Why Hydrogen?

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ABSTRACT

Modern civilization has grown reliant on plentiful, cheap and convenient energy from fossil fuels. Now, the reality of climate change has compelled us to reconsider how we both produce and use energy. The standardization provided by electricity as a clean carrier has proven ideal for stationary applications and has greatly improved our standard of living over the past century. When it comes to transportation, however, petroleum has won the battle for hearts and minds with its portability, concentrated form and relatively low cost. To make impactful change in transportation, we must provide choices that allow people to retain their sense of freedom and security while also reducing the impact on our environment. This paper offers some perspectives on oil and the challenges of creating an alternative for transportation that can compete with its many benefits.

Keywords: hydrogen, fuel cell, electric vehicle, mobility

1 CONTEXT

The year is 1881. Horses move us and our things from place to place. Labor comes from manpower and factories are clustered near flowing water to drive basic machines. Lighting on city streets and in our homes is fueled by oil, wax and gas with the ever-present hazards of fire and soot. New-fangled electric arc lights have begun to emerge for outdoor use and Thomas Edison, having just perfected his incandescent bulb, has unveiled his dream of clean, safe light for everyone [1]. The electric age has begun.

While Edison's light bulb got the press, it was useless without an electricity grid to power it. He and his contemporaries had to create and build the infrastructure that would make this new clean-energy carrier accessible and convenient for people to use. It's hard to imagine today how overwhelming these challenges were. Electricity was seen by people as a "mysterious fluid." Yet today we take all this for granted and electricity has proven to be an ideal energy form for our stationary needs. It has automated our lives and enabled entire industries that were unfathomable even to the visionaries who built it. But what about mobility?

Petroleum has come to dominate transportation. Figure 1 shows how transportation stands in stark contrast to all stationary uses of energy. There are many diverse sources of energy for our stationary power needs and contributions from renewable sources are growing rapidly. This is possible because the myriad uses we have for stationary power are connected to those diverse sources through a standardized carrier. It is interesting that in the early 1900s as many as one-third of cars on American roads were electric, but by the 1930s they were all but gone [3]. So what happened? Why isn't transportation still electrically powered today?

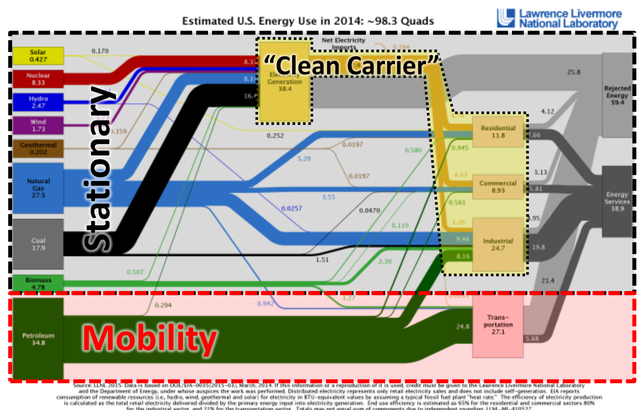

Figure 1 – Estimated U.S. Energy Use in 2014 [2]

2 CONVENIENCE

The introduction of gasoline in the early 20th century gave drivers something electricity couldn't: the freedom to travel long distances and refuel quickly. This saved people time and the convenience of oil became central to the economics and experience of mobility. Easy access to refueling points and 3-to-5 minute fill-ups gave drivers the perception of "infinite" range and freedom.

Merriam-Webster's online dictionary defines convenience as: *the quality or state of being available, easy to use, useful, or helpful*. [4] Something is convenient if it fits easily into our plans. If a vehicle is ready for us to use when, where and how we want, it is convenient. Given the choice between otherwise equivalent options, it is reasonable to expect most people to select the more convenient one and perhaps pay more for it.

