The Future of Low-Carbon Transportation Fuels

Christopher Yang and Sonia Yeh

Institute of Transportation Studies
University of California, Davis
Davis, CA 95616

Abstract. Petroleum fuel uses make up essentially all of transportation fuel usage today and will continue to dominate transportation fuel usage well into future without any major policy changes. This chapter focuses low carbon transportation fuels, specifically, biofuels, electricity and hydrogen, that are emerging options to displace petroleum based fuels. The transition to cleaner, lower carbon fuel sources will need significant technology advancement, and sustained coordination efforts among the vehicle and fuel industry and policymakers/regulators over long period of time in order to overcome market barriers, consumer acceptance, and externalities of imported oil. We discuss the unique infrastructure challenges, and compare resource, technology, economic and transitional issues for each of these fuels. While each fuel type has important technical and implementation challenges to overcome (including vehicle technologies) in order to contribute a large fraction of our total fuel demand, it is important to note that a portfolio approach will give us the best chance of meeting stringent environmental and energy security goals for a sustainable transportation future.

INTRODUCTION

Petroleum fuel uses make up essentially all of transportation fuel usage today and will continue to dominate 95% of transportation fuel usage in 2035 according to the Energy Information Administration's Annual Energy Outlook projection [1]. Biofuels make up the largest increase in the use of alternative fuels, to about 4% of fuel usage in 2035. The same projection also shows a 12% increase in greenhouse gas (GHG) emissions from transportation between 2010 and 2035 due to demand growth. As discussed in earlier chapters, fossil fuel use has many economic and environmental externalities, including our reliance on imported energy source that weakens our energy security, air pollution that impacts health and, of more recent concern, GHG emissions that contribute to changes in climate. While the focus of this chapter is on reducing fossil fuel use and GHG emissions, tackling all of the issues associated with petroleum dependence in transportation requires a coordinated effort involving reducing growth in travel demand, improving vehicle efficiency and a switch to cleaner, lower carbon fuels.

This chapter focuses on low carbon transportation fuels, specifically, biofuels, electricity and hydrogen, which are emerging options to displace petroleum-based fuels. Fuels such as electricity and hydrogen are intimately tied to the vehicle platform, though this chapter primarily focuses on the fuels themselves. This chapter also emphasizes fuel use for light-duty vehicles (i.e. passenger cars and trucks), which make up around 55% of energy use in the transportation sector, though fuels used in other modes of transportation will also be briefly discussed. There needs to be considerable technology development involved with widespread use of these fuels, including the development and deployment of vehicle platforms and infrastructure for production, transport and refueling. Each fuel has multiple “pathways” for production and delivery, which will determine their energy and emissions footprint and the benefits associated with their adoption (Figure 1). This chapter discusses the transition challenges to alternative fuels, particularly the infrastructure challenges, and the insights of making a transition to sustainable transportation over the long run.

