SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

A Research Summary for Decision Makers

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Chapter 5: Comparing Infrastructure Requirements

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For biofuels, electricity, and hydrogen to assume major roles as transportation fuels over the next several decades—as they must if we are to meet future goals for low-carbon transportation—one or more new fuel infrastructures will have to be developed. We define a fuel infrastructure as all of the components of the physical system needed to provide transportation fuels to the end user, including extracting primary resources, transporting them to a fuel production plant, processing them to produce transportation fuels, providing refueling sites, and delivering fuels to these refueling locations. In some cases one fuel infrastructure can depend on another (for example, the electricity system depends on other infrastructures that deliver coal or natural gas). In this chapter we will focus mainly on infrastructure issues for the particular fuel supply chain in question and less on the underlying infrastructures (for example, more on the hydrogen infrastructure itself and less on the natural gas or electricity infrastructure supplying energy to make hydrogen).

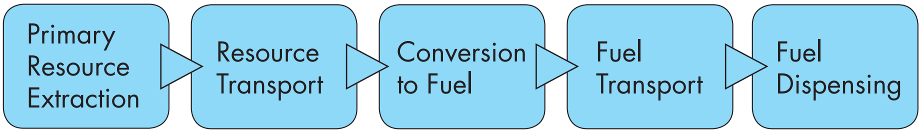
Today's transportation system is 97-percent dependent on petroleum-based liquid fuels. A vast petroleum infrastructure has developed over a century, encompassing worldwide oil exploration and production, long-distance transport of crude oil to hundreds of refineries, and an extensive network of pipelines and trucks delivering gasoline and diesel to terminals and refueling stations. Since 1980, the global capital expenditure to maintain and expand this massive infrastructure has averaged hundreds of billions of dollars per year, about 80 percent of which is devoted to finding and extracting crude oil, and the remainder to refineries, storage, and pipelines. Infrastructure costs are rising: the investment in petroleum fuel infrastructure between 2007 and 2030 is projected to be about $1 trillion in North America alone and $6 trillion globally.

In this chapter we discuss general considerations for building transportation fuel infrastructures and compare infrastructure challenges for biofuels, electricity, and hydrogen with respect to system design, resources, technology status, cost, reliability, and transition barriers such as compatibility with existing infrastructures. Finally, we discuss policies that might be needed to provide incentives for new infrastructure development.

Infrastructure Design and Deployment

A transportation fuel infrastructure needs to satisfy certain requirements: it must bring adequate supplies of fuel to consumers at a competitive and stable cost, it must be reliable and robust enough to resist disruptions (natural or human), and ideally it should impose minimal environmental costs and security risks. The infrastructures for each of the fuels we consider (biofuels, hydrogen, and electricity) will need to meet these requirements while at the same time placing different emphases on key infrastructure components. These different emphases result from the fact that the costs, technical challenges, and/or other important considerations and barriers are different for each type of infrastructure.

A GENERIC FUEL SUPPLY INFRASTRUCTURE



A generic fuel supply infrastructure has the components shown here.

Fuel infrastructures involve large capital and investment costs, and long-lived assets. Most are complex networks rather than single chains, with a wide resource base and feedstock transport, multiple conversion facilities, an extensive delivery system, and numerous points of use. For example, the electricity system uses diverse primary sources (fossil, renewable, and nuclear), numerous conversion power plants, an extensive transmission and distribution system, and potentially chargers in every garage.

Because of the high cost of building a major new infrastructure, it would be desirable to utilize existing infrastructure where possible. For instance, new "drop-in" liquid biofuels might be developed that would be compatible with the petroleum system and could use existing assets such as petroleum refineries, pipelines, trucks, and stations. Even if existing infrastructure could not be used directly with a new fuel, piggybacking on today's systems could reduce costs—for example, adding chargers for electric vehicles to homes that already have electricity service, or making hydrogen from natural gas already available at refueling stations.

Infrastructure for biofuels

An extensive infrastructure is required to supply liquid biofuels to a refueling station. It begins with feedstock production. The energy, material (fertilizer and water), and capital inputs required for this step can vary depending on the type of biomass used. First-generation biofuels are made primarily from food crops that produce sugars/starch or vegetable oil. Future generations of biofuels will be made from cellulosic materials as well, including agricultural and forestry wastes and also dedicated energy crops. Using waste products limits the input requirements because these inputs were already being used to produce the primary crop (food, fiber, or forest products); growing crops specifically for use as a transportation fuel feedstock requires more inputs.

