DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Net-Zero Carbon Fuels Tech Team Roadmap

April 2021

This roadmap is a document of the U.S. DRIVE Partnership. U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability) is a voluntary, non-binding, and non-legal partnership among the U.S. Department of Energy; USCAR, representing FCA US LLC, Ford Motor Company, and General Motors; five energy companies – BP America, Chevron Corporation, Phillips 66 Company, ExxonMobil Corporation, and Shell Oil Products US; four utilities – American Electric Power, DTE Energy, Duke Energy Corporation, and Southern California Edison; and the Electric Power Research Institute (EPRI).

The Net-Zero Carbon Fuels Tech Team (NZTT) is one of 13 U.S. DRIVE technical teams whose mission is to accelerate the development of pre-competitive and innovative technologies tenable a full range of efficient and clean advanced light-duty vehicles, as well as related energy infrastructure.

For more information about U.S. DRIVE, please see the U.S. DRIVE Partnership Plan, at www.vehicles.energy.gov/about/partnerships/usdrive.html or www.uscar.org.

Introduction

Rapid cost reduction and growth in deployment of renewable electric power generation resources have emerged as driving forces in decarbonization of the energy sector. Along with fuel source switching and gains in energy efficiency, the scale-up of renewable electricity generation has reduced the greenhouse gas emissions intensity of the US electric power sector [1]. As more and more solar and wind resources are deployed over the coming decades, this trend of decreasing carbon dioxide (CO_2) emissions intensity in the electric power sector is expected to continue. While many challenges lie ahead regarding load management, energy storage, long-distance transmission, and capacity factors, the path to decarbonization of the power sector is arguably straightforward.

Simultaneously, the transportation sector in the US has seen a rise in CO_2 emissions as increased activity in miles traveled or freight-tons moved has offset on-going vehicle efficiency gains [2] As such, the transportation sector passed the power sector as the lead emitter of greenhouse gasses in 2016 [3]. The transportation sector has been considered a hard to decarbonize sector with many large scale integrated models assuming it will be easier to find other net negative emissions technologies to offset transportation emissions rather than fully mitigate emissions from transportation [4]. But substantial changes have occurred in the transportation sector in the last ten years. Technological progress on batteries as well as the lower than expected cost of renewable electricity has led to major companies declaring large scale moves to EVs. Hydrogen and biofuels have also dropped in cost and advanced in technology substantially and are seen as potential cost-effective options to reduce GHG emissions in the sector.

There are sub-sectors of transportation that will be hard to electrify and there will be a long transition with legacy vehicles in all sectors for decades to come. As a result, even with widespread electrification of on-road vehicles, the need for energy-dense, carbon-based liquid fuels is projected to continue, especially in long-distance travel and transport, whether highway, marine, air, or rail [5].

Dependence on liquid fuels, which are mostly derived from fossil petroleum today, conflicts with the increasing desire from both public and private sectors to reduce overall greenhouse gas emissions from the economy. Thus, a future economy that will seek a reduction in greenhouse gas emissions while preserving transportation system functionality may not so much be a zero-*carbon* economy as much as it will be a *renewable*-carbon economy. Many questions exist regarding how such carbon-based fuels should be produced, where they will source their carbon and energy, and how they should be deployed at relevant scales while maintaining their reduced carbon footprint and sustainability characteristics. The US DRIVE partnership, as a longstanding government-industry collaboration providing regular interaction amongst technical experts, is well-suited to address this topic in the form of a Technical Team. Such a team can identify the

[1] https://www.eia.gov/todayinenergy/detail.php?id=26752
[2] https://www.eia.gov/todayinenergy/detail.php?id=42775
[3] https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions
[4] https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_summary-for-policymakers.pdf
[5] https://www.nrel.gov/docs/fy18osti/71500.pdf

hurdles to development of “net-zero carbon fuels” while simultaneously investigating and advancing solutions to enable their timely deployment, at scale, into the marketplace.

As with all US Drive work, this effort is based on life-cycle analysis. The term “net-zero carbon fuels” represents the aspiration to have net-zero CO_2 equivalent emissions on a life-cycle basis. Yet, the work on this tech-team involves a range of pathways that will have varying levels of GHG emission reductions, including some that yield net negative emissions on a life-cycle basis and others that still have some level of emissions. DOE’s Bioenergy Technologies Office (BETO) State of Technology documents that there are many pathways that have potential to achieve 80% or more reduction, for example.

