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Analysis of hydrogen fuel cell and battery efficiency

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Introduction

The electric sector is going under a major transformation to foster the ability to absorb and distribute efficiently the increasing number of renewable capacity connected to the grid. This means that renewable electrification can assist other sectors to decarbonise fast and on a large scale. The share of electric motors systems is projected to grow from the current 9% (Melroy et al., 2018) to around 30% (Waide & Brunner, 2011) of energy end-use. Those figures are significantly affecting the motor system numbers which are implicated into one of the two major decarbonisation options involving electrification, electric vehicles (EVs).

The transition towards a world free of carbon emissions will determine the future of this generation. The scale required for the energy transition is massive and affects every sector of the economy. Except electricity, hydrogen produced from renewable energy sources might be an alternative if cost effective and efficient production technologies can be developed.

As the world accelerating its effort to reduce – and even eliminate – the use of fossil fuels from the energy sector, electric vehicles have seen an incredible development over the last 5 years. The first 8 months of 2018, more than 1 million electric vehicles were sold around the world; while 2017 it took 11 months to reach that threshold (Insideevs, 2018). Despite there are many available brands, there are only two choices when it comes to powering electric vehicles: fuel cells or batteries. Both hydrogen and electricity for batteries can be produced from renewable sources. Japan has announces its intention to support and hydrogen and pledged to introduce 160 hydrogen stations and 40,000 fuel-cell vehicles by March 2021 (Tajitsu & Tsukimori, 2018). At first sight, hydrogen has all the benefits to replace fossil fuels. Compressed hydrogen energy per unit mass of nearly 40,000 Wh/Kg (*Hydrogen Fuel Cell Engines MODULE 1: HYDROGEN PROPERTIES CONTENTS*, 2001). Lithium ion batteries are able of achieving of 260 Wh/Kg, which is 151 energy per kg for hydrogen. Because of its energy density and its lightweight, hydrogen is being able to provide extended range without adding significant weight, which is a significant barrier of incorporating into aviation industry.

Hydrogen and battery efficiency comparison

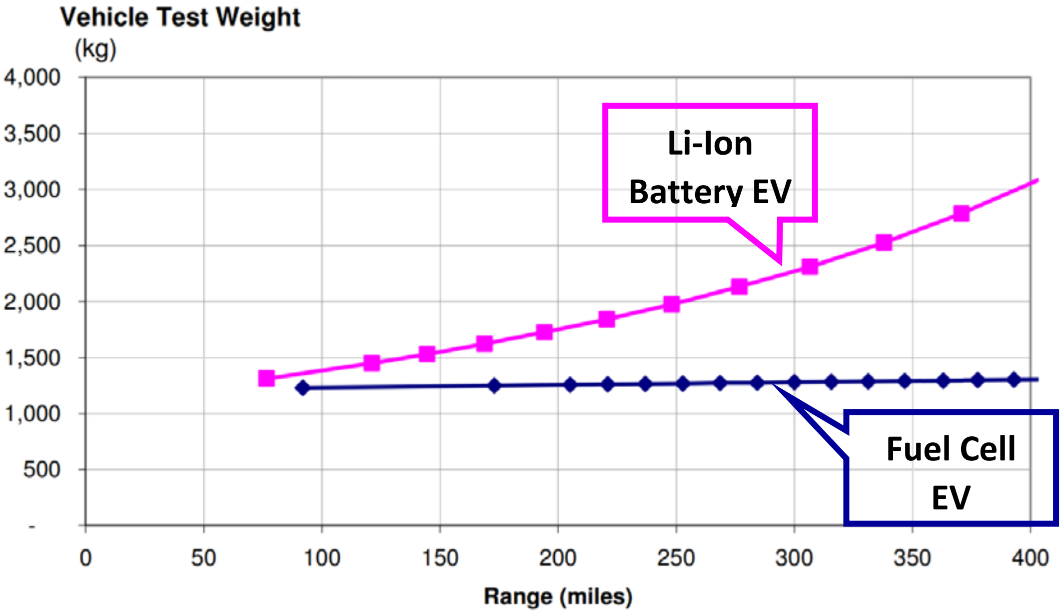

Figure 1: Calculated weight of fuel cell electric vehicles and battery electric vehicles as a function of the vehicle range. (Thomas, 2009)

Each kilogram of battery weight to increase range requires extra structural weight, higher torque motor, heavier brakes, and in turn more batteries to carry the extra mass. The weight compounding limits the vehicle range until a new improvement in the battery development improves the energy density per Kg. For hydrogen fuel cell vehicles, the weight compounding in not an issue. In addition, refuelling of the vehicle takes much less time with hydrogen, compared with recharging.

