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What is the Demand for Low-Carbon Liquid Hydrocarbon Fuels and Feedstocks?

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Abstract

Liquid hydrocarbons made from crude oil serve many functions: (1) a dense, easy-to-store, easy-to-transport energy source, (2) a method for daily-to-seasonal energy storage, (3) a chemical feedstock, (4) a chemical reducing agent and (5) a method to enhance high-temperature heat transfer in many furnaces and industrial processes. There are multiple methods to produce and use liquid hydrocarbons without increasing atmospheric carbon dioxide levels including (1) negative carbon emissions to balance carbon dioxide releases from burning crude-oil products and (2) producing liquid hydrocarbons from non-fossil feedstocks such as carbon dioxide or biomass. Understanding liquid hydrocarbon demand is the starting point in assessing options for producing and using liquid hydrocarbons without increasing atmospheric carbon dioxide levels. Our assessment is that U.S. demand for liquid hydrocarbons is unlikely to go below the equivalent of 10 million barrels per day of crude oil. The costs to replace liquid hydrocarbons increases rapidly at lower liquid hydrocarbon consumption rates. Hydrocarbon biofuels from cellulosic feedstocks can meet such demands but options based on more limited feedstocks (bio oils, sugars, etc.) can't meet such demands.

Keywords: Liquid Hydrocarbons, Liquid fuel demand, Biofuel.

I. INTRODUCTION

Unless we find a drop-in replacement for oil, we must not only replace oil but much of the U.S. infrastructure: pipelines, refineries, cars, aircraft, furnaces, chemical processes and a myriad of other systems. The development and deployment of oil-replacement technologies will take decades and trillions of dollars. *However, climate change (and probably the finite nature of oil supplies) must be effectively addressed on a significantly shorter timescale.*

Liquid hydrocarbons (gasoline, diesel, jet fuel, chemical feedstocks, etc.) are primarily made from crude oil with smaller quantities made from coal, natural gas and biomass. They are made from crude oil because it has been the lowest-cost feedstock. If crude oil had never existed, it is likely civilization would have invented these fuels and found feedstocks to produced them because of their useful properties. These hydrocarbons (C_xH_y) can be made in unlimited quantities from natural sources of carbon dioxide (such as from air or ocean) and large quantities from biomass. In both cases there is no net addition of carbon dioxide to the atmosphere. Stopping greenhouse gas emissions does not depend on whether we burn and use liquid hydrocarbons as fuels and chemical feedstocks. Stopping greenhouse gas emissions is about (1) changing the feedstocks used to produce liquid hydrocarbons or (2) finding replacements for the use of liquid hydrocarbons.

If carbon dioxide (CO_2) is the feedstock for production of liquid hydrocarbons, large quantities of hydrogen are required to remove the oxygen and add hydrogen to the carbon. If cellulosic biomass is the feedstock there is a tradeoff between the amount of biomass and hydrogen needed to produce a unit of hydrocarbon liquid product. Recent studies [1] indicate the potential for the U.S. to produce up to 30 million barrels per day of liquid hydrocarbons from cellulosic biomass at prices near $70/barrel of oil equivalent assuming that the cost of hydrogen is $2/kg. As a point of comparison, the U.S. currently consumes 18 million barrels of oil per day.

Different routes to decarbonization have different transition times and different costs. The starting point (this paper) is to understand the demand for liquid hydrocarbons and what part of that demand can be economically met with alternative technologies and where liquid hydrocarbons from alternative feedstocks are the preferred option.

II. EXISTING LIQUID HYDROCARBON (OIL) DEMAND

In 2019 oil was 36.7% of the primary energy input to the U.S. economy but supplied 48% of the total energy input to the final customer [2]. If one can replace crude oil with alternative feedstocks to produce liquid hydrocarbons, one decarbonizes about half the U.S. economy. The first use of fossil fuels is for energy production but included in those numbers are fossil fuels used as a feedstock for the production of various goods ranging from drugs to plastics. Many of these products contain carbon and a carbon-containing feedstock is required. Today the primary chemical feedstocks are oil and natural gas. Fossil fuels are also used as a chemical reducing agent to convert materials such as iron ore into iron. Coal in the form of coke is the primary chemical reducing agent but natural gas and liquid hydrocarbons can be used. Figure 1 shows the breakdown between the uses of fossil fuels in the U.S. industrial sector for energy versus these other uses of fossil fuels. About 6% of total fossil fuel consumption is not for energy production, but for these non-energy uses of fossil fuels that depend upon the chemical characteristics of these fuels. When considering the future demand for liquid hydrocarbons, these uses are the energy equivalent of 2.4 million barrels of oil per day.