Scope and Objectives

Recognizing the importance of this challenge, the U.S. DRIVE Executive Steering Group directed its Joint Operations Group to establish a Technical Team to investigate net-zero carbon fuels in May 2019. From this action, the Net-Zero Carbon Fuels Technical Team (NZTT, or Net-Zero) was initiated with the following Mission Statement:

Drive research, development, and demonstration of renewable energy solutions for the transportation sector through a consensus assessment of the carbon intensity, technoeconomic readiness, and challenges for volume implementation of net-zero carbon fuel pathways.

The scope of NZTT will be proposing and investigating solutions for generating carbon-based liquid fuels with a reduced carbon intensity (CI) such that, from a life cycle carbon accounting standpoint, they have a net carbon emissions profile approaching zero. The Tech Team will also perform process analyses to examine the conditions required for economic viability and allow eventual demonstration and ultimate commercialization of the most promising technologies. As stated above, today’s exclusive use of liquid fuels in parts of the transportation sector points toward the need for carbon-based liquid fuels but that are derived from low carbon-intensity sources. The main renewable options for liquid fuels are commonly considered to derive from biomass, such as corn, oilseeds, algae, and woody or herbaceous biomass, or from waste materials including fats, oils, and greases (FOGs), agricultural residues, municipal solid waste (MSW), and liquid biosolid waste from farms or sewage treatment. However, substantial work, including at DOE, has shown that gaseous sources of carbon, CO and CO_2, for example, also may represent viable pathways. All of these approaches are within scope of this NZTT effort. It is also important to recognize the range of conversion technologies that could be applied to these sources and the need for inputs such as hydrogen, heat and electricity that may be required. There are also risks and challenges with gathering, transporting, storing and processing the various feedstocks that must be considered. For example, this ranges from managing wet corn stover, to sorting MSW, to concentrating CO_2 from direct air capture or other point sources.

To evaluate the technological maturity and feasibility of various renewable fuel pathways, a technoeconomic analysis (TEA) is often used to provide estimates of the economic performance of complete fuel production processes. Such an analysis is done by assessing the overall material and energy inputs and outputs and costs, as well as the product potential of a process, based on its current state of technology development. This information is then used to identify the parameters that most significantly impact costs while also estimating the technical readiness of the technology for deployment at a relevant scale. In this case, such an analysis can usually be presented as the cost of fuel production for a given fuel volume. Complementary to a TEA, a life cycle analysis (LCA) is often performed as either a “well-to-wheels” or a more extensive “cradle-to-grave” analysis to assess the environmental impacts associated with the various stages of vehicle and fuel production and use, including resource extraction, feedstock growth and processing, conversion, distribution and end-use. Together, TEA and LCA provide insights into potential projected costs of new fuel pathway technologies and environmental performance improvements compared to existing fuels refined from fossil sources.

In an applied research and development setting, where technology exploration is directly tied to practical application and possible commercial deployment, the unit operations and process design for the renewable fuel being developed are often optimized to achieve the lowest minimum fuel production cost possible. Thus, fuel pathway design is typically optimized first in a TEA, followed by the same parameters being used to perform an LCA to determine the greenhouse gas emissions and other environmental impacts.

For the NZTT, the objective is to take an “LCA-centric” approach to assessing potential renewable fuel pathways, where the technology is optimized for reduced carbon intensity and the technoeconomics of these pathways are assessed to determine the associated cost of carbon mitigation for a given technology solution set. The NZTT will develop a consistent assessment of key performance metrics for each pathway considered in an effort to define the most promising solution sets for reducing the carbon intensity (CI) of transportation fuels. Once an initial assessment of the hurdles and costs associated with driving down the CI of a particular renewable fuel pathway is documented, it will be used to identify the specific technical barriers, research needs, and opportunities for regional optimization to inform pilot plant demonstration of fuel production pathways. Other sustainability metrics, such as water and land use, can also be examined where applicable.

Several advanced carbon management strategies will be investigated by the NZTT to determine their potential for lowering the CI of fuels. On the front-end, conventional biofuel inputs such as corn starch will be considered, as well as lignocellulosic biomass, algae, and waste streams such as MSW and, notably, CO_2. These will be selected to cover a wide range of potential feedstocks that vary in physical characteristics and CI in order to discern their costs and benefits regarding their ability to provide net-zero carbon fuels. A number of different conversion technologies will be considered to convert the feedstocks into liquid fuels. Several carbon mitigation strategies will be examined, such as the integration of atmospheric carbon capture, utilization, and/or sequestration, increased process electrification, renewable hydrogen utilization, and the co-generation of supplemental non-fuel products, among others.

