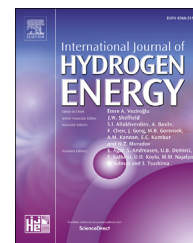


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Thermal Hydrogen: An emissions free hydrocarbon economy



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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 pre-empts 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.

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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, let's 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, CH₄), four electron bonds are stored in a molecule with an atomic mass of 16 (four electron bonds per unit of atomic mass). Electro-chemical 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.

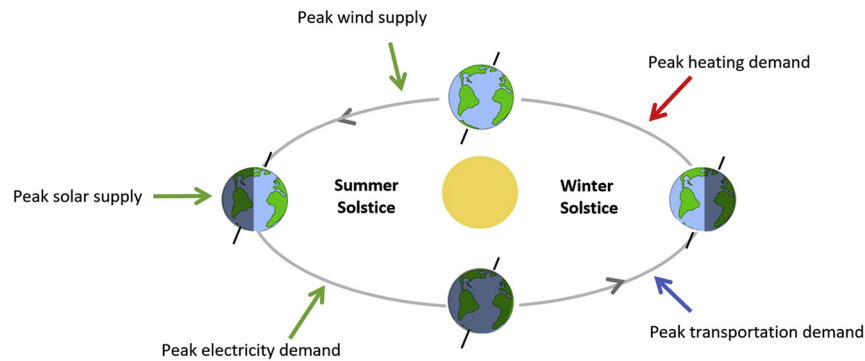


Fig. 1 – General seasonal energy supply and energy service demand patterns from the inland perspective in the northern hemisphere [6].

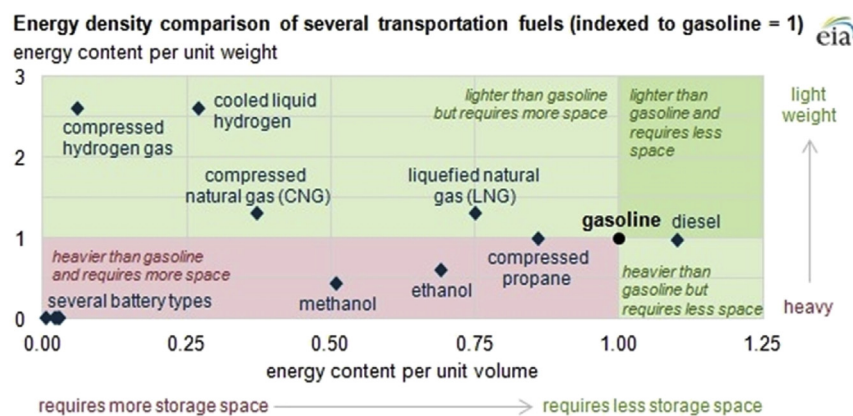


Fig. 2 – Energy density of various energy carriers [7].

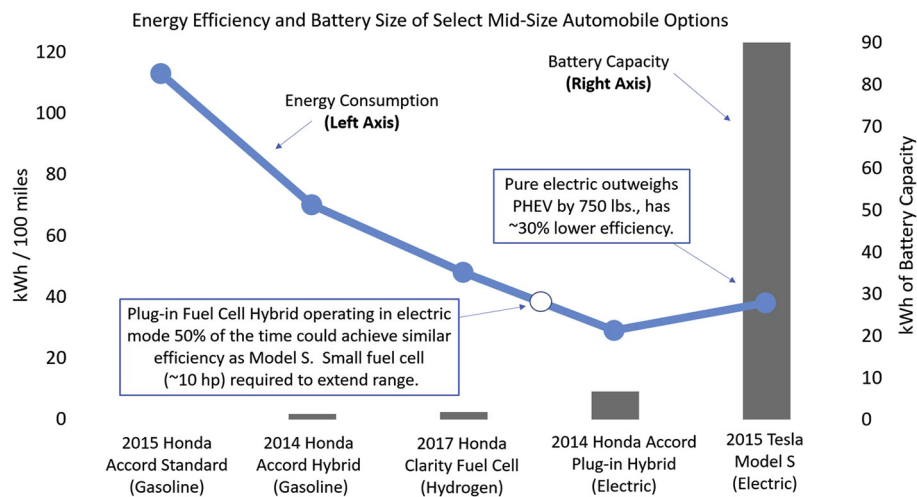


Fig. 3 – Energy required to drive 100 miles for different transportation options.

accelerating and decelerating weight and (climate controlled) space—not simply steady state power.

In Fig. 3 above, I show the energy and battery capacity requirements of five different mid-size transportation options. The figure shows that electrification generally increases the efficiency of transportation options except for the final step—from a plug-in hybrid to an exclusive battery electric

vehicle. Despite extensive use of aluminum and one of the most aerodynamic frontal areas in automotive history [13], the 2015 Tesla Model S sedan weighs 750 lbs. and requires ~30% more electricity per mile more than the 2014 Honda Accord Plug-in Hybrid [14].

If the physics of transportation were explored more robustly, plug-in fuel cell hybrids might be viewed to be just as

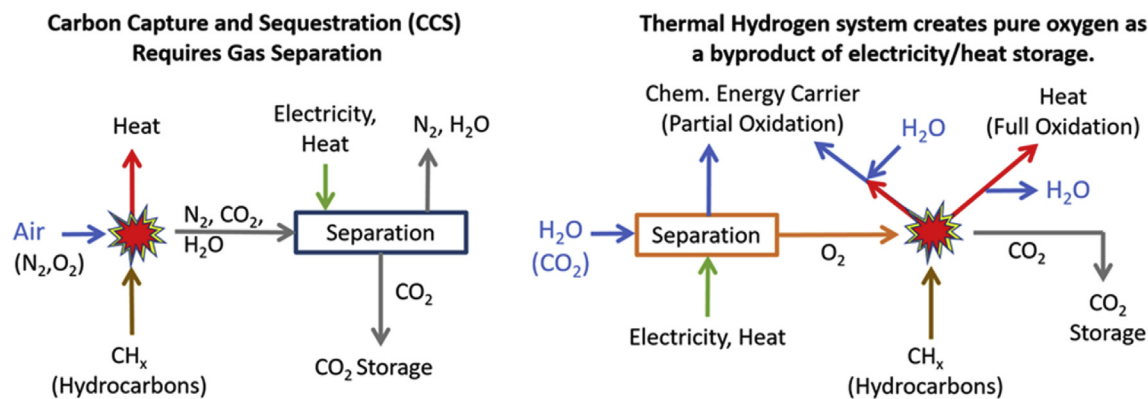


Fig. 4 – Basic concept of Thermal Hydrogen: an integrated energy system where the storage of excess heat and electricity through water splitting performed a simultaneous act of pre-combustion CCS.

efficient as battery electric vehicles [15]. Because fuel cells produce electricity and have an electric powertrain, every fuel cell vehicle to date has had a battery to provide regenerative braking and to assist with acceleration, just like a traditional gasoline-hybrid. If efficiency or grid powered transportation is desired, the battery capacity for fuel cell vehicles can simply be increased from what fuel cells use today (capacity of 1–2 kWh) to something more typical for plug-in hybrids (5–25 kWh). Hybridizing with a mid-sized battery pack would enable battery powered electricity to power most miles without the need for the very large battery pack required for extended range electric vehicles (60–100 kWh).

In Fig. 3 above, I estimate that a plug-in fuel cell hybrid could be just as efficient, if not more, than an exclusive battery electric vehicle. Let's assume that the plug-in fuel cell hybrid is charged frequently enough so that at least 50% of all miles can be powered by the grid. If the fuel cell mode uses 49 kWh/100 miles and battery mode uses 29 kWh/100 miles, per EPA specification, a 50/50 plug-in fuel cell hybrid would average around ~40 kWh/100 miles. Roughly speaking, that's the same efficiency as the Tesla Model S, ~38 kWh/100 miles.

In addition to being possibly the most efficient option, a plug-in fuel cell hybrid would presumably offer the lowest capital cost and most pragmatic heat and range options of any electric vehicle. For example, at \$190/kWh [16], the 90-kWh battery pack of the Tesla would cost \$17,000. Fortunately, such a large battery is not required to provide enough power to the drivetrain. A battery with just ~10 kWh can provide 175 hp [17].

Given that the battery provides necessary power, the fuel cell's purpose can be limited to range (keeping the battery above a minimum state of charge) and heating the cabin. The capacity of the fuel cell only needs to be as high as the average power demand of the vehicle. Even when a mid-size car is cruising at highway speed, the average power demand is close to ~10–20 hp. For example, Nissan has built a mini-van prototype of a plug-in fuel cell vehicle with a 25 kWh battery and a 7 hp solid oxide fuel cell [18].

