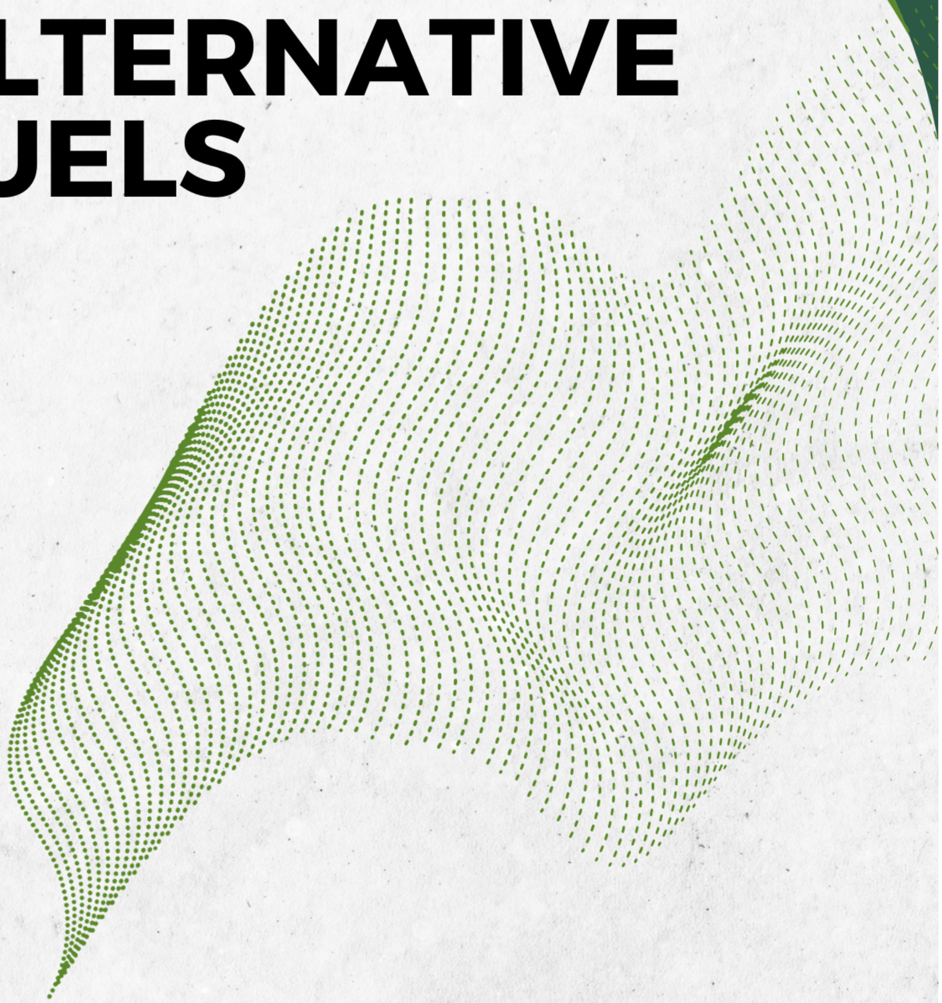
GREEN ALTERNATIVE FUELS



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Green Alternative Fuels

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Executive Summary

The success of the net-zero transition hinges on appropriate manufacture and use of alternative fuels in combination with a large-scale transition to carbon-free electrical power for much of the current fossil-fuel based economy. “Green” fuels, such as hydrogen and ammonia, are promising alternatives to fossil fuels because, if produced and used appropriately, they can deliver energy in a carbon-free manner.

The validity of proposals for the use of green alternative fuels hinges on:

1. Having no greenhouse gas emissions associated with the fuels over their life cycles
2. Appropriate use of such fuels for energy storage and transfer in a net-zero-emissions economy.

Moreover, it is important to emphasize that alternative fuels are not a one-to-one substitute for fossil fuels. Not only do they have low energy efficiency, but they also require carbon-free electricity for their production - electricity that could be more efficiently used directly in electrical applications. A key principle for implementation of alternative fuels like hydrogen and ammonia is to limit their use to applications where direct electrification is not possible.

When appropriately used, hydrogen production would account for **less than 8%** of the renewable electricity demand in a 2050 net-zero US economy, and would deliver no more than 3% of the total economy-wide energy demand. Examples of appropriate use of green alternative fuels include long-haul trucking and shipping, aviation, military applications, and the manufacture of steel.

The production of green alternative fuels must be consistent with “three pillars” as set out in the Hydrogen Production Tax Credits - additionality (new clean electricity supply), deliverability (clean electricity delivered from local sources), and hourly matching (accounting of clean electricity use in hydrogen production on an hourly basis). These guardrails are essential for preventing the undesired effect of an increase in emissions from fossil-fuel-based power generation. To advance the net-zero goal for 2050, the pillars must be a non-negotiable set of conditions upon which all green fuel production is based**.**

All fuels are lossy - when they are consumed they do not deliver the total amount of energy invested in their production, distribution and storage. They also can escape into the atmosphere during their production, distribution, storage and use. Preventing leakage of candidate green fuels such as hydrogen and ammonia is challenging. Moreover, leaked hydrogen chemically prolongs the lifetime of methane in the atmosphere, thereby contributing to global warming.

While green fuels can be consumed without producing CO_2-equivalent emissions or harmful pollutants, their production can generate significant CO_2-equivalent emissions. Moreover, when combusted in air they produce harmful pollutants. The promise of “green” production and “green consumption” is no guarantee that the actual methods of production and use are “green”. Most production methods of alternative fuels involve the use of fossil fuels as feedstock and/or the combustion of fossil fuels to generate the electricity used to produce the alternative fuels. These “gray” methods are often sold as “blue methods” when combined with carbon capture and sequestration, ostensibly to collect all the emissions associated with their production. Closer scrutiny of such proposals reveals that “blue” alternative fuels have significant net

CO_2-equivalent emissions associated with their production. Truly green alternative fuels require green electricity and carbon-free feedstock.

When green processes are not used to produce them, alternative fuels become false solutions to the problem of lowering greenhouse gas emissions. Manufacturing hydrogen or ammonia from fossil fuels perpetuates fossil fuel production and consumption without providing reductions in greenhouse gas emissions. Alternative fuel production from carbon-free feedstock using electricity from power plants that use fossil fuels also perpetuates fossil-fuel production and consumption. The use of carbon capture and sequestration to reduce the greenhouse gas emissions from the power plants requires considerable energy and does not address the emissions created in the process of extracting and refining the fossil fuels consumed. Such false solutions impede progress towards a net-zero economy.

The severity of the climate crisis, along with the interest in creating incentives to drive needed changes, creates opportunities for exploitation by special interest groups. Such groups propose activities that ultimately do not address the climate crisis and pose risk for exacerbating the situation. Some of these proposals are based on outright falsities and are deliberately misleading - for example, blending of hydrogen with natural gas, carbon capture for oil extraction, and carbon capture for fossil-fuel-fired power plants. Others require questionably large investment for the small potential net benefit - for example, “renewable” natural gas as a significant source of energy, and renewable green fuels as a means to power much of the economy. Proposals for these false solutions are supported by specious arguments made by special interest groups whose actions suggest that their own economic gain is prioritized over achieving net-zero goals. Supporting and implementing such proposals will jeopardize our future.

This paper examines the potential uses of green fuels, the energy and emissions costs of using them, the core principles of using them to best effect, and the limits to their use in a net-zero economy. We conclude that there is a limited role for alternative fuels and that too large a role for alternative fuels could impede the transition to a net-zero-economy. Finally, we provide specific guidelines for how they should be integrated into a net-zero electrified economy, including strict adherence to the “three pillars”.

Glossary and List of Units

Annual average power

The energy stored in fuels is consumed in varying amounts at various times. On average, the total annual production of fuel is consumed over a year. The equivalent power provided by the fuel can be found by dividing the total energy content of the quantity produced annually by the time in a year. For example, kWh of energy provided divided by 8760 hours in a year gives the average power in kW. In similar fashion the energy required to make the total annually produced quantity of a fuel can be expressed as an average power demand.

The use of average power is helpful for comparing energy demand and supply from a variety of sources. In this way, energy content in fuels and electricity demand can be compared directly. A useful benchmark for power delivery is the U.S. national grid capacity, which is about 1200 billion watts (GW), or 1.2 TW. Individual power plants provide billion-watt (GW) capacities. For example, Hoover Dam has a 2 GW capacity and generates about 0.5 GW of average power on an annual basis.

The energy recovered from fuels is less than their energy content. It is therefore important to consider efficiencies when assessing the electrical power required to replace a given fossil fuel demand. In general, one finds that replacing fossil-fuel-powered equipment and processes by modern electrically powered equipment reduces the energy demand considerably. Two notable examples are the replacement of internal-combustion-engine vehicles by battery-electric vehicles and replacement of forced-air natural-gas-powered furnaces by heat pump systems.

Green alternative fuels

The term “green alternative fuels” refers to fuels that use carbon-free electricity and have no net greenhouse gas emissions associated with their production, distribution, and use. Some of these fuels are also considered to be “zero-carbon” fuels, as they do not contain carbon and do not produce carbon dioxide emissions when consumed. Hydrogen and ammonia are two examples of zero-carbon green alternative fuels that have been proposed as alternatives to fossil fuels or as a way to provide energy through their use in fuel cells. While there are “green” methods being developed for producing these chemicals, current production methods generate greenhouse gas emissions and other forms of pollution. Therefore, green energy proposals that involve green alternative fuels must be scrutinized carefully to understand if the proposal will result in significant emissions reductions, taking the life cycle of the fuel fully into account.

Greenhouse gas emissions

Greenhouse gases (GHGs) warm the Earth by absorbing and emitting energy, thereby slowing the rate at which the energy escapes to space; they act like a blanket insulating the Earth. Different GHGs can have different effects on the Earth's warming. Two key ways in which these gases differ from one other are their ability to absorb energy (their "radiative efficiency"), and how long they stay in the atmosphere (their "lifetime").

The Global Warming Potential (GWP) allows comparisons of the global warming impacts of different gases. It is a measure of how much energy the emissions of 1 tonne of a gas will absorb over a given period of time, relative to the emissions of 1 tonne of carbon dioxide (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The time period traditionally used for GWPs is 100 years, although recently shorter time periods (20 years) have come into vogue in recognition of the impact of methane (natural gas). GWPs provide a common unit of measure, which allows analysts to add up emissions estimates of different gases (e.g., to compile a national GHG inventory), and allows policymakers to compare emissions reduction opportunities across sectors and gases. The GWP reflects the combined effects of heat absorption and lifetime for a greenhouse gas. For greenhouse gases other than CO_2 the GWP is used in determining the equivalent amount of CO_2 emissions, or CO_2e, that would produce a comparable warming effect to that of the non-CO_2 emissions.

CO_2 has a GWP of 1 regardless of the time period used, because it is the gas being used as the reference. CO_2 remains in the climate system for a very long time: CO_2 emissions cause increases in atmospheric concentrations of CO_2 that will last thousands of years.