Initial Tech Team Analyses Tasks

Much research has gone into both the technoeconomics of proposed renewable fuel pathways and the resulting GHG emissions profiles associated with those solutions. However, there is a lack of a systematic comparative analysis between different renewable fuel pathways as well as specifically targeting the cost and feasibility of net-zero carbon fuels. The U.S. DRIVE Partnership is well positioned to investigate the cost and practicality of various renewable fuel pathways delivering net-zero carbon fuels at relevant cost and scale. To this end, the NZTT will develop a consistent set of input assumptions and performance metrics – focusing on cost per gallon gasoline equivalent ($/GGE) and carbon intensity (gCO_2/MJ) – for a wide range of potential net-zero-carbon fuel production pathways. In its first year, the NZTT will analyze four distinct fuel pathways to determine their potential for net-zero carbon fuels. *The selection of these pathways is not meant to represent what the Department of Energy or U.S. DRIVE see as the most promising routes to low carbon fuels.* Rather, these four initial pathways were chosen in order to:

- Leverage a large existing library of literature and R&D
- Cover a breadth of existing bioenergy technologies in the most efficient way possible
- Construct a diverse library of carbon mitigation strategies that can be implemented across other fuel-related pathways for further investigation
- Provide a consistent framework for assessing technologies based on a common set of performance metrics, input assumptions and evaluation tools.

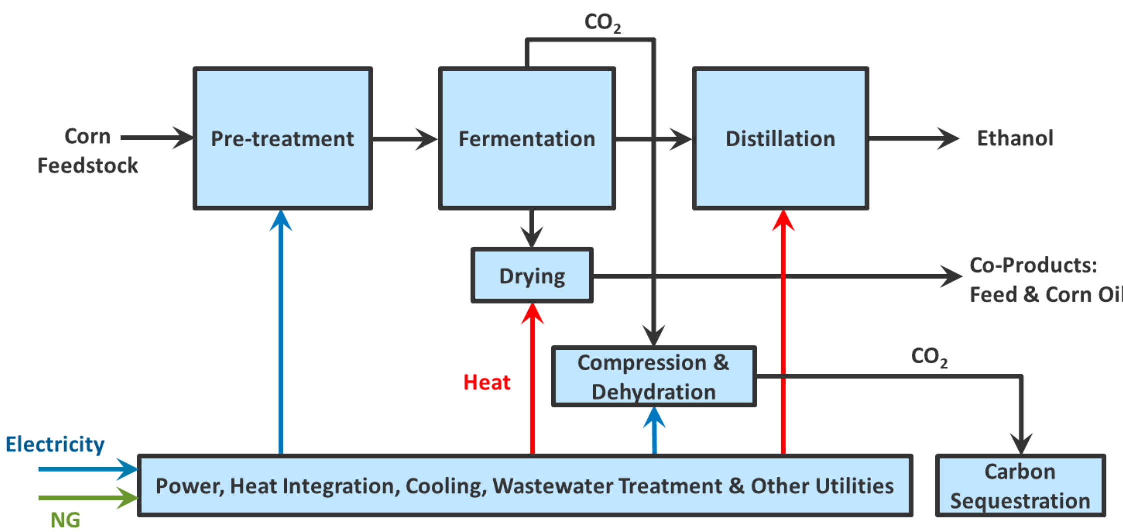
Many of the strategies for reducing the CI of fuels examined in this study will have a significant cost associated with their implementation. The goal of these analyses will be to gain an understanding of the costs and benefits associated with these processes and determine a relative cost of carbon mitigation for their potential use in delivering net-zero carbon fuels.