To summarize, electro-chemical storage has fundamental technical flaws leading to diminishing returns—range, weight, and a lack of a waste heat source which can be utilized for cabin heating. Rather than competitors, batteries and fuel

cells should be viewed as mutually dependent co-enablers of broader electric transportation.

Hydrocarbons in the electric vision: “Carbon Capture and Sequestration” (gas separation)

Finally, the third major technical hurdle of the electric vision is that hydrocarbons must also take on a gas separation problem. For hydrocarbons to become suppliers in the electric vision, hydrocarbons require a process called Carbon Capture and Sequestration (CCS). CCS requires a gas separation process to isolate or “capture” the CO₂ before it can be compressed into a liquid and sequestered (Fig. 4). CCS increases costs because the gas separation process requires additional equipment and then additional energy to operate that equipment. CCS power plants are estimated to require a cost premium of around ~30%² [19].

To summarize, the electric vision for deep decarbonization has multiple fundamental technical flaws. The inability to store electricity for long periods of time will result in infrequently utilized, capital intense, low carbon capacity. Electro-chemical batteries have weight, heat, and charging limitations and require excessive battery capacity to provide range. For emissions-free hydrocarbon utilization, an additional energy and capital intensive gas separation process is necessary. These technical flaws indicate diminishing returns, necessarily increasing costs, and an unacceptably low likelihood of universal success.

Methods

Thermal Hydrogen: a chemical energy carrier creates a gateway for hydrocarbons

Thermal Hydrogen offers a different vision for an emissions free energy economy where a chemical energy carrier complements the weaknesses of electricity and hydrocarbons

² The Allam Cycle is the possible exception. However, costs could be even lower with the Allam Cycle if the air separation process is not required.

under deep decarbonization. This is accomplished by using heat and electricity to split water (or CO_2)³ to create hydrogen and pure oxygen. As a chemical, hydrogen enables both portable and storable emissions free energy. However, what is unique about Thermal Hydrogen, as opposed to the typical “hydrogen economy”, is the use of the other byproduct of water splitting—oxygen. A supply of pure oxygen pre-empts the most expensive part of CCS, onsite gas separation, also known as the “Carbon Capture” portion of CCS. To clearly define the term Thermal Hydrogen, it is an energy system where an energy carrier is produced from water or CO_2 splitting and the residual pure oxygen utilized to pre-empt the “Carbon Capture” portion of CCS.

“Carbon Capture” is the most expensive part of CCS, and it is necessary because nitrogen contaminates the combustion process. Ambient air is roughly 21% oxygen and 78% nitrogen. When hydrocarbons are combusted with air, the vast majority of the products are nitrogen. CO_2 then needs to be “captured” from the nitrogen rich exhaust stream before it can be sequestered. This process is called post-combustion CCS because the gas separation process occurs after combustion.

Another method for mitigating carbon emissions is called pre-combustion CCS. Instead of CO_2 being captured from the exhaust, oxygen is “captured” from ambient air using an air separation unit (ASU). The pure oxygen is used for the combustion process as opposed to ambient air to yield water and CO_2 . Nitrogen is never given a chance to contaminate combustion and isn't present in the products. The products are only CO_2 and water, and because water and CO_2 are easy to separate, the CO_2 is considered “sequestration ready”. It can be compressed into a liquid and permanently sequestered underground. Another way to describe Thermal Hydrogen is a symbiotic system of chemical energy storage and pre-combustion CCS energy.

The contrast between post-combustion CCS and a Thermal Hydrogen system is shown in Fig. 4 above. On the left side of Fig. 4, a hydrocarbon undergoes full combustion with air; electricity and heat are used to provide the energy to “capture” the CO_2 from the exhaust where it is then sequestered. On the right side of Fig. 4, electricity and heat are used to separate water to create hydrogen and pure oxygen. The oxygen pre-empts the “capture” portion of a pre-combustion CCS process. Hydrocarbons are shown as having the option to use the pure oxygen to either undergo partial or full combustion to become either a chemical energy carrier or heat, respectively. For partial combustion, water is shown as a reactant. For full combustion, water is shown as a product. The difference between Thermal Hydrogen and CCS is that electricity and heat is used to separate water rather than a gas—to create two valued commodities rather than one.

The name *Thermal Hydrogen* is meant to convey the idea that an energy carrier and heat from the oxidation of hydrocarbons is necessarily involved. Furthermore, thermal energy (heat) can also assist water splitting or do it directly—either through heat assisted electrolysis or a process called thermochemical water splitting. It should be mentioned that

hydrogen can be used to provide heat directly either through combustion or combined heat and power (CHP). Using thermal energy directly on both ends of hydrogen production and consumption improves efficiency and is a sub-goal of the system. Direct use of thermal energy is also part of the inspiration of the name Thermal Hydrogen—to maximize efficiency, hydrogen should be used as an energy carrier for both electricity and heat.

Unlike the simpler “hydrogen economy”, hydrogen's purpose is broader than complementing electricity. Instead of “dumping” the pure oxygen created by water splitting, oxygen enables hydrocarbons to become an increasingly competitive, emissions free asset. Whether hydrocarbons are used to create an energy carrier (partial combustion) or electricity (full combustion), oxygen reduces costs by enabling simpler and more efficient thermodynamic cycles.

The use of pure oxygen negates the need for a steam boiler in both electricity and hydrogen production processes. For hydrogen production, auto-thermal reforming can be used instead of steam methane reforming. For electricity, the Allam Cycle can be utilized rather than a combined cycle. These changes result in lower capital costs and increased efficiency. The sequestration cost of CO_2 is estimated to be around ~\$5/t CO_2 [19], probably less than the commodity value of CO_2 [20]. Given that these costs roughly cancel out, pure oxygen allows the possibility of increasingly competitive hydrocarbons with decarbonization.

Productivity of pure oxygen for partial and complete combustion

In Fig. 4 above, the concept of Thermal Hydrogen is introduced and two options are shown for oxygen—partial combustion and full combustion. In complete combustion, the energy bonds of the hydrocarbon molecule are fully released as heat as the reactants fully develop towards the products CO_2 and H_2O (Fig. 5 below). With partial combustion, a limited amount of oxygen supply does not allow hydrocarbons to completely transform into CO_2 and H_2O .

In Fig. 5 above, I show the byproducts and the energy carriers created by different combustion processes. Partial combustion, the water gas shift, and several other combustion sub-processes are combined in auto-thermal reforming to yield hydrogen and CO_2 . With auto-thermal reforming, the exothermic reaction of partial oxidation effectively creates the heat for steam reforming. There is no waste heat, hence the prefix “auto”.

The significance of partial vs. complete combustion is the productivity of pure oxygen. Whereas full combustion produces water, partial combustion with auto-thermal reforming consumes water. The difference is notable because the water consumed for reforming also provides hydrogen and oxygen itself, substantially decreasing the amount of oxygen from water splitting required per unit of energy carrier created.

In Fig. 6 below, I show how much electrical energy is required to create a kilogram of oxygen using electrolysis (assume 70% efficiency, 48 kWh/kg H_2) and then how much energy that kilogram of oxygen would theoretically yield during partial or complete combustion. If oxygen is used to create hydrogen, it can create three times as much hydrogen

³ Later in this paper, I will introduce an “Organic” variant of a “Thermal Hydrogen” economy where syngas is the energy carrier instead of hydrogen.