- Methane (CH_4) is estimated to have a GWP of 27-30 over 100 years, but a GWP exceeding 80 over an initial period of 20 years. CH_4 has a considerably shorter half-life than CO_2. But as indicated by its higher GWP CH_4 absorbs much more energy than CO_2. The net effect of the shorter lifetime and higher energy absorption is reflected in its 100 year GWP being much smaller than its 20 year GWP. Reductions in methane emissions will have a more significant short term impact on curbing climate warming than reductions in carbon dioxide emissions. The CH_4 GWP also accounts for some indirect effects, such as the fact that CH_4 is a precursor to ozone, and ozone is itself a GHG.
- Nitrous Oxide (N_2O) has a GWP 273 times that of CO_2 for a 100-year timescale. N_2O emitted today remains in the atmosphere for more than 100 years, on average.)
- Chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are sometimes called high-GWP gases because, for a given amount of mass, they trap substantially more heat than CO_2. The combined effects of chemical stability and heat absorption result in GWP values in the thousands or tens of thousands.
- Investigation of the GWP of hydrogen is a relatively recent development, which requires more serious attention than it has received, given the leaks of this gas that can be anticipated if the volumes of production of green hydrogen grow substantially (up to 5+ times) compared to the current volumes. One recent paper presents the current state of understanding of hydrogen's indirect GWP potential through its interactions with other gases in the atmosphere.[1] Its 100 year GWP is estimated in the range of 9-14. Four main climate impacts are associated with increased hydrogen levels: (1) longer methane (CH_4) lifetime and hence increased methane concentrations, (2) enhanced

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[1] See Sand, M., Skeie, R.B., Sandstad, M. *et al.* A multi-model assessment of the Global Warming Potential of hydrogen. *Commun Earth Environ* **4**, 203 (2023). https://doi.org/10.1038/s43247-023-00857-8

production of tropospheric ozone (O_3), which is harmful to health, and changes in stratospheric O_3, (3) increased stratospheric water vapor (H_2O) production, and (4) changes in the production of certain aerosols.

Pressure

psi	pounds/square inch. Atmospheric pressure is roughly 14.7 psi at sea level.
psia	absolute pressure in psi.
psig	"gauge pressure" or the pressure relative to the 1 atmosphere background in psi. A gauge pressure of 30 psi is approximately 44.7 psia
Pa	Pascal or N/m^2. One atmosphere is approximately 0.1 million Pa (0.1 MPa), or 100 thousand Pa (100 kPa). 1 bar = 100,000 Pascal = 100,000 Newtons(N)/m^2 = 100,000 N / (100*100 cm^2) = 10 N/cm^2

bar - one bar is one atmosphere

Standard temperature and pressure (STP)

The current International definition of STP is a temperature of 273.15 K (0 °C, or 32 °F) and an absolute pressure of 10^5 Pa (100 kPa, or 1 bar).

Mass

kg	on Earth, 1 kg of mass weighs approximately 2.2 pounds (lbs)
tonne	Metric Ton, or 1000 Kg (roughly 2200 lbs). Herein we use "t" to refer to a metric ton or tonne.

Power

W	Watt. One Watt represents energy flow of 1 Joule/second (J/s).
kW	kilowatt, or 1000 W

Energy

Wh	Watt-hour. 1 Wh is the amount of energy transferred by a power of 1 W in 1 hour. As 1 hour is 3600 sec, 1 Wh is the equivalent of 3600 J.
kWh	One kWh is 1000 Wh. One TWh (terawatt hour) is 10^{12} Wh or 10^9 kWh. 1 Gigajoule (10^9 joules) is the equivalent of 277.8 kWh, and 1 Megajoule (MJ) is the equivalent of 277.8 Wh or 0.2778 kWh.
BTU	The British Thermal Unit is a measure of thermal energy - the amount of energy required to increase one pound of water on degree Farenheit. One BTU is the equivalent of 1,055 Joules (J), and 0.2931 Wh.

Direct electricity vs. Indirect Electricity

Electricity is used directly as a source of energy for lighting, heating, cooling, and refrigeration and for operating appliances, computers, electronics, machinery, and public transportation systems (and more recently private transportation systems such as BEVs – battery electric vehicles).

In contrast, indirect electricity refers to applications in which electricity plays a role in producing fuels that are then used as the direct source of energy in an application, to generate heat via combustion or electricity in fuel cells. In electricity-to-fuel-to electricity supply chains there is a loss of energy at each stage of energy conversion, which can be significant and reduces the overall or end-to-end energy efficiency of the application compared to those applications where electricity can be used directly.

Energy per mass of fuel

Energy content of a fuel is often expressed as terms of the energy released in combustion of the fuel in oxygen. The combustion process produces water vapor and condensing this water vapor releases a significant amount of energy. The High Heating Value (HHV) calculation includes this energy while the Low Heating Value (LHV) does not. Energy content per mass of fuel is generally expressed in terms of its LHV.

Typical values for the LHV are stated in millions of Joules per kilogram, or MJ/kg. They can also be expressed in terms of kWh/kg. Energy required to produce a given mass of fuel can be expressed in similar fashion. Because large production quantities are often discussed, larger units are used. For example, 10 kWh/kg is the equivalent of 10,000 kWh/tonne, which is the same as 10 MWh/tonne, or 10 MWh/t.

In the case of ammonia (NH_3) the fuel can be consumed directly, or it can be split to recover just the hydrogen content. If ammonia is used as a vector for hydrogen, the energy inputs and outputs are often stated in terms of energy per kg of H_2 (e.g. kWh/kgH_2) instead of energy per kg of NH_3 (e.g., kWh/kgNH_3). As the hydrogen molecule is 3/17 the mass of the ammonia molecule, the energy per kg of H_2 is greater than the energy per kg of NH_3 by a factor of 17/3.

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The Need for Alternative Fuels

Over the past decades, scientific research has clarified the extent to which accumulation of anthropogenic greenhouse gases in the Earth's atmosphere has impacted the climate, and the evidence of perilous consequences continues to grow. More than three decades ago, at the Toronto Conference on the Changing Atmosphere, scientists warned that consequences of not addressing climate change could have consequences "second only to a global nuclear war" [1]. As floods, droughts, wildfires, hurricanes, and other natural disasters are playing out with increasing frequency, populations are experiencing emotions of worry, anxiety, and grief about the consequences of climate change. Studies show that those who are especially vulnerable to the effects of climate change have more profound negative emotions about its perils [2].

The ubiquitous fossil fuels used to provide power for transportation, electricity generation, industrial processes and heat for commercial and residential buildings are responsible for the majority of accumulated carbon dioxide emissions over the past century. For generations, their energy density and relative chemical stability have enabled their widespread integration into the energy supply chain.

A "renewable" source of energy requires a seemingly limitless supply or the ability to regenerate the source of the energy. Energy from wind and the sun have seemingly limitless supply, whereas green fuels - fuels that have no associated undesirable emissions - must be regenerated from the byproducts of their consumption.

When a green fuel is consumed, it produces energy by chemical reaction. To generate the green fuel, the reaction products must be processed to produce new fuel. For example, when hydrogen reacts with oxygen, energy is given off and water is produced. To make more hydrogen fuel, water must be dissociated into hydrogen and oxygen, which requires at least as much energy as was given off by the reaction of hydrogen and oxygen. In general, the energy required to produce the fuel exceeds the energy provided by the fuel. In the case of fossil fuels, that energy was provided by high pressures and high temperatures over geological timescales. By contrast, for lack of a large naturally produced reserve, renewable fuels must be produced more rapidly - at least as rapidly as they are consumed - and the energy demand to produce them is immediate.

> *...renewable fuels must be produced ... at least as rapidly as they are consumed - and the energy demand to produce them is immediate.*

If one draws a parallel between a new energy technology and fossil fuels, renewable energy in the form of wind, water, and solar power have more in common with fossil fuels than do green alternative fuels. Natural forces over geologic time scales created a vast reserve of crude oil and methane. Similarly natural forces provide a vast energy reserve in the form of wind, radiation from the sun, and flowing water. To extract the energy, we harvest what is naturally provided.

Fossil fuels have been perceived as low-cost affordable fuels because large quantities of the unrefined fuels were produced over millions of years. Moreover, the perceived low cost of fossil fuel production has been maintained through a combination of heavy subsidization of the fossil-fuel industry [3] and the lack of proper accounting for the environmental and health costs associated with their use [4]. Over the past several decades and much more recently, geopolitical instability coupled with profiteering has demonstrated that prices for these fuels can be quite volatile in the United States, regardless of local supply and costs of production.

While carbon-free electricity generation from solar and wind power is possible on a variety of scales, sunlight and wind cannot be stored and transported. Therefore, electricity generation from sunlight and wind must be coupled with some form of storage technology to provide a stable source of electricity. Energy storage methods include batteries, thermal energy storage, mechanical storage, hydro storage, and chemical storage [5]. To further reduce or moderate the demands on electricity generation from renewables, energy efficiency improvements in equipment and system designs are also important. For example, modern heat pumps can outperform fossil-fuel powered furnaces, and district heating can make use of waste heat to improve overall energy efficiency of communities.

Coupled with the appropriate storage technology, wind and solar power can be used to provide zero-carbon alternatives to fossil fuel use throughout the economy. The most challenging applications include industrial processes requiring high temperatures (e.g., processes that use blast furnaces), and applications where the amount of battery storage required makes their use impractical (e.g. long-haul trucking). In such cases, the use of zero-carbon or low-carbon fuels becomes attractive. Some analyses suggest that wind and solar power in combination with hydropower and battery storage will provide a stable supply of electricity nationwide [5]. Others see alternative fuels as playing a role in power and electricity generation [6]. Alternative fuels are also believed to be necessary to address the needs in heavy industry and long-haul transportation. Regardless of one's view of the intermittency of solar and wind for electricity generation, there is likely a need for carbon-free fuels that can be stored, transported, and distributed safely.

Truly zero-carbon fuels must not emit carbon dioxide or other greenhouse gases (GHG's) when used to provide energy. Their production processes must also be GHG-emission-free. Two potentially zero-carbon fuels attracting attention are hydrogen [7, 8] and ammonia [6, 7]. Ideally, when combusted in pure oxygen, hydrogen will produce water and heat. Similarly, ammonia will produce water, nitrogen and heat. Furthermore, both of these fuels can be reacted with oxygen electrochemically in fuel cells to produce electricity and water vapor.

Possible combustion applications for these fuels include internal combustion engines, combustion-driven turbines for electricity generation, and replacement of natural gas in furnaces and boilers. While the combustion processes for these fuels do not produce carbon dioxide, their combustion in air generally results in the production of oxides of nitrogen (NO_x) [9,10,11], and nitrous oxide (N_2O) [12, 9, 10, 13]. NO_x has environmentally harmful effects, and N_2O has more than a hundredfold higher global warming potential than carbon dioxide. Further complications involve achieving the desired combustion characteristics with respect to power production and efficiency [9, 11].

The success of the net-zero transition hinges on appropriate manufacture and use of the alternative fuels in combination with a large-scale transition to electrical power for much of the current fossil fuel economy. A combination of carbon-free technologies must be implemented to produce electricity, to store electricity, and to store energy. Zero-carbon fuels hold promise for storing energy in materials that can be transported and distributed for later use in production of heat or electricity.

A rational set of choices for use of the most promising zero-carbon fuels must consider the overall greenhouse gas emissions reduction plan, the ability to produce and use the fuels without such emissions, and the ability to use the fuels without production of other pollutants. Moreover, the safety of the fuel usage in the chosen application, and the risks associated with leakage of the fuels are important considerations.

The same challenges that drive the need for alternative fuels - reduction of greenhouse gas emissions, environmental concerns, and price stability - create implicit constraints on their use. Taking these concerns into account, there is a need to reconfigure the energy economy to be less reliant on fuels and a need to make appropriate choices for the use of alternative fuels.

> *...there is a need to reconfigure the energy economy to be less reliant on fuels and a need to make appropriate choices for the use of alternative fuels.*

The Leaky Bucket

Fuels are like energy buckets; they are a means to store energy for use on demand. The energy storage characteristics of fuels, however, can be compared to those of a leaky bucket. For fossil fuels and green fuel alternatives, the energy invested in producing the fuel is greater than the energy stored in the fuel. Because of the difference between the energy input and the energy content of the fuel, energy is lost before the fuel is consumed.

In the case of fossil fuels, the energy to produce the fuel was provided by natural processes over millions of years. By contrast, the green fuel alternatives are produced relatively quickly using zero-carbon energy and renewable feedstock. Regardless of how the energy input is provided, the difference between energy input and energy content is a form of energy loss - our bucket has leaks.

The energy required to process, store, and distribute fuels constitute additional losses, thus making our bucket even more leaky. As the fuel is consumed, the efficiency with which the energy content is transferred to the intended activity produces yet more leaks in our bucket.