2.1 Convenience Penalty

On-road vehicle electrification is underway. Many new zero-emissions electric models are being introduced by car manufacturers around the world. As options for electric vehicle powertrains are considered, the most significant impact on customer convenience lies with how the electricity is stored on board and what the customer must do to "recharge" this storage. The two options for pure electric vehicles are: 1) on-board storage using rechargeable batteries, or 2) on-board storage as hydrogen for use with a fuel cell engine. In both cases, as with a gasoline vehicle, users must "recharge" the energy storage "tank" on the vehicle periodically. For battery-electric vehicles (BEV) this means connecting to an electricity source and "charging-up." For gasoline and hydrogen fuel cell vehicles (FCEV) this means refilling the storage tank with a separate, fluid energy "carrier". The time spent "recharging" can, in certain situations, represent an *inconvenience* for the customer. Although there will be times where recharging could be scheduled, say, during periods when the customer didn't want to use their car, it stands to reason that this is not likely to *always* be the case for most users. People use their cars for many different types of trips. Therefore, a majority of people are likely at some point to experience an inconvenience in the use of their car caused by having to recharge or refuel it. We all experience this inconvenience today every time we visit a gas station to fill up. We can define a "Convenience Penalty" (*CP*) as a result of having to recharge one's vehicle as follows:

$$CP \equiv \frac{time\ spent\ charging}{time\ spent\ driving} \tag{1}$$

Equation (1) measures the time an operator wants to be driving, but must recharge in order to continue their trip. This is effectively the user's wait time as a fraction of the user's planned driving time. It applies to any particular "mission", or trip, the user undertakes. It can be thought of as the non-value added time for that particular trip and equations (2) and (3) below are equivalent to equation (1).

$$CP = \frac{rate\ of\ miles\ consumed\ on\ a\ trip}{rate\ of\ miles\ added\ while\ charging} \tag{2}$$

$$CP = \frac{average\ power\ consumed\ on\ a\ trip}{average\ power\ added\ while\ charging} \tag{3}$$

Some obvious characteristics of *CP* are:

- A lower *CP* is better.
- *CP* can be reduced by driving slower, reducing the numerator of (2). This is somewhat artificial, as the absolute time needed to recharge on a "slow" trip remains the same.
- *CP* can be reduced by operating a smaller, lighter or more efficient vehicle, reducing the numerator of (3).
- You can avoid *CP* altogether by keeping the length of your trips below the range of your vehicle in order to schedule a charge. Short trips to and from work in a BEV are one example if charging stations are available at work. This specific example would even represent a net convenience *improvement* over gasoline because the user would never have to visit a gas station, so long as they only use the vehicle for commuting.
- The probability of experiencing *CP* can be reduced by increasing the range of the vehicle, increasing the denominator of (1).
- *CP* can be reduced by increasing the rate of charging the vehicle, decreasing the numerator of (1) and increasing the denominator of both (2) and (3).

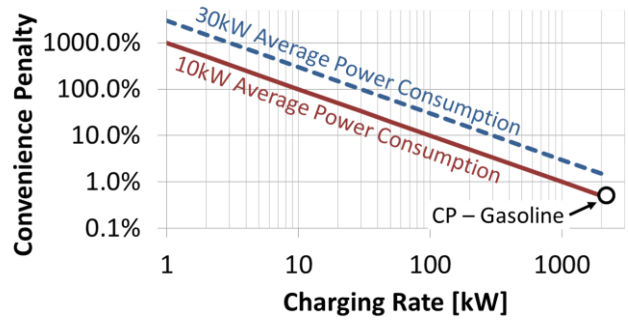

Figure 2 – *CP* vs. Charge Rate for Two Example Vehicles

2.2 Charging Rates

As shown in Figure 2, *CP* can be reduced by increasing the "charging rate" for the vehicle. Below are sample calculations comparing the required rate for three different vehicle configurations based on **312 miles of driving replenished in 3 minutes** (present range of Toyota's Mirai FCEV [7]). Assuming an average speed over the 312 miles of 30mph, this represents a *CP* of less than **1%**. This means that less than 1% of the time you want to be driving you are "inconvenienced" by having to refuel/recharge.

Gasoline car with fuel economy of 35.0 miles per gallon.
➔ Consumes 8.9 gallons of gasoline (129MJ/gal) [5]; refill in 3 minutes. Equivalent energy flow of **6.4MW** into the fuel tank.
Toyota Mirai with fuel economy of 66.0 miles per kg [6].
➔ Consumes 4.7 kg of hydrogen [120MJ/kg] [5]; refill in 3 minutes. Equivalent energy flow of **3.1MW** into the fuel tank.
Tesla Model-S with fuel economy of 2.8 miles per kWh [6].
➔ Consumes 111kWh of electricity; refill in 3 minutes. Equivalent energy flow of **2.2MW** into the battery.