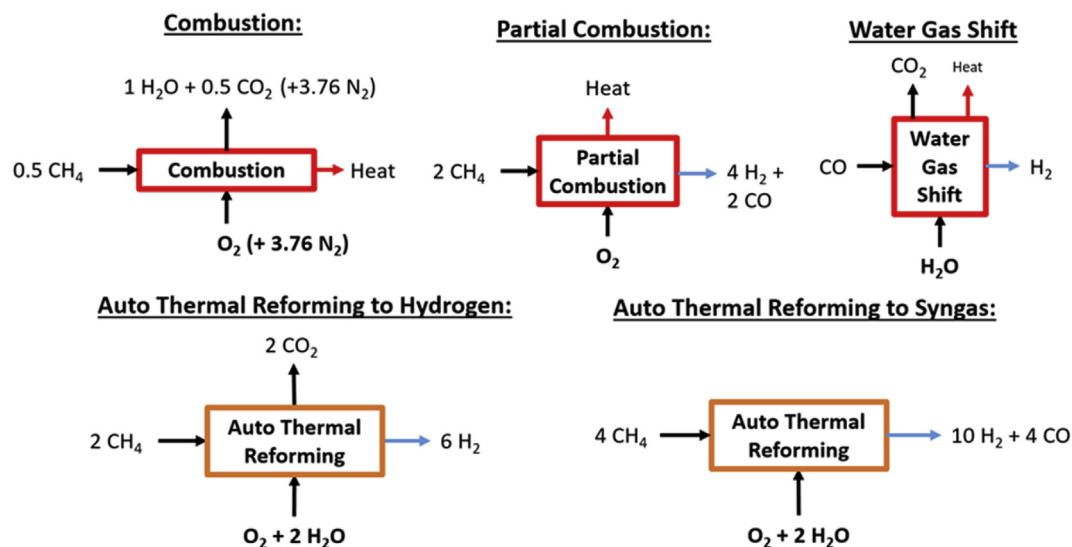


Fig. 5 – Complete and partial combustion processes. Entering from the left is the amount of methane required to either fully or partially combust 1 mol of O_2 (except WGS). Coming out at the top of the box are the wasted byproducts of the reaction and to the right are the intended energy carriers.

energy as it would if it were used to create heat with complete combustion.

Fig. 6 shows that pure oxygen is much more productive at producing energy carriers than heat. This is convenient because of the cost structure of electrolysis. Electrolyzers have relatively low capital costs (further explored below) and relatively high fuel costs. The economic viability of electrolysis is largely dependent on the cost of the energy inputs, electricity and heat. Therefore, the productivity of oxygen when used to produce hydrogen is very convenient. Hydrogen produced from hydrocarbons can minimize the amount of hydrogen required from water splitting. If water splitting can be minimized, the amount of electricity and heat demanded for electrolysis can be minimized, too. Given that low fuel costs are imperative for the competitiveness of electrolysis, minimizing the electricity demand gives electrolysis the best chance for being cost effective.

Full combustion for hydrocarbons

Hydrocarbons can use the pure oxygen from water splitting either create heat with full combustion or to create chemical energy carriers with partial combustion. For the most part, it is logical for hydrocarbons to use pure oxygen supply for partial combustion. Given that full combustion uses so much oxygen, it does not make sense to use the oxygen from water splitting to be used mostly for creating heat (electricity). A cheap oxygen supply would imply cheap water splitting which indicates a large amount of excess electricity on the grid. If there is excess electricity on the grid, there is little incentive to use the oxygen to produce more electricity.

It should also be noted that hydrocarbons are chemicals that contain hydrogen. It makes physical sense that the chemical energy supply source would be the most competitive supply source for chemical energy carriers. Wind and

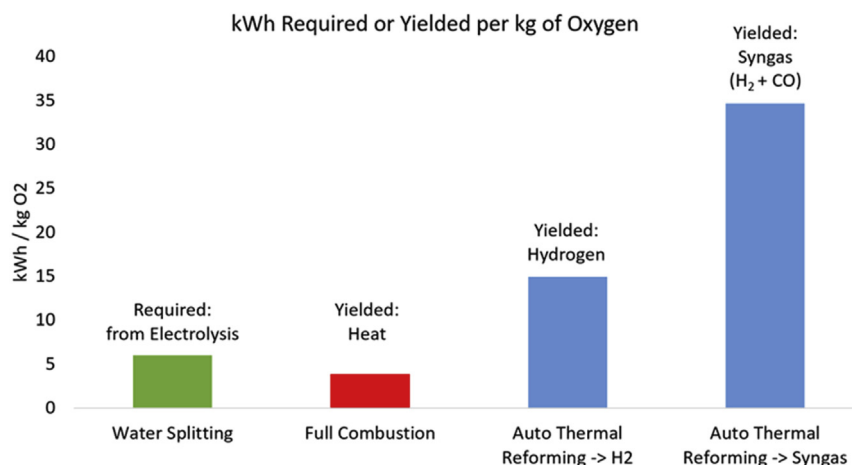


Fig. 6 – Electricity required to split a kg of oxygen (assume 48 kWh/kg H_2 , or 70%), heat yielded from full combustion of a kg of oxygen with methane, hydrogen or syngas yielded from auto-thermal reforming with a kg of oxygen and methane.

photovoltaic energy create power or electricity directly and an additional conversion to a chemical energy carrier would result in some energy loss. Nuclear energy is a source of heat that can create electricity or hydrogen directly with about the same efficiency (~50%). Hydrocarbons are the only source of energy that can more efficiently become a chemical energy carrier rather than electricity. Reforming is around ~75% efficient whereas power production is limited to around ~50%.

Therefore, it doesn't seem logical that renewable energy and nuclear energy would be most competitive at producing chemical energy carriers and hydrocarbons most competitive at producing electricity. By and large, as I'll show below, renewable energy should be used to create electricity, hydrocarbons to create chemicals energy carriers, and nuclear heat as the intermediary balancing electrical and chemical energy carriers.

The competitiveness of hydrocarbons as a chemical energy carrier does not necessarily mean pure oxygen from water splitting should always be used for partial combustion, either. Electricity prices are volatile; it would also seem logical to assume that at least at certain times, using oxygen for electricity production (full combustion) makes sense from a storage perspective. Below, I explain how hydrocarbons can most cost effectively produce electricity using pure oxygen. I introduce this technology first because the same technology might be useful for designing a nuclear reactor in a Thermal Hydrogen economy.

In Fig. 7 below, a schematic for an Allam Cycle is shown. In the Allam Cycle, the hydrocarbon is combusted using pure oxygen to produce supercritical CO₂, and the supercritical CO₂ is used directly as the working fluid in the turbine itself instead of steam. The significance of the Allam Cycle for Thermal Hydrogen is the ability to use pure oxygen for electricity production in the most efficient way possible. There are multiple pre-combustion CCS power plant cycles that consume pure oxygen (i.e. oxy-fuel or Integrated Gasification and Combined Cycle). However, these plants utilize steam as the working fluid in the turbines. Supercritical CO₂ has superior thermodynamic properties compared to steam because it is twice as dense as a supercritical fluid. It is a novel approach because the reactants of combustion are the working fluid of the turbine.

The advantage of the Allam Cycle is its efficiency at consuming hydrocarbons, and, by extension, oxygen. Net-Power is currently developing the Allam Cycle technology and their specifications indicate an efficiency of 48% and 53%

(HHV) with coal and gas, respectively [21]. If pure oxygen from water splitting were used, as shown in Fig. 5, neither the capital costs nor the efficiency penalty of the ASU is required. This increases efficiency of the Allam Cycle to 58% and 64% (HHV) for coal and gas, respectively [21,22].

Universal Energy Plant: maximizing the utilization of capital intensive capacity

The advantage of using supercritical-CO₂ as the working fluid of the turbine is not exclusive to hydrocarbon combustion. Other non-chemical, high temperature heat sources, such as nuclear or concentrated solar energy, can also use supercritical CO₂ as the working fluid for the turbine. Those heat sources would simply require a larger heat exchanger than the Allam Cycle because there is no heat gain through combustion.

For nuclear or CSP, the advantage of using CO₂ as the working fluid is not just efficiency. Because both power plants use the same working fluid, it could be practical for nuclear and hydrocarbon energy to be hybridized to use the same power block. In the Allam Cycle, 97% of the mass entering the turbine is re-heated CO₂ [21]. Only 3% of the mass entering the turbine are pure oxygen and the fuel. Given the small mass required for the combustor, it is reasonable to think that an increased mass flow on the nuclear side could enable the combustor to increase heat input during times of peak demand. Using this design, the hydrocarbons could be integrated as a “peaking resource” on the same power block and would only require its own combustor and excess turbine capacity.

The hybrid design enables pure oxygen and hydrocarbons to provide “peaking” or “load following” electricity services. However, even with the help of hydrocarbons and excess turbine capacity, the nuclear reactor might still have to take on a low utilization problem. Given the intermittency of renewables, it is likely that grid prices will occasionally collapse during periods of excess supply. In this situation, the nuclear reactor's heat, and by extension, its appreciable capital investment, is wasted.