The “well-to-tank” energy cost of producing gasoline is roughly 25% of the energy content of the fuel [14]. The efficiency of internal combustion engines in automobiles is in the range 30% - 40%. From an energy cost perspective, 125% of the energy content of the gasoline is spent and only 30 - 40% is recovered. The net energy efficiency is thus 24 - 32%.

In addition to energy loss “leaks”, fuels can spill or leak during transfer and storage, and the storage vessels can also leak. The smaller the fuel molecules the more challenging it becomes to minimize leaks. Molecular hydrogen is considerably smaller than fossil fuels, having a molecular diameter of about 0.1 nm, compared to 0.3 nm for ammonia and 0.4 nm for methane. Therefore, the challenges for minimizing leakage of green fuels are considerably greater than for methane, which already has well-documented leakage problems, resulting in higher greenhouse gas emissions as well as higher energy bills for natural gas customers.

If losses from the leaky bucket are to be minimized, the fuel is best transported over short distances and stored for short times prior to use.

Estimates for the energy required to produce, compress, and store hydrogen suggest that the energy “cost” for hydrogen exceeds the energy content - lower heating value (LHV) - by roughly 41% (based on information from Refs. 5 and 62 and Table LB1 below). If used in fuel cell applications (e.g. fuel cell vehicles) with efficiencies of 63% (tank to wheel), the net energy efficiency for hydrogen would be roughly 45%. In short, the initial energy loss in producing the fuel is akin to spillage when filling the bucket, and the transport, storage, and efficiency losses are akin to leaks in the bucket. If losses from the leaky bucket are to be minimized, the fuel is best transported over short distances and stored for short times prior to use.

Comparison of Energy Densities - What’s in the Bucket?

The effective energy density of a combustion fuel is related to the energy released through combustion. The energy released through combustion divided by the mass of the fuel is the gravimetric energy density. The combustion energy divided by the volume of the fuel is the volumetric energy density. Energy densities of some common fossil fuels, hydrogen and ammonia are listed in Table LB1.

Gravimetric energy density expresses the relative energy released on a per-mass basis. Highly combustible materials with low molecular weights have high gravimetric energy densities. The volumetric energy density expresses the relative energy released on a per-volume basis. Highly combustible materials with high mass densities have high volumetric energy densities. Diesel and gasoline - common liquid fossil fuels - have comparable gravimetric energy densities in the range of 50 MJ/kg. Because of appreciable mass densities, their volumetric energy densities are considerable - in the range 30 - 40 MJ/L. By comparison, methane and natural gas (which contains methane) have considerably lower mass densities but comparable gravimetric energy densities (~ 50 MJ/Kg).

The volumetric energy density of methane is a thousand fold lower (1/1000) than that of diesel or gasoline. Low volumetric energy density translates to high volumes for practical amounts of a supply of stored energy. Methane and natural gas can be liquified to bring the volumetric energy density closer to that of diesel or gasoline fuel. They can also be stored under high pressure to reduce the storage volume requirements. Both high-pressure and liquid storage methods are used for natural gas.

Table LB1. Energy storage characteristics of some common fossil fuels, hydrogen, and ammonia.

Fuel	Mass density	Gravimetric Energy Density	Volumetric Energy Density	Energy Density, Compressed Gas*	Energy Density, Liquid
	kg/m^3	MJ/kg	MJ/L	MJ/L	MJ/L
Diesel	839	45	38	N/A	38
Gasoline	698	46	32	N/A	32
Natural Gas	0.85 (@STP)	47.1	0.034 (gas @ STP)	7.6 @ 3600 psig and 25 °C	20.8 @-162°C and 14.7 psia
Methane	0.72 (@STP)	50	0.036 (gas @ STP)	8.0 @ 3600 psig and 25°C	21 @-162 °C and 14.7 psia
Hydrogen	0.089 (@ STP)	120	0.011 (gas @ STP)	2.4 @ 3600 psig and 25°C	8.5 @ -260 °C and 14.7 psia
Ammonia	0.76 (@STP)	18.8	0.014 (gas @ STP)	N/A	13 @ -33 °C and 14.7 psia 11 @ 150 psia and 25°C

Energy densities are based on LHV's. Data in the table were obtained or derived from information found in Ref. 11 and Refs. 15, 16, 17, 18, and 19. *Calculations for volumetric energy density of gases use the gravimetric energy density and the ideal gas law. The values for compressed gas are, therefore, approximations.

For hydrogen and ammonia to be practical fuels - whether for combustion or for fuel cell applications - they must be densified for storage and delivery.

Like methane, two green alternative fuels - hydrogen and ammonia - are gases at room temperature. Compared to methane, they have even lower volumetric energy densities. Hydrogen has a high gravimetric energy density - three times that of diesel and gasoline. By comparison, ammonia has a lower gravimetric energy density than diesel or gasoline. For hydrogen and ammonia to be practical fuels - whether for combustion or for fuel cell applications - they must be densified for storage and delivery.

Both hydrogen and ammonia can be liquefied. Ammonia is a liquid at 145 psi at room temperature and also at atmospheric pressure to -33 ºC. Hydrogen is a liquid at atmospheric pressure and -260 ºC. Therefore, the refrigeration requirements are considerably more severe for hydrogen than for ammonia. Hydrogen can be compressed as a gas in high-pressure cylinders to increase the volumetric energy density. Higher volumetric energy densities are achievable for liquid ammonia

Energy Requirements to Manufacture Green Fuels

According to DOE's 2020 PEM electrolyzer stack efficiency targets, 51 kWh of energy is required to produce one kilogram of hydrogen, assuming the 65% electrolyzer efficiency rating achievable in 2022 [19]. An estimate that includes losses in production, compression, and storage is 59 kWh/kgH_2 [5]. The information on the DOE website suggests ultimate electrolyzer stack efficiencies of 77% (referenced to the LHV for hydrogen) and ultimate energy targets of 43 kWh/kgH_2. Some projections are that by 2035 the electrolysis energy cost could drop to 41.5 kWh/kgH_2 and, accounting for compression and storage (5.6 kWh/kgH_2), the energy per kg will drop to 47 kWh/kgH_2 [62]. Thus, for every million tonnes of hydrogen produced per year, the current effective renewable power required is 6.7 GW and is expected to drop to 5.4 GW.

Because capacity factors range from 0.2 to 0.5 for power plants driven by renewable energy sources, a given renewable electricity demand requires generating capacity in the range of double to quintuple (2 - 5 times) the demand. The capacity factor depends on the type of energy source (i.e., solar or wind) and location of the power generating plant. The ability to meet peak demands also requires added capacity. Thus, an average demand of 6 GW can require a generating capacity of 24 GW or higher.

Ammonia is produced by the Haber-Bosch process, in which hydrogen and nitrogen are reacted at elevated pressures and temperatures in the presence of a catalyst [20]. MacFarlane et al present a roadmap for scale-up of ammonia production starting with an initial phase of scaling the current Haber-Bosch production process, followed by a second phase that uses green hydrogen, and a third phase that uses a method that bypasses the Haber-Bosch process, producing ammonia by electrochemical conversion of N_2 to NH_3 [21]. It is important to note that the initial phases using fossil-fuel generated electricity to power the Haber-Bosh process or produce the hydrogen input to the process work against the required rapid transition to net-zero GHG emissions. This point is discussed further in the Prioritize the Right Things section.

For green ammonia production using the Haber-Bosch process and green hydrogen, production scenarios with specific energy consumption of ~9.9 kWh/kgNH_3 have been modeled [22]. Suggested values of specific energy consumption for ammonia production are in the range 10 - 12 kWh/kgNH_3 [23]. Per kg H_2, these values translate to a range of 57 - 68 kWh/kgH_2, and assume 48 kWh/kgH_2 - 55 kWh/kgH_2 for producing the hydrogen feedstock. With expected improvements in electrolyzer stack efficiencies, the energy required to produce 1 kg of hydrogen stored in ammonia could be in the range 51 - 55 kWh/kgH_2. If the ammonia is to be used directly as a fuel, it must be compressed or liquified and stored, and those energy costs are in addition to the values stated above.

The “round trip efficiency” (power-to-fuel-to-power) is estimated to be 38.6% ammonia and 42.6% for hydrogen [24]. If ammonia is used to deliver hydrogen, additional energy of 1.4 kWh/kgNH_3, or 8 kWh/kgH_2 is required to “crack” (i.e. release the hydrogen from) the ammonia [23]. The hydrogen will then need to be compressed and stored at an energy cost of 5.6 kWh/kgH_2. These additional costs further reduce the “round trip efficiency” for using ammonia as a vector for hydrogen.

The energy requirements to produce green fuels translate to significant electricity costs. Levelized costs for renewable electricity are currently in the range of \$0.03 - \$0.05/kWh [25]. (NB: Levelized costs are for electricity generation only and not transmission.) Based on this range of electricity cost, the cost of electricity to produce hydrogen is in the range ~ \$1.25 - \$2.50 per kg H_2. This cost does not account for capital investment, compression and storage, or distribution costs for hydrogen.

The electricity cost for ammonia is in the range ~ \$1.50 - \$3.20 per kg H_2, not accounting for capital investment, “cracking” to recover the hydrogen, compression and storage, or distribution costs. The lower costs are based on improved electrolyzer stack efficiencies (41.5 kWh/kgH_2) for both hydrogen and ammonia, and lower estimates of additional energy costs (9 kWh/kgH_2) for ammonia production; the higher costs are based on current electrolyzer stack efficiencies (51 kWh/kgH_2) and higher estimates of additional energy costs for ammonia production (13 kWh/kgH_2).

In the United States, the approximate annual production amounts for hydrogen and ammonia are respectively 10 million and 17 million metric tons [26, 27]. From the specific energy consumption values stated above - 51 kWh/kgH_2 for hydrogen and 10 kWh/kgNH_3 - one can estimate that “green” production of these fuels would require respective average annual carbon-free electricity demands of 58 GW and 19 GW, not accounting for losses.

For hydrogen, there is an energy cost of 5.6 kWh/kgH_2 for compression and storage. If ammonia is used to store and deliver hydrogen, there is an energy cost of 8 kWh/kgH_2 for cracking the ammonia in addition to 5.6 kWh/kgH_2 for hydrogen compression and storage. These added energy costs increase the annual power demand to 65 GW for annual production of hydrogen and 24 GW for the hydrogen stored in the annual production of ammonia.

Based on projections for 2035 including compression and storage losses, annual production of 10 tonnes of green hydrogen would require an annual average power of 54 GW of carbon-free electricity. The three tonnes of hydrogen stored in 17 tonnes of ammonia would require 22 GW of carbon-free electricity, not accounting for the energy cost of compressing and storing the ammonia.

Using the annual amounts of hydrogen and ammonia stated above one can estimate how much average power they could deliver if used as fuels. The estimates depend on the efficiency of energy conversion for the intended application. In fuel cell applications, assuming a fuel cell efficiency of 63%, the annual amounts of hydrogen and ammonia stated above would deliver respective average powers of 24 and 7.2 GW if used in hydrogen fuel cells. Combustion applications, with their lower efficiencies - lower than 50% - would reduce the respective annualized powers to below 19 GW and 5.1 GW, based on the respective LHV for hydrogen and ammonia. Thus, if green fuels were used to drive turbines to produce the electricity, the effective power demand required to produce the fuels - 58 GW for hydrogen and 19 GW for ammonia - would exceed the delivered power by a factor of 3.1 for hydrogen and a factor of 3.7 for ammonia, not accounting for losses.

