SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

A Research Summary for Decision Makers

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Conclusion: Key Findings and Paths Forward

Revolutionary changes in transportation will be required to meet societal goals for climate, environment and energy security. Through STEPS we explored the role of alternative fuels and vehicles in this revolution, focusing on biofuels, electricity and hydrogen. We assessed the prospects for new fuels and vehicles, and compared their characteristics, costs, and benefits across multiple dimensions. From this knowledge base, we have begun to develop scenarios for how these new technologies might transform the transportation sector over the next several decades and what policies would be needed to support the transition. In this conclusion, we take stock of what we have learned so far, and identify critical questions going forward.

Summary of Key Findings

1. Insights about Individual Fuel/Vehicle Pathways

Biofuels

- There are a large number of pathways for biofuels production. The costs and benefits of biofuels vary greatly, depending on the specific pathway taken.

- With current (or "first generation") biofuels production technology, the lowest-cost biofuels do not provide major environmental benefits. Some represent marginal improvements over petroleum while others are actually worse than petroleum fuels in terms of environmental impacts.

- Advanced biofuels now under development could provide significant environmental benefits. The first commercial-scale biorefineries are expected to produce large quantities of advanced biofuels by 2015. If these technologies prove to be viable, rapid expansion could take place in the United States to meet the 2022 requirements of the Renewable Fuel Standard. Advanced biofuels are expected to have small greenhouse gas footprints, but face some of the same indirect land-use change challenges as conventional biofuels if cultivating their feedstocks displaces food crops.

- Biofuels can be blended with gasoline or diesel and used in existing vehicles, which eases their introduction into the transportation system. Advanced liquid biofuels require few vehicle changes, and some biofuels (so-called "drop-in" biofuels) can be compatible with existing petroleum infrastructure. Liquid biofuels have an advantage over other petroleum alternatives (hydrogen and electricity) in serving sectors such as aviation and freight that require easily transportable, energy-dense fuels.

- Biofuels can make limited but significant contributions to a sustainable transportation energy supply. STEPS research on the supply potential of biofuels shows that advanced biofuels from waste, residues, and energy crops grown on marginal land could provide between 2 percent and 16 percent of transportation energy in the United States in the next decade. (These biomass sources would avoid potential negative impacts of energy crops grown on agricultural land.) An additional 5 percent could come from conventional corn and soy-based biofuels. In total, we estimate it would be possible to meet 6.5–22 percent of U.S. transportation fuel demand (15–45 billion gallons gasoline equivalent per year) with biofuels costing $3–4 per gallon gasoline equivalent (gge). Biofuel costs would increase sharply above this level of demand because of biomass supply constraints. This result depends on advancements in conversion technologies, the development of reliable feedstock supply chains, and the participation of potential biomass suppliers.

- Balancing sustainability with increasing biofuel production requires the consideration of many factors. Capturing all these factors within a policy and regulatory framework will be challenging.

Electricity

- While plug-in electric vehicles (PEVs) offer significant long term potential for environmental benefits and oil displacement, they also present a radical departure from conventional vehicles in terms of efficiency, range, utility, flexibility, and the refueling experience. There is a range of possible configurations for plug-in electric vehicles including pure battery cars, and plug-in hybrids that rely partly on batteries and partly on engines using fuels such as gasoline or biofuels. STEPS research on PEVs has attempted to better understand different electric vehicle designs and their resource utilization and emissions impacts, especially when in the hands of consumers, as driving and charging behavior influence the potential benefits of PEVs.

- Costs of batteries are a key issue for adoption of electric vehicles, although these costs are coming down. Automakers are making major commitments to plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), and models are entering the market. For PHEVs, there is a trade-off between vehicle cost, which is higher for larger battery models, and fraction of miles run on electricity. The high cost of batteries may encourage use of small-battery PHEVs even beyond early markets.

- Our work indicates that most drivers will charge at home at night. This requires home chargers (which can be built as needed) as part of the larger electric power system. As many as 50% of U.S. consumers may have access to plug in at home and even more if charging at work is an option.

- The existing grid is capable of sustaining projected increases in electric vehicles for decades to come. Further, our studies suggest that lack of public charging infrastructure will not impede the market for PEVs in its initial years.

- Electricity offers a huge low-carbon resource base and large potential benefits in terms of reducing GHG emissions and air pollutants and displacing oil. With the current average U.S. grid mix, there is relatively little GHG benefit for PEVs compared to gasoline hybrids. To realize potential GHG benefits of PEVs it is necessary to substantially decarbonize the electricity supply over time by incorporating renewables and fossil electricity with carbon capture and sequestration.

Hydrogen and fuel cell vehicles

- Hydrogen and fuel cell vehicle technologies are progressing rapidly and could be commercially ready by about 2015. Hydrogen fuel cell vehicles offer high efficiency, good performance, a greater-than-300-mile range, and a fast refueling time. Larger vehicles could be powered by fuel cells, and the consumer could use FCVs much like today's gasoline vehicles. Many major automakers have committed to introducing fuel cell vehicles. Remaining issues are fuel cell system cost and durability and hydrogen storage cost.