However, the occasional oversupply of electricity is a hidden opportunity for nuclear energy. The times that the nuclear power plant would idle are the same times when excess electricity is present at the facility. In order to keep the nuclear reactor fully utilized, the heat could be redirected to an electrolyser, and inexpensive electricity from the

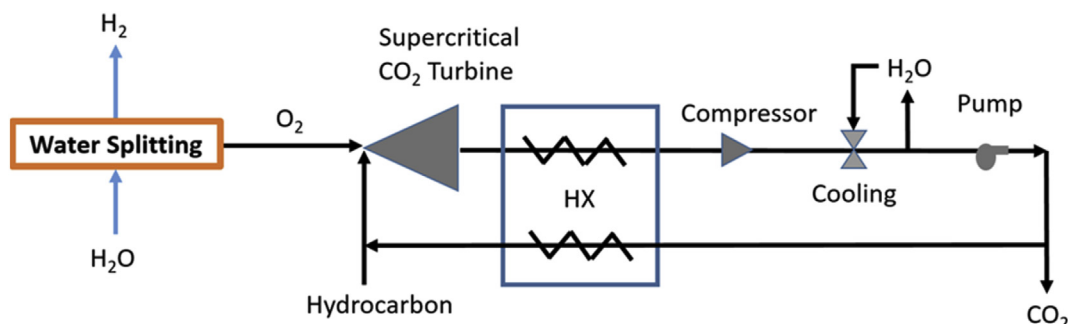


Fig. 7 – Thermal Hydrogen process where oxygen is used in an Allam Cycle power plant.

grid could assist, or “top off” heat provided by the nuclear reactor.

Heat-assisted electrolysis makes sense from an efficiency perspective in addition to an operational one. Electrolysis is an endothermic reaction and the heat would proportionally reduce the amount of electrical energy required for electrolysis. Effectively, the electrolyser serves as a battery for both waste heat and excess electricity. Another reason for this design is to shift the low utilization problem completely away from the nuclear reactor and onto electrolysers and turbines which have lower capital costs.

Fig. 8 shows a “Universal Energy Plant” concept. It is a hybrid power plant/electrolyser that can use multiple sources of energy as fuel: electricity, heat, or chemical energy. These energy sources are accommodated by oversizing the turbine and electrolyser of the plant. Excess electricity on the grid can be stored using heat assisted electrolysis. Hydrocarbons are used as a peaking power plant emissions free. Nuclear heat can achieve full (and direct) utilization because it can either produce power or assist electrolysis.

Below in Fig. 9, the concept of a “Universal Energy Plant” is shown within a broader schematic of the Thermal Hydrogen economy. In the lower left, the non-chemical heat sources, nuclear and CSP, have the option to either produce electricity or assist water splitting. In the upper right corner, plug-in fuel cell hybrids serve transportation. At the bottom right, pure oxygen is used to reform hydrocarbons. These assets are used to serve three different energy services: stationary load, mobile load, and heat.

This broadened view shows that Thermal Hydrogen minimizes the capital intensity of a deeply decarbonized grid. The most capital intensive assets of the system are highlighted in bold font—wind/PV, nuclear/CSP, and batteries. The introduction of a chemical energy carrier provides storage and minimizes the capacity required of these assets. Instead of the utilization problem being absorbed by renewable capacity, nuclear reactors, and batteries, it is absorbed by less capital intensive electrolysers and turbines. In doing so, pure oxygen is created to pre-empt the “Carbon Capture” part of CCS and enable more efficient thermodynamic cycles.

The Thermal Hydrogen economy: efficient use of (thermal) energy

The most effective argument in favor of the electric vision is that it must be more energy efficient than a hydrogen economy. The view is that heat energy is lost when producing hydrogen from electricity, and then lost again when hydrogen is converted back to electricity. However, this view is too simplistic because it assumes a narrow system boundary. It is assumed that the purpose of hydrogen is limited to that of a battery—electricity storage.

However, most of the hydrogen use in this economy is related to heat—hence the name. Hydrogen combustion is technically just as efficient as electric resistance heating, but the former is storable. Furthermore, heat is not necessarily “lost” by fuel cells; it is recoverable in combined heat and power processes and it is used to reduce weight (heat loss through rolling resistance friction). Therefore, the efficiency of hydrogen consumption depends on whether it is used as just a battery or whether its co-benefits (heat and energy density) are capitalized.

On the production side of hydrogen, efficiency depends on pathway. Electrolysis is about ~70% efficient resulting in appreciable heat loss. However, electricity is not a primary source of hydrogen production in the Thermal Hydrogen economy. In the scenarios below, electricity provides less than 20% of the energy used to make hydrogen. The rest is provided by heat based energy sources that find a more efficient pathway through hydrogen.

For hydrocarbons, the hydrogen pathway is advantageous because reformation is around ~75% efficient whereas power production is closer to ~50%. Even if a fuel cell never plugged in, such as the Honda Fuel Cell in Fig. 3 above, hydrogen would still be a competitive pathway for hydrocarbons. Given these efficiency assumptions and the EPA fuel economy estimates, the Honda fuel cell vehicle requires 15% less hydrocarbon energy overall than the all-electric Tesla.

If nuclear heat is used directly to split water, it can create hydrogen for about the same efficiency that it could create electricity. This can be accomplished with heat assisted

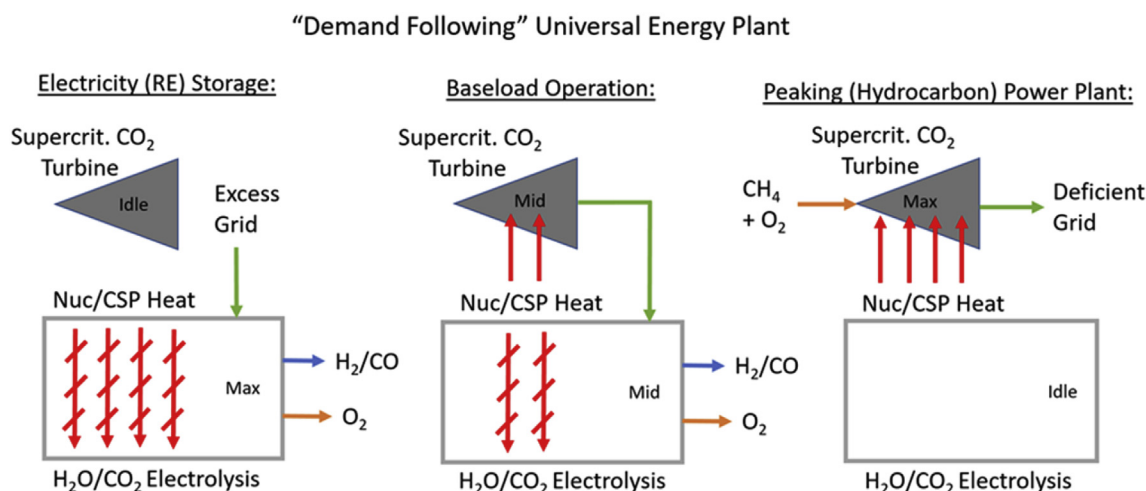


Fig. 8 – Universal Energy Plant: electricity storage, full heat utilization, and peak hydrocarbon power output.

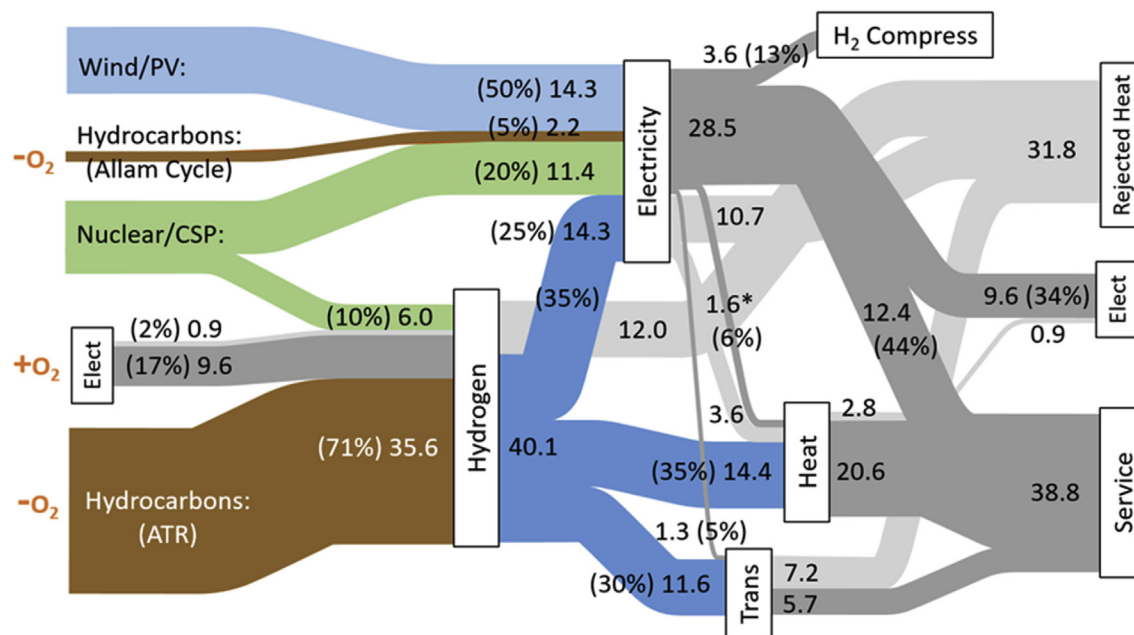


Fig. 10 – Sankey diagram of 2014 U.S. Energy System in quads using “balanced” approach described above. Asterisk indicates electric heating has COP of 3.0. Numbers may not add up due to rounding.