> *The notion of large-scale usage of green fuels to address the energy needs of a significant fraction of the economy is … fundamentally flawed and is not supported by the immutable facts concerning the energy requirements to produce them.*

When used in fuel cells, the ratio of power demand to power delivery would be lower - 2.7 for hydrogen and 3.3 for ammonia, taking losses into account. Using the values for electricity demand based on projected electrolyzer efficiencies - 54 GW for hydrogen and 22 GW for ammonia - the respective ratios would be 2.3 and 3.1. These values account for losses associated with compressing and storing hydrogen and cracking ammonia, but do not account for energy costs associated with compressing and storing the ammonia. The notion of large-scale usage of green fuels to address the energy needs of a significant fraction of the economy is, therefore, fundamentally flawed and is not supported by the immutable facts concerning the energy requirements to produce them.

Storage, Distribution, and Safety

Large-scale shipping and pipeline transfer is considerably more challenging for hydrogen than for ammonia [28]. Because of the higher achievable volumetric energy density and somewhat less significant challenges for storage and distribution, ammonia has been considered for use as a hydrogen carrier. The hydrogen stored in the ammonia is then released by a separation process called “cracking” at the point of use [29].

Hydrogen can be stored as a compressed gas under high pressure over relatively long periods. Larger-scale storage is also possible at elevated pressures in geological formations, such as salt caverns. Whether stored in pressurized piping or geological formations, the storage infrastructure for hydrogen requires additional capital investment and the operation, and maintenance costs add to the net cost per kg [30].

Effective storage times for liquid hydrogen and liquid ammonia are limited because of boil-off. The higher boiling point for ammonia makes it possible to keep the boil-off to much lower levels - as low as 0.03% to 0.10% per day [28]. Either fuel in liquid form requires energy to liquefy and store it at sufficiently low temperatures. The longer the liquids are stored, the more energy is expended, thereby lowering the net amount of energy recovered from the fuels.

For small-scale storage of ammonia pressurized bullets at (10 bar) are used. The bullets have a maximum capacity of 270 tonnes [28]. For large scale storage, ammonia is cooled to -33 deg C at 1 bar, and the storage tank capacity ranges from 4,550 to 50,000 tonnes [28].

Both hydrogen and ammonia pose significant safety risks for handling and use. The energy required to ignite hydrogen is 1/15th of the energy required to ignite methane [31]. Ammonia, by contrast, is toxic. Its odor threshold of 5 ppm is considerably lower than the concentration at which short term exposure is potentially dangerous (35 ppm) or at which it can cause harm (100 - 1000 ppm) [32]. For social acceptance of hydrogen or ammonia, leaks and accidents will have to be minimized as production, storage, and distribution are scaled up.

Depending on intended application, distribution of the fuel can be to point of sale or directly to appliances in residential and commercial buildings. An example of direct distribution to appliances is the blending of hydrogen with natural gas for heating and cooking. The motivation for blending is to improve energy efficiency and reduce natural gas usage.

The National Renewable Energy Laboratory (NREL) has assessed the technical aspects of blending hydrogen with natural gas from low levels to completely replacing the natural gas with hydrogen. A report issued by NREL clearly states the challenges with such a strategy [33]. Among the concerns are the impact of hydrogen on the integrity of the pipes and distribution lines, flame stability at high concentrations of hydrogen, and the need to modify appliances as the hydrogen/methane blend ratio is increased.

Pollution from NO_x formation is yet another concern, particularly for gas turbines and high hydrogen blend ratios. NO_x abatement adds cost. Absent more stringent pollution standards, NOx emissions will likely be as much as or greater than emissions from current turbines using methane combustion. As the siting of industrial and utility-scale combustion equipment tends to be disproportionately near poor and disadvantaged communities, these communities would continue to be disproportionately impacted by NO_x pollution.

In addition to safety risks, hydrogen poses some global warming risk. Hydrogen is not a greenhouse gas by itself, but it can increase the lifetime of methane in the atmosphere, and can have other indirect effects as well. Because of these indirect effects from interaction with other gases in the atmosphere, hydrogen is considered to have a global warming potential (GWP) between 6 and 16 [34, 35, 36].

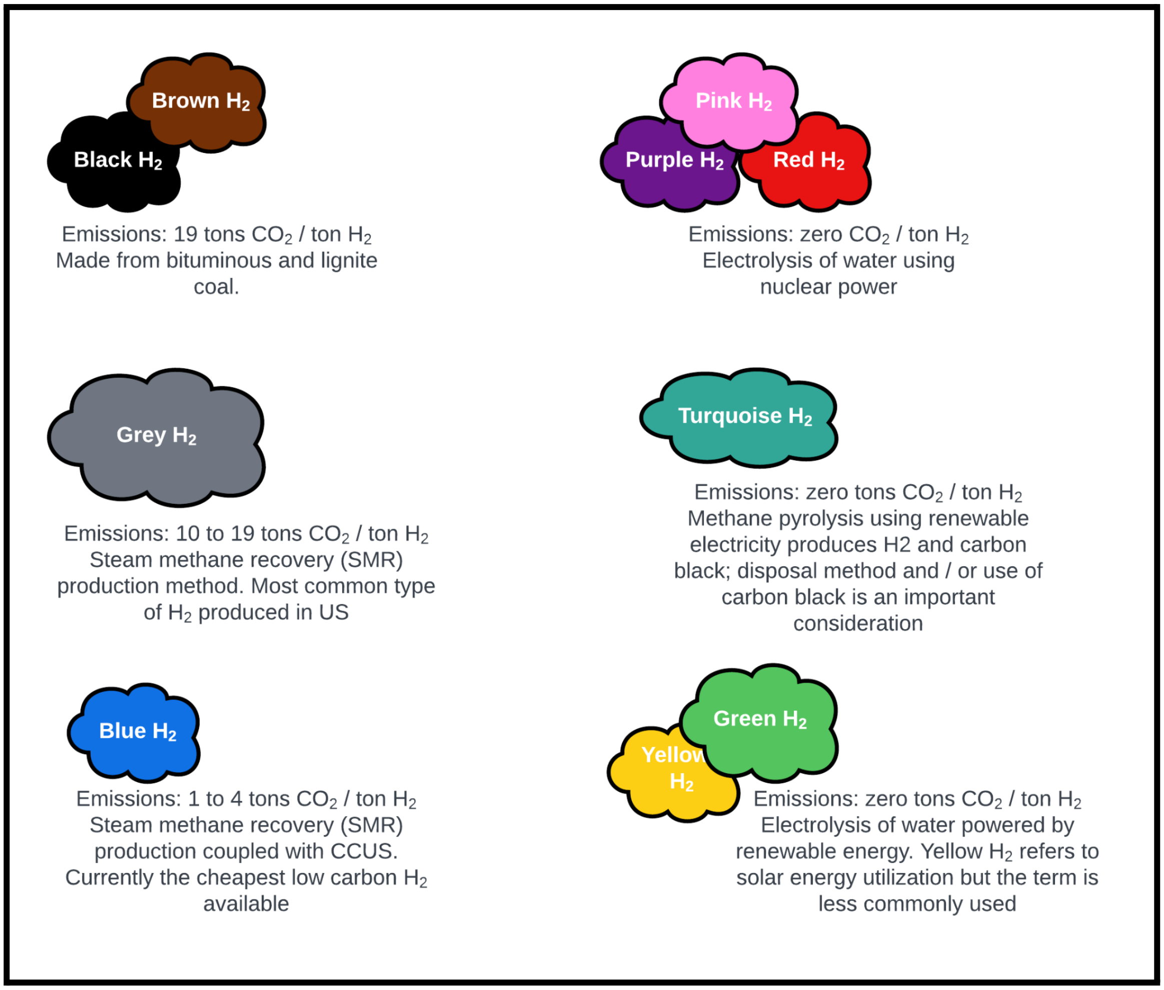
...the widespread scale-up of hydrogen use to address national and global energy needs is neither an energy-efficient nor a zero-emissions approach to reducing GHG emissions.

If hydrogen were used to address a significant portion of the US energy demand - for example 1.2 TW of annualized demand - the leaked hydrogen would produce CO_2-equivalent greenhouse gas emissions. Assuming that 50% of the energy input is recovered from the hydrogen - a somewhat higher net efficiency than achievable today - hydrogen leakage in the range 1 - 3% would produce effective CO_2-equivalent emissions between 38 and 300 million metric tons CO_2e, based on the range of GWP values mentioned above. These values are roughly between 0.7% and 5.5% of total US emissions. More detailed estimates suggest that if most of the US energy demand were addressed using green hydrogen, the CO_2-equivalent emissions from hydrogen leakage could be as high as 10% of current emissions [37]. Thus, the widespread scale-up of hydrogen use to address national and global energy needs is neither an energy-efficient nor a zero-emissions approach to reducing GHG emissions.

The “Rainbow” of Hydrogen and Ammonia

Hydrogen and ammonia can be produced by a variety of chemical processes using feedstocks with hydrogen in their chemical structure. Most of these methods use feedstocks containing carbon and hydrogen, but, as an alternative, water can be used as a feedstock to produce hydrogen and oxygen by electrolysis. It is important to note that not all hydrogen production is emissions-free. The relative amounts of GHG emissions associated with the hydrogen production process are indicated by use of a color to describe the hydrogen produced by the process. Presented below are color classifications that are found on the websites of Nationalgrid.com and ainnovation.org [38].

The “colors” of hydrogen shown on the left side in Figure RB1 - Black, Brown, Grey and Blue - describe hydrogen produced with concomitant greenhouse gas emissions. The colors listed on the right side of the figure - Purple, Pink or Red, Turquoise, and Yellow and Green - are used to describe hydrogen produced without greenhouse gas emissions. In this category, all but Turquoise use electrolysis of water, and the differences in “color” relate to choice of carbon-free electrical power. Turquoise hydrogen is used to describe hydrogen produced by pyrolysis of methane using renewable electricity. This method requires use or disposal of the carbon black waste product from the process.



Emissions: 19 tons CO_2 / ton H_2
Made from bituminous and lignite coal.

Emissions: zero CO_2 / ton H_2
Electrolysis of water using nuclear power

Emissions: 10 to 19 tons CO_2 / ton H_2
Steam methane recovery (SMR) production method. Most common type of H_2 produced in US

Emissions: zero tons CO_2 / ton H_2
Methane pyrolysis using renewable electricity produces H2 and carbon black; disposal method and / or use of carbon black is an important consideration

Emissions: 1 to 4 tons CO_2 / ton H_2
Steam methane recovery (SMR) production coupled with CCUS. Currently the cheapest low carbon H_2 available

Emissions: zero tons CO_2 / ton H_2
Electrolysis of water powered by renewable energy. Yellow H_2 refers to solar energy utilization but the term is less commonly used

Figure RB1. “Colors” and associated CO_2 emissions for hydrogen produced by various methods.

A similar classification system applies to ammonia. Gray or Brown indicates conventional production by the Haber-Bosch process using nitrogen and hydrogen obtained by steam reformation of methane, which produces CO_2. Blue refers to ammonia made by conventional production coupled with carbon capture and storage to reduce the CO_2 emissions. The captured CO_2 is often used in enhanced oil recovery instead of sequestering it permanently. The Green and Turquoise labels follow those for hydrogen.

A Credible Transition to Net-Zero

Zero-carbon, zero-net-carbon and renewable carbon fuels

Achieving a net-zero economy requires a combination of zero-carbon, zero-net-carbon, and renewable carbon fuels, in addition to carbon offsets. This approach is necessary for maintaining a reliable and resilient energy supply. The blend of fuels and carbon offsets must be adjusted over time to reduce GHG emissions and to achieve net-zero emissions.

Although zero-carbon fuels are ideal, they are not available at the required scale and they are not simple drop-in solutions for combustion-driven processes and equipment. Furthermore, the transition to a net-zero economy will take time. In the short term - over the next 10-15 years - zero-net-carbon and renewable-carbon fuels can be used to help achieve net reduction of greenhouse gas emissions.