After analysis of these initial four pathways in the first year, the NZTT will then identify and work on additional pathways, carbon and energy sources, and advanced techniques, such as:

- Low-carbon electricity sources with different intermittency and cost profiles (e.g., wind, solar, geothermal, biomass, nuclear)
- Various carbon sources including purpose-grown biomass (wood, grasses, algae); crop residues and MSW; wet wastes such as food waste and sewage sludge, and CO_2 from point sources and direct air capture
- Hydrogen production options
- Carbon Capture, Utilization and/or Sequestration
- Additional biochemical, electrochemical, and thermochemical processing steps

The four selected pathways for initial analysis are the following:

1. **Traditional Corn Starch-to-Ethanol w/ Carbon Capture, Utilization and/or Sequestration (CCUS)**

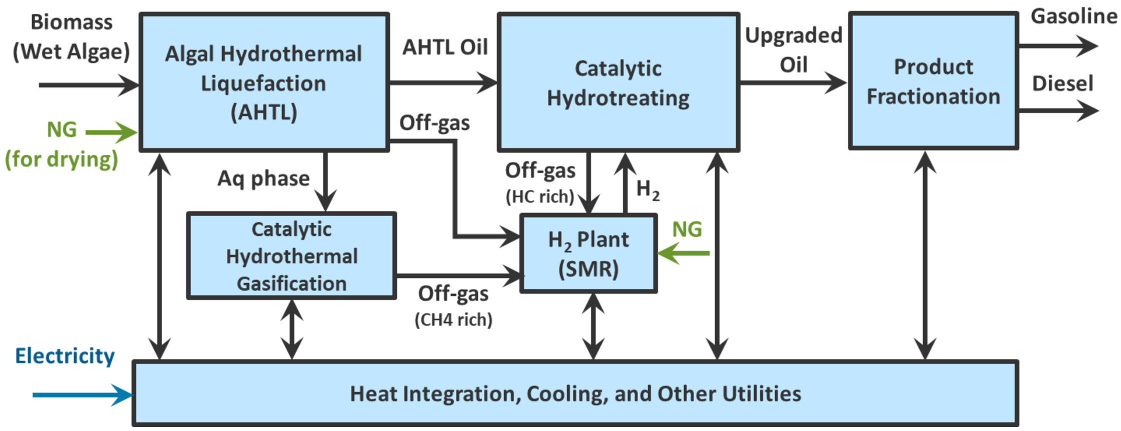


Case 1: Corn Ethanol with Carbon Capture and Sequestration block flow diagram

Currently, the most widely used renewable transportation fuel in the US is corn ethanol. It is produced by converting the starch within corn to sugar, followed by fermentation. For every molecule of ethanol produced in this process a molecule of CO_2 is also evolved, generating an extremely concentrated stream of CO_2 that is especially amenable to conversion into additional ethanol product (CCU), or for direct sequestration (CCS). The capture of biogenic CO_2 from fermentation is unique because, unlike most carbon capture from fossil fuel combustion, it requires significantly less separation. Thus, purification, dehydration, and compression of fermentation CO_2 streams can be accomplished at relatively low cost and is currently in place at numerous plants across the US for utilization in the food and beverage industry, among others. The wide distribution of corn ethanol plants across the US makes it a potentially attractive option for early implementation, at scale, of fuels with a significantly reduced carbon intensity.

In order to better understand the near-term potential of this option, the NZTT will investigate the reduction in CI that can be achieved at a biorefinery that deploys CCUS and other advanced carbon management strategies. In addition to capturing fermentation CO_2, the capture of other on-site sources of CO_2, such as those related to heating and drying will be considered. There is also an opportunity in subsequent years to assess the biochemical conversion of lignocellulosic feedstocks, each with varying CIs themselves, as well as switching to the use of renewable sources of energy at the biorefinery and the incorporation of CO_2 utilization into the process.