In either case, this biomass must be collected and transported to a biofuel production facility, commonly in trains and trucks. Because of the low energy and spatial density of biomass, feedstock transport can account for a significant portion of the energy input to biofuel production.

The conversion of biomass into a biofuel can be a complex process and differs widely depending upon the type of biomass being converted and the technologies being employed. Currently, the major processes for biofuel production involve the production of alcohol from sugars/starch via biological fermentation, and the production of biodiesel via transesterification.

Conversion of sugar or cellulosic-based biomass to biofuels requires processing and separating the materials to yield sugars that can be fermented. Next-generation fuel production could also involve thermal treatment (for example, gasification or pyrolysis).

The transport of a biofuel is similar to the transport of petroleum products like gasoline and diesel. Some forms of biofuel might be transported in the existing gasoline and diesel distribution infrastructure, but some forms cannot. For example, pure ethanol is a gasoline substitute but cannot be transported in gasoline pipelines because of its tendency to absorb water and its corrosiveness. By contrast, ethanol blended with gasoline at concentrations of 10 to 20 percent can be transported without infrastructure changes, and if "drop-in" biofuels were produced they could be co-transported with existing fuels.

Infrastructure for hydrogen

Hydrogen can be produced either on-site or in a centralized facility. The infrastructure required for on-site production is much less extensive than that required for centralized production. For on-site production, the infrastructure is confined primarily to the refueling station, where energy resources (natural gas or electricity) are delivered using existing infrastructure. At the refueling station, these energy resources can be converted to hydrogen using steam reforming or electrolysis and then compressed, stored, and dispensed to fuel cell vehicles.

Centralized production of hydrogen requires more capital-intensive infrastructure investments and is justified only with large demands for hydrogen. Large central plants for producing hydrogen can use many different resources, including fossil fuels (natural gas or coal), biomass, or electricity. The choice of energy resource will dictate the type and scale of the first stages of fuel infrastructure. For example, hydrogen plants can be built at sites for renewable electricity generation (wind or solar farms) or have energy resources delivered to them (biomass, coal, natural gas, or electricity via the grid). In either case, these primary energy resources are not unique to hydrogen but are developed for other purposes as well, such as electricity production.

Once hydrogen is produced, the remainder of the supply chain infrastructure is unique to the hydrogen fuel pathway. Because hydrogen is a gas, storage and delivery are more energy intensive and costly than for a liquid fuel. There are several different methods for delivering hydrogen to the refueling station, including compressed gas truck, liquid hydrogen truck, and pipeline. The choice of method depends upon many factors, including demand density, transport distances, and size of refueling stations (see Chapter 3). Refueling stations make up the last piece of the hydrogen fuel supply chain; they have equipment for compression, storage, and fuel dispensing to vehicles.

Infrastructure for electric vehicles

Similar to other fuels, electricity for use in vehicles requires an infrastructure that consists of the entire system of extracting primary energy resources, converting those resources into electricity, distributing it to the point of use, and then providing a way to recharge batteries. Unlike the other fuels, electricity is already in widespread use for a variety of purposes, so much of this infrastructure already exists and can be used to provide electricity to vehicles as well. As a result, analysis of infrastructure for providing fuel to electric vehicles is largely focused on the point of refueling—the vehicle charger.

It is expected that most drivers of plug-in electric vehicles (PEVs) will refuel primarily at home, so much of this recharging infrastructure will be concentrated there. However, there is also significant activity in the development of public charging infrastructure. The thinking is that some level of public access to charging away from the home is needed to overcome the range limitations of pure battery electric vehicles (BEVs), though the appropriate balance between private and public charging equipment will depend on the mix of BEVs and plug-in hybrid electric vehicles (PHEVs), and the needs and preferences of their drivers. There is some evidence that public recharging stations may be needed to reassure drivers (that is, to ease "range anxiety") without being used very often. Aside from that concern, public charging will need to be ubiquitous if electricity is to displace most petroleum fuel usage because many drivers do not have access to overnight off-street parking.