Refilling at these rates with gasoline or hydrogen is achievable with existing hose and nozzle technologies. Achieving an electric charge at 2.2MW is challenging. It represents a 20C charging rate for the 111kWh battery in the example. The most powerful existing BEV chargers are on Tesla's "Supercharger" network. These operate at an advertised power of approximately 120kW [7]. At this rate, 111kWh takes 55 minutes to fill, resulting in a *CP* of 9%. Drivers utilizing this charger must wait approximately 18 times as long to fill up as drivers of gasoline cars. A secondary implication of charging this slowly is that, to have the same probability of queuing as a gasoline network, 18 times more recharge posts than gasoline nozzles would need to be available.

While future batteries may be able to endure a 20C charge rate, the real impediment to charging a BEV this quickly is the infrastructure. The power level to achieve *CP* less than 1% is on the order of that carried by high voltage transmission lines. To carry such power with raw electricity requires very large, stiff conductors which typically operate at many thousands of volts. These factors would make it difficult, if not impossible, for a human to connect their car to such a charger. It is not likely that such charging rates will ever be practical, especially when considering impact a 3-minute burst of 2.2MW would have on the local electrical distribution grid. The problem isn't the battery. The problem is the energy carrier itself.

3 CUSTOMER CHOICE

How essential is a rapid recharge? Statistics on driving habits show that many existing BEVs satisfy the majority of people's average weekday needs [8].

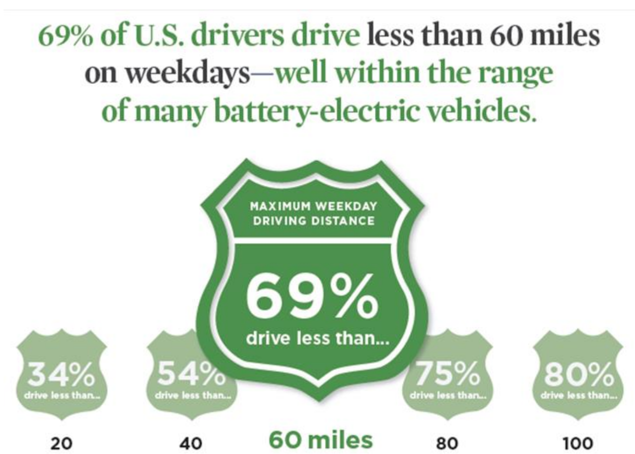

Figure 3 – Union of Concerned Scientists EV Statistics [8]

These statistics are compelling. Nearly three-quarters of the U.S. population could be driving an available BEV today. The problem is that most people don't make car-buying decisions based on how they use their car on weekdays. A car is one of the most significant purchases we make in our life and we expect it to satisfy all of our needs, on weekdays, on weekends and especially in an emergency. While you could rent a gasoline car for weekend or vacation trips, this represents another type of inconvenience, one that might be acceptable to innovators and early adopters, but not likely to the majority of drivers. To make a substantive impact on emissions for the transportation sector we must reach the majority.

A car purchase is an emotional decision. Beyond the financial factors, we count on our cars to move us around safely, securely and on-demand. With a gasoline car, the consequence of running out of gas is usually a call to roadside assistance and a quick trip to the gas station. "Range anxiety" is a term that describes the emotional impact BEV drivers experience due to short range, long charge time and uncertain or highly variable state of charge for the battery in their car. This is, in effect, worry about being inconvenienced or worse. The possibility, even if unlikely, of your family becoming suddenly stranded, having to wait hours to charge up their car in an unknown place goes deeper than anxiety. Behavioral Economists refer to this as the Possibility Effect, which causes people to become risk-averse [9]. Given the choice, most buyers are likely to stick with the status-quo, gasoline-powered car—that is, unless they are given the choice of a clean car with the convenience of gasoline.