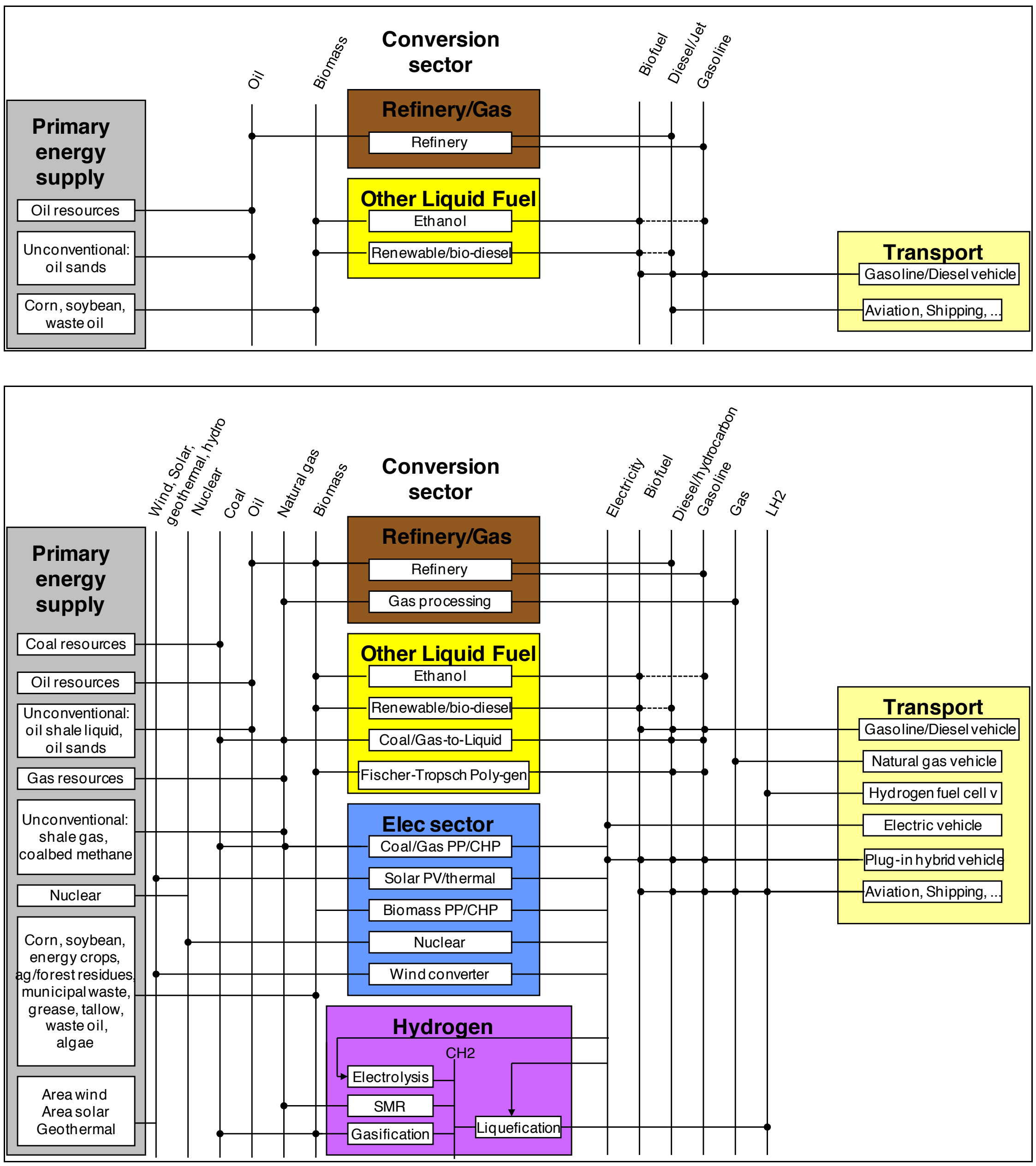

FIGURE 1. Current (top) and potential future (bottom) transportation fuel sources, conversion technologies, fuel types and vehicle technologies.

BIOFUELS AS A TRANSPORTATION FUEL

While biofuels can comprise of a range of forms, including liquid, solids and gaseous forms, this chapter focuses only on high energy-density liquid fuels used as a substitute for petroleum-based fuels. As shown in Table 1, biofuels can be produced from a wide array of potential biomass feedstocks and technology. Thus, biofuels can have potentially very different fuel properties, energy use, emissions and other impacts (such as environmental impacts in land use and water requirements) throughout their production lifecycle, including cultivation, transport and conversion to biofuels. Biomass feedstocks for liquid fuel production can be categorized into four types: lignocellulosic biomass, sugars/starches, oils and animal fats, and algae. These feedstocks can come from a variety of sources including grain-based crops (such as corn or soy), oilseeds and plants (such as oil palm and sugarcane), agricultural residues, energy crops, forestry resources, industrial and other wastes, and algae. The technology for the conversion of these feedstocks to a liquid fuel can also take several different forms, including biological, chemical and thermochemical processing (Table 1). First generation biofuels, those that are commercially available today, include sugar- and starch- based ethanol (and other alcohol fuels), which is a gasoline substitute and vegetable oils and biodiesel, which are diesel substitutes. Advanced biofuels are derived from pathways currently in development and include alcohol fuels from cellulose, algal-based fuels, and thermochemical conversion of biomass to hydrocarbon that can be converted to a full range of fuels including gasoline, diesel fuel and jet fuel that meet the same specifications as today's petroleum fuels.