Widespread infrastructure for electricity generation and distribution already exists, and this infrastructure has quite a bit of underused capacity. Even with significant penetration of BEVs and PHEVs in the next few decades, electricity demand for recharging these vehicles will make only a minor contribution to total electricity demands. Thus, there may not be a need for additional generating capacity to meet this additional demand. If PEV adoption is concentrated in certain neighborhoods, this could require some upgrades to distribution infrastructure. STEPS researchers have analyzed how the addition of PEV recharging will change the pattern of electricity generation and affect emissions from electricity generation.[1] Over the long term as PEV demands grow and affect the overall timing of electricity demands, this could induce changes in the mix of generation capacity that would be used to meet all demands.

Resource Issues

Fuel infrastructure supply chains begin with primary resource extraction. Each fuel faces different resource challenges, especially given the imperative to adopt a low-carbon primary supply over time.

Many different kinds of biomass resources could be converted to biofuels, each of which has different environmental impacts (see Chapters 1 and 12). The total biomass resource available for biofuel production is constrained by a variety of economic and environmental factors that can vary regionally. Competing uses for biomass—for example, to generate renewable power and heat—could further reduce the biomass resource base available for transportation fuel production. Global estimates suggest that 10 to 30 percent of transportation fuel needs could be met with biofuels, with biofuels playing a larger role if vehicles are made more efficient and biomass productivity is increased.

Hydrogen and electricity could access a much wider primary resource base, including low-carbon options such as fossil fuels with carbon capture and sequestration (CCS), renewables (solar, wind, biomass, hydro, geothermal), and nuclear. In theory, the availability of low-carbon resources should not be a limiting factor for either electricity or hydrogen, although the higher cost of zero-carbon pathways could increase fuel costs.

Technology Status

For biofuel infrastructure, the largest technology gap is the need to develop low-cost, low-net-carbon, advanced biofuel production methods for cellulosic ethanol and Fischer-Tropsch (F-T) liquids (diesel-like liquid fuels compatible with the existing petroleum infrastructure). The technologies to harvest, store, and transport biomass feedstocks, and to store and deliver biofuels, are mature, although scale-up is needed for biofuel transport systems to reach low costs. Technical improvements in crop yields and productivity could also be very important to the overall role of biomass in the energy system.

For electricity, one of the major technical issues is development of a low-carbon supply. As shown in Chapters 6 and 9, electric vehicles do not represent much of an improvement over gasoline hybrids in terms of greenhouse gas emissions unless the grid is substantially decarbonized. Another technology gap is the implementation of a "smart grid" that can manage the time-changing demands for charging a fleet of electric vehicles, and time-variable renewable energy sources. Finally, bulk storage for electricity could play a role in a future grid heavily dependent on variable renewable electricity sources such as wind and solar, and in serving time-varying vehicle-charging demands. Improved batteries that could accommodate fast charging could influence the relative role of fast charging in the electricity infrastructure.

Commercial technologies to produce hydrogen from fossil fuels and to deliver and store it are already in use in the chemical industry today. However, there is a need to develop technologies for cost-effective low-carbon production. Hydrogen from coal or natural gas with CCS, hydrogen from biomass gasification, and electrolytic hydrogen powered by low-carbon electricity are all low-carbon options. In general, production options based on thermochemical processing of hydrocarbons will offer lower costs than electrolytic hydrogen. Hydrogen storage is another area where technical breakthroughs could transform the design and cost of infrastructure.

Cost Considerations

Some factors that influence infrastructure cost are technology maturity, scale economies in both fuel production plants and delivery systems, geography-specific factors including location and costs of feedstocks for fuel production, geographic density of demand, and compatibility with existing energy systems.

For biofuels, technology advancement and scale-up of biorefineries are the most important factors in reaching competitive costs. As shown in Chapter 1, the cost of biorefineries is the largest single cost in the supply chain (about 85 percent of the investment), with fuel delivery costs playing a much smaller role. The capital investment for mature biorefineries is expected to be about $3–5 per gallon gasoline equivalent (gge) per year. Studies by Parker et al. suggest that to produce between 12 and 46 billion gge per year in the United States in 2018, the investment in biorefineries would total between $100 billion and $360 billion (see Chapter 1). This could supply enough biofuels to meet between 5 and 21 percent of the projected U.S. demand for transportation fuel in 2018 at an average infrastructure capital investment cost of several thousand dollars per car. Biofuel delivery systems would add another 15 to 20 percent to the cost.