Fuel Cell Vehicle (FCV) Efficiency

Hydrogen requires more energy to produce and it usually found in water, hydrocarbons (such as methane) and other organic material. The biggest challenge which prevents from being used as an energy storage mechanism comes from being able to efficiently extracted from the previous mentioned compounds. One process to extra the hydrogen comes from a method called "steam-methane reforming reaction[1]". Despite it is the most common method for industrial production of hydrogen, it requires a lot of energy for heat, which results to high inefficiency.

Another method to produce hydrogen is "electrolysis". While the energy that requires for that process can be generated by renewables sources, it requires more energy input than steam reforming and it ends up of losing 30% of energy from the original energy input from the renewables (Arnold, 2017). A slightly more efficient method of producing hydrogen is "Proton Exchange Membrane" (PEM) electrolysis with a loss of only 18% (S Badwal S Giddey F T Ciacchi, 2006).

Additional, there is more energy loss from the transport and storage of the produced hydrogen. Hydrogen has low density in gas and liquid format, so to achieve sufficient energy density we have to increase its actual density. The most efficient method is to compress the hydrogen to 680 atm but that requires about 13% of the total energy content of the hydrogen itself (Bossel & Eliasson, 2009).

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[1] Steam reforming is a method for producing hydrogen, carbon monoxide, or other useful products from hydrocarbon fuels such as natural gas. This is achieved in a processing device called a reformer, which reacts steam at high temperature with the fossil fuel.

Alternatively, the hydrogen can be liquefied cryogenically but with an efficient loss of 40% (Makridis, n.d.).

After the production and storage of hydrogen, a viable hydrogen infrastructure requires that hydrogen can be delivered from the origin of production to the end point of use. The production site of the hydrogen can have a significant impact on the cost and the delivery. A centrally located facility, capable of producing large amounts of hydrogen, can produce in lower prices but it cost more to deliver the hydrogen because the end point of use is far away. A distributed production facility can produce hydrogen on the place of demand with low delivery cost. However, the cost to produce is higher because the production volume is less. Due to the current and tested infrastructure of delivering energy through pipes, we have to assume that the hydrogen would be transferred by truck and pipelines where the energy losses can range from 10% to 40% (Interstate Natural Gas Association of America, 2010).

Another reason why efficiency is reduced by using hydrogen is the tank-to-wheel conversation efficiency. For hydrogen fuel vehicles, the hydrogen in the tank must be reconverted into electric power, which is done through fuel cell. According to the U.S. Department of Energy, the fuel cell technology has the potential of achieving 60% of efficiency, with most of the rest of the energy lost as heat (U.S. Department of Energy, 2011). However, in order to provide more clarity on this figure, this paper will use 47% as the efficiency of the PEM fuel cell (Pellow, Emmott, Barnhart, & Benson, 2015).

Battery Efficiency

Lithium Ion batteries have seen extensive development for the last 20 years in response for the increase in electric vehicle sales. The energy density of Lithium Ion batteries has nearly doubled between the periods of the mid-1990s to the mid-2000s (Thangavelu & Chau, 2013).