Some administrative constraints were also set. To serve seasonal electricity demand, at least 30% of all electricity must come from chemical fuels—either hydrogen or hydrocarbons. No more than half of wasted heat from fuel cells or the combustion of hydrogen is usable for combined heat and power or for heat assisted electrolysis, respectively. It is also assumed that 25% of heating services are electrified.⁴ Grid powered batteries are assumed to provide approximately one third of light duty transportation. The rest of transportation was assumed to be served by fuel cells.

Given these assumptions, an Excel based model using Solver can adjust variables to ensure that supply and demand in the system is balanced while meeting certain constraints. These constraints also include an administratively set amount of permissible renewable energy. Whatever electricity is not served by renewables or chemical fuels is served with nuclear.

In Fig. 10 above, I introduce a scenario named “Balanced”. In this scenario, it is assumed that 50% of electricity is produced from renewables and 25% produced from hydrogen. The remaining 25% is supplied with nuclear and hydrocarbon heat from a “Universal Energy Plant”.

The “Balanced” scenario shows a mix of energy suppliers and energy carriers that could be considered both realistic and efficient. 20% of the pure oxygen supply was used for direct combustion in the Allam Cycle, and 80% of oxygen was used to make hydrogen with auto-thermal reforming.

Approximately 30% of all electricity supply was used for electrolysis, but this electricity accounted for less than 20% of the energy required to make hydrogen. The implication is

favorable in multiple ways. It indicates energy efficiency because 80% of hydrogen came from heat based resources. It also indicates a system that could be reasonably cost effective because consumption of excess electricity was minimized. In 2014, the utilization rate, or capacity factor, of U.S. electricity capacity was ~45%. This implies that the theoretical potential of the electricity sector is closer to ~25 quads, nearly the amount of total electricity required for the “balanced” scenario above.

It should also be noted that the reliability and flexibility of the electric grid in Thermal Hydrogen would be extraordinary. Almost half of all electricity demand is flexible and half of electricity production is from dispatchable resources. Furthermore, the reliability of the electricity system could be backed with the distributed electricity capacity of plug-in fuel cell hybrids. Let's presume that just half of all vehicles in the U.S. have 10 hp fuel cells to provide range for their plug-in hybrid. At 7.5 kW each, the fuel cells could theoretically add 1 TW of electricity capacity, or approximately the same capacity as the entire U.S. electricity sector.

Results

Estimating the competitiveness of (Thermal) Hydrogen

The above economy-wide model is necessary to show that the energy system has enough flexibility to fully utilize the most capital intensive resources—renewables and nuclear—yet satisfy electricity demand reliably. The economy-wide energy balance is also necessary to estimate the balance of energy sources required to produce hydrogen. The average cost of hydrogen is determined by how much electrolysis vs. auto-thermal reforming is required. If all oxygen from electrolysis

⁴ An appreciable amount of heat is already electrified in the modern energy system. This analysis assumes that 25% of the heat that was not electrified in 2014 is electrified in the Thermal Hydrogen economy.

is used for electricity production, then the cost of electrolysis less the value of oxygen would indicate the net cost of hydrogen. If all the oxygen were used for making hydrogen, up to 75% of total hydrogen produced would come from hydrocarbons via auto-thermal reforming.

Below, a cost estimate is provided where 30% of hydrogen comes from electrolysis and 70% of hydrogen comes from auto-thermal reforming. For the baseline case, I will assume \$5/MMBTU for the cost of the hydrocarbon (modeled as natural gas). I'll also assume that the cost of the electricity for electrolysis is \$30/MWh. This corresponds to the marginal cost of a 50% efficient hydrocarbon power plant. Theoretically, in a deeply decarbonized grid without transmission constraints, CCS power plants ought to set the market clearing price since they have the highest marginal costs of any non-hydrogen power plant. Table 1 below shows the cost estimates for electrolyzers and auto thermal reformers.

In Fig. 11 below, the cost assumptions from Table 1 are used to estimate the cost per kg of hydrogen created. The cost of auto-thermal reforming is assumed to have 20% lower capital costs than steam methane reforming [26]. As expected, the cost of hydrogen from electrolysis is not competitive with hydrocarbon reforming.

However, given that the oxygen from the electrolyser enables up to three times as much hydrogen from auto-thermal reforming, most hydrogen costs will be dictated by the cost on the hydrocarbon side, not the electrolyser side. The combined cost of the electrolyser and auto-thermal reforming are shown in the right column in Fig. 11 below.

According to the above assumptions, steam methane reforming would cost around \$1.20/kg H₂. However, the Thermal Hydrogen combination would presumably be

competitive because of other co-benefits. In addition to not having carbon emissions, 20% of the oxygen production was sold to the electricity sector for peak power; these benefits are currently not included. Furthermore, electricity and O&M costs for a hybridized electrolyser should be significantly lower than for a stand-alone electrolyser [27].

Furthermore, another advantage of Thermal Hydrogen over steam methane reforming is reliability through diversity. The costs of hydrogen are fairly evenly spread over multiple cost components, and this would imply a relatively stable price for hydrogen. In Fig. 12 below, I show the sensitivity of the cost of hydrogen to different variables. The range shown in the cost category indicates how much Table 1 costs were adjusted. The figure shows how much the overall average cost of hydrogen would change as a result.

In Fig. 13 below, I use the vehicle efficiencies assumed in Fig. 3 to estimate the cost to drive 100 miles using different transportation fuels. I assumed that the distribution cost of hydrogen as \$1/kg H₂ [28], bringing the total central cost estimate from \$1.60/kg H₂ up to \$2.60/kg H₂. Gasoline was assumed to cost \$2.50/gal and electricity was assumed to cost \$0.10/kWh.

Fig. 13 below shows that the fuel cost of a fuel cell vehicle can be competitive with the fuel cost of a battery exclusive vehicle. However, there is a great amount of uncertainty as to which one would cost less in practice. In both cases, a large portion of the retail costs depend on distribution costs, which I will discuss in further detail below. It can, however, be safely said that the electric options should have cheaper fuel costs than the petroleum options. Not only do the electric options (fuel cells/batteries) use energy more efficiently, their energy suppliers are local. It makes sense that they should be more competitive than a vehicle that inefficiently uses an energy carrier whose price is set by global demand.

Competition and choice: the options of Thermal Hydrogen

Given that most places in the world have strongly preferred energy supply options, perhaps the most important economic attribute of Thermal Hydrogen is its supply optionality and distribution versatility. No one source of energy is imperative

Table 1 – Baseline cost component estimates.		
	Electrolysis	Auto-thermal reforming
Capital costs [25,26]	\$400/kW	\$150/kW
O&M [25]	\$50/kW-year	\$10/kW-year
Fuel	\$30/MWh	\$5/MMBTU
Utilization	50%	90%
Efficiency	70%	80%

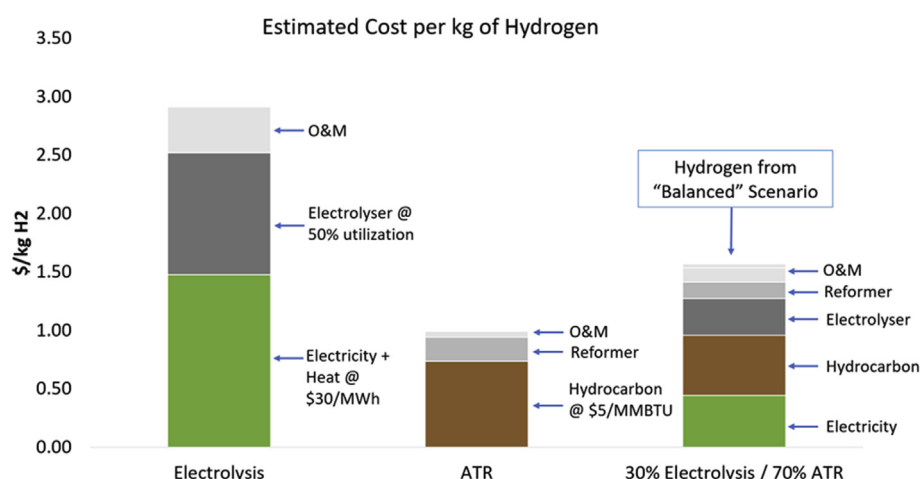


Fig. 11 – Average costs of hydrogen from different sources. ATR stands for auto-thermal reforming.