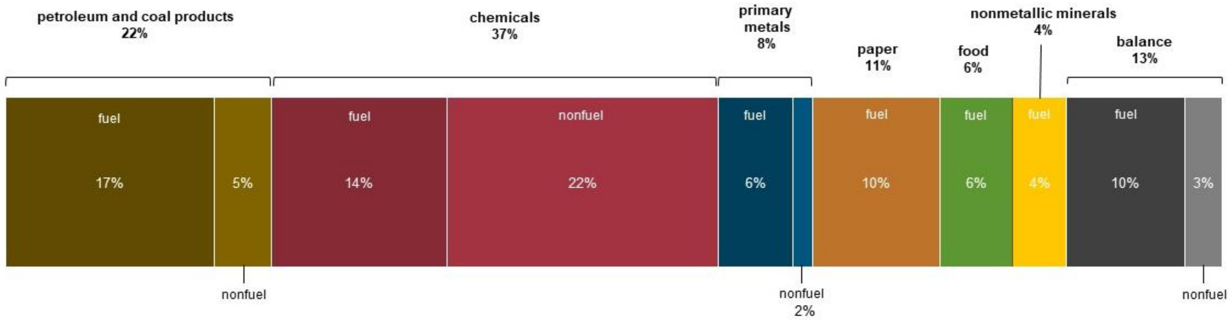

Fig. 1. Manufacturing energy fuel and nonfuel consumption by industry, 2018 (%) [3]

Table 1 shows the products produced from crude oil in the United States [4]. Total oil consumption is about 18 million barrels per day. The largest single use is gasoline for transport, representing a demand of about 8 million barrels of crude oil per day. However, many other products are also produced; thus, the challenge is replacing all the hydrocarbon products produced from crude oil.

III. LIQUID FUEL TRANSPORT DEMAND

Liquid hydrocarbon fuels are used in transportation because of their high energy density per unit volume and mass compared to any other class of chemicals that exist as liquids at near atmospheric pressure and temperature. If fossil fuels did not exist, it may well be that diesel and jet fuel would have been discovered and manufactured for their remarkable properties including high energy density and safety in handling. There are severe economic penalties involved in transitioning from hydrocarbon fuels to batteries or other energy sources in aircraft or heavy trucks where an added kilogram of fuel necessarily requires one less kilogram of cargo. Aviation consumes about a million barrels per day and diesel fuel consumption is the equivalent of about 3 million barrels of oil per day.

TABLE 1. PRODUCTS PRODUCED FROM CRUDE OIL IN THE UNITED STATES

Products (U.S.)	**Consumption (10^6 b/d)**
Gasoline	8.034
Distillate fuel oil (diesel & heating oil)	3.776
Hydrocarbon gas liquids (HGLs)	3.197
Kerosene-type jet fuel	1.078
Still gas	0.611
Asphalt & road oil	0.342
Petrochemical feedstocks	0.286
Petroleum coke	0.260
Residual fuel oil (Shipping)	0.217
Miscellaneous products & other liquids	0.152
Lubricants	0.100
Special napthas	0.045
Aviation gasoline	0.011
Kerosene	0.008
Waxes	0.004
Total	18.120

The largest U.S. crude oil market is for cars and light trucks—about 8 million barrels per day of oil equivalent in the form of gasoline. The continued efficiency improvements in cars and trucks [5] reduces this demand over time. The future light-duty vehicle fuel options [6] include (1) replacement of fossil-fuel gasoline with biofuels or hydrogen, (2) hybrid vehicles, (3) plug-in hybrid vehicles and (4) all-electric vehicles. Hybrid vehicles burn some type of fuel and have batteries on-board. When the vehicle slows down or goes down the hill, the battery is charged. When the vehicle accelerates or goes up the hill, the battery provides power. The battery enables the engine to operate in its most efficient modes most of the time. It has been estimated that an all-hybrid fleet could reduce gasoline consumption by up to 30%.