Zero-carbon fuels contain no carbon and therefore produce no CO_2 when combusted in air. As mentioned earlier, hydrogen (H_2) and ammonia (NH_3) are examples of zero carbon fuels. Both can be combusted in air [12, 9, 11, 39, 6, 8], and both can be used in fuel cells to produce electricity through electrochemical reaction with oxygen [7]. In addition, NH_3 can be used to store and deliver H_2. While their use does not directly lead to CO_2 emission, their manufacture can lead to emissions if renewable electricity and carbon-free feedstocks are not used. Moreover, their combustion can generate NO_x emissions.

Zero-net-carbon fuels have carbon content derived from existing carbon emissions. For example, they can be produced by using electricity and existing CO_2 as a feedstock to make hydrocarbon fuels [40], such as ethanol, that can be converted to jet fuel [41]. Thus, their use has the potential to produce no additional CO_2 in the atmosphere [41]. Zero-net-carbon fuels do not result in any reduction in CO_2 emissions. Rather, zero-net-carbon fuels avoid future increases in CO_2 emissions. When fossil fuels are used to generate electricity, however, production of these fuels will result in net CO_2 emissions, because the amount of CO_2 feedstock is less than the CO_2 emissions from producing them [42]. On the other hand, if renewable electricity is used, it could have replaced fossil-fuel-generated electricity. In neither case are CO_2 emissions reduced.

As discussed in Ref. 41, renewable carbon fuels come from biomass, fats, oils, greases, agricultural residues, municipal solid wastes, and liquid biosolid wastes. Currently, the most popular renewable carbon fuel is corn-based ethanol. The fermentation process for sugar derived from corn can produce high-purity CO_2, which is used in the food and beverage industry.

When renewable fuels are completely combusted, a CO_2 molecule is given off for every carbon in the molecule [41]. Renewable carbon fuels can only be considered carbon-neutral when the CO_2 generated by producing them and combusting them is taken up by the biomass used to produce the same amount of fuel. Widespread use of renewable carbon fuels would do little to reduce the amount

> *Widespread use of renewable carbon fuels would do little to reduce the amount of CO_2 in the atmosphere. If used as substitutes for fossil fuels …renewable carbon fuels would lower the rate of increase of atmospheric CO_2.*

of CO_2 in the atmosphere. If used as substitutes for fossil fuels, however, carbon-neutral renewable carbon fuels would lower the rate of increase of atmospheric CO_2.

Whether produced industrially from CO_2 or created biogenically, zero-net-carbon and renewable carbon fuels rely on chemical reactions wherein hydrogen displaces oxygen in CO_2. The hydrogen used for industrial synthesis must be “green” (i.e. no greenhouse gas emissions result from its production), which could lead to competition for use of green hydrogen directly as a fuel and as a reactant in chemical processes for production of zero-net-carbon fuels.

In principle, carbon offsetting to achieve net-zero CO_2 is also a method of lowering CO_2 in the atmosphere. In the case of biofuels this would mean purchasing offsets for any CO2-equivalent emissions resulting from the production of the biofuels. Carbon offsets are controversial, however, and may not deliver the reductions advertised [43]. If regulated properly, carbon offsetting could be beneficial, but at this time we can not recommend this approach.

The choice of applications for green alternative fuels dictates the production demands for such fuels. Because green production of such fuels requires significant amounts of electrical energy from renewable power, the choice of applications directly impacts the demand for renewable electricity. Thus, a rational set of recommendations for use of green alternative fuels must be made in the context of an overall transition to a net-zero-carbon economy.

Pathways

A set of recommendations for how to make the transition to a net-zero economy is often called a pathway. A pathway describes how the energy demands for the different sectors of the economy will be met while reducing greenhouse gas emissions over time. A pathway that calls for significant reductions in emissions to occur in the near term, considers: (i) what zero-emission and low-emission technologies are available today, and (ii) how they can be implemented effectively. If all the required technology exists today, the pathway describes the timeline for transitioning the various economic sectors. If other technology will be required, the pathway describes implementing what can be done today to start significant emissions reductions, and further describes investments in technology development. The technology developments might be required in ten or twenty years to help make the additional emissions reduction needed to get to a net-zero economy.

> *From the standpoint of addressing the climate crisis, a path based on electrification and renewable energy is the only kind of pathway that drives deep reductions in greenhouse gas emissions.*

From the standpoint of addressing the climate crisis, a path based on electrification and renewable energy is the only kind of pathway that drives deep reductions in greenhouse gas emissions. Pathways that involve significant reliance on electricity generated with renewable energy also involve energy storage. As mentioned earlier, there are several different types of energy storage technologies and techniques. There is no requirement that all the energy storage needs be met by a single approach. For example, electrical storage batteries can be used to address intermittency of renewable energy sources, and green fuels can be used to store and deliver energy to activities that do not have access to grid electricity and for which use of batteries is impractical because of weight considerations. In addition, a variety of storage techniques can be used to lower energy demand for heating and cooling of communities. The important point is that during times where energy production (electrical, thermal, chemical, etc.) exceeds the local demand, energy can be stored in a variety of ways to address future demand or demand in other locations. While green fuels are an energy storage medium, they are not the only storage medium. The choice of energy storage method can be tailored to the intended application in the context of a pathway to a net-zero economy.

Some pathways have been proposed with the belief and understanding that all or most of the required technology exists today. Others rely on technology that has not been demonstrated at the required scale. In addition to disagreement about what is possible or what will be possible in the future, there is disagreement about whether proposed pathways would lead to sufficiently rapid reductions in emissions in the near term. Further clouding the discussion of appropriate and credible pathways to Net Zero are proposals to make significant investments in scaling up activities that are claimed to help reduce emissions, but might actually impede progress towards a net-zero economy. This set of conflicting ideas and interests is illustrated in the discussion below.

Various pathways for transition to net-zero have been proposed, and some of them prolong the use of fossil fuels, either directly or by proposing "transitional" use of blends of "green fuels" with fossil fuels. For example, in the Princeton report on Net-Zero America four of the five suggested pathways to net-zero use natural gas for electricity production [44]. In these pathways, carbon capture is used along with the fossil fuel combustion. Although carbon capture is considered an emission reduction technology, Jacobson et. al and Sudhir [45, 42], show in their publications and presentations that carbon capture produces more carbon dioxide-equivalent emissions (CO_2e) than are captured if fossil fuels are used to generate electricity on the grid.

Although the Princeton report indicates a negative carbon intensity by 2050 for these four pathways, they rely heavily on carbon capture and storage, which has not been proven at the necessary scale, either for capture or reliable storage or sequestration. Moreover, it can be shown that natural gas (if used without carbon capture) produces more CO_2-equivalent emissions than coal over a 20 year period [46].

The fifth pathway in the Princeton report is one of substantial electrification and substantial renewable energy ("E+RE+") and is considered a viable pathway [44]. In the E+RE+ pathway, some biomass is used for electrification and production of hydrogen. The CO_2 produced from biomass combustion is captured and combined with hydrogen to produce synthetic net-zero-carbon fuel, which can be used in hard-to-decarbonize areas such as aviation. Since renewable energy is used for this process, it produces zero net CO_2. From the standpoint of addressing the climate crisis, the E+RE+ path is clearly preferable to the others. *Authors' note: That four of the proposed five pathways use natural gas for electricity generation is possibly related to funding sources for the project on which the Princeton report is based. BP and Exxon Mobil are acknowledged among the sources of funding and support for the work.*

Jacobson et al propose pathways to an economy powered 100% by wind, water (hydroelectric), and solar power (WWS) [46]. The evolution of the end-use energy demand from ~100% mix of fossil fuels, nuclear power, and biofuels/bioenergy to 100% WWS for one such pathway for the U.S. is shown in Fig. ACT1. In the analysis supporting the 100% WWS pathway, current annualized energy demand for all fuel sources is converted to an effective average power demand. As fossil-fuel-driven processes and equipment are replaced by processes and equipment that run on electricity, the effective average power demand from fossil fuels is replaced by lower average power demand from the more efficient electrical processes and equipment. At the end of the transition to 100% WWS, the total power demand is about half the present power demand from all sources. That demand is more than twice the current electrical power demand and is about the same as the current electrical power generation capacity. Because 100% WWS power production has a lower effective capacity factor than power produced by the current mix of sources, the required electrical power generation capacity to meet the electricity demand for 100% WWS is four to five times higher than the current US electrical power generation capacity.

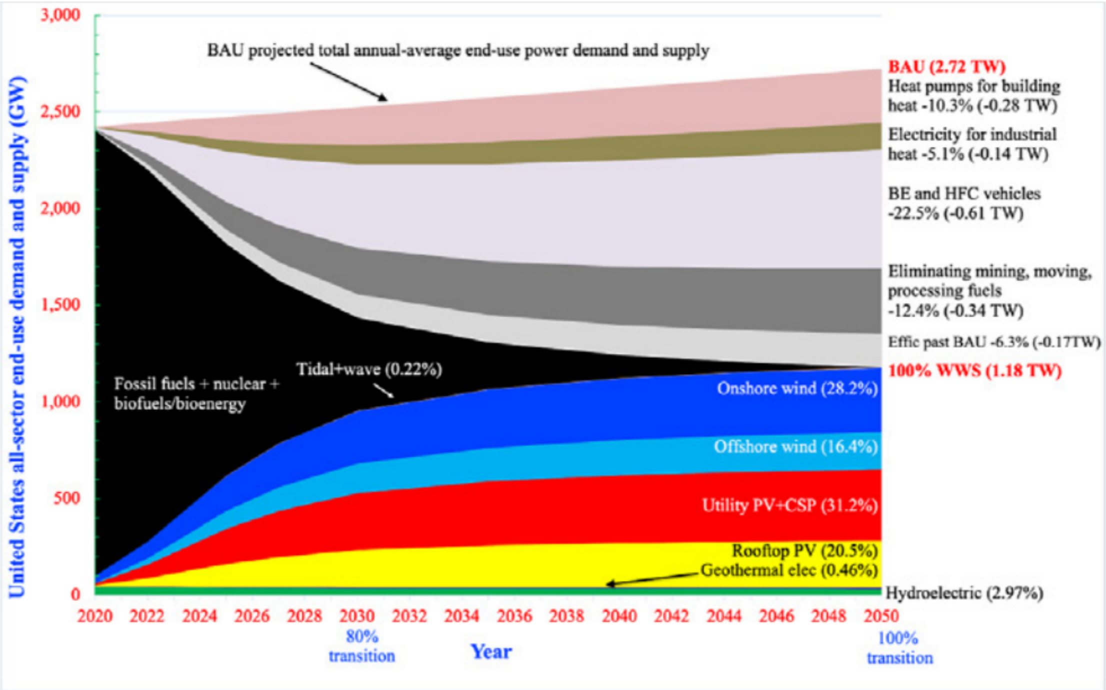


Figure ACT1. Timeline for transitioning the United States to 100% WWS by 2050, with 80% by 2030. Five types of reductions in energy requirements occur along the way. *Reprinted from [5] with permission from Mark Jacobson*.

In the 100% WWS pathway, it is envisioned that hydrogen can be used in fuel cells for long-haul trucking, shipping, heavy military vehicles and equipment and other applications where batteries or direct electrical power are impractical. From an energy use standpoint the energy consumed in producing the hydrogen, coupled with the fuel cell conversion efficiency compares favorably with the energy that would be consumed if fossil fuels were mined, processed, distributed and combusted to fill the same energy needs [46]. From a resource balance standpoint, however, the challenges in expanding production of zero-carbon electricity have the potential to force a choice between either making progress on decarbonizing the economy or providing a zero-carbon option for applications under consideration for green fuel usage. The role of hydrogen in the 100% WWS pathways is therefore limited to provide energy to only the applications that are most difficult to decarbonize.

Interactive On-Line Simulator to Help Assess Strategies

In addition to reports and journal articles that describe pathways, there are interactive simulators that help policy makers understand the impact of public policy. The En-ROADS climate solutions simulator, developed by Climate Interactive and the MIT Sloan School, is a notable example. Accessible at https://www.climateinteractive.org/, En-ROADS is a free, user-friendly interactive tool for exploring the global effects of many possible climate solutions.