- Hydrogen will require a new fueling infrastructure and infrastructure build-out is currently the rate limiting factor for introducing hydrogen vehicles. Early infrastructure "cluster" strategies that co-locate vehicles and stations in lighthouse cities could allow good fuel access for consumers even with a sparse, relatively low-cost early fueling network. Although hydrogen will be more costly than gasoline initially, costs will become competitive as demand grows and the system scales up.

- In the near term, most hydrogen will probably come from natural gas. Many very low-carbon supply pathways are available for future hydrogen supply including renewable hydrogen and fossil hydrogen with carbon capture and sequestration. In the long term, low-carbon hydrogen could cost $3–4/gge, competing with gasoline at $2–3/gallon on a cents-per-mile basis.

- Hydrogen fuel cell vehicles could play a major role in a future light-duty vehicle market beyond 2025, but realizing this will require strong stakeholder coordination and policy and consistent support during an initial transition period.

- Hydrogen offers a huge low-carbon resource base and large potential benefits in terms of reducing GHG emissions and air pollutants and displacing oil. With the current hydrogen production (mostly from natural gas), well-to-wheels GHG emissions would be about half those of a conventional gasoline ICEV; there is a modest GHG benefit for FCVs compared to gasoline hybrids. To realize the full potential GHG benefits of FCVs it is necessary produce hydrogen from low-carbon sources such as renewables or fossil with carbon capture and sequestration.

2. Pathway Comparisons

There are many promising fuel/vehicle pathways but no single clear winner among electricity, hydrogen, and biofuels. Each fuel faces unique challenges, and each could play a role for different consumer needs, regions, and transportation sectors. Rather than down-selecting now among electricity, hydrogen, and biofuels, we see potential roles for each, and a need for flexibility to keep multiple pathway options open.

Technology status and timing: Vehicles

- Several promising new types of vehicles will be ready for initial deployment over the next few years. These include battery electric vehicles, which are starting to appear now as plug-in hybrids and full battery cars, and hydrogen fuel cell vehicles, which are slated for market introduction by about 2015. Our assessments suggest that fuel cell vehicle technology is about as mature as battery electric vehicle technology, and commercial-ready fuel cell vehicles will lag electric vehicles by only a few years, not by several decades. Most automakers see roles for both battery and fuel cell technologies in a future electrified light duty vehicle fleet. It is important to note that improved efficiency of gasoline internal combustion engine vehicles (ICEVs) and hybridized drivetrains could significantly reduce GHG emissions and oil use while alternative vehicle and fuel technologies are developed, and that current ICEV technologies could utilize biofuels with relatively minor changes.

Technology status and timing: Fuel infrastructure

It is technically feasible to build new fuel infrastructures for biofuels, electricity, or hydrogen. Each faces infrastructure challenges that differ among fuels and conversion pathways.

- For biofuels, the main infrastructure issue is developing advanced biorefineries that can produce biofuels at large scale with competitive costs and low net carbon emissions. New biomass delivery systems will be needed to collect biomass and bring it to biorefineries, but the technologies for biomass harvesting and transport are well known. Liquid biofuels are relatively easy to store and transport, and require few vehicle changes to implement. Some biofuels may be at least partly compatible with the existing petroleum delivery and refueling infrastructure.

- Electricity is already widely available to consumers, and it is unlikely that battery electric vehicles will have a major impact on the grid for several decades. (A large number of PEVs will need to be driven in a region before power plants are operated differently or new ones are required.) The main near-term infrastructure needs are new in-home chargers plus some public fast chargers to facilitate longer-distance travel. (Availability of secure charging sites at home or work will impact ultimate market penetration of EVs.) In the longer term, integration of charging demands (via smart grid concepts) will need to occur as part of the larger evolving electric power system, and a low-carbon electricity supply will be needed.

- Hydrogen requires infrastructure changes throughout the supply chain: new hydrogen production and delivery systems and a network of refueling stations. Successful introduction will require close coordination of vehicle and infrastructure deployments in carefully chosen geographic areas or lighthouse cities to finesse the "chicken or egg" problem. The largest near-term infrastructure issue is more logistical than technical: finding strategies for low-cost build-out until hydrogen demand is large enough to exploit economies of scale. Before 2025, hydrogen fuel will likely be produced from natural gas via distributed production at refueling stations, or, where available, excess industrial or refinery hydrogen. Beyond 2025, central production plants with pipeline delivery will become economically viable in urban areas and regionally. For the long term, low-cost, low-carbon hydrogen production technology will be needed.

Consumer behavior

Understanding consumer behavior is important for market introduction of alternative-fuel vehicles and infrastructure, and to realize maximum benefits from these technologies.

- For battery electric vehicles, it is critically important to understand the trade-offs among battery size, vehicle cost, and consumer travel and recharging behavior. Our study of vehicle recharging behavior showed that more new vehicle buyers may be pre-adapted for vehicle recharging than estimated in previous analyses (about half have access to charging when parked at home) and that the success of EVs in meeting energy and emission goals depends on users' recharging and driving behavior as much as or more than on vehicle design.