TABLE 1. Biofuel feedstock and production pathways. Adapted from Parker et al. [2]

Feedstock category	Feedstock type	Conversion technologies
Starch-based and sugar-based biomass	Corn, sugarcane, sugar beet, sweet sorghum	Bioethanol through hydrolysis and fermentation
Ligocellulosics	Forest biomass, herbaceous energy crops, agricultural and food production residues, municipal solid wastes	Cellulosic ethanol through hydrolysis and fermentation, upgrading of pyrolysis oils to gasoline, Fischer Tropsch diesel
Lipids	Seed oils, yellow grease, animal fats	Fatty acid to methyl esters (FAME), hydro- treatment of fatty acids to hydrocarbons (FAHC)
Algae		Transesterification

Conversion of biomass into a biofuel can take many forms. Commercially available conversion processes used for first generation biofuels include biological fermentation (via yeast) of sugars into ethanol, and chemically catalyzed transesterification of oils/fats and alcohols into biodiesel (and glycerol co-product). More advanced processes are currently being developed and refined, including ethanol production from lignocellulosic biomass (e.g. wood, grass, and straw) requiring conversion of cellulose and hemicellulose into component sugars, thermochemical conversion of lignocellulosic biomass via gasification and a Fischer-Tropsch synthesis process into diesel fuel, and algae biofuels, which require development of cultivation, separation of cells and oils and conversion to useful fuels.

While biomass resources are plentiful, not all is technically, economically and environmentally viable for conversion to transportation fuels. Estimates of US biomass indicate that it could be sufficient to supply somewhere around 80-100 billion gallons of gasoline equivalent of biofuels per year. Depending upon vehicle efficiency and projections of future travel demand, this could be anywhere from approximately 1/3 of transportation fuel demand in 2050 in a business as usual case to nearly all transportation fuel demand in highly efficient and electrified demand future [3]. Limiting the use of specific biomass resources because of sustainability concerns will reduce the availability of these fuels even further. Limitations on sustainable biofuel supply will play an important role in determining the extent to which petroleum fuels can be displaced by biofuels [4].

The sustainability of biofuels is an important question and is dependent on the specific feedstock and conversion pathway to produce the biofuel. While there is no agreed upon definition of sustainability, many different metrics and potential impacts have been proposed and can be considered as contributors to a fuel's sustainability or lack thereof – ecosystem/habitat disruption, deforestation, soil quality impacts, direct and indirect GHG emissions, other air and water pollution, water usage, competition with food crops, and land conversion [4]. These negative impacts are important to quantify because they can mitigate or even exceed the environmental benefits that using biofuels is supposed to provide. The challenge in assessing these impacts is that there is both a wide variety of potential biomass feedstocks and conversion technologies as well as the fact that agriculture is widely variable based upon land quality, soil quality, precipitation patterns, etc, which make generic discussions of feedstock/conversion pathways less useful.

While some transportation modes can be electrified (such as light-duty plug-in electric vehicles, PEVs, or fuel cell vehicles, FCVs), other modes, specifically aircraft, marine shipping, and heavy-duty trucks are most likely to use liquid fuels for the next few decades because of vehicle range and fuel energy density issues. Given that these modes are projected to have significant travel demand growth [1], a low carbon biofuel is perhaps the only option for lowering the GHG intensity in these transportation modes.

