is expected to continue to accelerate with price reductions and improvements in energy density of batteries. However, to achieve equivalence as a complete replacement for ICE vehicles, the range and charging time must be resolved. Energy storage and recharging rates that are equivalent in range to ICE vehicles appears to be unfeasible for BEVs in the near term. Using large inter-changeable battery packs could combat this, however standardization across manufacturers would be required to enable compatibility [44].

The Tesla P100D proves that it is possible to produce BEVs capable of travelling long distances with short stop times. This currently comes at a large cost, but advances in battery technology and increased manufacturing scale will reduce this. Unlike BEVs, mass adoption of HFC vehicles is unlikely due to the high cost and low efficiency of the system, coupled with the need for significant development of new infrastructure.

8. References

1. *Monthly Plug-In Sales Scorecard*. 2017 [cited 2017 2/2/2017]; Available from: http://insideevs.com/monthly-plug-in-sales-scorecard/.
2. *Benefits and Considerations of Electricity as a Vehicle Fuel*. 2017 [cited 2017 23/02/2017];
   Available from: http://www.afdc.energy.gov/fuels/electricity_benefits.html.
3. Ford, R., J. Stephenson, M. Scott, J. Williams, D. Rees, B. Wooliscroft, O. University of, S. Centre for, Z. New, I. Ministry of Business, and Employment. *Keen on EVs : Kiwi perspectives on electric vehicles, and opportunities to stimulate uptake*. 2015.
4. *Electric vehicles to be 35% of global new car sales by 2040*. 2016 [cited 2017 28/02/2017]; Available from: https://about.bnef.com/blog/electric-vehicles-to-be-35-of-global-new-car-sales-by-2040/.
5. *Electric Vehicles Programme Overview*, 2016. p. 4.
6. Lambert, F. *Tesla quietly upgraded its Superchargers for faster charging, now capable of 145 kW*. 2016 [cited 2017; Available from: https://electrek.co/2016/07/20/tesla-supercharger-capacity-increase-145-kw/.
7. *Monthly electric and hybrid light vehicle registrations*. 2017 7/04/2017]; Available from: http://transport.cwp.govt.nz/research/newzealandvehiclefleetstatistics/monthly-electric-and-hybrid-light-vehicle-registrations-dec-2016/.
8. *Smaller, cheaper Toyota Mirai fuel-cell car coming in 2019*. 2016 [cited 2017 2/2/2017]; Available from: http://www.greencarreports.com/news/1103847_smaller-cheaper-toyota-mirai-fuel-cell-car-coming-in-2019-company-says.
9. *Monthly Light Vehicle Registrations, March 2016*, 2016, Ministry of Transport.
10. Duncan, J., *Electric Vehicles: Impacts on New Zealand's Electricity System*, 2010, Centre for Advanced Engineering, University of Canterbury - Report. p. 21.
11. Miller, P., *Automotive lithium-ion batteries.* Johnson Matthey Technology Review, 2015. **59**(1): p. 4-13.
12. Hua, T.Q., R.K. Ahluwalia, J.K. Peng, M. Kromer, S. Lasher, K. McKenney, K. Law, and J. Sinha, *Technical assessment of compressed hydrogen storage tank systems for automotive applications.* International Journal of Hydrogen Energy, 2011. **36**(4): p. 3037-3049.
13. Fischer, M., M. Werber, and P.V. Schwartz, *Batteries: Higher energy density than gasoline?* Energy Policy, 2009. **37**(7): p. 2639-2641.
14. Rosenman, A., E. Markevich, G. Salitra, D. Aurbach, A. Garsuch, and F.F. Chesneau, *Review on Li-Sulfur Battery Systems: an Integral Perspective.* Advanced Energy Materials, 2015. **5**(16): p. n/a-n/a.
15. Åhman, M., *Primary energy efficiency of alternative powertrains in vehicles.* Energy, 2001. **26**(11): p. 973-989.
16. Moore, R.M., K.H. Hauer, S. Ramaswamy, and J.M. Cunningham, *Energy utilization and efficiency analysis for hydrogen fuel cell vehicles.* Journal of Power Sources, 2006. **159**(2): p. 1214-1230.
17. Estima, J.O. and A.J. Marques Cardoso, *Efficiency Analysis of Drive Train Topologies Applied to Electric/Hybrid Vehicles.* IEEE Transactions on Vehicular Technology, 2012. **61**(3): p. 1021-1031.
18. *How Vehicles Are Tested*. 2017 [cited 2017 23/02/2017]; Available from: http://www.fueleconomy.gov/feg/how_tested.shtml.

