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Batteries: Higher energy density than gasoline?

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ABSTRACT

The energy density of batteries is two orders of magnitude below that of liquid fuels. However, this information alone cannot be used to compare batteries to liquid fuels for automobile energy storage media. Because electric motors have a higher energy conversion efficiency and lower mass than combustion engines, they can provide a higher *deliverable mechanical* energy density than internal combustion for most transportation applications.

1. Introduction

Policy makers are comparing gasoline alternatives in response to peak oil, pollution, greenhouse gas (GHG) emissions, and foreign energy dependence. Compared to alternatives including biofuels, and hydrogen fuel cell technologies, battery electric vehicles (BEVs) have superior technical viability, performance, existing infrastructure, and efficiency. For instance, the present California grid is capable of charging the majority of the state's cars (if electric) during off peak hours with less cost (Lemoine et al., 2008) and GHG emissions (Unnasch and Browning, 2000) than would powering the same number of cars with gasoline or biofuels.

Yet, electric travel is often dismissed (Borenstein, 2008; Chu, 2008) because the low energy density of batteries (compared to liquid fuels) is inappropriately applied to the mechanical energy needs of vehicles (Fig. 1). Stored potential energy must be transformed into mechanical energy to be of use to the vehicle, and electric motors convert energy many times more efficiently than comparable internal combustion engines (ICEs). Our model[1] compares commercially available (year 2008) electric and ICE vehicles yielding a higher effective energy density for electric vehicles for the majority of daily transportation needs: those not requiring long-range travel without recharge.

Fig. 1 compares the caloric energy densities of energy storage media, the mass energy density[2] calculated as

$$\rho_c = \frac{U_f}{m_f}, \tag{1}$$

where U_f is the stored energy (lower heating value of the fuel or battery energy) and m_f is the mass of the fuel or battery. Battery energy density is smaller than that of liquid fuels by two orders of magnitude. However, the relevant energy is not *gross caloric energy stored*, but rather *net mechanical energy delivered to the wheels*, ηU_f, where η is the "stored energy to mechanical work" conversion efficiency and includes contributions from regenerative brakes as well as frictional losses in the transmission. Additionally, a motor and transmission is necessary to convert the stored energy to mechanical work, so the relevant mass should include the drive train mass, m_d: the motor or engine, electrical control and power converters, transmission, exhaust, and all associated parts and fluids. We introduce an *effective* energy density:

$$\rho_E = \frac{\eta U_f}{m_f + m_d}, \tag{2}$$

the ratio of stored energy delivered to the wheels divided by the mass of the fuel and drive train. This effective energy density (Fig. 2) depends on the amount of stored energy on board, which determines the maximum range that the vehicle can drive on one "fill up". As the driving range is increased from zero (a car with an empty gasoline tank, or no batteries) to infinity, ρ_E increases from zero, asymptotically approaching $\eta\rho_c$ for infinite range. While this asymptotic value is greater for liquid fuels, effective energy density for shorter ranges is higher for electric storage because of the lower mass of electric motors and drive trains. The "crossover range" (below which electric power systems have a higher energy density than gasoline) for lithium ion batteries is about 120 miles (190 km).

The crossover range varies with automobile. ICE vehicles that are more overpowered (large trucks and sports cars) have heavier engines and lower efficiency resulting in a crossover range of greater distance. Economy and hybrid cars (see Fig. 3) both have

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[1] Available on supplementary material.

[2] We neglect the volumetric energy density, as the volume of autoparts is subjective, and the results will be similar to those relating to mass energy density.

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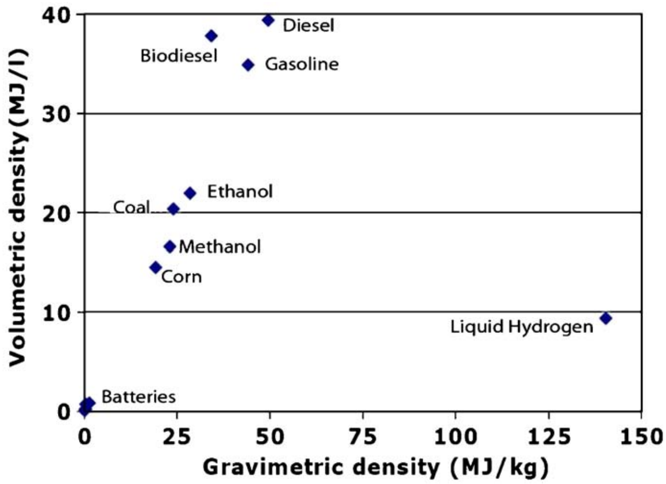

Fig. 1. Caloric energy density of batteries and liquid fuels, (Chu, 2008) according to Eq. (1).