Plug-in hybrid vehicles have a heavier battery package that enables the vehicle to go on shorter trips without using the motor and to recharge by plugging into the electrical grid. A combustible fuel is used on longer trips. The owner can use fuel or electricity depending upon their relative prices. All-electric vehicles have larger battery packages to enable longer distances and significantly higher costs partly driven by the costs of raw materials in the batteries.

The choice of vehicle technology has massive economic and social implications. Internal combustion engine (ICE) vehicles have the lowest initial costs while all-electric vehicles have the highest costs. Most of the ownership cost of cars is the initial cost of the vehicle—the fuel costs are a smaller fraction of lifetime ownership. Social decisions to electrify light vehicles reduces the standard of living of the bottom 60% of society because the primary expenditure is in the vehicle, not the fuel.

Unless there are radical changes in battery chemistry, electric vehicles will remain significantly more expensive than ICE vehicles because of the much larger quantities [7] of higher-priced materials such as lithium, nickel, and cobalt in these systems. Light vehicles with ICEs are cheap to manufacture because they are made of low-cost materials—mostly steel (iron and carbon) and plastic (carbon and hydrogen). With only a small number of exceptions, the cost of any material is inversely proportional to its abundance in the earth's crust. The existing car batteries are made of relatively non-common elements resultin in higher costs than ICEs.

The battery cost challenge is seen in the EIA [8] survey for the total capital cost of installed utility storage batteries over time. The capital cost has leveled off above \$500/kWh. The earlier decreases in capital costs were driven by scaling up production. The leveling off partly reflects the larger fraction of total costs associated with the materials of construction. The projected demand [7] for lithium, nickel and other battery materials is expected to increase by more than a factor of 10 with the expectation of rising prices for several decades as new mines come into production to meet the larger demand.

Plug-in hybrid electric vehicles and all-electric vehicles obtain much of their energy from the electricity grid; thus, their economics must include the impacts on the grid where the two types of vehicles may have radically different impacts on the cost of electricity delivered *to all customers*—not just vehicle owners [9].

About 40% of the delivered cost of electricity is associated with transmission and distribution [10], the balance is in the cost of electricity production. If the additional electricity demand occurs at times of existing peak electricity demand, large expansions of the electricity grid are needed that increase electricity prices for *every customer*. In contrast, if there is added electricity demand at times of low total electricity demand, the average price of electricity may go down because the grid is delivering more electricity to the customer without grid expansion. The fraction of the cost of delivered electricity from building and maintaining the grid goes down.

From the perspective of the electricity grid, there is a major difference between all-electric vehicles and plug-in hybrid electric vehicles. With a plug-in hybrid vehicle, there is assured transportation for the vehicle owner if the battery is not charged by burning a combustible fuel. It is viable to limit recharging to times of lower electricity demand resulting in greater utilization of the transmission/distribution system and thus lower the average cost of delivered electricity for all electricity customers. In this context, a recent study [11] examined likely times when electric vehicles will be recharged and found that most recharging will be done in the early evening shortly after the sun sets—the time of peak daily electricity demand. This recharging pattern is caused by work schedules and single car families that want assured car availability. Such an electric-vehicle future results in an expensive electricity system for everyone.

A recent review [9] of the many studies on all-electric vehicles concluded "Overall, a complete benefit-cost assessment, even at the regional scale, is still missing that considers the entire extent of values, enablement costs, and the perspectives of all stakeholders, including the utilities, EV owners, charging station owners and rate payers." From the perspective of the electricity grid, an all-electric vehicle fleet implies large grid and power plant capacity expansion to meet a peak demand and likely major increases in electricity prices to all customers.

The above considerations suggest long-term decreases in light-vehicle demand for liquid transport fuels; but, rapidly increasing costs to society if attempt to fully electrify the light-vehicle fleet. Plug-in light-duty hybrid vehicles avoid most of these challenges because they combine the cheap storage capabilities of liquid hydrocarbon fuels on an hourly to seasonal basis with the capability to recharge much smaller batteries when low-cost electricity is available. While one can make a case to reduce combustion fuel demand by two thirds for light-vehicle transportation via electrification, complete electrification is likely to become very expensive.