For hydrogen, recent studies by the National Academies and others suggest that the capital investment for mature infrastructure would be $1,400–2,000 per light-duty vehicle served, depending on the pathway. The National Academy of Sciences (NAS) found that building a fully developed hydrogen infrastructure serving 220 million vehicles in the United States in 2050 would cost about $400 billion over a period of about 40 years.[2] (The NAS scenario is based mostly on fossil-fueled hydrogen with CCS and biomass hydrogen. Electrolysis-based pathways could cost more to build.) Early infrastructure investment costs per car (to serve the first million vehicles) would be higher ($5,000–10,000 per car).

The investment cost for electric vehicle infrastructure is difficult to estimate because the electric generation, transmission, and distribution system is shared by multiple end users. Moreover, the grid will undergo a transformation toward lower-carbon resources independent of the introduction of PEVs. A recent study by the U.S. Department of Energy suggested that it would cost between $800 and $2,100 to install a charger in a typical home, in part because of circuit upgrades to accommodate "level 2" charging, and in part for metering and utility interface.[3] And some fraction of costs for smart grid upgrades would be borne by PEVs among the other demands. If charging of PEVs were primarily confined to off-peak hours, this would increase the utilization of existing power plants and reduce the average cost of supplying electricity. There could be benefits with regard to system reliability, depending on how smart-grid technologies are implemented. Thus, benefits as well as costs to the electricity system might accompany the large-scale use of electric vehicles.

Reliability and Resilience

Because energy is an important part of lifeline systems that touch almost every aspect of modern society, an energy supply chain is considered a critical infrastructure system. In view of the extreme vulnerability of such systems to disasters and disruptions (as evidenced by the World Trade Center terrorist attack in 2001, the tsunamis in 2004 and 2011, and hurricanes Katrina and Rita in 2005), infrastructure security, especially reliability and resilience, has become an important issue to be addressed in renewable energy infrastructure system design. More specifically, it is important to plan for potential disruptions caused by feedstock fluctuation, demand and price spikes, and unexpected facility failures caused by natural disasters and human errors.

Strategic supply chain management aims at finding the best supply chain configuration—including location setup, procurement, production, storage, and distribution—to support efficient operation of the whole supply chain. On the other hand, reducing redundancy and buffers, which improves the system efficiency under normal conditions, may make the supply chain more vulnerable to unexpected events such as supply shortage, demand spike, technological failure, or attacks and disasters. Because different components of the supply chain are so interdependent, failure of one component might reverberate through the entire supply chain.

From the viewpoint of the physical structure of an energy supply chain, storage facilities hedge against disruptions in two important ways: (1) by storing energy, they provide a buffer for the system to adjust to fluctuations in supply and demand, and (2) by redistributing energy over space and time, they increase the self-healing ability of the system. Simulating these systems using advanced stochastic modeling approaches (approaches that estimate probability distributions of potential outcomes by allowing for random variation in one or more inputs over time) considering a wide range of future possibilities may produce results that hedge better against future uncertainties.

Compatibility with Existing Infrastructure

Current liquid biofuels such as ethanol are at least partly compatible with existing petroleum infrastructure in that they can be blended with petroleum-based fuels at concentrations of up to 10 to 20 percent without infrastructure changes. The main issues with ethanol transport in existing infrastructure have to do with its water absorption and corrosiveness. Transporting neat ethanol or E85 is also feasible but requires its own infrastructure. Future “drop-in” biofuels produced via gasification and Fischer-Tropsche synthesis might be able to use the petroleum storage and pipeline system. An interesting question is whether the existing petroleum delivery system is located in the right places for ready access by future large biorefineries. In the United States, for example, a majority of biorefineries would be sited in the Midwest and Southeast, but the petroleum pipeline system is focused in the Gulf Coast area. Given this geographic mismatch, some new biofuel infrastructure might be required anyway to bring “drop-in” biofuels to existing gasoline and diesel terminals.