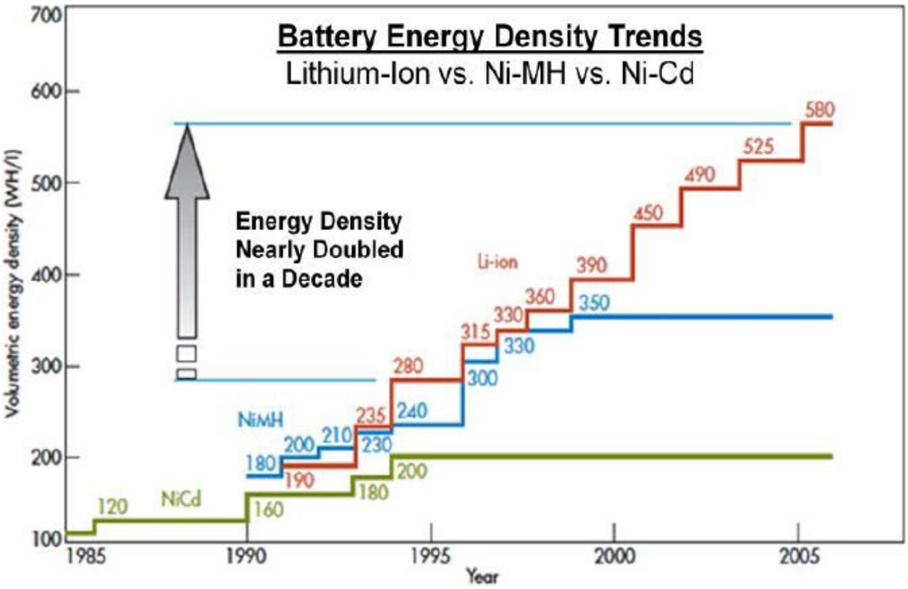

Figure 2: Improvements in Lithium-Ion battery technology has allowed it to see substantial improvements in energy density.

In the case that the energy used to recharge batteries comes from renewable sources, we have to consider the transmission losses to the grid. Using the EU for transmission and distribution losses, the average value is 6% (OECD/IEA, 2014). In addition, the charging infrastructure has an efficiency loss of only 1% (M., 2014).

Like hydrogen fuel cell, batteries have inefficiencies and losses. The grid provides AC power while the batteries store the power in DC. For the conversion, there is a need of a charger with a peak efficiency of 95% (Guépratte, Jeannin, Frey, & Stephan, 2009).In addition, due to the fact that most of the electric vehicles are using AC motors, an inverter is needed. The peak efficiency of a high quality inverter can be close to 95% (Fedkin & Dutton, n.d.). Finally, Lithium Ion batteries can lose energy due to leakages. An estimate for the charging efficiency can be close to 90% (Toman, Cipin, Cervinka, Vorel, & Prochazka, 2016).

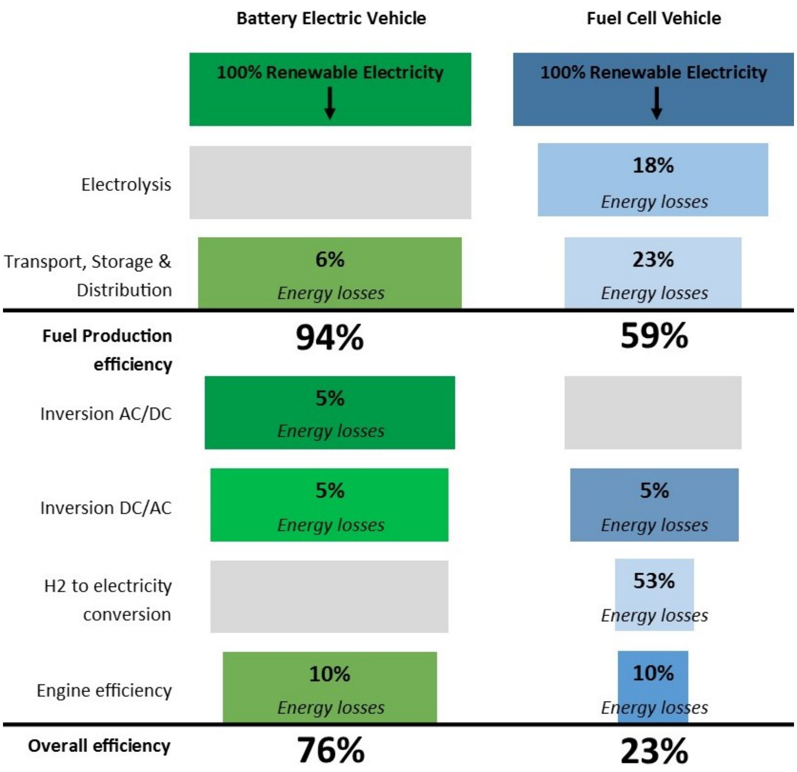

Figure 3: Comparison of the efficiency of two types of power-trains

According to the best-case scenario of having high efficiency rates across the whole procedure, battery electric vehicles provide the most efficient solution to power a vehicle. So, despite the fact that the fuel cell vehicle might be able to go further with full tank of hydrogen compared to a battery powered, the cost that is needed to fully charge the tank is higher due to energy losses and the inefficiencies. The cost per kilometre is a little more than 3 times greater for hydrogen.