4 FORK LIFT MODEL

Electric fork lift trucks are an ideal model to study the factors affecting choice and expectations for electric vehicles. They have been around for more than 100 years and there is no larger or older population of electric vehicles on the planet. Over one million lift trucks were sold worldwide in 2014 and more than half of these were electric. [10] Productivity is everything in material handling and productivity in this business is analogous to convenience in our daily lives. Labor time can account for more than half the cost of moving goods around a warehouse, leading fork lift fleet managers to try a wide variety of strategies to improve productivity with electric trucks including: park and charge; fast-charge; opportunity-charge; and battery swapping. With each of these approaches comes truck down-time, forced time when the asset is unproductive while its energy supply is replenished. Down time is the convenience penalty—time the truck could be working but can't. Approaches like fast-charge and opportunity-charge attempt to overcome *CP* through scheduling, but this relies heavily on operator discipline and fleet management. If one driver forgets to plug in their truck on break, the consequence can be a stranded truck that needs to be towed back to a charger. On the surface it appears that the battery is the problem, but the real issue is with the energy carrier. Raw electrons are simply inconvenient for applications where the function is to move things around.

As our cars become more and more automated and the use of ride-share services increases, it's tempting to imagine that the issues of *CP* will go away. While riders in these cases will be more isolated from convenience issues related to energy, the managers of the fleets and operators of the vehicles will not. It becomes an issue of productivity and cost. Incremental assets are needed to serve a given number of passengers the longer vehicles are off the road for charging. As the fork lift industry demonstrates, recharge time is critical to asset utilization. In an effort to reduce these energy management issues, more than 9,000 fuel cell systems powering fork lifts have been deployed in North America as of 2015. [11]

5 SOCIETAL BENEFITS

Hydrogen can be thought of as portable electricity. Hydrogen is everywhere and in almost everything. It's simple and it's clean. Just like raw electricity, it's only a carrier of energy and it can be generated from all the same energy sources. There are also some distinctive renewable pathways to generate hydrogen such as anaerobic digestion, solar-catalysis and thermo-chemical water splitting. Hydrogen can be used with a fuel cell to power an electric vehicle, but unlike raw electricity, hydrogen is transportable. It allows the fuel to be managed separately from the vehicle, which provides substantial infrastructure and production flexibility. With 3-minute fill-ups, the customer experiences the convenience of a traditional fuel, along with the benefits of a clean, electric drivetrain.

Just like Edison's lightbulb, the challenge with electric cars lies in the infrastructure. And just like the grid built for stationary power, it will take substantial investment by society to build a clean-carrier network to support mobility. Hydrogen has the potential to provide a complimentary, parallel network of clean energy, delivering resiliency, redundancy and security to our aging electrical grid. The *portable electric age* could be upon us. Edison didn't invent the smartphone, but his inventions enabled it. What life-changing innovations might come from a totally new form for clean energy?

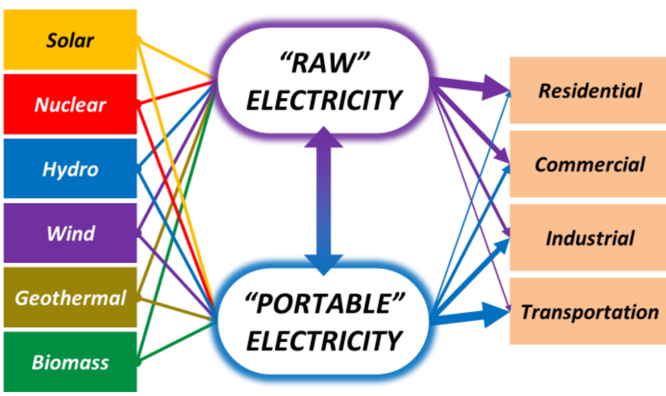

Figure 4 – Resilient, Clean Energy Carrier Network

6 CONCLUSION

People love their cars. Our vehicles provide a high standard of living and have become an essential part of modern life. We have come to expect ever-increasing levels of reliability and convenience in all aspects of our transportation. So when it comes time to purchase a car, only a select few "early adopters" will be willing to forego the comfort and ease of the status quo. For the majority of car-buyers, however, concerns about safety and convenience will dominate their choice.

Transitioning to clean cars is fundamentally a human challenge, not a technological one. Many existing technologies are capable of connecting our cars to renewable energy. Implementing these is easy compared with the challenge of convincing people to change. If people are going to willingly move away from oil, they must have options that do not require compromise. Today, no electric vehicles are more convenient than gasoline. But all that could change with the availability of the right clean energy carrier. We need a clean carrier that standardizes diverse, carbon-neutral energy sources while maintaining convenience for transportation. We need a clean carrier that truly replaces oil.

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