The infrastructure for PEVs will likely be based on home recharging plus a network of public “fast charge” stations to facilitate long-distance travel. The electricity system reaches most homes, and about 50 percent of these households appear to be well adapted for private recharging (see Chapter 2). Changes to the electric transmission, distribution, and generation systems will take place over a long time, and with a trend toward low-carbon sources and smart-grid technologies to manage time-variable renewable sources and demands. These developments should be synergistic with adoption of PEVs.

There is little opportunity to use hydrogen directly in existing energy systems, and a new dedicated infrastructure would be needed (see Chapter 3). In the early stages of infrastructure development, hydrogen might rely on truck delivery of small quantities of “merchant” hydrogen produced from natural gas, moving toward on-site hydrogen production at stations and eventually toward centralized production of low-carbon hydrogen with pipeline delivery. It has been suggested that hydrogen could be blended at up to 15 percent by volume with natural gas without infrastructure changes, but there would be only a modest environmental benefit to this approach. For large quantities of pure hydrogen, a new dedicated production and delivery system would be needed.

Both electricity and hydrogen rely on other underlying infrastructures that deliver feedstocks to production plants. Expanding use of either carrier could require an expansion of the underlying feedstock infrastructure as well. (For example, to make large quantities of hydrogen from coal would require extra rail and barge capacity to deliver coal to hydrogen production plants.)

REQUIREMENTS FOR BUILDING INFRASTRUCTURE SUPPLY CHAINS

Infrastructure requirements are summarized here for each fuel along the entire supply chain. Opportunities to use existing infrastructure are highlighted in boldface.

	Hydrogen	**Electricity**	**Biofuels**
Resource extraction and collection	**Use existing infrastructure for fossil resources (natural gas, coal)**. New infrastructure may be needed for expanded use of renewables, CCS.	**Use existing infrastructure for fossil resources (natural gas, coal)**. New infrastructure may be needed for expanded use of renewables, CCS.	**Use some food crops, and wastes produced as part of existing agriculture, forestry, urban systems**. Wastes require collection; energy crops require dedicated operation.
Resource transport	**Use existing infrastructure for fossil resources or electricity**. New transport system may be needed for biomass-to-H2 plant.	**Use existing infrastructure for current resources**. New transport system may be needed for biomass-to-power plant.	Transport by truck or rail. Low biomass energy density limits transport distances.
Conversion facility	**Initial supply from merchant H2 system**. New on-site reformers or electrolyzers, or large-scale central reformers, gasifiers (w/CCS), or electrolyzers needed.	**Use existing electric generation infrastructure**. New power plants or retrofits may be needed for renewable electric production, CCS.	New biorefineries (including feedstock processing and conversion) needed.
Fuel transport	Use trucks or pipelines (for central H2 production).	**Use existing distribution infrastructure**. May require upgrades in some places.	**Use existing infrastructure for "drop-in" biofuels**. New transport system needed for pure ethanol/E85.
Fuel dispensing/charging	Hydrogen refueling station network needed. Early options could include in-home or neighbourhood refueling.	In-home chargers and some public chargers needed.	**Use existing stations for "drop-in" biofuels**. New liquid fuel stations needed for pure ethanol/E85.

Transition Issues and Timing

Biofuel internal combustion engine vehicles could be introduced rapidly. The rate of biofuel adoption will be determined by investments in biorefineries, and to a lesser extent associated biofuel delivery infrastructure. The Renewable Fuel Standard in the United States requires production of 36 billion gallons of biofuel per year by 2022, which will require a tripling of current biofuel production capacity. (Reaching even higher levels of biofuel production in the longer term would require increased biomass productivity and breakthroughs in biofuel conversion technologies, or both.) The enticing possibility of future "drop-in" biofuels could potentially delay investments in nearer-term biofuels like ethanol that are less compatible with the petroleum system.

For electricity, vehicle adoption rates will be the main factor determining the transition time. For PEVs to capture major market share, battery costs must come down by a factor of 3 to 5 through technology advances and manufacturing scale-up (see Chapters 4 and 9). Early infrastructure availability should not be a major issue for battery cars. Electric infrastructure is ubiquitous and many consumers could readily adopt home charging. The existing electricity grid (generation, transmission, and distribution) should have enough underutilized capacity to handle millions of PEVs without major changes (see Chapter 2). In the longer term, the evolution of a smart grid should help enable wider use of electric vehicles. A low-carbon grid will be required for PEVs to achieve deep cuts in well-to-wheels carbon emissions.