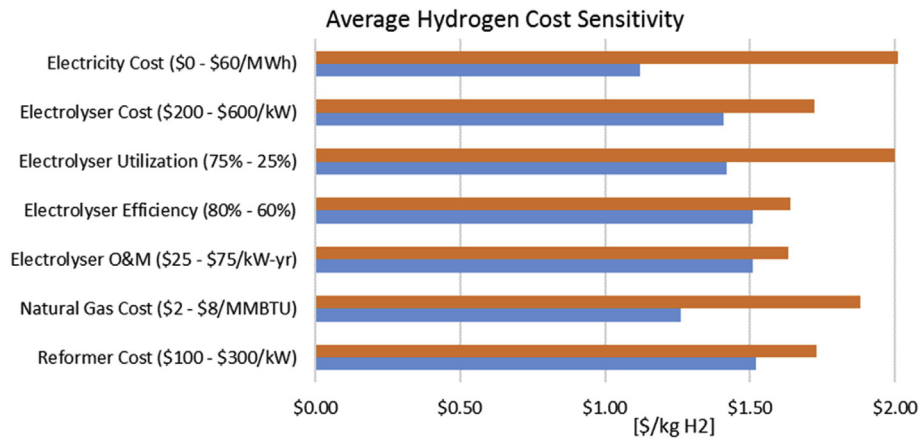


Fig. 12 – Costs of hydrogen sensitive to different cost assumptions.

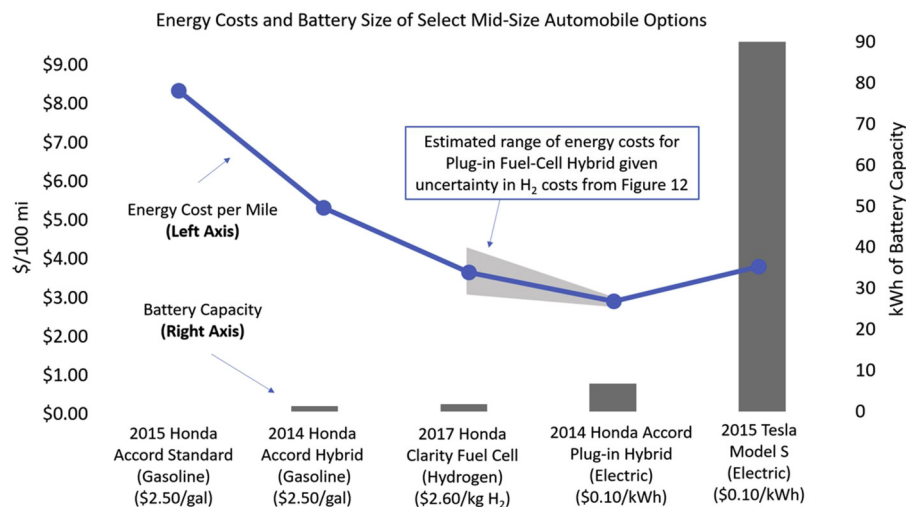


Fig. 13 – Estimated cost to drive 100 miles of select mid-size automobiles.

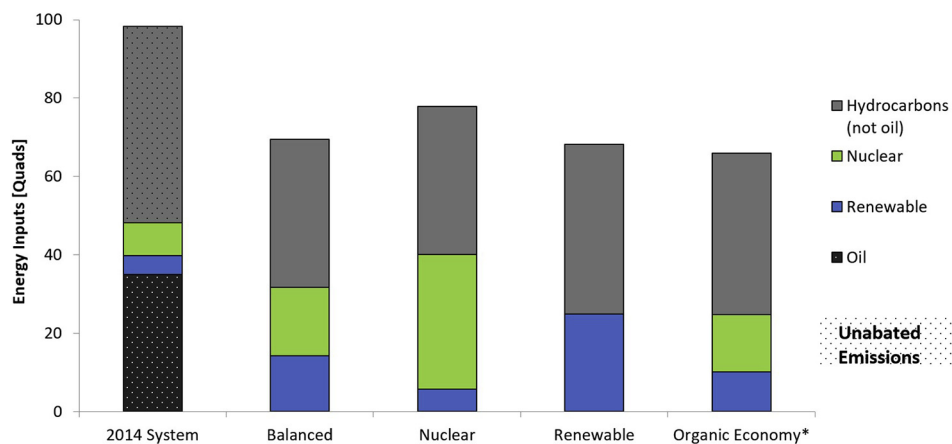


Fig. 14 – Possible energy supply combinations to decarbonize all sectors with Thermal Hydrogen. “Organic Economy” will be described below.

though any energy supply source could dominate. In Fig. 14 above, I perform the same overall electricity, hydrogen, and oxygen balance as above for three more scenarios. In each scenario, heating and transportation services are met with the same energy carrier balance and constraints as above. In the “Nuclear” scenario, renewable energy is limited to 20% of the electricity sector. In the “Renewable” scenario, nuclear energy is not allowed and renewable energy supplies 65% of electricity. The “Organic” is the same as the “Balanced” scenario except the hydrogen is distributed using hydrogen energy carriers (ammonia and methanol), and this will be described further below.

Using coal and/or biomass for Thermal Hydrogen

In the analyses above, I assumed that natural gas would be the hydrocarbon of choice for all processes. This was done for simplification of stoichiometric calculations as coal is a far more complex compound than natural gas (CH_4). However, coal can be used in the Allam Cycle or in auto-thermal reforming if it is first gasified into a syngas. Coal gasification can reduce costs because the use of a lower cost fuel ($\sim \$2/\text{MMBTU}$) can offset the premium required for gasification equipment.

It should be noted that gasification requires an additional partial oxidation process not required for natural gas. It is intuitive to think that coal might require twice as much oxygen from water splitting since coal is twice as carbon intensive as natural gas per unit of heat provided. However, the oxygen in CO_2 may come from the oxygen in steam and not necessarily oxygen from water splitting. In gasification and in auto-thermal reforming, the steam supplied contributes hydrogen as well as oxygen.

Therefore, coal gasification will require some additional water splitting compared to natural gas, but the amount is mitigated by the supply of steam used in gasification. NetPower has estimated that the coal and natural gas versions of its Allam Cycle power plants are competitive [29]. Given that coal and gas are competitive for NetPower when oxygen is supplied using an air separation unit, it is reasonable to believe that coal would remain competitive as Thermal Hydrogen increases the availability of oxygen.

It is also worth noting that coal can be co-gasified with biomass which would result in net negative CO_2 emissions, also known as Bio-Energy with Carbon Capture and Storage (BECCS). The most salient economic argument against the use of biomass is the cost and emissions of transporting moisture rich biomass. However, if whole-sale hydrogen could be used to fuel the transportation, both the costs and emissions of transit can be reduced. Net negative emissions could be a significant breakthrough because it can “buy time” by negating past carbon emissions. Additionally, negative emissions might be needed to compensate for some other practically impossible GHG emissions to offset, such as meat production in agriculture.

Macro-economic supply side effects of Thermal Hydrogen

Broadly speaking, Thermal Hydrogen can be cost effective because it uses lower costs fuels more efficiently. In the scenarios modeled above, gas was the hydrocarbon modeled for

simplicity, but any hydrocarbon could also be used. Therefore, the energy sources with the longest supply (renewables, nuclear, and coal/gas) displaces whatever type of energy is in shortest supply (oil). Furthermore, the CO_2 that results from Thermal Hydrogen processes can be used to further increase oil supply through CO_2 -flood Enhanced Oil Recovery (EOR).

These energy substitutions encourage macro-economic growth because of favorable supply side energy effects. The price of oil will generally always be highest because its portability enables its price to be set by global demand. Thermal Hydrogen will cause domestic demand for oil to decrease and domestic supply to increase because of EOR. Therefore, whichever country implements Thermal Hydrogen first would be positioned to enjoy a massive increase of oil export revenue.