2. **Algae-to-hydrocarbons**

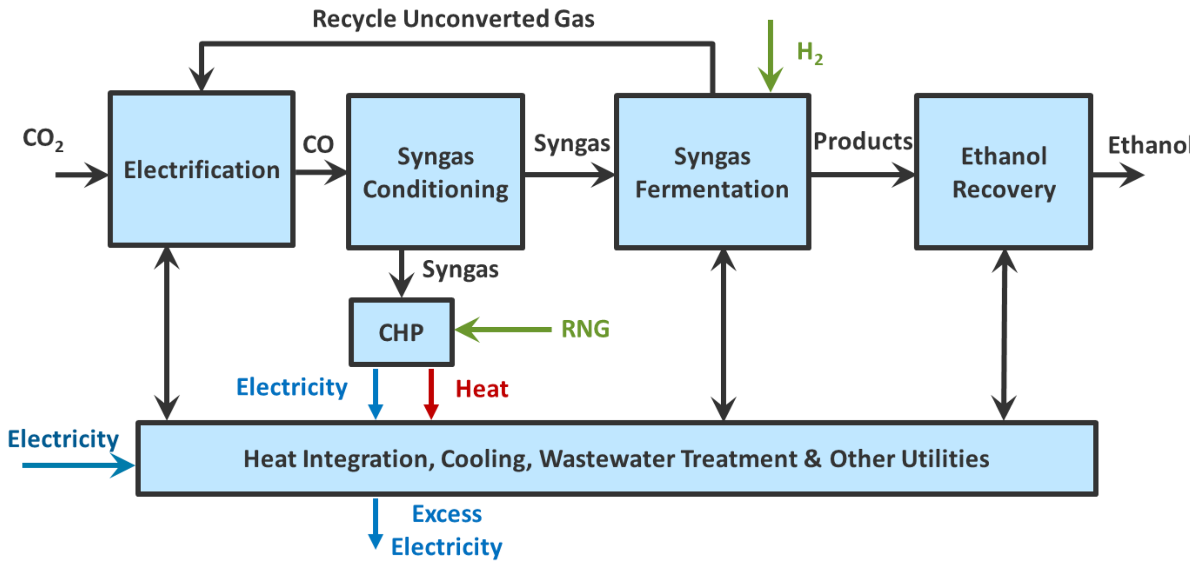


Case 2: Algae Hydrothermal Liquefaction block flow diagram

Algae have been widely studied as a potential source of carbon for the production of renewable fuels because of their ability to be grown in marginal non-agricultural areas as well as their high lipid content and high areal productivity. Several pathways have been studied for producing algal biofuel, with one of the most common utilizing a lipid-accumulating strain of algae from which lipids are either extracted and converted to biodiesel through transesterification or lipids are hydrotreated and converted into a renewable diesel blendstock. Another approach to algal conversion lies in hydrothermal liquefaction (HTL), which utilizes heated water under pressure to convert wet microalgae to an HTL oil, which can then be hydrotreated to produce fuels. In addition to algae, wet waste feedstocks such as fats, oils and greases and residual organics in wastewater are amenable to HTL treatment.

For this analysis, the NZTT will leverage existing research into HTL to explore innovative approaches to reducing the CI of algal biofuels. The integration of renewable electricity into the process will be investigated. This will include an examination of how the source of the hydrogen used to upgrade the HTL oil changes the overall GHG profile and cost potential of the finished fuel. Sourcing hydrogen from water electrolysis using renewable electricity will be compared to hydrogen sourced from nuclear power or steam methane reforming (SMR) in conjunction with CCUS.