As an example, for a first scenario that holds the increase in global temperature to 1.5 °C by 2100, see Fig. ACT2. Shown in Fig. ACT2a is energy from primary sources plotted over time during a transition from fossil fuels to predominantly renewable sources by 2100. The accompanying reduction in greenhouse gas emissions is shown in Fig. ACT2b. This pathway also markedly decreases air pollution, as shown in Fig. ACT2c. The plots for “baseline” in Figs. ACT2b and ACT2c are for the “business as usual” scenario. Note that, in contrast to the 100% WWS scenario for the US (Fig. ACT1), global energy demand continues to rise over time as developing nations gain increased access to clean energy.

In this first scenario, reductions in greenhouse gas emissions are accomplished by:

- A carbon price that reached $150/ton over ten years
- Electrification and improved energy efficiency of transport
- Electrification and improved energy efficiency of buildings and industry
- Reduction of emissions of methane, N_2O, and Hydrofluorocarbon gases by 70%
- Reduction of deforestation and mature forest degradation by 5%/year
- Afforestation of 75% of the available land
- Agricultural soil carbon sequestration and biochar used at 100% of their potential
- Enhanced mineralization used at 70% of its potential.

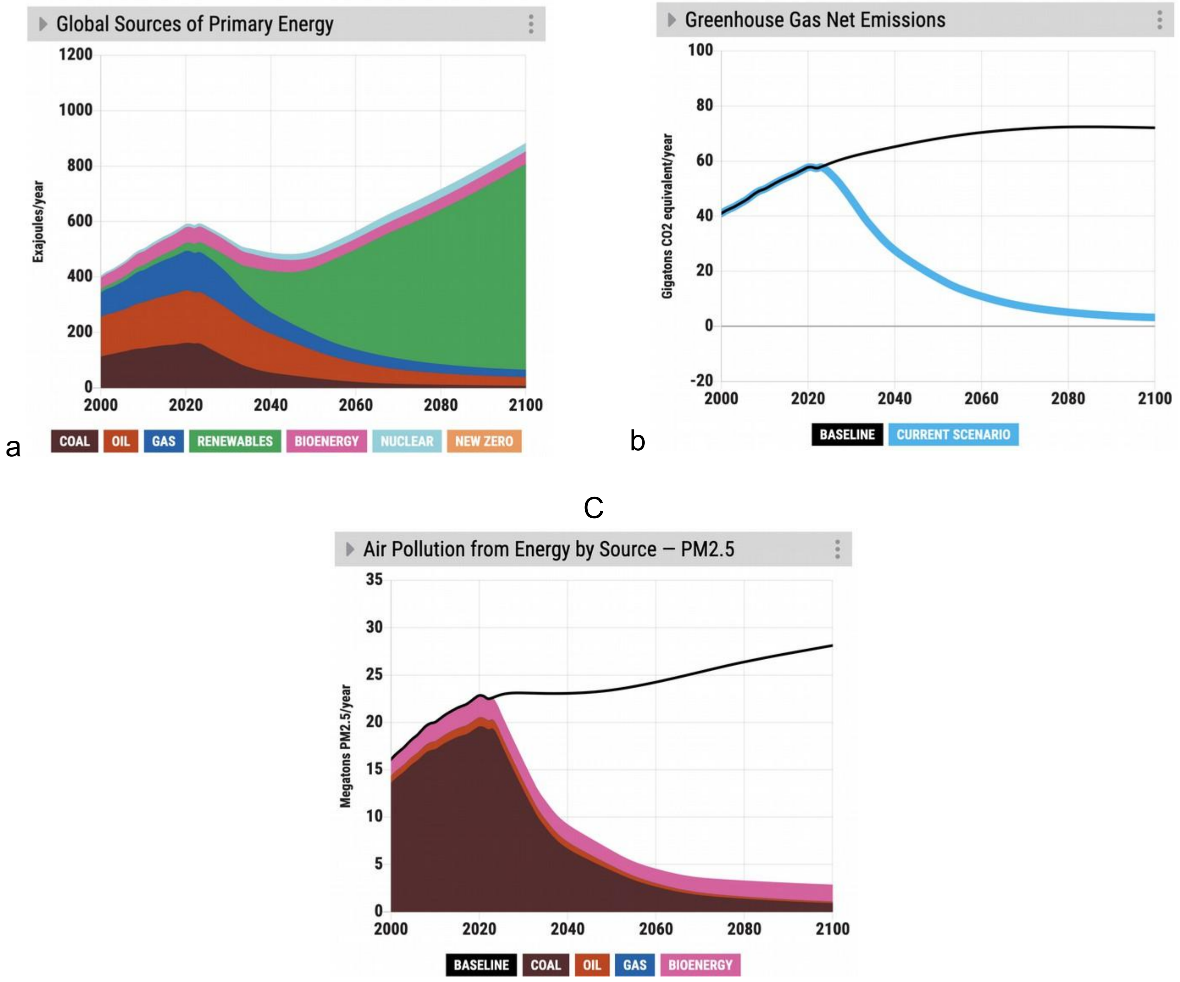


Figure ACT2. Results plotted out to the year 2100 for the En-ROADS simulation “first scenario”: a) Energy sources b) Greenhouse gas emissions and c) Air pollution. “Baseline” in b) and c) is for “Business as usual”.

There are many other combinations of solutions that produce similar results, but not all promising solutions turn out to be effective. In a second scenario, global temperature increases by 2.9 °C by 2100. The results for this scenario are plotted in Fig. ACT3. As shown in Fig. ACT3a, the mix of sources of primary energy changes over time, but the amount of fossil fuel usage remains fairly constant after 2030, with renewable sources growing slowly out to 2100. The accompanying greenhouse gas emissions profile is shown in Fig. ACT3b which shows emissions dropping by roughly 30% relative to the “business-as-usual” scenario. This pathway also results in persistent air pollution as shown in Fig. ACT3c.

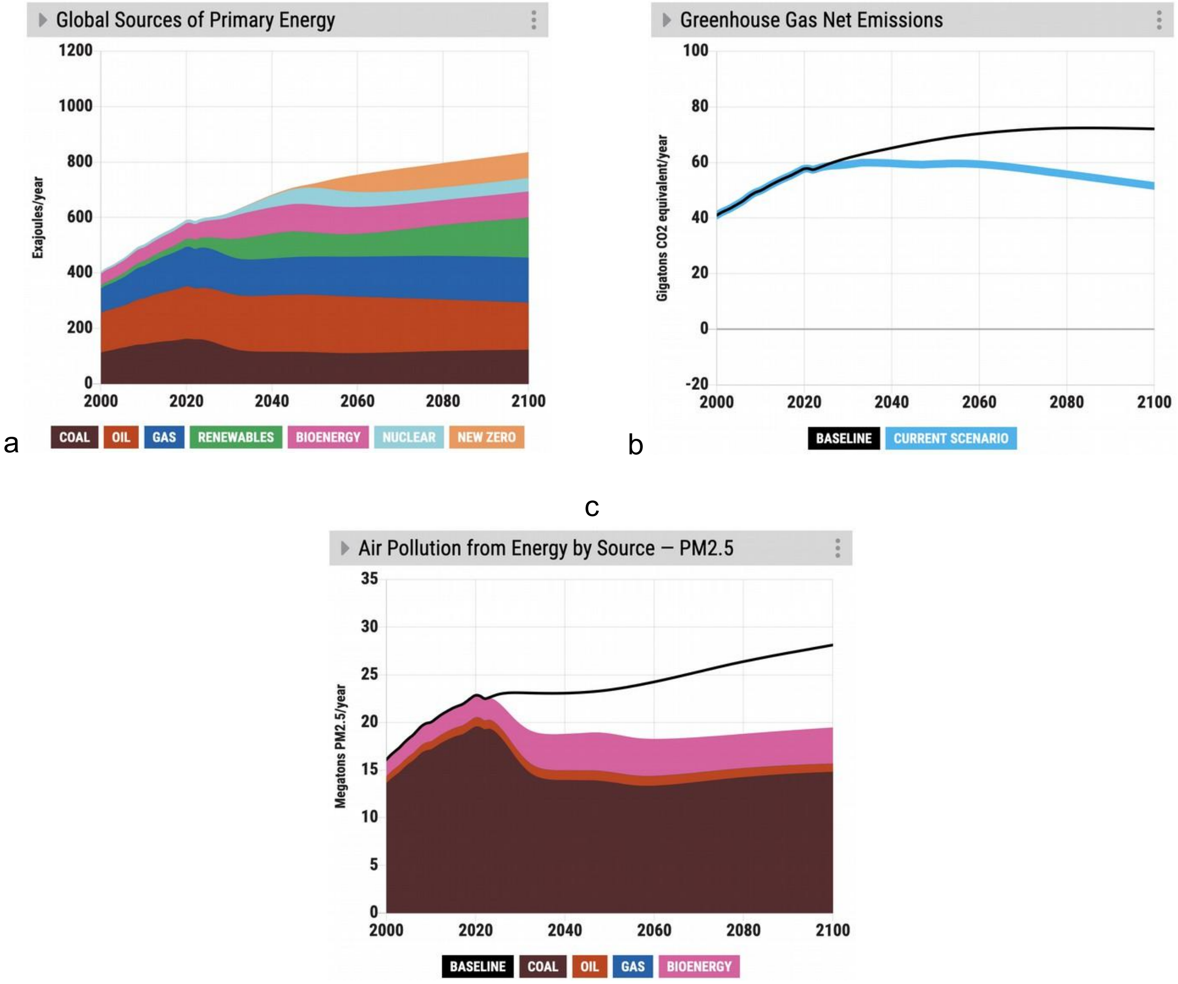


Figure ACT3. Results plotted out to the year 2100 for the En-ROADS simulation "second scenario": a) Energy sources b) Greenhouse gas emissions and c) Air pollution. "Baseline" in b) and c) is for "Business as usual".

This second scenario relies on:

- Highly subsidized nuclear power
- A major breakthrough in new zero-carbon energy
- Carbon capture and storage
- Generating electricity with woody biomass
- Direct air capture reaching 100% of its potential
- Lower population growth

Greenhouse gas emissions and pollution are somewhat lower for the second scenario than for the "business-as-usual scenario". The 2.9 °C temperature increase by 2100 is also a slight improvement over the business-as-usual scenario, which would result in an increase of 3.6 °C by 2100. None of these slight improvements, however, would prevent a disastrous outcome: the likely consequences of a 2.9 °C increase are calamitous, and the failure to reduce emissions significantly would result in further temperature increases well beyond 2100.

Credible Proposals

Credible proposals for pathways involve economy-wide analyses and quantitative assessments of what emissions reductions can be achieved with currently available technology. It is important to distinguish between these economy-wide pathway proposals and the proposals for significant funding or incentives to produce rapid growth in specific activities, such as carbon capture, blending hydrogen with natural gas, and large-scale production of hydrogen. Whereas the economy-wide pathways are focused on achieving a net-zero economy, the narrow proposals for funding and scale-up of specific activities are focussed on seeking profit for a small group of stakeholders. While the justification for supporting the hopeful profiteers is often couched in terms of addressing environmental concerns, the proposals are incompatible with a credible pathway to Net Zero. Unfortunately such proposals, if carried out, would delay or otherwise impede the transition to a net-zero economy.

A practical path for the transition to net-zero carbon emissions depends critically on an honest assessment of the quantities of lower-carbon and no-carbon fuels that can be made available, given the need for rapid expansion of renewable electricity production. If something can be powered directly by renewable electricity, it will add less to the total electricity demand than if it is powered by zero-carbon fuel made using renewable electricity.