ELECTRICITY AS A TRANSPORTATION FUEL

Plug-in electric vehicles are powered, at least in part, by electricity from the electric grid that is stored in an onboard battery. They can be either plug-in hybrid electric vehicles (PHEVs), which can run on electricity or gasoline or battery electric vehicles (BEVs), which run entirely on electricity. PEVs are much more efficient than conventional internal combustion engine vehicles (ICEVs) running on petroleum fuels. In addition, electricity is a decarbonized energy carrier that provides solutions to US petroleum dependence and local air pollution concerns. In addition, electricity can be made from a wide range of domestic resources, including low carbon resources, which can reduce the carbon intensity of fuels. PEVs are beginning to be commercialized in 2011 and make up a tiny fraction of vehicle sales.

While batteries are the key technology for the success of PEVs, the fuel electricity supply and infrastructure side of the equation is also important to understand from a technology and deployment perspective.

PEVs need to be plugged in to “refuel” the onboard batteries, which can range from about 3 kWh for a low-range PHEV to over 25 kWh for a longer range BEV. While current PEVs can be recharged at a conventional 120V outlet (often called level 1 charging), the rate of energy transfer is quite slow (~1-2 kW). To recharge more quickly, it is necessary to use higher voltage and current and a dedicated PEV charger (often called electric vehicle supply equipment or EVSE). Level 2 charging is 240 V and up to 40 amps for up to 9 kW while level 3 charging is being designed to allow for very fast charging (up to 80% of battery capacity in less than 30 minutes). An EVSE will use a standardized plug (e.g. SAE J1772).

Given the low penetration of PEVs, it is not surprising that there are very few PEV chargers deployed. However, there is concern that deployment of home-based charging equipment could be an issue if PEVs are to be widespread and electricity is to be a primary fuel for light-duty transportation. A survey by Axsen and Kurani [5] found that only about 50% of new vehicle buyers have a 120 V outlet within 25 feet of their household vehicle parking space and only 35% within 10 feet. Others have noted that in urban areas such as San Francisco, less than 20% of cars are parked overnight in dedicated off-street parking. Beyond home-based charging, deployment of public infrastructure is likely needed to increase the utility of PEVs and to ease drivers’ “range anxiety”. Public infrastructure would be useful at the workplace, at retail establishments, along major highways, and other activity centers. Charging times will be much longer than refueling a gasoline tank (30 minutes to several hours), and argue for co-locating charging while drivers are engaged in other activities (e.g. shopping, work). Studies are underway to understand the best locations for public infrastructure to minimize costs while maximizing utility and utilization.

The supply of electricity is an important part of the equation for electrified transportation. Electricity is already produced in large quantities and in the near-term, the amount of electricity that would be demanded from PEVs would be a tiny fraction of total electricity generation [6]. In California for example, charging of one million PEVs (about 4% of total LDVs) would only require about 1% additional electricity generation. Regardless, charging a PEV requires the grid to respond by providing more electricity and the operation of the grid is such that timing of when PEVs charge can be an important factor.

The electricity grid is collection of power plants and transmission and distribution facilities that produces and delivers electricity to end users and is structured to meet continually changing electricity demands by using a number of different power plant types. Some are baseload facilities (often large coal or nuclear plants) that are designed to operate continuously and at low cost, while peaking power plants (often fired with natural gas or oil) are operated only a handful of hours per year when demand is highest and are more costly to operate. The mix of power plants that make up the grid varies significantly from one region to another—based on local demand profiles, resource availability and cost, and energy policy. The timing of conventional electricity demands and of PEV charging demands will impact the types of power plants that are used to meet the additional demands and their associated emissions.