3. CO_2-to-carbon monoxide to jet fuel via an ethanol intermediate

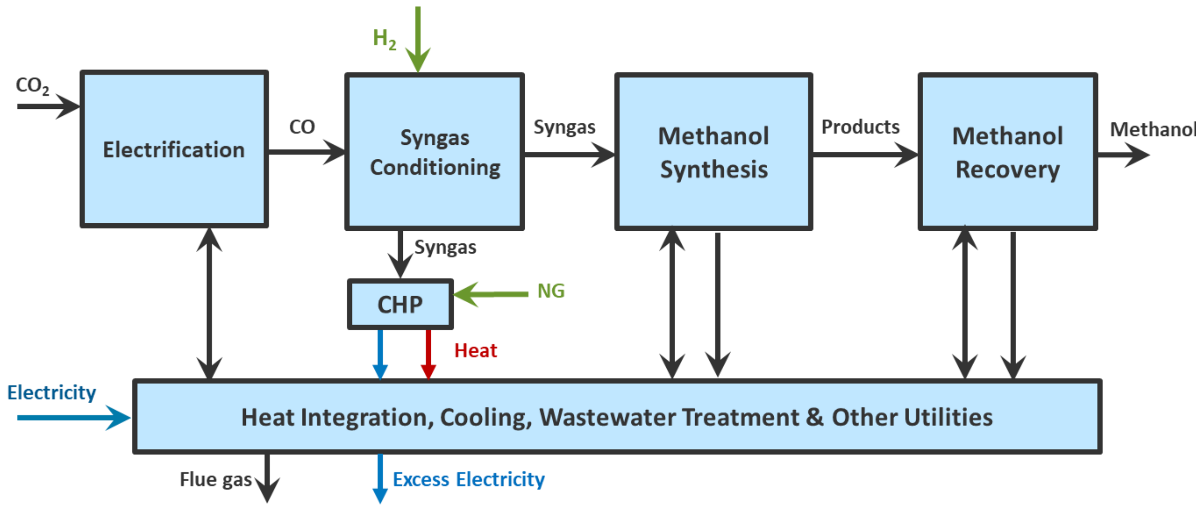


Case 3: CO_2 conversion to ethanol block flow diagram

As the deployment of renewable power generation increases, interest in leveraging zero-carbon electricity for production of liquid transportation fuels grows. While applying this electricity to generate hydrogen by splitting water has been studied for many years, the utilization of electricity to directly reduce CO_2 has received significant recent attention as a way to generate net-zero carbon fuels. However, the ability of electrocatalytic reduction of CO_2 to provide such fuels relies heavily on how efficiently the electrical energy can be converted into chemical bonds; as the number of electrons transferred onto CO_2 increases, the energy, carbon, and economic efficiency of the process generally decreases. Thus, generating hydrocarbons of chain lengths similar to those found in current transportation fuels strictly from electrochemical reduction remains a difficult proposition.

Given these important factors, the NZTT will focus on leveraging electricity to generate single carbon (C1) intermediates for subsequent upgrading via various established routes. For this third case, the Tech Team will initially examine CO_2 electroreduction to carbon monoxide (CO), followed by acetogenic fermentation to ethanol for eventual conversion to jet fuel. The cost and management of renewable electricity used are key sensitivities to the prospect of such a pathway. In addition to those variables, this work could also be used to compare a thermochemical route for generating CO, alternative intermediate upgrading strategies and various carbon sources (i.e. different sources of CO_2 or biomass gasification for generating syngas) in order to better understand the costs/benefits of using CO_2 as a feedstock.

4. CO_2-to-methanol to gasoline



Case 4: CO_2 conversion to methanol block flow diagram

Using the same rationale as described in Case 3, the NZTT will consider methanol as an alternative CO_2-derived intermediate for subsequent upgrading to net-zero carbon fuels (gasoline in this instance, following an existing biomass gasification design case). This will allow for an assessment of the tradeoffs associated with generating methanol indirectly (via syngas intermediate) or directly via electrocatalysis, as well as a similar sensitivity analysis to the price and intermittency of zero-carbon electricity and hydrogen. This can also be used for an investigation of thermocatalysis versus electrocatalysis for generating methanol and for additional methanol upgrading strategies. The potential for methanol as a final fuel itself will also be assessed and discussed. As described in Case 3, this pathway can consider various CO_2 sources (i.e. different CO_2 feedstocks or gasification scenarios) in order to gain a full understanding of the costs and benefits associated with various technology combinations.

Approach and Timeline

This Tech Team will perform the initial TEA and LCA analyses described above to understand the potential of several illustrative near-term options for generating renewable carbon fuels with a low carbon footprint. These initial analyses will incorporate advanced carbon management techniques into several existing renewable fuel pathways that already exist in the literature and have previously been examined by the research community and the DOE National Laboratories. These initial activities will help determine the rough boundaries of 1) the magnitude of CI reduction possible for different technologies to provide net-zero carbon fuels and 2) the change in fuel production costs associated with implementing these carbon management technologies.

These initial analyses will occur in Year One to evaluate what is possible and identify the most promising opportunities for lowering the CI of renewable fuels. The results of the Year One investigations will be externally published following approval of the U.S. DRIVE leadership team. After the first analyses have been produced, the Tech Team will use this information to narrow or expand certain areas of interest where applicable to maximize the cost-effectiveness of net-zero-carbon fuels.

Using the insights gained in the first year, the NZTT will identify and implement the R&D needed to address the near-term opportunities or barriers associated with net-zero carbon fuels during Year Two. This will include identifying the technical progress that is required to reduce uncertainty for deploying these technologies at the sub-pilot and pilot scale to assess process integration and commercial viability. In addition, the Team will expand its scope to address additional fuel production pathway options and perform TEA and LCA investigations of alternative technologies and feedstocks. These will be chosen in order to extend the coverage of the net-zero landscape to opportunities that are currently at a lower TRL but have potential advantages in the longer term.