Additional costs will affect further the price per kilometre like the cost of the construction of the facility and the profit of the hydrogen station. At the moment, the above mentioned energy losses and inefficiencies are driving the market where the majority of investment and research is forward to battery electric vehicles.

Table 1: Average Electricity Price on EU is 0.20 € (“Electricity price statistics - Statistics Explained,” n.d.)*, Hydrogen price/Km: 9.5 €* (Kolb & Siegemund, 2017)

	Tesla Model 3 (75kWh)	**Toyota Mirai**
Price to fully charge or fill	15 €	47.5 €
Range (km)	499	502
Price/km	0.030 €	0.095 €

Market Analysis

On a survey contacted on 2017 found that, 62% (KPMG, 2017) of automotive executives believe battery-powered vehicles will fail, with hydrogen offering the true breakthrough for electric mobility. The executives argued that the development and installation of a brand new infrastructure will take time and the recharging time it is required for the battery will be an obstacle to mass acceptance of electric mobility.

However, the market for the last 5 years has been driven by significant increase in the sales of plug-in sales due to its significant overall efficiency and incentives by the governments. The worldwide plug-in vehicles sales are increasing with an average of 50% per year (Table 2) while the sales of hydrogen fuel cell vehicles from 2013 until end of 2017 were 6,364 (Research and Markets, 2018).

Table 2: Plug-in sales growth compared to previous year.

	2015	2016	2017	2018 (November)
Worldwide	71.73%	41.29%	57.83%	39.67%
Europe	94.54%	15.10%	39.93%	15.27%
USA	-5.24%	36.49%	25.57%	56.57%