Charging during off-peak hours will tend to flatten the demand profile, reducing the need for additional generating capacity and lowering the average cost of electricity. Charging at peak demand times will increase capacity requirements, while lowering the utilization of existing plants and increasing electricity costs. If charging could be controlled to occur when it was most optimal, PEV demand could respond to grid conditions. Given that cars are parked approximately 95 percent of the time and potentially plugged in for a large fraction of the time they are parked, this is a real possibility. The smart grid, incorporating intelligence and communication between the supply and demand sides of the electricity equation, is needed in order to realize the full benefits of this vehicle charging flexibility. Managing vehicle recharging requires a smart charging system that enables communication between the customer and utilities. Consumers may give the utility or system operator some control over their charging in exchange for lower rates. This type of charging interface can also permit vehicle charging emissions to be appropriately tracked and allocated, which will become increasingly important as states and countries adopt low-carbon fuel standards and impose caps on GHG emissions in different sectors.

The carbon intensity of average US electricity is higher than for gasoline, but this is due to the fact that electricity is an intermediate energy carrier, which has already been converted from a primary energy resource, and can be used with very high efficiency (conversion of stored energy in a battery into mechanical work on the vehicle). Gasoline and diesel, on the other hand, are fuels that have been slightly modified from the original primary energy resource (crude oil) to achieve specific properties suitable for internal combustion engines. These fuels are converted at much lower efficiency to mechanical work on board the vehicle. Thus, while the carbon intensity of electricity (measured in grams of carbon dioxide equivalent emissions per mega joule, gCO2/MJ) is higher than that of gasoline and diesel, the carbon per mile of travel from a PEV can be much lower than that of a conventional or even hybrid vehicle. In addition, the carbon intensity of electricity will gradually be reduced as renewable generation increases and due to other carbon policies.

Of course, the supply of electricity differs in different regions of the country. Some areas, such as the west coast and the Northeast states have lower electricity carbon intensity (due to higher hydropower resources) than other areas, such as the Midwest States where relatively higher portions of electricity are generated from coal. These differences in regional electricity will impact the relative benefits of PEVs vs gasoline vehicles.

While there is the potential for electrification of light-duty vehicles, other transportation sectors are less likely to electrify. Rail, buses and delivery trucks also offer some potential for running on grid electricity. However, after LDVs, the main energy and emissions contributions from transportation come from aviation, heavy-duty long-haul trucking and marine shipping. These sectors present significant challenges to electrification and will likely rely on high-density liquid biofuels (or potentially hydrogen) in order to reduce their fuel carbon intensity.

HYDROGEN AS A TRANSPORTATION FUEL

Hydrogen has been widely discussed as a long-term fuel option to address environmental and energy security goals [7]. FCVs that use hydrogen are significantly more efficient than conventional vehicles, using less energy to produce a mile of vehicle travel. Additionally, the fuel can be made from a wide variety of domestic and low carbon resources, providing solutions to the oil dependency and carbon challenges. While FCVs have not yet been commercialized, several automakers have announced plans to introduce vehicles in the 2015 timeframe.

Like electricity, hydrogen is an energy carrier that is produced from a primary energy resource. Almost any energy resource can be converted into hydrogen, although some pathways are superior to others in terms of cost, environmental impacts, efficiency, and technological maturity. Currently in the US, about 9 million tonnes of H_2 are already produced each year (enough to supply about 30 million FCVs), mainly for industrial or refinery purposes. Natural gas reforming accounts for 95% of current H_2 production in the US and in the near-term, along with coal, should continue to be the least expensive method to produce H_2. In the longer-term, continued use of fossil resources to produce H_2 would necessitate the use of carbon capture and storage (CCS) technologies to minimize the GHG emissions from H_2 production. Additionally, H_2 can be produced from biomass in a production process similar to that from coal (gasification). Electrolytic hydrogen production can also be an important H_2 production technology in the longer-term and offers the potential for zero carbon production from renewables such as solar and wind.