IV. ENERGY STORAGE DEMAND

Fossil fuels provide two primary functions: (1) an energy source and (2) a low-cost energy storage system that enables energy production to better match energy demand. The storage challenge may create a major long-term demand for cheap-to-store liquid hydrocarbons. We use about 100 quads of energy per year in the U.S. with about 6 weeks of stored energy with more energy storage in the winter and less in summer. U.S. energy storage includes a 90-day supply of oil, a 30-day supply of natural gas, over a 100-day supply of coal and 6 to 9 months of nuclear fuel in reactors. Energy storage addresses daily to seasonal changes in energy demand while providing assured energy in the face of hurricanes, earthquakes, and multi-week weather events. Six weeks of storage is 3.4 million GWhs; that is, the U.S. storage requirements are measured in millions of gigawatt-hours [12]. A million gigawatt hours requires about 1.8 million barrels of oil equivalent per day.

To understand the scale of the energy storage challenge, consider options to provide a million gigawatt hours of storage for the electric sector. The U.S. Energy Information Agency [8] reports installed costs of utility-scale batteries over time with costs leveling off near $500/kWh. A million gigawatt hours of storage is $500 trillion—about 20 times the size of the U.S. economy. Today 99% of U.S. electricity storage is hydroelectric pumped storage—553 GWh [13]. The costs are substantially less than batteries [14]. If we use hydro pumped storage, we would need to expand the total U.S. pumped storage capacity by a factor of 1800 for a million gigawatt hours of electricity storage.

The addition of non-dispatchable wind and solar may dramatically increase storage requirements in the electric sector. The U.S. Energy Information Agency [15] has estimated the levelized cost of electricity for solar ($31.30/MWh), on-shore wind ($31.45/MWh) and offshore wind ($115.04/MWh) in good locations. The levelized cost of storage using batteries is $121.86/MWh—about four times higher than the cost of making electricity. Today stored natural gas burnt in gas turbines with low storage costs enables wind and solar by avoiding the high cost of battery systems while providing assured supplies of electricity. The question is what replaces natural gas in its role as stored energy—one option is the use of liquid hydrocarbons.

Separately there is the seasonal storage challenge. In the United States most of the heating demand is met by burning natural gas. The peak monthly demand for natural gas in January over the base-load demand for natural gas is about equal to the total electricity production [16]. There is about a factor of two difference in the seasonal output of solar at the mid-latitudes [17] that peaks in summer implying a massive added seasonal impact on energy storage requirements if any significant amount of the heating load is provided by electricity from solar. This seasonal storage challenge is met by fossil fuels, primarily natural gas. If cheap-to-store liquid hydrocarbons replace any significant fraction of this demand, it implies a major increase in liquid hydrocarbon demand.

From a broader perspective, in a low-carbon world, there are only four affordable energy storage options at the million gigawatt hour scale [12].

Nuclear fuel. Most nuclear reactors are refueled every 18 to 24 months in the United States. Reactors have massive quantities of energy storage in the form of nuclear fuel.

Gaseous fuels. A large fraction of the hourly to seasonal variations in energy demand is met by natural gas stored in massive underground storage facilities that decouple steady-state production from demand. The projected path forward is a conversion of gaseous fuels to hydrogen that can use the same underground storage system [16, 18].

Liquid hydrocarbon fuels. This is the primary form of energy storage for the transport sector but also a storage mechanism for heating demand and electricity production.

Heat storage. Heat storage has not been historically used on a large scale because of the availability of storable fossil fuels, but heat storage may become important in a low-carbon economy. The heat source for storage can be nuclear, concentrated solar power or low-price electricity converted to heat.

Systems [19] have been developed (Fig. 2) that integrate heat storage, liquid hydrocarbons, and hydrogen with electricity generation. Such systems are used in some existing concentrating solar power (CSP) plants and are planned for advanced nuclear plants. Cold fluid from heat storage is heated by a nuclear reactor or CSP facility with hot fluid sent to a hot storage tank. Hot fluid from the storage tank is sent to the power block to produce electricity and/or to supply industrial heat users. The peak power block output may be several times the peak output from the nuclear or CSP facility. Heat storage capacity may enable energy storage for up to a week. If very low-price electricity is available, it can be converted into stored heat for later use. Seasonal peak demands can be met by using energy sources such as liquid hydrocarbon fuels and hydrogen to heat the storage fluid.