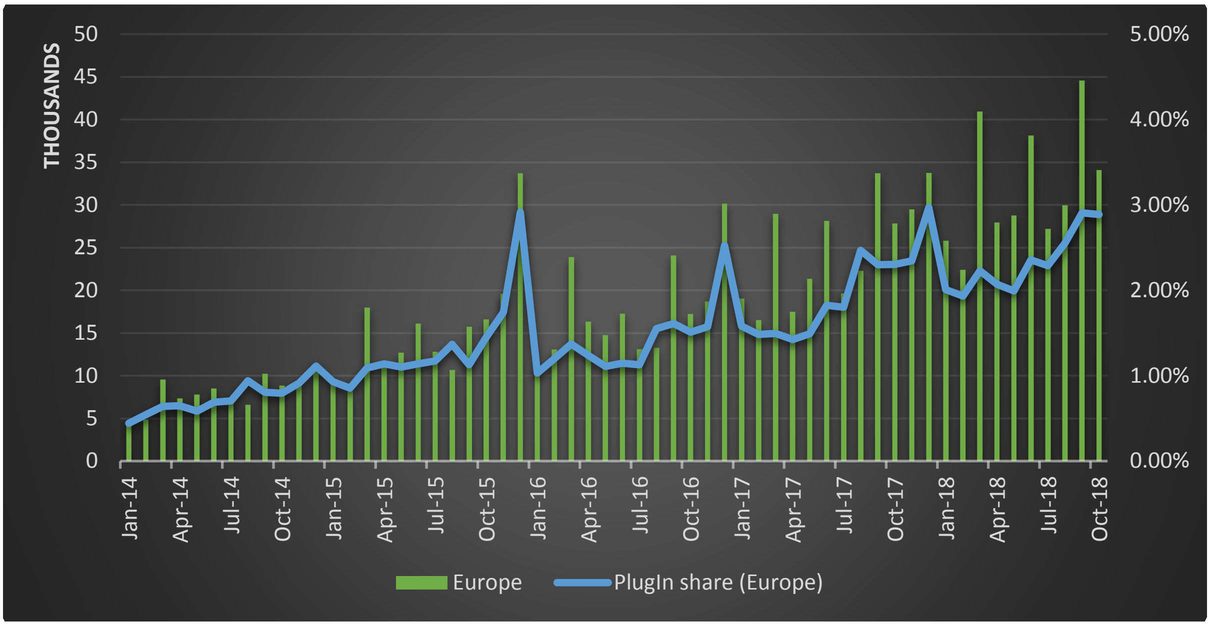

Figure 4: Europe Plug-In Vehicle Sales and its market share.

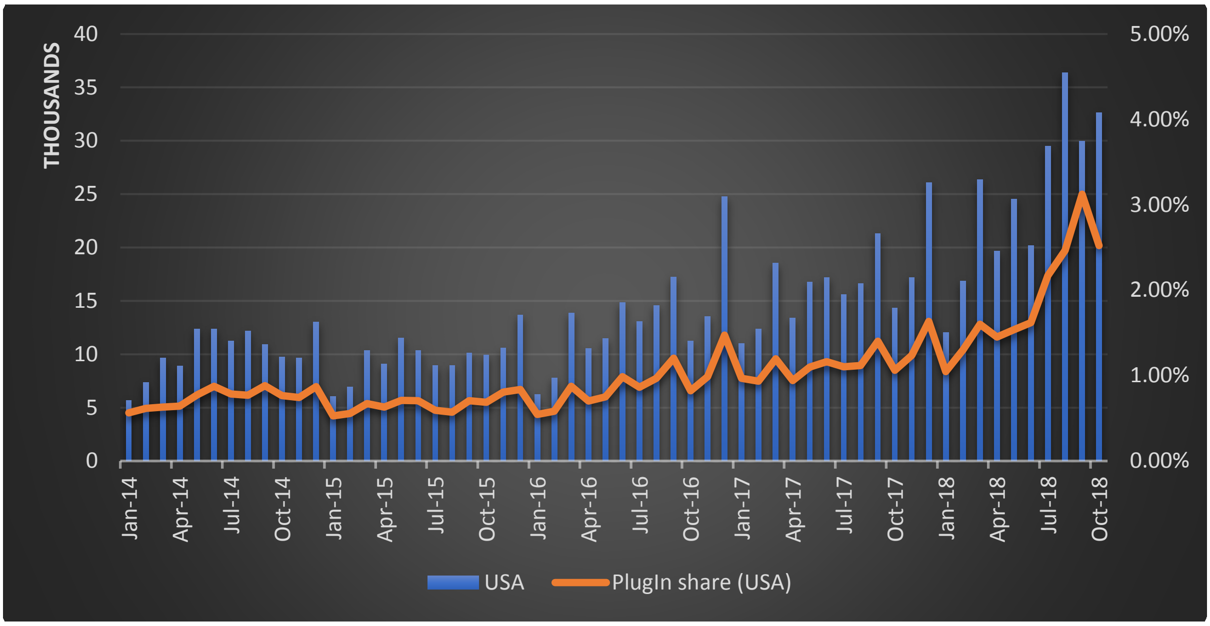

Figure 5: USA Plug-In Vehicle Sales its market share.

Conclusion

Passenger cars driven by electric motors (EVs) have higher well-to-wheel efficiency than cars with an internal combustion engine (ICE) powered by fossil fuels. Concerns about battery capacity and range provide a technological incentive to further increase energy efficiency. The same is true for electric buses and trucks. However, EV motor efficiency depends on the load profile and system boundaries, which complicates how this is evaluated.

There is a potential for hydrogen fuel cells to successfully implemented to long-haul lorries, train, and ambulances that would benefit from longer driving ranges and the development of infrastructure could be easily deployed in order to fuel up to their bases. Nevertheless, based on the current methods of producing, storing and converting hydrogen to electricity, the inefficiencies would limit the increase of share to the vehicle market.

The electric vehicle sales growth will continue with a greater pace as long as the battery cost is declining and the energy density is being improving. Significant innovations in battery chemistry will be required to maintain the growth and supply challenges with cobalt must be solved.

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