Year Two will also involve an assessment and report of the policy and regulatory environment in which net-zero carbon fuels would exist. The NZTT will analyze the potential regulatory/policy challenges relevant for the technical pre-competitive R&D pathways in NZTT's scope and how they would affect the deployment of net-zero carbon fuels, collaborating with other agencies as needed. Additionally, the NZTT can provide the technical data needed regarding the potential of net-zero carbon fuels to federal leadership upon request. The NZTT will reach out to other existing global administrative groups to better understand and more quickly evaluate regional approaches to carbon reduction.

The third year of this Tech Team will integrate with other DOE and U.S. DRIVE initiatives where it is warranted. Based on completed analysis and R&D in the first two years, the NZTT, with U.S. DRIVE leadership approval, will externally publish a report summarizing the overall learnings and develop a timeline for the production of fuels that achieve established thresholds of CI reduction, cost and volume potential. This will include evaluating the region-specific potential for siting future facilities that will take advantage of regional feedstocks to produce net-zero carbon fuels by drawing on geographically- relevant resource sets to address commercial viability. These findings of the NZTT will serve to inform BETO's current biorefinery scale up strategy.

Key Issues and Challenges for Net-Zero Carbon Fuels

The NZTT will support the U.S. DRIVE Partnership by considering in its assessment a wide variety of technologies and criteria that affect both the final CI and cost of a renewable fuel and its potential readiness for market introduction. In doing so, the team will also elucidate challenge areas where focused analysis, research and development can be of greatest impact in enabling the market uptake of low-carbon fuels

Carbon Source and Cost

In the US, biomass and waste streams represent a rich source of renewable carbon for generating fuels and chemicals. These resources differ in the inherent amount of energy present, from the energy-dense sugar extracted from corn, to the more recalcitrant energy present in lignocellulose or municipal solid waste, or CO_2 which is notable for having no accessible energy. Even though CO_2 is difficult as a feedstock due to its oxidation state, it is a readily available carbon source the must be considered when developing renewable technologies. Defining the CI of renewable fuels is highly dependent on the chosen source and should be carefully assessed.

Similarly, the cost of these carbon feedstocks plays a pivotal role in assessing the technoeconomic feasibility of net-zero fuels. This can vary widely depending on feedstock quality, location and regional policies. For example, some waste feedstocks can have low or negative costs, such as food wastes and concentrated CO_2 streams, depending on the location and local regulations. Other feedstocks, such as agricultural and forest residues may have prices that fluctuate based on time of year and region of the country. Finally, atmospheric CO_2 capture is energy intensive but is possible at all locations and seasons, and may be a necessary mitigation action in the long-term. The tradeoff between these is central to developing net-zero carbon fuels. The NZTT will also consider direct air capture (DAC) of CO_2 as a potential option for providing a low carbon feedstock for fuel synthesis processes. These analyses will explore the general technical readiness of DAC and how technology improvements and cost reductions could affect the use of DAC CO_2 as a feedstock. This will involve other DOE offices beyond those in the Office of Energy Efficiency and Renewable Energy as needed.

Electricity Cost and Carbon Intensity

The cost and CI of electricity across the US are on downward trajectories due in part to the deployment of wind and solar energy resources. Electricity is an element of many fuel pathways, regardless of the carbon source. For CO_2 as a feedstock, the importance of electricity is obvious as it is used (via thermocatalysis, electrocatalysis, etc.) to provide the energy embedded within the fuel. Similarly, several other more conventional pathways to renewable fuels rely on electricity in the process, such as biomass deconstruction during pretreatment, enzymatic hydrolysis during biochemical conversion, or electricity used to run ponds during algae cultivation. In a scenario where 1) the process is focused on the lowest CI possible and 2) the cost of renewable electricity is reduced, it will become beneficial to incorporate more electricity into the pathways where possible.

The NZTT analyses will probe technologies that take advantage of low-cost renewable electricity sources by assessing production pathways and storage scenarios. The inherent intermittency of renewable electricity could hamper an industrial process, necessitating the need for upstream buffering of feed streams or for reduced unit operation capacity factors. It may also present an opportunity, where excess renewable energy is stored in chemical bonds of an intermediate product (i.e., Power-to-Gas) that can later be released when needed to either reduce fuel production costs or to help balance an increasingly variable renewable electrical grid. (In addition to energy storage, intermittency may also be balanced by diversification, interconnection, generation curtailment, demand shifting, and fossil backup generation. Fortunately, the electricity generation market already involves dynamic economic considerations.) These factors, along with the possibility of leveraging dedicated, off-grid renewable resources will be considered and investigate with consultation from relevant DOE efforts, such as Renewable System Integration.