A practical path also depends on setting realistic expectations about the extent to which an existing fossil fuel can be replaced and the length of time over which a partial replacement should be considered as bridge solutions. For example, blending hydrogen with natural gas has been proposed for reducing methane consumption in residential gas appliances and in production of electricity by natural-gas-powered turbines [47]. The range of hydrogen blending with natural gas is 5 to 20 percent with very little decrease in greenhouse gas emissions – approximately 6-7 percent [47]. This small decrease in emissions is used to justify maintaining the current natural gas infrastructure and also to invest in upgrades to the infrastructure to better handle the hydrogen/methane blend. If such investment continues, when a serious effort is made to curtail the use of natural gas, there will be a larger quantity and greater financial burden of stranded assets (pipelines and other gas distribution infrastructure) than there would be with a systematic transition away from gas-fired heating systems and power plants. In addition to slowing the transition to a net-zero economy, increased blending of hydrogen with natural gas enhances the amount of oxides of nitrogen in the combustion products and elevates the concern about hydrogen leaks from pipelines, furnaces, and other equipment. Blending hydrogen with natural gas to heat homes and to generate electricity neither presents a pathway to eliminating carbon dioxide emissions, nor makes efficient use of the energy required to produce the hydrogen. Moreover, as a bridge solution, the practice would slow the reduction of emissions and incentivize investment in infrastructure that would have to be left as stranded assets in order to make significant progress in emissions reductions by curtailing the use of natural gas.

In a comprehensive net-zero transition plan, plans implemented to drive down emissions from Agriculture, Residential and Commercial Buildings, and other sectors will drive down waste production, natural gas usage, fertilizer usage, and other aspects of current consumption patterns. There is currently significant policy support for renewable natural gas (RNG) or biogas, which is derived from a variety of waste streams and [48] as an alternative to fossil-fuel based natural gas. Widespread scale-up of RNG or biogas production from waste sources, however, works against the overall reductions in waste needed to drive to net zero. In addition, leakage of methane, whether of fossil-fuel origin or from waste or biogas, is an issue. RNG combustion should be localized to the source of the methane with minimal distance of travel through pipes and no long-distance ground transportation for the collected methane.

The use of green fuels as part of a credible pathway to net-zero requires that their production and use be engineered to minimize greenhouse gas emissions. Furthermore it requires that pollution from their production and use be minimized to an acceptable level, where any acceptable level does not include burdening disadvantaged communities with the consequences of the pollution. Finally, implementation of green fuels in a credible pathway to net-zero must not prolong the use of fossil fuels. In a credible pathway, the use of green alternative fuels in the U.S. will represent 8% or less of the total electricity demand and will likely address less than 3% of the total energy demand [5, 62]. The U.S. net-zero green hydrogen annual demand of Ref. 62 assumes the same annual production levels of ammonia as in 2020. Development of substitute chemicals for ammonia, both for fertilizer and non-fertilizer applications is assumed. In this scenario, the use of hydrogen for steel manufacture, long-distance transport, and ammonia will require green hydrogen production levels of roughly 1.4 times the current annual hydrogen production levels.

Practical waste stream from combustion of green fuels

Although green fuels hydrogen (H_2) and ammonia (NH_3) neither contain carbon nor produce carbon dioxide (CO_2) when consumed, they do make oxides of nitrogen (NO_x) and nitrous oxide (N_2O) when combusted in air [10, 49]. The combustion characteristics of hydrogen in air greatly enhance NO_x production relative to the levels produced in fossil fuel combustion. In the case of ammonia, the presence of nitrogen in the fuel itself greatly enhances NO_x formation during combustion.

The most effective way to avoid NO_x production in using hydrogen or ammonia as fuels is to avoid their combustion in air. As combustion in pure oxygen is neither a practical nor an affordable option, fuel cells are the best option. Fuel cells do not use combustion processes to react hydrogen fuel with oxygen. Rather, they use electrochemical reactions to extract the reaction energy, and the reaction product is water.

Energy demand arguments aside, using combustion processes to extract energy from hydrogen or ammonia not only requires considerable redesign and engineering of the combustion equipment, but also requires considerable redesign and reengineering of the pollution abatement equipment. The currently feasible low levels of NO_x from hydrogen combustion come with compromises around cost, efficiency, and performance [49]. Compromises in any or all of these attributes only make combustion of these fuels a less attractive option for meeting energy demand. Moreover the compromise engineering solution will likely be comparable to or worse than fossil fuel combustion with respect to pollution from NO_x in the absence of significant pollution abatement and oversight costs.

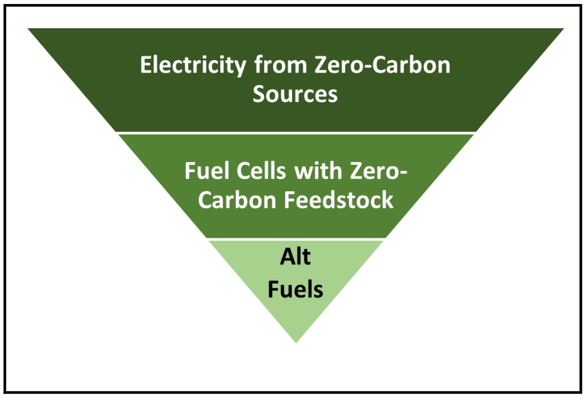
Green fuels and fertilizer production

The green fuels discussed above - hydrogen and ammonia - are used in the production of fertilizer. Other uses of hydrogen include refining petroleum, treating metals, and processing foods. Large-scale hydrogen and ammonia use would require significantly more production capacity than currently exists. Moreover, current fertilizer use contributes noticeably to greenhouse gas emissions - roughly 2% of US and global GHG emissions from production, transportation, and use [50]. Reducing fertilizer usage, in combination with green production of fertilizer will reduce greenhouse gas emissions from the fertilizer industry, while helping drive scale up of production of alternative fuels.

Reduction of fertilizer use can have additional benefits. Reduced fertilizer use by adopting regenerative agriculture practices improves soil carbon sequestration. Excessive fertilizer use actually counteracts soil carbon sequestration [51]. Soil biology (microbes, fungi, plants, insects, animals, etc.) naturally provides nutrients, including nitrogen via nitrogen-fixing microbes, to plants. The plants in turn feed the microbes (with carbon containing compounds, sugars, etc.) in an ecological exchange. Over time, soil increases in volume as organic matter accumulates, and this sequesters carbon. Introduced artificial fertilizer counteracts this process by disturbing the natural ecology and the symbiosis between different life forms. The plants having no need for additional nitrogen stop feeding the microbes that would normally supply it, causing degradation of the ecosystem and reduction in biological activity and associated carbon sequestration. Reducing fertilizer use in agriculture therefore has the triple benefit of reducing emissions (from fertilizer production), reducing fertilizer runoff - which degrades natural ecosystems - and enhancing soil carbon sequestration [52, 53].

Prioritize the Right Things

Transitioning our Energy Sources



Default Solution: economy-wide electrified systems using power from zero-carbon sources enable rapid reduction of emissions. These reductions are possible by converting fossil-fuel-powered systems and appliances to run on electrical power and/or replacing them with systems and appliances that run on electrical power. In addition, emissions will continue to drop significantly as the renewable electricity capacity from regional grids and local plants is brought on line.

Special Solution: Green alternative fuels are best used for applications that are difficult to electrify directly. Vehicles for long-haul trucking, shipping, and heavy military and naval craft can use fuel cells powered by green alternative fuels. Industrial processes, such as steel manufacturing, can also use green hydrogen to significantly reduce greenhouse gas emissions associated with production. Having economy-wide electrification helps ensure that the energy and chemical demands for these applications can be met with green alternative fuels.

Transitional Solution: Alternative low-carbon fuels likely will be needed to draw down emissions until fuel cells and the supporting infrastructure are widely available and/or they are replaced with zero-carbon options. For example, life-cycle analysis completed by Argonne National Laboratory found that emissions from 100% biodiesel (B100) are 74% lower than those from petroleum diesel [54]. While using low-carbon fuels provides a transitional solution for reducing emissions until fuel-cell or other zero-emission solutions become available, the lower-carbon fuels should be: (i) a direct replacement for fossil fuels, (ii) produced and used locally to minimize transportation, and (iii) phased out when zero-carbon solutions are available.

Using the right tools for the right job

A simple summary comparison is presented in Table PRT1 below for Direct Renewable Energy, Green Fuel with Combustion and Green Fuel with Fuel cells. (NB: “direct” is used here to indicate that the electricity is delivered directly to the application without the use of an intermediate energy carrier, such as hydrogen). A green box indicates that the choice of energy source is favorable, a yellow box indicates some level of concern or disadvantage, and a red box indicates significant concern or disadvantage.

Table PRT1. Summary comparison of Direct Renewable Electricity, Green Fuel Combustion and Green Fuel used in fuel cells. Green shading indicates favorable, red indicates significant concern or disadvantage, and yellow indicates some level of concern or disadvantage.

	Direct Renewable Electricity	Green Fuel / Combustion	Green Fuel / in Fuel Cells
Relative Energy Efficiency	🟩	🟥	🟥
Portability	🟥	🟩	🟩
Land/Shore Usage Concerns	🟨	🟨	🟨
Relative Pollution Concerns	🟩	🟥	🟩
Safety Concerns	🟩	🟥	🟨
Appliance Retrofit Concerns	🟩	🟥	🟩
Transmission Line / Storage and distribution Concerns	🟨	🟨	🟨
Concerns about prolonging fossil fuel usage	🟩	🟥	🟥
Possible Enhancement using District Energy or non-fuel storage methods	🟩	🟥	🟥

It is important to note that Direct Renewable Electricity faces opposition with respect to siting and construction of power plants as well as transmission lines. In addition to requiring renewable electricity, green alternative fuels require electrolyzer plants to convert the electricity into chemically stored energy in the fuels. Moreover the required electrical generating capacity for a green fuel to address a given energy demand is considerably higher than what is required for meeting the same demand with direct renewable electricity. As summarized in the table, taking all the considerations into account suggests that direct renewable electricity should be used except where it is simply not practical and if green alternative fuels must be used, fuel cells should be considered instead of combustion engines.

When planning a major project, it is important to consider the tools available and the requirements for the project. If our "project" is to decarbonize the U.S. economy, our requirements are that we reduce greenhouse gas emissions while maintaining the ability to provide energy for all sectors of the economy. Consider a collection of possible tools that includes fossil fuels, zero-carbon fuels, and direct renewable electricity. Clearly, fossil fuels are not the right tool for any job within this project, so we are left with zero-carbon fuels and direct renewable electricity.

While we would like to generate enough direct renewable electricity to meet the energy needs of the economy and complete the project, we recognize that some parts of the economy cannot function efficiently using direct renewable electricity. We must therefore consider using our green alternative fuels to address those needs. Unfortunately, we still need renewable electricity to produce the green alternative fuels. Moreover, to make up for the energy losses from using the fuel, we will need more than double the amount of energy for that demand.

In addition to choice of tool, we find that one tool can be used in two different ways - the green alternative fuels can be used in fuel cells to produce electricity, or they can be combusted to produce heat or mechanical energy. In comparing our tools - direct renewable electricity and green alternative fuels in combustion-driven or fuel-cell-driven equipment, there are several things to consider. From a relative energy efficiency perspective, the green alternative fuels are disadvantaged. From a portability perspective, direct renewable electricity is disadvantaged. Electric vehicles with sufficient battery capacity overcome the portability disadvantage, but when scaled to long-haul trucks, the battery weight makes this approach impractical. If we choose to use green alternative fuels, we can consider an internal-combustion engine converted or otherwise designed to use green alternative fuels, or we can consider fuel cells, which convert chemical energy into electricity to drive an electric motor. As we get into the details of this kind of choice, there are yet more things to consider, including pollution, safety, appliance retrofits to be able to use the alternative fuels.

Both renewable electricity and green fuels require land or off-shore areas for production and distribution - electricity requires transmission lines, and alternative fuels require storage and distribution, as well as equipment capable of using the fuels as an energy source. Transitioning to a 100% renewable electricity economy has been, and continues to be, impeded by a combination of NIMBYism and special interests. A study of 53 renewable energy projects (solar, wind, geothermal, transmission) across 28 states showed that nearly half of the projects were canceled due to delays and opposition. Impacts on land value and environment have been the most cited reasons used to prevent these projects from proceeding [55]. It is interesting to note that a 100% renewable-energy-powered economy would require additional land area of less than three quarters of the current area devoted to the fossil fuel industry [5].

