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Thermal Hydrogen: An emissions free hydrocarbon economy

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ABSTRACT

Envisioned below is an energy system named Thermal Hydrogen developed to enable economy-wide decarbonization. Thermal Hydrogen is an energy system where electric and/or heat energy is used to split water (or CO_2) for the utilization of both byproducts: hydrogen as energy storage and pure oxygen as carbon abatement. Important advantages of chemical energy carriers are long term energy storage and extended range for electric vehicles. These minimize the need for the most capital intensive assets of a fully decarbonized energy economy: low carbon power plants and batteries. The pure oxygen preempts the gas separation process of “Carbon Capture and Sequestration” (CCS) and enables hydrocarbons to use simpler, more efficient thermodynamic cycles. Thus, the “externality” of water splitting, pure oxygen, is increasingly competitive hydrocarbons which happen to be emissions free. Methods for engineering economy-wide decarbonization are described below as well as the energy supply, carrier, and distribution options offered by the system.

Introduction

The current “consensus” or accepted vision for deep decarbonization could be described as follows: “Clean up electricity. Electrify everything. Simple.” [1] In other words, electricity is viewed as the only energy carrier required for deep decarbonization. Therefore, to begin this research, I will describe why economy wide decarbonization with electricity as the sole energy carrier results in diminishing returns. The identification of the technical limitations of electricity will help shape the engineering philosophy behind Thermal Hydrogen.

The electric vision: infrequently utilized metal

Due to the limitations of electricity as an energy carrier, it is unlikely that it will be fully decarbonized and then used to provide all energy services. Electricity is not a chemical and it is not storable; it is the movement of electrons—extremely fast, efficient, and does not produce emissions at the point of consumption. However, these technical strengths come with drawbacks: electricity must change energy forms to be stored. For many energy services, economic efficiency yields to a more versatile, chemical energy carrier—hydrocarbons. For example, the modern energy system utilizes the energy

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density and storability of hydrocarbons to provide electricity reliability, range for automobiles, and high temperature heat.

Because electricity is not storable, redundant power plant capacity is required to ensure that demand is supplied reliably. Typically, to meet reliability requirements, power plant capacity must exceed the expected peak demand by ~15%. Even if reliability were not required, "load following" generators with lower utilization rates are required due to the seasonal and diurnal demand for electricity. For example, coal and natural gas combined cycle (NGCC) power plants achieved utilization rates of only ~55% in the United States in 2015 [2]. The overall utilization rate of U.S. power plant capacity in 2015 was ~45% [3].

The cost of underutilized capacity in the modern electricity system is reasonably contained by the low capital costs of unabated hydrocarbon power plants. Unabated hydrocarbon power plants tend to have higher marginal costs and lower capital costs. Decreasing their utilization does not have a dramatic effect on their average costs. For example, if an NGCC power plant reduced its utilization from 100% to 50%, the average cost of the power generated would increase by only ~20%.[1]

However, the cost of underutilized capacity will be exacerbated when low carbon power plants replace unabated hydrocarbon power plants. Marginal (fuel) costs for renewable and nuclear power plants are not appreciable, and hydrocarbon power plants with Carbon Capture and Sequestration (CCS) are also relatively capital intense compared to their unabated counterparts. Therefore, infrequent utilization of increasingly capital intense power plants implies very high average costs as higher fixed capital costs are spread over fewer MWh's.

As a counter-example, lets imagine the utilization of a power plant with no marginal costs (renewables or effectively nuclear) were reduced by 50%. Because there are no marginal costs, reducing the utilization of this plant would increase costs by roughly 100%. Therefore, being competitive under the technically feasible utilization rate isn't all that is required to compete under deep decarbonization. Utilization, which becomes increasingly challenging with decarbonization, is critical for low carbon power plants to maintain competitiveness.

Further exacerbating the issue of low utilization (or redundant electric capacity), the combined seasonal supply of wind and solar energy does not coincide with the seasonal demand for energy services [4,5]. As Fig. 1 shows, wind and solar tend to occur earlier in the year and the demand for various energy services (electricity, transportation, and heat) occurs during opposing seasons. Therefore, complete decarbonization of electricity, particularly with heavy penetration of wind and solar energy, will require either seasonal storage of electricity or seasonal use of low carbon power plant capacity [4].

Many view electro-chemical storage (batteries) as the solution for resolving the issue of decreasing utilization. However, electro-chemical storage is also capital intensive and seasonal use similarly implies very high average costs. If used for diurnal storage, the battery would have the opportunity to perform energy arbitrage 365 times per year, giving it a reasonable chance of justifying its capital costs. However, if a battery is used to shift electricity from spring to fall, it will only perform energy arbitrage once per year, at which point it is not a serious economic option.

Transportation in the electric vision

For transportation, (lithium-ion) batteries are not a pragmatic, let alone perfect, substitute for a chemical energy carrier (hydrocarbons). Lithium is the lightest metallic element with only 3 protons, but it is still a metal, and this creates fundamental technical challenges. Charging a battery requires moving a chemical through an electrolyte to make new chemicals, and the process of making new chemicals limits energy transfer speed. A chemical energy carrier can be refueled orders of magnitude faster because the chemical is simply moved rather than created. Electric charging speed can be increased but at the expense of efficiency, or, at extreme rates, the integrity of the battery.

In addition to the range issue, another formidable challenge of an electro-chemical energy carrier is its low energy density. If the service of transportation is moving weight and volume, then transporting additional weight and volume must necessarily detract from that service.

In Fig. 2 below, I show a relatively well-known chart from EIA quantifying the energy density of chemical fuels and batteries on both a volumetric and mass basis. Generally, every chemical fuel is order(s) of magnitude more dense than batteries. The physical reason is that the energy bonds of hydrocarbons are far more dense than the energy bonds of batteries. In the case of natural gas (methane, CH_4), four electron bonds are stored in a molecule with an atomic mass of 16 (four electron bonds per unit of atomic mass). Electrochemical bonds are inherently less dense. There is just one energy bond per lithium molecule, cathode molecule, and anode molecule.

The weight of batteries does have a significant impact on the overall vehicle weight, and by extension, the efficiency of battery powered transportation. For an exclusive battery-electric vehicle to provide range, excessive weight is required for the battery and for a sturdier, heavier frame to support that battery. This creates a positive feedback loop of decreasing efficiency: the weight of the vehicle decreases efficiency, so more batteries are required, and so on. Consider that the Tesla Model X curb weight is 50% heavier than a compact SUV yet has similar passenger volume [8,9]. In fact, the Model X is so heavy that it cannot legally cross the Brooklyn Bridge and qualifies for the so-called "Hummer Tax Credit" [10,11]. The battery of an electric car might not create much waste heat itself but it does create waste heat through the friction caused by increased rolling resistance.

Many view battery electric vehicles as necessarily more "efficient" than vehicles that use chemical energy carriers. However, the efficiency metric typically used misrepresents the service of transportation as steady state power (kW). As a result, fuel cells vehicles are misinterpreted as being half as efficient as exclusive battery electric vehicles [12]. Transportation service is more complex: it is the act and

[1] Assume \$1000/kW, fixed charge factor of 10%, \$15/kw-year O&M, and marginal costs of \$33/MWh.

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