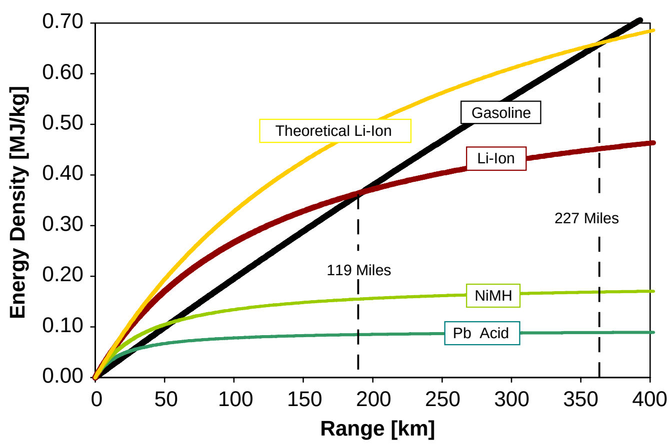

Fig. 2. Effective energy density for a sports car according to Eq. (2). Although gasoline drive systems (black) reach much higher energy densities for long-range applications, electric drives have higher energy density for shorter-range travel. Batteries shown: present lithium ion (red), theoretical maximum of lithium ion (yellow), nickel metal hydride (green), and lead acid (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

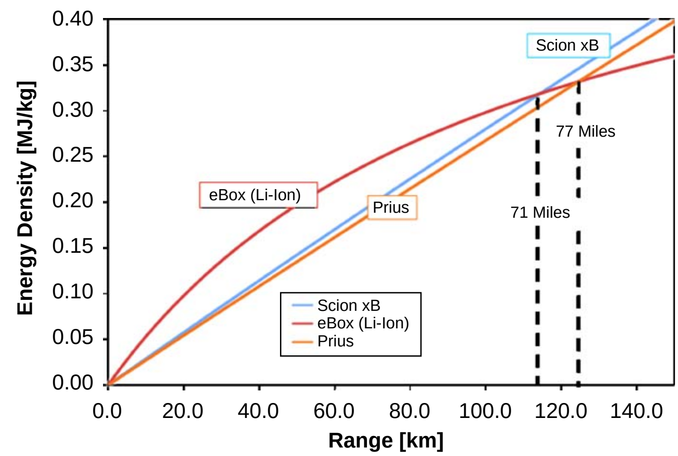

Fig. 3. Effective energy density for an economy and hybrid car according to Eq. (2). Scion xB is the gasoline car and it follows the trend for a gasoline car as Fig. 2. The hybrid car is the Prius, which ultimately reaches a higher energy density than the BEV but due to the extra mass of having both an electric and gasoline drive, the crossover range is somewhat higher than for the ICE Scion.

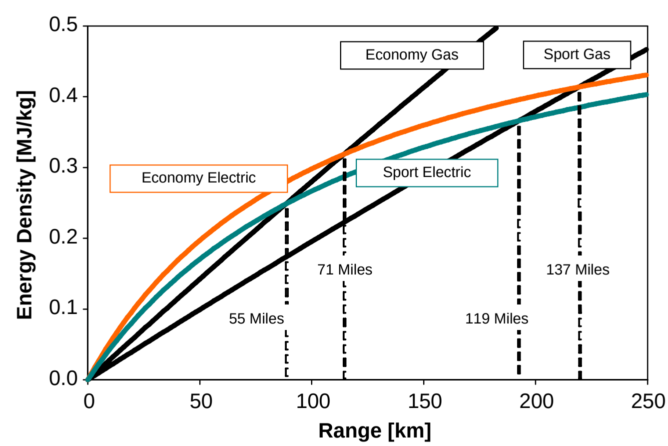

Fig. 4. Effective energy density ranges for gasoline and electric vehicles.

crossover ranges between 70 miles (115 km) and 80 miles (130 km). Hybrids have a greater efficiency than regular economy cars, but have a slightly lower effective energy density due to the extra mass of carrying both an ICE and electric motor.

Increasing range presents no challenge for ICE travel, amounting to increasing the size of the gas tank. However, increasing the range of the BEVs requires more batteries, considerably increasing mass. Conversely, lowering range allows the BEV to have a greater energy to mass ratio compared to ICEs. Fig. 4 indicates that even the lower crossover range of the economy cars exceeds the needs of the vast majority of American trips—especially if this range is for one-way transportation, possible with charging capability away from home (Fig. 5).