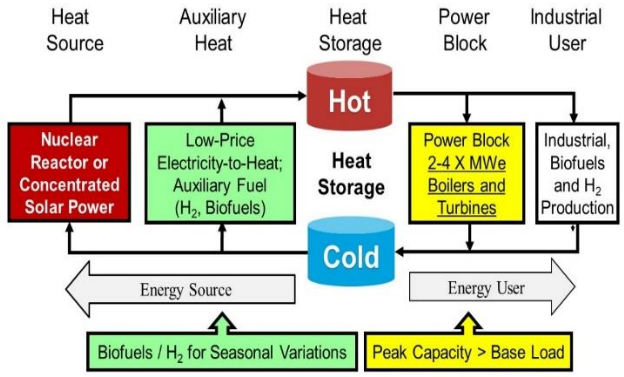

Fig. 2. Variable Heat and Electricity with Heat Storage to Match Production with Demand

The question is what replaces the several million gigawatt-hours of very-low-cost energy storage provided by fossil fuels? *Transfer of any significant fraction of the energy storage currently in the natural gas or coal systems results in millions of barrels per day of liquid hydrocarbon fuel demand*.

V. NEW MARKETS

Fossil fuels are embedded into our industrial economy to meet requirements that are not generally recognized. We have identified one such "new" market but there may be other markets that have not been recognized and that represent a hidden demand for liquid hydrocarbons.

The high-temperature heat demands (>500ºC) of industry are primarily met by burning fossil fuels. Most energy studies assume that future high-temperature heat needs will be provided by electrical heating or burning of hydrogen. However, in most high temperature processes heat is partly or primarily transferred from the burning fuel to the colder object via radiative heat transfer. Radiative heat transfer makes a campfire feel warm and is enabled by carbon particles in the flame which convert heat energy into a form that can be radiated to the person.

In contrast, if hydrogen is burned or air is electrically heated, there is almost nothing in the hot gases to convert that heat into radiant heat. In hydrogen facilities this creates a safety challenge [20] where burning hydrogen from a leak is not be visible and may not be radiating large quantities of heat. Special sensors are used to detect such burning hydrogen to detect fires and prevent people from walking into super-hot invisible flames.

Some carbon may need to be added to hydrogen [21] or electrically-heated hot air in high-temperature applications to transfer high-temperature heat from non-fossil energy sources to whatever is being heated. The quantities of hydrocarbon fuels for such uses is not well understood.

VI. CONCLUSIONS

The U.S. Energy Information Agency [22] business-as-usual case for the United States shows small changes in total liquid hydrocarbon demand between now and 2050. Electric and hybrid vehicles may reduce gasoline demand but increases in areas such as air travel increase the demand of other liquid transport fuels. The business-as-usual case reflects the economic reality of the unique characteristics of hydrocarbon fuels that make finding economic replacements very difficult.

Based on the above considerations, our engineering judgement is that the likely liquid hydrocarbon demand for the United States in a low-carbon world is near 10 million barrels of oil equivalent per day but under some circumstances could be as high as 20 million barrels of oil equivalent per day. This assumes large policy and tax incentives to minimize fossil fuel consumption. Stated another way, the costs of reducing liquid hydrocarbon demand below 10 million barrels per day becomes very high—significant increases in hydrocarbon fuel prices have limited impact on demand because of the unique functional characteristics of these liquids. The higher estimates of liquid hydrocarbon demand occur when constraints on (1) vehicle electrification because of increasing prices for nickel, lithium and other battery materials and (2) replacing some of the energy and energy storage functions of natural gas and coal. The likely competition in these energy/storage markets is hydrogen as a replacement for natural gas and coal.

Such demands have major implications on viable options for liquid hydrocarbon fuel production. In terms of biofuels, such quantities are only possible if the feedstock is abundant cellulosic biomass [1]. The resource base for traditional biofuels (plant oils, sugars, carbohydrates, etc.) are insufficient at this scale. If liquid hydrocarbons are made from natural carbon dioxide sources, one needs a very large resource base such as air or seawater—secondary carbon dioxide feedstock resources are insufficient. The costs of hydrocarbon liquid fuels from carbon dioxide feedstocks is substantially greater than from biomass because of the greater energy input to capture and convert carbon dioxide into liquid hydrocarbons. The third option is using crude oil with offsetting negative carbon emissions—but where the total negative emissions potential is not well defined.

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