In Fig. 15a and b below, I show the energy use and approximate fuel costs of the 2014 U.S. Energy system vs. the “Balanced” Thermal Hydrogen scenario described above. Instead of the high price of oil being internalized, imports are eliminated and domestic supply is exported.

Some may view the increase in oil supply negatively because decreased oil prices encourage petroleum use. However, the fear of decreasing oil prices is inconsistent because any move towards decarbonization will have a similar price effect due to decreased demand for oil. In the electric vision, the success of battery electric transportation positively reinforces the competitiveness of gasoline. This feedback loop bodes poorly for the universal eradication of unabated gasoline use in the electric vision.

The difference between Thermal Hydrogen and the electric vision is that oil has an emissions free supply path that does not require gas separation, and this will keep its price from bottoming out. The falling oil price will be a boon for global economic growth because regions of the world that have not been able to afford energy for decades will suddenly have access. It will also enable Thermal Hydrogen to be used anywhere in the world—not just where coal, natural gas, or biomass are available.

Using carbon to assist distribution: the organic Thermal Hydrogen economy

It could be argued that the inefficiency or impracticality of hydrogen is hidden in its distribution. Hydrogen must be compressed to a very high pressure because of its low density; it also leaks and requires far more energy to be piped. There is also the “chicken and egg” conundrum. If part of the purpose of hydrogen is to provide range for electric vehicles, then its supply must be made ubiquitous to be useful. Given these reasonable reservations, I will introduce below a so called “organic” variant (as in organic chemistry) of Thermal Hydrogen. In the organic Thermal Hydrogen economy, carbon derived chemical energy carriers, such as syngas (H_2 and CO), methanol (CH_3OH), or ammonia (NH_3), are used as hydrogen energy carriers.

Syngas (H_2 and CO) is stored and transported similarly to natural gas and can serve as an emissions free substitute to hydrogen for fuel cell applications. Syngas can be used by solid oxide fuel cells (SOFC) and the exhaust can be recycled. SOFCs differ because oxygen crosses the electrolyte to meet the fuel (H_2 and CO). In hydrogen fuel cells, the hydrogen crosses the

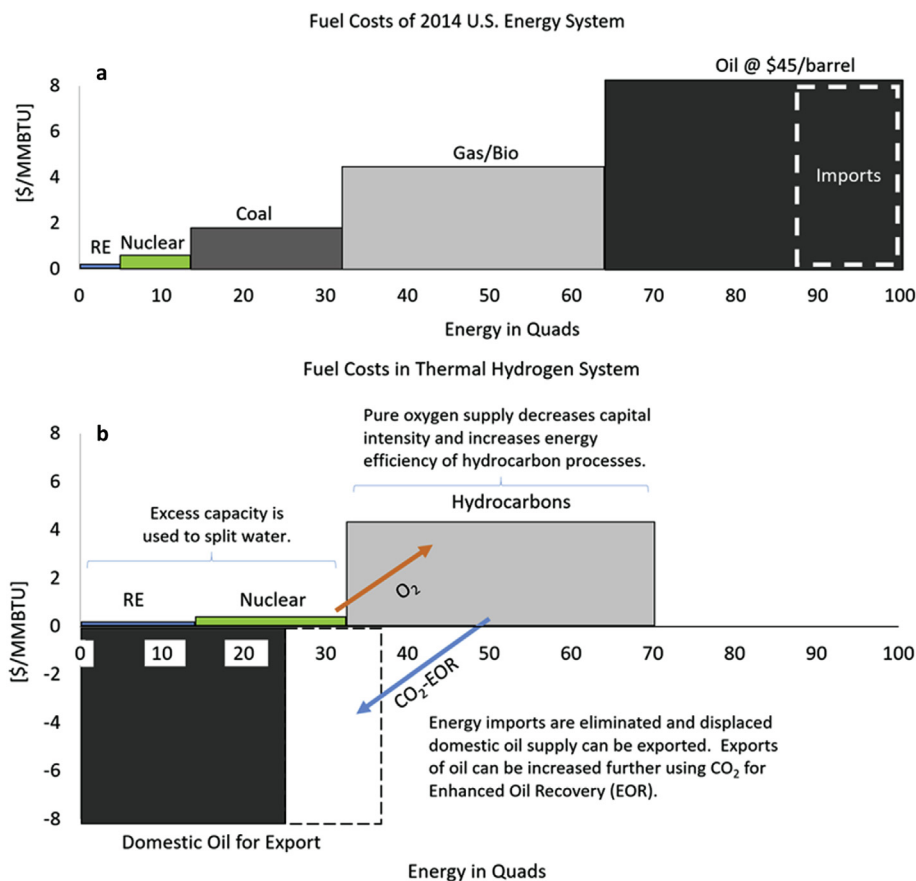


Fig. 15 – a: Estimated energy use and fuel costs of the 2014 U.S. Energy System. b: Estimated energy use and fuel costs of the “Balanced” Thermal Hydrogen scenario. It is assumed that domestic oil supply is exported.

electrolyte to meet oxygen. The difference is that the exhaust of the SOFC is not diluted with nitrogen. The electrolyte of the SOFC is effectively an air separation unit; a second source of pure oxygen is created by the air filtration. This allows the exhaust to produce only carbonated water, H₂O and CO₂, as opposed to H₂O diluted with nitrogen. This could be stored on-board, recollected at the gas station, and eventually dispensed to the CO₂ pipeline network for sequestration.

There are several key advantages not related to distribution for using syngas rather than hydrogen. Auto-thermal reforming to syngas (H₂, CO) requires less than half the oxygen as auto-thermal reforming to hydrogen. The reason is that only enough oxygen is supplied to form CO, no CO₂. So, not only does CO act as an insulator for hydrogen during transport, it increases efficiency by decreasing the amount of water splitting required.

Another key advantage of the organic system is that it allows for the net production of water. The hydrogen in hydrocarbons eventually meets with oxygen from the atmosphere to produce water. This happens in all hydrocarbons processes but is usually released to the atmosphere as steam. If the CO₂ is going to be recycled, an opportunity is created to also recycle the water. As shown in the figure below, for every mole of methane used, 2 mol of water are created.

In Fig. 16, I show a schematic where syngas acts as the chemical energy carrier of Thermal Hydrogen. All chemical

reactions are balanced ideally. Co-electrolysis of CO₂ and water was assumed to produce syngas and oxygen.

Syngas can be an emissions free energy carrier if it is used for fuel cells which recycle the exhaust. However, it cannot be used for combustion because it would result in CO₂ emissions (albeit significantly reduced emissions). To fully decarbonize the economy without needing hydrogen piping at all, another hydrogen energy carrier will be required for combustion.

One option for minimizing hydrogen piping is to use CO₂ electrolysis instead of H₂O electrolysis. The CO can be piped to the city gates and the CO can be reformed into hydrogen via the water gas shift reaction. Alternatively, the CO could be reformed into hydrogen within the auto-thermal reformer. If the reformers can be located near the point of consumption, hydrogen piping could possibly be avoided entirely. The idea is to pipe the ingredients to make hydrogen (CO, O₂, and CH₄), not hydrogen itself.

Another idea for distributing hydrogen could be to use ammonia as the hydrogen energy carrier. Ammonia, NH₃, can be distributed similarly to natural gas and produces no CO₂ emissions upon combustion. Ammonia can be created for reasonable cost using the Haber-Bosch process where hydrogen and nitrogen are combined over a catalyst.

The hydrogen for ammonia can be created by Thermal Hydrogen processes and the nitrogen can be created by the “Carbon Capture” process of CCS. For every mole of O₂ created

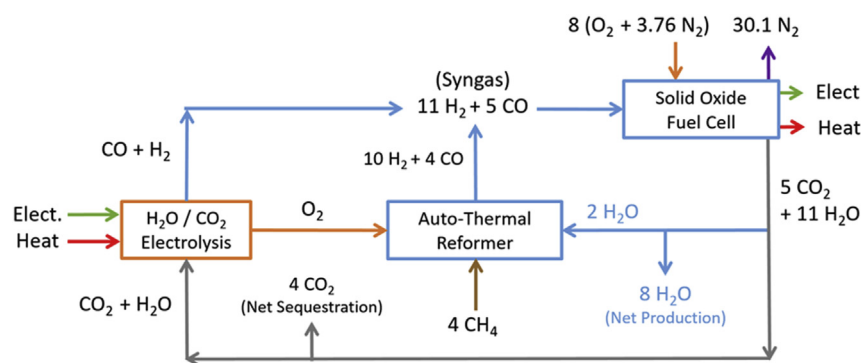


Fig. 16 – Fuel cell use in the “Organic” Thermal Hydrogen economy.