Hydrogen infrastructure includes all of the components associated with producing, delivering and providing H_2 to the vehicle at a refueling station and can generally be categorized into two types: on-site and central production. Onsite production uses existing energy distribution methods for electricity or natural gas to allow for H_2 production at the refueling station (via electrolysis or natural gas steam reforming). Central production of hydrogen would require delivery of hydrogen, via compressed gas trucks, liquefied H_2 trucks or gaseous pipelines, to the refueling station. Over the near- to medium-term, H_2 infrastructure is likely to be comprised primarily of onsite H_2 stations, while over time it is expected to transition to an infrastructure primarily composed of central production and delivery [7], which is lower cost when demand is high enough [8].

One of the key issues regarding the deployment of hydrogen infrastructure is the so-called “chicken-and-egg” problem, which deals with the problem of ensuring that both the H_2 refueling infrastructure and FCVs will have access to the other as they are being deployed. One approach to dealing with this issue of near-term station infrastructure is to coordinate the deployment of vehicles and fuels in targeted locations or “lighthouse” regions . This will ensure that the few stations that are built will have sufficient FCVs that will demand H_2 and vice versa. Additionally, a “cluster strategy” is an even more targeted, coordinated introduction of hydrogen vehicles and refueling infrastructure in a few focused geographic areas such as smaller cities within a larger region [9]. This approach provides acceptable customer convenience (in terms of driving distance to the nearest station) and reliability for FCV customers, while reducing infrastructure costs.

Over the longer-term, if H_2 and FCVs are widely used, the H_2 infrastructure will become a massive energy system that will rival the current oil and gas infrastructure for production, delivery, storage and refueling. This system could consist of a number of large H_2 production facilities and a large distribution network (pipelines and trucks) that supply a widespread refueling station network. Each of these technologies are at a reasonable state of technology development given the widespread use of H_2 in industrial settings and H_2 station demonstrations. However, these individual components have not been combined into an optimized, reliable energy system. This along with implementation and deployment challenges associated with large-scale infrastructure (i.e. investment, permitting and public acceptance) are the main challenges to H_2 infrastructure, rather than purely technical issues.

Estimated costs for hydrogen fuel at the large scale indicate that H_2 could be cheaper per mile than even advanced gasoline vehicles[7]. However, the challenge is that in the near term, both H_2 fuels and FCVs will be more expensive than conventional vehicles running on gasoline. This provides an important policy challenge to incentivize investments in lower cost, lower carbon outcomes in the face of potentially many years of higher costs.

Like electricity, hydrogen may be most useful in the light-duty sector, but has some applicability in other transportation subsectors. Fuel cell buses and delivery trucks are also potentially viable technologies. However, low energy storage density for H_2 is likely to limit its use as a fuel in long-haul trucks, aircraft and marine applications. Because of these limitations, low-carbon liquid fuel, such as biofuels, are needed to meet transportation energy demands in these sectors.

SUMMARY

Considering the technologies and resources that are available to us, there are several alternative fuel sources that can significantly reduce our reliance on imported oil, improve air quality, and GHG emissions. However, the transition to cleaner, lower carbon fuel sources will need significant technology advancement, and sustained coordination efforts among the vehicle and fuel industry and regulators over long period of time in order to overcome market barriers, consumer acceptance, and unaccounted externalities of imported oil in their fuel price. In addition, policies are also needed to ensure that the environmental performance of these new fuel sources, including GHG emissions and environmental impacts, perform better than fossil fuel and to avoid any unintended consequences that these new fuel sources may present [4, 10].

Unique Fuel Infrastructure Challenges

There are varying degrees of challenges associated with infrastructure design and deployment for each of the three fuel types, biofuel, hydrogen and electricity. These are shown in Table 2.

The infrastructure challenges for biofuels center on biomass feedstock production, collection and transport [2], and in the short term, the delivery of bioethanol and biodiesel to refueling stations and building up the refueling infrastructure for dispensing biofuels that can only be used in flex-fuel vehicles, including E85 (ethanol mixed with gasoline up to 85% by volume) and high-blend of biodiesel such as B80, B90 and B100. Over time, however, when advanced biofuels such as FT fuels and hydrocarbon-based biofuels mature, the infrastructure needs for distributing, delivering and refueling will go away.