2. Methodology

We compared similar vehicles (see footnote 1): The Tesla Roadster (BEV) is compared to the Lotus Elise (ICE). These two

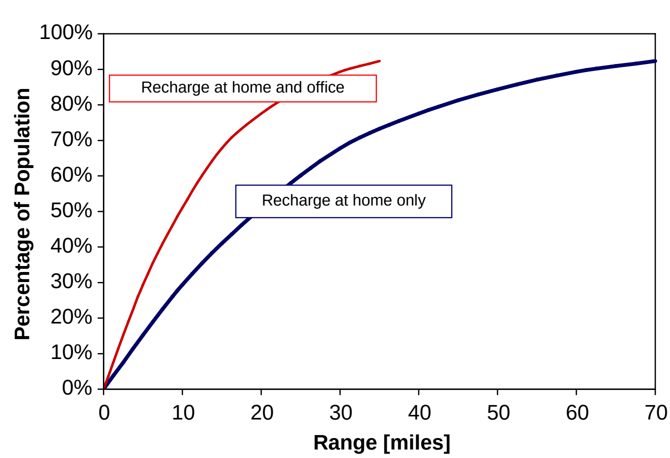

Fig. 5. Portion of American automobile travel needs satisfied as a function of automobile range (DOT, 2003). If cars can be charged at away-from-home destinations, cars with half the full range satisfy transportation needs (red).

sports cars have nearly identical bodies and performance. The Ebox (BEV), Scion (ICE), and Prius (hybrid), were compared for economy vehicles. The Ebox is made by retrofitting a Scion with an electric motor, so these two vehicles are mechanically identical. The Prius is somewhat different, but has similar performance and drag coefficient to the Scion and Ebox.

Because efficiency is strongly dependent on driving style, relative efficiencies were found by comparing EPA mileage estimates for each BEV to the corresponding ICE vehicle (see our calculations on online supplemental material). These ratios alone are sufficient to compare the vehicles. In order to arrive at approximate *absolute* energy densities we used published electric motor (90%) and battery storage (86%) efficiencies, and assumed a 10% contribution from regenerative brakes. The absolute energy densities of the ICE vehicles were found by scaling the absolute efficiency of the corresponding electric vehicle with the EPA efficiency ratio. So deviations in the absolute efficiencies of the electrical processes will not affect the comparison of the two kinds of vehicles.

3. Power density qualification

Arbitrarily short-range electric vehicles are not possible because of the limited Li ion battery *power density* of about 1 kW/kg. The power requirements for the Tesla Roadster require a 200 kg battery, or a minimum range of 125 km (80 miles). Additionally, in a low state of charge, the battery experiences enhanced degradation under maximum power load, which can be prevented by reducing delivered engine power when the battery is in a low state of charge. Both the Tesla and Ebox have extremely high acceleration. Lower power BEVs, corresponding to present economy cars, will be able to have smaller battery packs, range, mass, and cost.

4. Discussion

In the technical and societal transition we have begun, we have the opportunity to rethink how we use energy, and in particular how we use energy for transportation. Present ICE vehicles are the standard each new technology is judged against. If a new technology presents an added inconvenience (such as shorter range), it is found untenable. However, ICE-related inconveniences (oil changes, visits to the gas station, higher probability of breakdown, etc.) are accepted as given. Moreover, ground transportation as we know it, is likely to change because the related "inconveniences" of fuel availability, emissions, and political consequences will become significant. We can now ask ourselves, "what do we need?", "what are the costs?", and "what are we willing to do?". Electrical travel distinguishes itself as an immediate answer today in terms of technology, performance, and infrastructure, and is presently the most appropriate technology for the vast majority of our ground transportation needs. Infrequent, long-distance travel needs can be met with rental cars, public transport, and (in many families) a second car. Most automobile trips are less than 20 miles. A 100-mile BEV, will outperform the comparable ICE (higher power/mass ratio), and be cheaper (lifecycle costs including fuel) (Werber et al., 2009). While the BEV is already ideal for many Americans, as the charging infrastructure and battery technology improve, the BEV will be the most appropriate vehicle for an ever-increasing portion of the population.

Acknowledgements

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Appendix A. Supplementary materials

The online version of this article contains additional supplementary data. Please visit doi:10.1016/j.enpol.2009.02.030

References

Borenstein, 2008. Cost, Conflict and Climate: US Challenges in the World Oil Market. In: Borenstein, S. (Ed.), Center for the Study of Energy Markets Working Paper #177, University of California Energy Institute, Revised June 2008.

Chu, A., 2008. American physical society physics of sustainable energy at UC, Berkeley, March 1–2, 2008 opening talk by Steve Chu, director of Lawrence Berkeley National Laboratory; associated paper: (Chu, S., Chapter 1, Science of Photons to Fuels). In: Hafemeister, D., Levi, B., Levine, M., Schwartz, P. (Eds.), Physics of Sustainabile Energy. American Institute of Physics Press, College Park, MD.

DOT, 2003. Source: DOT OmniStats, Vol. 3(4) October 2003.

Lemoine, D.M., Kammen, D.M., Farrell, A.E., 2008. Eviron. Res. Lett. 3, 014003.

Unnasch, Stefan, Browning, Louis., CARB, May 2000, Fuel Cycle Energy Conversion Efficiency Analysis.

Werber, M., Fischer, M., Schwartz, P.V., 2009. Batteries: Lower Cost than Gasoline? Energy Policy, in press, doi:10.1016/j.enpol.2009.02.045.