Hydrogen Sourcing

Hydrogen is a critical aspect of many renewable fuel pathways as it chemically displaces the oxygen that is inherent in not just CO_2 but almost all biogenic sources of carbon. Currently, most hydrogen in the US is sourced from steam methane reforming (SMR) of natural gas, which has significant CI. The alternative source of hydrogen from low temperature water electrolysis will be one obvious source examined here, however other sources will be investigated, such as high-temperature solid oxide electrolysis and SMR+CCS, which can produce hydrogen from fossil resources with a low carbon footprint.

The NZTT will work with the DOE Hydrogen Fuel Cell Technologies Office and their H2@Scale program team to assess current and potential cost curves for production of low-carbon hydrogen as an input into fuels synthesis processes as well as production sources and distribution. These analyses will explore all potential pathways for the introduction of zero CI hydrogen into the fuel production process along with the value generation associated with potential co-products such as oxygen.

Logistics and Regionality

While liquid fuel products can be moved from production source to market at relatively low cost, production process inputs such as biomass, CO_2, H_2 or energy may incur significant costs for movement and/or storage. For example, the Midwest US might be advantageous for both agricultural-based biomass or waste fermentation CO_2 inputs and wind energy, while the Southwest US might present an opportunity for MSW conversion coupled with low-cost solar. Similarly, the regionality associated with geological storage sites for CCS must also be considered. In assessing production at scale, the NZTT anticipates the need to address the impact of regionality of these resources and determine how that effects the costs for a given process.

Fuel Products and Value Assessment

The ideal liquid fuel is energy dense, burns efficiently, generates low criteria emissions, and is compatible with existing distribution channels and legacy vehicles. Where trade-offs present themselves with respect to these criteria, the NZTT will consider such attributes in assessing various fuel production options. While CI and cost will be assessed, the team can leverage other efforts such as the DOE Co-Optima team to assess the combustion and emissions performance trade-offs of potential alternative net-zero-carbon fuels as the need arises. Markets beyond the light-duty fleet, including marine, aviation and heavy-duty transportation, can be examined and their economic viability and impacts assessed.

Policy Environment and Technology Demonstration

Recent technical advances in exploration and extraction have unlocked growing reserves of petroleum at historically affordable prices. This fact, along with the relatively high costs associated with making net-zero carbon fuels, suggests that low-carbon alternatives will have near-term challenges in the marketplace. While it will not be the role of the NZTT to propose or advocate for specific policies, the team will investigate possible policy impacts and regulatory concerns in an effort to understand how the large-scale implementation and demonstration of net-zero carbon fuel is affected.

The NZTT will develop technical reports summarizing the learnings from each year and will inform strategies for regionally optimized, economically viable net-zero carbon fuel production solution sets that can advise BETO's current scale up strategy and provide insight to entities considering commercialization. Demonstration at increasingly large scale is critical to understanding the technical and economic viability of these technologies and to de-risk eventual commercial scale investments by industrial partners.

Conclusion

Public and private interest in reducing transportation-related carbon emissions is intensifying, while at the same time a growing global middle class is demanding transportation services (both personal mobility and goods movement) at an unprecedented scale. Reconciling these demands will require a full range of transportation energy solutions, from batteries, to hydrogen, to net-zero carbon liquid fuels. This drive for net-zero carbon fuels coincides with an electricity sector that is concurrently reducing both the cost and the carbon intensity while working to address the inherent intermittency of renewable sources. The intersection of these trends presents an opportunity that the U.S. DRIVE Partnership is well-suited to address.

The Net-Zero Tech Team has strong support from a broad range of industry players and DOE offices as well as a full roster of experts eager to tackle the problem. This ensures that significant expertise will be applied to the stated challenge of decarbonizing the full array of transportation modes while preserving consumer choice and minimizing societal cost. In keeping with its mission, it is the expectation that the NZTT will analyze key low-carbon fuel pathways and compare them for their potential to produce net-zero carbon fuels at meaningful volumes in a timely manner. The team will also deliver solutions for overcoming technical barriers through focused research and development activities that lead to pilot plant demonstration to prove out commercial viability and scalability. Fulfillment of the NZTT mission will allow the United States to provide solutions and remain competitive in a global transportation system that values options in low-carbon transportation.