Electricity is a widely used energy carrier so fuel electricity will primarily use components of this well-established supply chain. The key infrastructure issue for electricity is the deployment of home and public charging equipment. Another important concern for electricity infrastructure is that distribution systems (i.e. transformers and substations) may need to be upgraded in order to handle the additional demands from PEVs at the circuit level.

H_2 production, transport and refueling stations are the primary infrastructure components that will require continued technology development and significant investment. Since H_2 will use existing primary energy resources, their collection and transport are not major issues. Most of the infrastructure issues are discussed in the hydrogen section above.

TABLE 2. Comparison infrastructure design and deployment challenges for alternative fuel sources, including hydrogen, electricity and biofuels. Grayed out boxes are areas that present special challenges that require more attentions and efforts.

	Central Hydrogen	Electricity	Biofuels
Resource collection extraction	Use existing infrastructure for fossil resources (natural gas, coal)	Existing infrastructure	Wastes require collection, energy crops require dedicated operation, part of larger Ag system
Resource transport	Existing infrastructure	Existing infrastructure	Low energy density limits transport distances
Conversion facility	Large-scale reformers/gasifiers	Existing infrastructure	Biorefinery (including feedstock processing and conversion)
Fuel transport	Trucks or pipelines	Existing infrastructure	Conventional biofuels (ethanol and biodiesel): rail, trucks and barge as well as inter-modal facilities for the transfer of feedstock or fuel
		distribution may require upgrades	Existing infrastructure for biogasoline, FT fuel, and bio-hydrocarbon fuels
Fuel refueling	New H2 refueling stations	Widespread vehicle chargers	Dedicated refueling stations for conventional biofuels (ethanol and biodiesel)
			Existing infrastructure for biogasoline, FT fuel, and bio-hydrocarbon fuels

Table 3 summarizes the key transitional challenges for the alternative transportation fuels, hydrogen, electricity and biofuels. From the resource perspective, because of the diversity of resources available for both hydrogen and electricity, there should not be any resource limitations associated with these fuels, whereas biomass availability is a key issue surrounding the widespread use of low-carbon biofuels.

From a fuel infrastructure technology perspective, H_2 production, storage and delivery and biofuel production are key areas that need further development, while electricity has no major infrastructure technology needs. From an economic perspective, fuel infrastructure is quite costly, especially when demand for fuel is low and economies of scale are not realized. Large production facilities for hydrogen and biofuels are major economic considerations for investment and technology development. Hydrogen stations are another key area with relatively high near-term costs [11]. While PEV chargers can be expensive on a per vehicle basis, because they are introduced incrementally, they require relatively modest total costs in the near term. Finally, for H_2 and electric vehicles, the rate of vehicle adoption is likely to determine the rate of infrastructure deployment, while the use of biofuels can be less dependent on specific vehicle sales and deployment of fuel infrastructure can be more rapid when advanced biofuel technologies mature.

TABLE 3. Comparison resource, technology, economic and transitional issues for hydrogen, electricity and biofuels.

	Hydrogen	Electricity	Biofuels
Resources	Diversity of resources available for H_2 production	Diversity of resources available for electricity production	Limits on providing enough low-carbon and sustainable biomass
Technologies	Hydrogen production (fossil conversion and electrolysis) and storage are critical technology	No major technology limitations for infrastructure	Biorefineries are critical technology
Economics	High initial costs – large economies of scale associated with stations and central production	Relatively low initial investment costs for home charging compared to other fuels	Biorefineries are primary cost and scale dependent
Transitions	Vehicle adoption will determine the rate of infrastructure deployment, requires significant coordination	Vehicle adoption will determine the rate of infrastructure deployment	Rapid deployment of biofuels in next few decades due to federal policy

CONCLUSIONS AND RECOMMENDATIONS

Alternative fuels, particularly those reviewed in this chapter, are an essential tool for helping to reduce the overall impacts of transportation fuel use, including the dependence on imported oil, air pollution and GHG emissions. While each fuel type has important technical and implementation challenges to overcome (including vehicle technologies) in order to contribute a large fraction of our total fuel demand, it is important to note that a portfolio approach will give us the best chance of meeting stringent environmental and energy security goals for a sustainable transportation future. It will be important to nurture all technologies along because we do not yet know which technologies will provide the most cost effective emissions and petroleum usage reduction while appealing to consumer preferences.