The rate of hydrogen vehicle adoption will strongly influence the transition rate. As with electric vehicles, there is a need to buy down the cost of hydrogen vehicles through technical advancement and manufacturing scale-up. Hydrogen faces an additional transition barrier: the “chicken and egg” problem. Early adopters of hydrogen vehicles must be sure of a convenient, cost-effective fueling network, while early fuel suppliers must be sure that there are enough vehicles to use their stations. To assure adequate fuel supply, it will be important to collocate the first vehicles and early infrastructure in “lighthouse cities.” STEPS researchers have developed placement strategies for early vehicles and infrastructure that could achieve good fuel accessibility with a very sparse station network, but implementing these will require close coordination among automakers and fuel suppliers, and strong policy support.

FACTORS LIMITING THE RATE OF DEPLOYMENT OF NEW FUEL INFRASTRUCTURES

The rate-limiting factors for infrastructure deployment are summarized here for each fuel.

	Hydrogen	**Electricity**	**Biofuels**
Resources	No major resource limitations, due to diversity of resources available for hydrogen production.	No major resource limitations, due to diversity of resources available for electricity production.	Limits on providing enough low-carbon biomass for all transportation.
Technology gaps	No major technology limitations for delivery infrastructure. Low-cost, low-C hydrogen production needed (renewable, CCS). Fuel cells are critical for vehicles.	No major technology limitations for delivery infrastructure. Low-cost, low-C electricity production needed (renewable, CCS). Batteries are critical for vehicles.	No major technology limitations for delivery infrastructure or vehicles. Biorefineries are critical technology.
Costs	High initial costs for small, underutilized stations until number of hydrogen vehicles rises. As hydrogen demand increases, hydrogen costs decrease, because of scale economies associated with central hydrogen production, delivery systems, and hydrogen stations.	Initial infrastructure costs should not be a limiting factor for PEVs: home chargers have relatively low initial investment costs because they can be added one at a time. Need for public charging and distribution upgrades could raise costs.	Biorefineries are primary infrastructure cost. Need to build large-scale biorefineries for low fuel costs.
Transitions	Need for coordinated, geographically focused deployment of vehicles and infrastructure.	Rate of vehicle adoption, which will determine the rate of infrastructure deployment.	No vehicle-related limitations. Rate of deployment of biofuels and biorefineries in next few decades (RFS) will determine transition rate.

INFRASTRUCTURE INVESTMENTS NEEDED TO SUPPORT 10 PERCENT OF U.S. LDVS USING HYDROGEN, ELECTRICITY, OR BIOFUELS

As an example of the infrastructure investments needed to support introduction of new vehicles, we sketch in the table below the infrastructure that would be needed to support about 10 percent of U.S. light-duty vehicles (20 million vehicles) using hydrogen, electricity, or biofuels. Even at this relatively modest level, which might be reached by 2025, tens of billions of dollars would be needed to build infrastructure. For hydrogen, investments would occur primarily in production and delivery; for biofuels, biorefineries are the major capital cost; and for electricity, in-home chargers make up the majority of the infrastructure cost. Building a larger-scale infrastructure (serving 50 percent of U.S. vehicles) would cost at least five times as much.

	Hydrogen	**Electricity**	**Biofuels**
Fuel consumption (assumed vehicle fuel economy)	5 billion kg H2/yr 0.6 EJ/yr (60 kg H2/mi)	90 billion kWh/y 0.33 EJ/y (300 Wh/mi)	12 billion gge/yr 1.4 EJ/yr (25 mi/gge)
Primary resources required (EJ/y)	To supply all hydrogen from natural gas would require about 0.8 EJ/y, about 3% of total natural gas use in the United States today.	In the near term (2020), there will be a growing use of renewable electricity. Future grid scenarios imply a mix of low-carbon sources by 2050.	Corn (about 30% of 2008 supply) Forest wastes, 0.4 EJ/y (24 million tons of estimated 61 million tons available) Ag. residues, 0.5 EJ/y (33 million tons of estimated 238 million tons available) Municipal solid waste, 0.4 EJ/y (29.5 million tons of estimated 135 million tons available)
Fuel production plants (number of plants, average size [bbl oil equiv/day or GJ/d])	24 central biomass H2 plants (30–200 tonnes H2/day); most H2 production via 1–2 tonne/day on-site natural gas reformers at refueling stations	28 GW at 35% capacity factor = nighttime electricity from 28 1000-MW coal or nuclear plants or 10,000 3-MW wind turbines (~ total installed wind capacity today) (28 GW < 5% of U.S. electricity generation capacity)	150 corn ethanol plants 76 cellulosic biorefineries 16 biodiesel plants