19. Bruce, P.G., S.A. Freunberger, L.J. Hardwick, and J.-m. Tarascon, *Li-O2 and Li-S batteries with high energy storage.* Nature Materials, 2012. **11**(2): p. 172.
20. Gu, M., Y. He, J. Zheng, and C. Wang, *Nanoscale silicon as anode for Li-ion batteries: The fundamentals, promises, and challenges.* Nano Energy, 2015. **17**: p. 366-383.
21. Lee, J.-S., S. Tai Kim, R. Cao, N.-S. Choi, M. Liu, K.T. Lee, and J. Cho, *Metal–Air Batteries with High Energy Density: Li–Air versus Zn–Air.* Advanced Energy Materials, 2011. **1**(1): p. 34-50.
22. Ma, Y.W., H.Z. Zhang, B.S. Wu, M.R. Wang, X.F. Li, and H.M. Zhang, *Lithium Sulfur Primary Battery with Super High Energy Density: Based on the Cauliflower-like Structured C/S Cathode.* SCIENTIFIC REPORTS, 2015. **5**: p. 14949.
23. Zhang, Y., L. Wang, Z. Guo, Y. Xu, Y. Wang, and H. Peng, *High-Performance Lithium–Air Battery with a Coaxial-Fiber Architecture.* Angewandte Chemie, 2016. **128**(14): p. 4563-4567.
24. Liu, J.Y., X.X. Li, J.R. Huang, J.J. Li, P. Zhou, J.H. Liu, and X.J. Huan, *Three-dimensional graphene-based nanocomposites for high energy density Li-ion batteries.* JOURNAL OF MATERIALS CHEMISTRY A, 2017. **5**(13): p. 5977-5994.
25. Debe, M.K., *Electrocatalyst approaches and challenges for automotive fuel cells.* Nature, 2012. **486**(7401): p. 43.
26. *Your safe driving policy*, 2010.
27. Korosec, K. *Tesla's battery swap program is pretty much dead*. 2015 [cited 2017 2/2/2017]; Available from: http://fortune.com/2015/06/10/teslas-battery-swap-is-dead/.
28. Linklater, D. *BMW and Charge Net to create 'electric highway' in NZ by 2018*. 2016 [cited 2017 2/2/2017]; Available from: http://www.stuff.co.nz/motoring/84704171/BMW-and-Charge-Net-to-create-electric-highway-in-NZ-by-2018.
29. Cole, J. *400 "Ultra-Fast" 350 kW Charging Station Network Planned By 4 Automakers For Europe*. 2016 [cited 2017 2/2/2017]; Available from: http://insideevs.com/400-ultra-fast-350-kw-charging-stations-planned-by-4-automakers-in-europe/.
30. Burow, D., K. Sergeeva, S. Calles, K. Schorb, A. Börger, C. Roth, and P. Heitjans, *Inhomogeneous degradation of graphite anodes in automotive lithium ion batteries under low-temperature pulse cycling conditions.* Journal of Power Sources, 2016. **307**: p. 806-814.
31. Liu, P., R. Ross, and A. Newman, *Long-range, low-cost electric vehicles enabled by robust energy storage.* MRS Energy & Sustainability, 2015. **2**.
32. Nykvist, B. and M. Nilsson, *Rapidly falling costs of battery packs for electric vehicles.* Nature Clim. Change, 2015. **5**(4): p. 329-332.
33. Simpson, A.P. and A.E. Lutz, *Exergy analysis of hydrogen production via steam methane reforming.* International Journal of Hydrogen Energy, 2007. **32**(18): p. 4811-4820.
34. *TOYOTA COROLLA 2014-2017*. 2017 [cited 2017 2/2/2017]; Available from: http://rightcar.govt.nz/vehicle-detail.html?q=g33761&bc=1|40||2|1254||&keywords=Toyota%20COROLLA&Make=Toyota&Model=COROLLA&selected=g33761.
35. Mazloomi, K., N.B. Sulaiman, and H. Moayedi, *Electrical efficiency of electrolytic hydrogen production.* International Journal of Electrochemical Science, 2012. **7**(4): p. 3314-3326.

36. Bossel, U., *Does a Hydrogen Economy Make Sense?* Proceedings of the IEEE, 2006. **94**(10): p. 1826-1837.
37. Pellow, M.A., C.J.M. Emmott, C.J. Barnhart, and S.M. Benson, *Hydrogen or batteries for grid storage? A net energy analysis.* Energy Environ. Sci, 2015. **8**(7): p. 1938-1952.
38. *Central versus Distributed Hydrogen Production*. 2017 [cited 2017 2/2/2107]; Available from: https://energy.gov/eere/fuelcells/central-versus-distributed-hydrogen-production.
39. Page, S. and S. Krumdieck, *System-level energy efficiency is the greatest barrier to development of the hydrogen economy.* Energy Policy, 2009. **37**(9): p. 3325-3335.
40. Ellingsen, L.A.W., B. Singh, and A.H. Stromman, *The size and range effect: lifecycle greenhouse gas emissions of electric vehicles.* ENVIRONMENTAL RESEARCH LETTERS, 2016. **11**(5).
41. Kelly, G., *History and potential of renewable energy development in New Zealand.* Renewable and Sustainable Energy Reviews, 2011. **15**(5): p. 2501-2509.
42. Miotti, M., J. Hofer, and C. Bauer, *Integrated environmental and economic assessment of current and future fuel cell vehicles.* The International Journal of Life Cycle Assessment, 2017. **22**(1): p. 94-110.
43. Lemon, S. and A. Miller, *Electric vehicles in New Zealand: from passenger to driver? Wellington, New Zealand: a National Energy Research Institute invited white paper, May 2013*, 2013, University of Canterbury. Electric Power Engineering Centre - Report.
44. Brown, S., D. Pyke, and P. Steenhof, *Electric vehicles: The role and importance of standards in an emerging market.* Energy Policy, 2010. **38**(7): p. 3797-3806.