The following are the main recommendations with respect to making the transition to a future of sustainable transportation fuels:

Research is important - Fundamental and applied research in needed by academic communities and stakeholders to improve technologies associated with fuel production, conversion, storage, and utilization as well as scientific understanding of sustainability impacts of these fuels. This research can help to guide R&D as well as investment decisions by government, industry and other stakeholders.

***Policies can help level the playing field* -** Policy incentives are needed to directly incentivize the development and use of low-GHG/sustainable fuels through performance-based standards and market mechanisms. Policies such as GHG emissions standards for automobiles or the low carbon fuel standard (LCFS) [12] are essential for putting the different fuels (and vehicle platforms) into a common framework with which they can be assessed. They allow industry the flexibility to choose different options and approaches to ensure that the targets are met with lower compliance costs.

***Sustainability standards should be developed* -** Effective sustainability policies are needed to prevent impacts on ecologically sensitive areas, air and water pollution, and competition with food resources. Continuous monitoring and assessments of unintended consequences within or beyond the production areas will be essential for the successful transition to a sustainable transportation future.

REFERENCES

1. EIA. *Annual Energy Outlook 2011 with Projections to 2035*. 2011; Available from: http://www.eia.doe.gov/oiaf/aeo/aeoref_tab.html.
2. Parker, N., et al., *Development of a biorefinery optimized biofuel supply curve for the Western United States.* Biomass and Bioenergy, 2010. **34**: p. 1597-1607.
3. McCollum, D. and C. Yang, *Achieving deep reductions in US transport greenhouse gas emissions: Scenario analysis and policy implications.* Energy Policy, 2010. **37**(12): p. 5580 - 5596.
4. NAS, *Liquid Transportation Fuels from Coal and Biomass Technological Status, Costs, and Environmental Impacts*. 2009, National Academy of Sciences: Washington, DC.
5. Axsen, J. and K.S. Kurani, *Anticipating plug-in hybrid vehicle energy impacts in California: Constructing consumer-informed recharge profiles* Transportation Research Part D, 2010. **15**: p. 212-219.
6. Lemoine, D.M., D.M. Kammen, and A.E. Farrell, *An innovation and policy agenda for commercially competitive plug-in hybrid electric vehicles.* Environmental Research Letters, 2008(1): p. 014003.
7. NRC, *Transitions to Alternative Transportation Technologies--A Focus on Hydrogen*. 2008, National Research Council.
8. Johnson, N., C. Yang, and J.M. Ogden, *A GIS-Based Assessment Of Coal-Based Hydrogen Infrastructure Deployment In The State Of Ohio.* International Journal of Hydrogen Energy, 2008. **33**(20): p. 5287-5303.
9. Nicholas, M.A. and J.M. Ogden, *An Analysis of Near-Term Hydrogen Vehicle Rollout Scenarios for Southern California. Research Report UCD-ITS-RR-10-03*. 2010, Institute of Transportation Studies, University of California, Davis.
10. Searchinger, T., et al., *Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change.* Science, 2008. **319**(5867): p. 1238 - 1240.
11. Ogden, J. and C. Yang, *Chapter 15. Build-up of a hydrogen infrastructure in the US.* in *Perspectives of a hydrogen economy*. eds. M. Ball and M. Wietschel. 2009: Cambridge.
12. Sperling, D. and S. Yeh, *Low Carbon Fuel Standards.* Issues in Science and Technology, 2009(2): p. 57-66.