	Hydrogen	Electricity	Biofuels
Fuel distribution network (type, extent in miles, compatibility w/existing system)	9,000 miles hydrogen pipeline in urban areas; most production on-site	Use electricity transmission and distribution system. May need "smart grid" upgrades.	Additional 7,000 rail tank cars; rail receiving yards at 25% of fuel terminals
Vehicle refueling or recharging interface (number of stations)	18,000 stations total: 14,000 on-site SMR, 4,000 pipeline stations	Home recharging + fast-charge stations on interstates	None if cellulosic biofuels are "drop-in"; 20,000 E85 stations if all ethanol
Cost breakdown for infrastructure capital investment	$38 billion total: $4 B biomass plants, $9 B pipelines, $21B on-site SMRs, $4B pipeline stations	$16–42 billion total: $800–2,100 per vehicle for in-home chargers	$50–70 billion; more than 80% of investment is for biorefineries, rest is for biofuel delivery system

Policies to Encourage Infrastructure Development

A variety of policies, listed in this book's introduction, are driving toward lower-carbon fuels and zero-emission vehicles. These are covered in more detail in Part 4. Realistic policies should recognize the large capital investments and long planning horizon to build the new fuel supply infrastructures required to enable new types of vehicles. In some cases, new vehicle types (such as battery electric fuel cell cars) are mandated while the corresponding energy infrastructure is not. Increasingly, policy should seek to encourage the whole pathway (vehicle and fuel) with incentives so that different stakeholders are motivated strongly enough to participate and coordinate in infrastructure transitions.

Summary and Conclusions

- Each fuel type (hydrogen, electricity, and biofuels) faces infrastructure deployment challenges, which differ by pathway.

- Liquid biofuels are relatively easy to store and transport, and require few vehicle changes to implement compared to the fundamentally new drive trains needed for electric vehicles and hydrogen fuel cells. Some biofuels may be at least partly compatible with the existing petroleum delivery and refueling infrastructure. The main technology gap is development of low-cost advanced biorefineries. The rate of biorefinery deployment will determine the rate of biofuel adoption. Ultimately, availability of biomass is the factor that will limit how much biofuel (and biofuel infrastructure) will be deployed.

- Hydrogen requires the biggest infrastructure changes: new hydrogen production and delivery systems and a network of refueling stations. The main technology gap is development of low-cost, low-carbon hydrogen production technology. Successful introduction will require coordination of vehicle and infrastructure deployments in carefully chosen geographic areas.

- Electricity is already being produced and delivered to users, so the main near-term infrastructure needs are new home chargers. In the longer term, integration of charging demands will occur as part of the larger electric power system, and a low-carbon electricity supply will be needed. The infrastructure build-out rate will be paced by the rate of market penetration of electric vehicles.

- Both electricity and hydrogen could utilize large low-carbon resources. Continued development of low-cost, low-carbon supplies is needed for both electricity and hydrogen.

Notes

1. C. Yang and R. W. McCarthy, "Electricity Grid: Impacts of Plug-In Electric Vehicle Charging," *Environmental Management* 43 (June 2009), 16–20.
2. National Research Council, Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, *Transitions to Alternative Transportation Technologies: A Focus on Hydrogen* (Washington, DC: National Academies Press, 2008), available from http://www.nap.edu/catalog.php?record_id=12222.
3. K. Morrow, D. Karner, and J. Francfort, "Plug-in Hybrid Electric Vehicle Charging Infrastructure Review," INL/EXT-08-15058 (Idaho National Laboratory, November 2008).