Offshore production of green fuels can be powered by wind turbines similar to those used in offshore wind generation of electricity. An off-shore hydrogen production platform is being tested on pilot scale by Lhyfe [56]. The floating electrolyzer plant produces hydrogen from sea water. No electrical connections to the shore are required. While this approach is modular and scalable, it forces a doubling of the renewable electricity production to address a given energy demand when compared to direct renewable electricity. If ammonia is produced as the alternative fuel, it forces a tripling of the energy required to address a given demand. The doubling or tripling of the energy requirements, based on projections for 2035 and beyond, translates to proportionately more wind turbines and larger electrolyzers and thus more area. In the near term, the energy requirements are even more severe. For a limited set of applications, the added energy cost might be justifiable.

In addition to the above mentioned considerations, there are indirect impacts associated with choice of "tool". In the case of green alternative fuels, there are non-green methods of production that involve fossil fuels. Moreover, specious proposals to produce "green" fuels are based on plans that either use fossil fuels or fossil-fuel-generated power to produce the alternative fuels. Wide-scale promotion of green alternative fuels without attention to the details of their production can prolong the use of fossil fuels and the concomitant greenhouse gas emissions. By contrast, renewable electricity can be combined with district energy or non-fuel energy storage to further reduce energy demand and further drive emissions reductions.

Rules for green fuels

If a fuel is to be synthesized from electricity and portrayed as "green", it is key that it meet some important criteria: (1) it must not be made from electricity derived from fossil fuel combustion; and (2) it must not, by taking green electricity from a grid, cause the grid operator to use fossil fuels for electricity generation and (3) there must be accounting for every hour of electricity usage to provide proof that no fossil-fuel derived electricity was used in production of the fuel.

These requirements are formally defined by the three pillars - additionality, deliverability, and hourly time matching - laid out in the Inflation Reduction Act. These conditions must be met in order to qualify for tax credits for clean hydrogen [57, 58] (see "No Cheating!" for details). They are important for ensuring hydrogen production does not end up creating more GHG emissions.

These criteria can be extended to green fuel production in various settings. There are many green fuels currently in development other than hydrogen and ammonia. The production setups can vary greatly, and what makes sense in one setting might not work in another.

No Cheating!

The "three pillars" of the IRA's Hydrogen Production Tax Credits are guardrails to prevent an increase in emissions from fossil-fuel-based power generation.

Additionality: Only newly developed clean electricity resources, not already serving the grid, are allowed to qualify as clean supply for electrolyzer loads.

Deliverability: Electrolyser loads must be located in the same region as the clean electricity resources.

Hourly Matching: Electrolyser loads must match the clean electricity portfolio production in every hour.

Source: Evolved Energy Research, Centre for Strategic & International Studies

The three pillars are a critical requirement to help guide all green fuel production and usage. These must be a non-negotiable set of conditions upon which all green fuel production is based.

Yuri Project in Australia Off-grid project with 10MW electrolyser, 18MW solar PV, and battery located next to anhydrous green ammonia production facility.	Additionality ✓ Deliverability ✓ Hourly matching ✓
OFFSET Project in the Netherlands Offshore, off-grid wind farm connected to floating electrolyser and ammonia production platform. Green ammonia to be shipped via shuttle tankers	Additionality ✓ Deliverability ✓ Hourly matching ✓

The three pillars are a critical requirement to help guide all green fuel production and usage. These must be a non-negotiable set of conditions upon which all green fuel production is based.

Prioritizing societal implementation of net-zero technology

A zero-carbon economy is an essential goal for addressing the causes of and the impact of global warming. The window of opportunity to take action to avert disaster is closing ever more quickly. Therefore, GHG emissions must be reduced systematically and as rapidly as possible. Moreover, as emissions are reduced the use of fossil fuels must not be prolonged. Achieving this goal requires widespread electrification of the economy in combination with generation of zero-carbon electricity. While the majority of the economy can be updated to use zero-carbon electricity directly, there will be some need for zero-carbon fuels to provide energy for applications for which direct electrification is not practical. Zero-carbon fuels should not be considered as an energy source for the economy as a whole. The primary focus should be on electrification of the vast majority of the economy. The development of green alternative fuels should be supported in proportion to the energy demand represented by applications that are difficult to electrify directly.

Widespread electrification requires:
- Expanding the electrical grid and enhancing grid resiliency
- Expanding capacity to generate electricity from renewables
- Increasing production of zero-carbon fuels
- Phasing out of fossil fuels as quickly as possible
- Driving the transition to widespread electrification
- Encouraging societal-wide attitudinal changes required to achieve zero carbon

Expanding the grid. Without an expanded and more resilient grid, potential electrification of the economy will be limited and likely vary widely by geographic region. Further use of renewable energy will also be limited and generating capacity underutilized.

Zero-carbon electricity. Without zero-carbon electricity, emissions reductions will be impossible. Because generation of electricity from renewable energy sources (wind, water, solar) is variable, some have suggested that widespread electrification will result in an unstable grid. Concerns about the intermittency of renewable energy sources are often used to argue for load-balancing power plants. The perceived need for load-balancing plants then is used to argue for fossil fuel powered plants or for green-fuel-powered plants. It is also used to argue for increased use of nuclear power. By contrast, Jacobsen et al. [5] have done a detailed analysis of what is required for widespread electrification, powered by renewable energy. In their analysis, they consider a variety of energy storage methods, and they conclude that a modest capacity of battery storage, in combination with other forms of energy storage is sufficient to address the intermittency of renewable energy sources. They consider batteries with 4-hr storage at their peak discharge rate. The 4-hr batteries can be used in sequence for longer storage times in multiples of 4 hours.

Regardless of whether one accepts that renewable energy can be implemented to provide a sufficiently stable energy supply, addressing intermittency by continuing to rely on non-renewable energy sources works against significant emissions reductions. Continuing investment in fossil fuel power plants perpetuates and exacerbates the crisis we are facing. Similarly, addressing intermittency by an outsized investment in green alternative fuels diverts resources from building out renewable clean grid capacity while providing an opportunity to continue to use fossil fuels for the production of “gray” or “blue” versions of the alternative fuels, also prolonging the crisis.

Addressing intermittency by focusing solely on nuclear power raises false hopes that a straightforward zero-carbon non-renewable solution is at hand. Electricity from nuclear power is significantly more costly than electricity from renewable energy [59]. However, extending the life of existing nuclear power plants would offer a relatively low-cost approach to providing additional time to build up renewable energy capacity and address the intermittency issue. Expanding the use of nuclear power is not a generally accepted approach to reducing emissions, as evidenced by significantly different views, recent policy decisions and histories in France, Germany and Japan. Recent advances in small modular reactors - SMR’s [60] - and microreactors [61] might address some of the concerns that drive opposition to increased use of nuclear power. SMR’s however, have many of the same drawbacks as conventional nuclear power plants, and microreactor technology is still under development and is not available for immediate use to address the climate crisis.

Until renewable energy sources provide a significant fraction of the total electrical power capacity, the priority should be on producing more zero-carbon electricity from renewables in combination with building energy storing systems into the grid, buildings, and communities.

Increasing production of zero-carbon fuels. Some applications in the economy will be very difficult to electrify with direct power from the grid. Such applications include long-haul trucking, shipping, and heat-intensive industrial processes. Green alternative fuels can be used to address such applications, but they are not a "silver bullet" for decarbonizing the majority of economic activity. As suggested earlier green alternative fuels such as hydrogen and ammonia can be used to decarbonize current fertilizer production. In combination with agricultural practices that reduce fertilizer consumption and improve soil health, green hydrogen and green ammonia can eliminate a significant source of agricultural greenhouse gas emissions. Expanding production capacity of hydrogen and ammonia beyond today's levels should be focused on ensuring that all production is converted to green processes, and added capacity of green alternative fuels is used to address the applications that are difficult to electrify.

Phasing out of fossil fuels as quickly as possible. How quickly the US and other countries can phase-out fossil fuels will be linked to the rate of grid expansion, the rate of economy-wide electrification, and the degree to which the public supports the transition to a zero-carbon economy. While incentives and market forces can help guide the economy to transition to net-zero carbon, a systematic approach is essential for driving the transition to occur as rapidly as possible. A rapid transition is now required to avoid the most devastating effects of climate change. Our collective inaction over the past several decades has already made significant impacts unavoidable.

Progress requires that we overcome widespread promotion by the petroleum industry, many politicians, and others of false solutions cast as sensible measures to address the climate crisis. Such false solutions include:

- Natural gas as a "clean solution" to generating electricity
- Natural gas as the feedstock for hydrogen
- Carbon capture from various sources as a cost-effective alternative to electrification
- Blending of hydrogen with natural gas to reduce emissions

Compared to coal, natural gas is "clean", but compared to renewable energy it is quite "dirty". When natural gas is used as a feedstock to make hydrogen, the emissions far exceed the benefit from the hydrogen being carbon free. If one attempts to capture the carbon dioxide to make "blue hydrogen", the net greenhouse gas emissions are still significant, and the storage or sequestration of the captured carbon dioxide is often not even considered. Rather, the carbon dioxide is sent for use elsewhere in the economy, only to be released to the atmosphere eventually. Carbon capture technology is expensive, energy intensive, and not up to the tasks for which it is touted as a "solution". When greenhouse gas emissions have dropped significantly, perhaps development of such technology might be considered for net removal of carbon dioxide from the atmosphere. The current technology, however, creates more problems than it solves. Finally, emissions reductions by blending hydrogen with natural gas are insignificant and quite limited for the blending levels currently considered safe. The blending "solution" is often sold as an intermediate solution in transition to 100% hydrogen - an endpoint that is problematic from the standpoint of safety, infrastructure costs, and the likely need to replace appliances with ones that can run on pure hydrogen. Moreover, the widespread use of an alternative green fuel for applications that can be readily converted to run on electricity is disadvantageous from an energy use standpoint and works against prioritizing the right things.

Driving widespread electrification. If resistance to other efforts to change public behavior is a guide (e.g, switching to unleaded gas, using seat belts, increasing recycling, etc.) then electrification of the economy will likely require significant policy changes and regulations. New requirements will need to be established - requirements that new buildings and new appliances be carbon neutral. Incentives will be helpful to encourage upgrades to make existing construction more energy efficient and upgrades to convert appliances from fossil fuels to electricity. In addition, there must also be disincentives to continuing to emit. Some cities have adopted Building Energy Use Disclosure Ordinances that require owners of certain buildings to track and report energy use and emissions. These ordinances can then be updated to drive emissions reductions by setting a price on emissions and requiring owners to reduce emissions or pay non-compliance fees. A recent example of such a Building Energy Use Disclosure and Emissions Reduction Ordinance is the one passed by the city council of Cambridge, MA.

Attitudinal Changes to Help Achieve Zero Carbon. Updated policies, regulations, and public pressure will help move the US toward zero carbon, but a change in personal attitude is also required. Such change can be rapid and widespread given a catastrophic event. The mobilization of the United States after the attack on Pearl Harbor in World War II is often cited as an example. While WWII resulted in rationing many common goods, people were also willing to make additional sacrifices and change personal behavior. Industry also made rapid changes to support the war effort. Without widespread public support, the range of behavior changes required for achieving zero carbon will be nearly impossible. Creating that support can start by building public awareness of the issues and framing the changes required in a way that individuals can understand and implement.

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JEC_WTTv5_ Appendix 1_Pathways 1_Oil and Gas.xlsx
of the report. Results are summarized in the summary tab of the workbook. Details on which the summarized results are based are included in separate tabs for each fuel type. The report, appendixes, and workbooks can be downloaded from
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