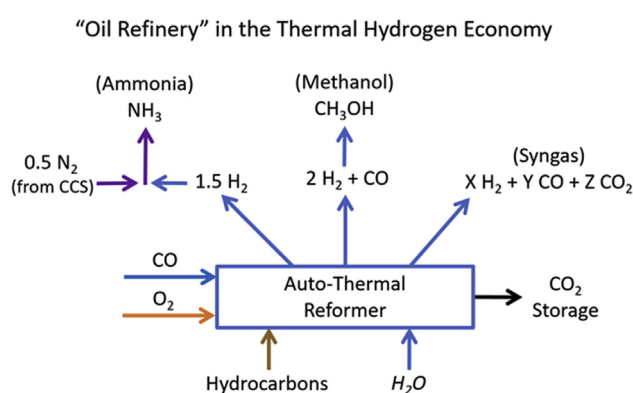


Fig. 17 – Auto-thermal reforming in the “organic” variant of Thermal Hydrogen.

by an air separation unit, 3.76 mol of pure N_2 are created. So, for every mole of CH_4 combusted in a CCS power plant, there is an opportunity to create 15 mol of NH_3 . Assuming an efficiency of 50% for CCS power plants, each kWh of electricity creates enough nitrogen for 13 kWh of ammonia. In the balanced scenario above, approximately 21 quads of hydrogen are used for combustion—either for heat or for power production. Converting this hydrogen to ammonia would require the nitrogen from approximately 70 GW of CCS power plants (1.6 quads, ~7% of all electricity production).

In Fig. 17 below, I show how an auto-thermal reformer in the “organic” economy might operate to enable hydrogen energy carriers without the need for hydrogen piping. The reformer serves effectively the same function as an oil refinery in the modern economy. In the figure, I show three different products leaving the reformer: hydrogen, syngas with a certain H_2 to CO ratio, and then syngas with any H_2 to CO ratio. The pure hydrogen is combined with pure nitrogen to form ammonia, NH_3 . The syngas that has the ratio of 2 mol

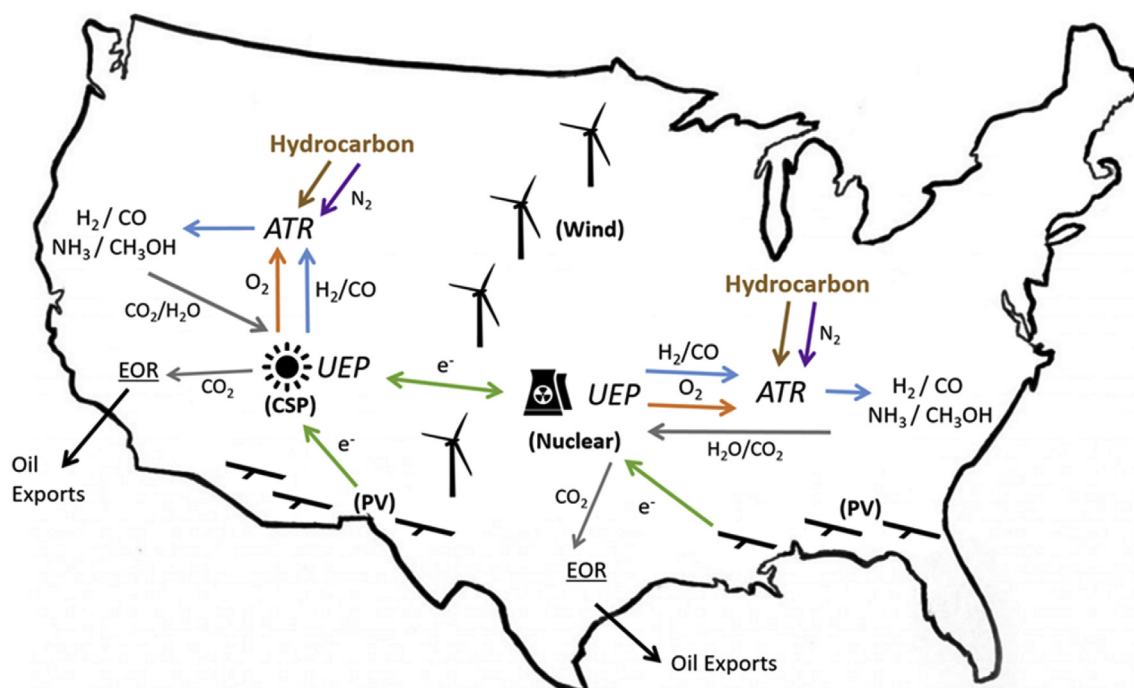


Fig. 18 – Vision for creating and distributing hydrogen energy carriers.

of hydrogen to 1 mol of carbon monoxide is converted into methanol for distribution. The methanol can be converted back into syngas using the waste heat from the fuel cell. The auto-thermal reformer is also envisioned to produce general syngas which can have any ratio of H_2 to CO. The syngas would presumably be less expensive and certain gas stations may be incentivized to distribute syngas directly to fleets, for example.

To summarize, ammonia can serve as a substitute to natural gas combustion and methanol can serve as the substitute for gasoline. In Fig. 14 above, where I estimated the total energy required for different economies, the energy required for the “organic” economy is shown. In the “organic” economy, half of the chemical energy carriers are assumed be ammonia, and the other half are assumed to be methanol. Unlike the Thermal Hydrogen economies modeled above, some gas separation is required because ammonia production requires nitrogen. However, because so much pure nitrogen is present in air, very little CCS is required. Even though 65% of the organic energy economy is produced by hydrocarbons, only ~8% of the hydrocarbons require “Carbon Capture”.

The drawbacks of using ammonia and methanol as hydrogen energy carriers are the heat lost during ammonia and methanol production (~10%) and the additional catalysts required. However, this may be preferable to the capital and energy requirements of hydrogen compression. In the hydrogen economies modeled above, approximately 3.5 quads of electricity was used for hydrogen compression alone [24]. Between less water splitting and less compression, the organic scenario required ~15% less electricity than the “Balanced” scenario, and used slightly less energy overall.

Fig. 18 above shows how hydrogen could be created and distributed from the interior of the United States to the coasts using Universal Energy Plants (UEP), auto-thermal reformers (ATR), and hydrogen energy carriers. The Universal Energy Plants are located in the interior of the United States to ensure that they can use the excess transmission capacity to purchase cheap renewables when available. The byproducts of electrolysis are transported to auto-thermal reformers where they are combined with hydrocarbons and steam to make emissions free energy carriers. The energy carriers are distributed to load, and the CO_2/H_2O from SOFC's is recycled and sent back to the ATR's or UEP's. CO_2 production is sequestered or used as a commodity for EOR, for example.

Conclusion

The costs of an energy system can broadly be divided in two categories: capital (fixed) and energy (variable). The Thermal Hydrogen system envisioned above is engineered to minimize the capital intensity of a completely decarbonized energy system. This is accomplished by fully utilizing the capacity of the most capital intensive energy suppliers—renewable energy and nuclear energy. Their excess heat and electricity is combined to split water, and then both byproducts are used to decrease the capital intensity of the system. The hydrogen (or CO) is used to provide seasonal heat and electricity storage, reducing the total low carbon electricity capacity required. Relatively small fuel cells can provide range and reduce the

need for batteries by an order of magnitude. The pure oxygen negates “Carbon Capture” and enables less capital intensive thermodynamic cycles for hydrocarbons.

With the capital intensity of the system significantly reduced, the question then turns to energy efficiency, and this is where most skepticism remains for hydrogen. Most reason that both the creation and use of hydrogen must necessarily result in wasted heat. This would be true if the services of hydrogen were limited to that of a battery—i.e. just electricity storage. However, it is named *Thermal Hydrogen*, in part, because most of the hydrogen, over 80%, comes from heat. And then most of the hydrogen is used for heat related energy services—either through combustion, combined heat and power, or by preventing the heat loss caused by rolling resistance (heavy batteries). In addition, the pure oxygen from water splitting enables hydrocarbons to use the most efficient pathways possible. On an economy-wide basis, I've shown that hydrogen could be nearly as efficient as electricity if it is used as an energy carrier for both electricity and heat.

In conclusion, the costs of an energy system are capital and energy. The all-electric vision might require the least amount of energy, but it is hopelessly capital intensive. The promise of Thermal Hydrogen is an emissions free economy that is both capital and energy efficient—not by leaving certain energy suppliers and carriers behind, but by enabling all energy suppliers through the creation of a new energy carrier.

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