- For hydrogen, early station placement is an important factor influencing refueling convenience and consumer acceptance. We found that strategic co-location of early hydrogen vehicles and stations in clusters can greatly improve fuel accessibility for early consumers while reducing initial infrastructure costs. Initially a sparse network of less than 1% of gasoline stations may be enough to assure fuel availability.

Regional transition issues

- Geography and regional issues such as availability of primary resources and size and spatial density of demand are key factors influencing fuel and pathway choice. Unlike in the current petroleum-based system, we might see a variety of primary sources being used to make a diverse set of transportation fuels.

Costs

- When mass produced, advanced vehicles are likely to cost $3,000–10,000 more than comparable gasoline internal combustion engine vehicles. PHEVs are estimated to cost $4,500–7,000 more depending on the battery size, FCVs $3,600–6,000 more, and pure battery cars $9,000–20,000 more.

- Fuel costs from early hydrogen refueling systems will be higher than gasoline. Once the infrastructure reaches full scale, it will be possible to supply large amounts of low-carbon hydrogen from biomass or fossil with CCS at $3–4/gge (electrolytic hydrogen would likely cost more). With projected large-scale advanced biorefinery technology, biofuels could become competitive with other liquid fuels at $3–4/gge. Biofuel costs increase sharply above a certain level of demand because of biomass supply constraints.

- A variety of fuel/vehicle options (including plug-in hybrids and hydrogen fuel cell vehicles) could become cost competitive on a life-cycle cost basis with gasoline internal combustion engine vehicles between 2020 and 2030. However, it will be more difficult for pure battery cars to compete even if batteries reach their cost goals. This assumes there is continued technical progress, the vehicle technology is mass produced, the fuel infrastructure is scaled up, and gasoline is priced at $2.5–4/gallon. (The life-cycle cost includes vehicle, fuel, and other operating costs.)

- During a 10- to 20-year transition period, new vehicles and fuels will be more expensive than incumbents, and significant investments will be required to bring them to the point of breaking even with gasoline vehicles. Total investment costs to get to the break-even point are estimated to be tens to hundreds of billions of dollars spent over the next 10 to 20 years.

- When external costs such as air pollution damage, climate change, and energy supply insecurity are taken into account in a social life-cycle cost framework, alternative-fuel vehicles become more competitive with gasoline vehicles.

Primary resources

- Ultimately, the availability of low-cost, sustainable biomass, and competing uses in other parts of the economy, will limit how much biofuel will be deployed in transportation. Because of these limitations, biofuels might be used in sectors like air and marine transport where a liquid fuel is preferred.

- At present most electricity and hydrogen are produced from fossil sources. Demand for electricity and hydrogen for vehicles will be small before 2025, because of the small numbers of electric and hydrogen vehicles in the fleet, and will have relatively small impact on primary resource use. In theory, both electricity and hydrogen could utilize vast low-carbon resources, including biomass, hydro, geothermal, and intermittent renewable energies like wind and solar and fossil energy with carbon capture and sequestration. Primary energy availability should not be a major constraint for either electricity or hydrogen, but continued development of low-cost, low-carbon conversion technologies is needed.

Environmental impacts

- There is considerable scope for reducing GHG emissions compared to today's gasoline vehicles. Well-to-wheels GHG emissions depend sensitively on the particular conversion pathway for biofuels, electricity, and hydrogen. The GHG signature of biofuels is sensitive to the conversion process and to indirect land-use considerations. There are many low-carbon pathways for electricity and hydrogen that rely on renewables or fossil fuels with carbon capture and sequestration (CCS). Unless CCS becomes a reality, though, using electric or hydrogen vehicles in conjunction with a heavily coal-based fuel supply offers little or no benefit compared to gasoline hybrids.

- Plug-in electric vehicles and hydrogen fuel cell vehicles would have significant ancillary benefits in terms of reduced air pollutant emissions and oil use.

- Sustainability issues associated with land, water, and materials impacts of alternative fuel pathways compared with petroleum-based gasoline and diesel are important, but much work remains to be done on understanding and measuring these impacts.

- It is unlikely that material use will impose serious constraints on vehicle technology development in the long term. However, short-term material price volatility and sustainability impacts due to extraction activities need to be considered and mitigated whenever appropriate. Constraints on platinum supplies for fuel cells or lithium for batteries are not likely be long-term "show stoppers," assuming continued progress in reducing materials use and expanded recycling.

- The sustainability impacts of fuel production on water resources need to be compared at the local and regional levels. Concerns about local impacts on water availability, water quality, and ecosystem health should be carefully evaluated. The relative importance of water aspects compared to other aspects of the shift to a new transportation energy system—such as effects on GHG emissions, soil quality, biodiversity, and economic sustainability—must be weighed.

3. Reaching Societal Goals for Sustainable Transportation: Scenarios and Transition Issues

Building on the knowledge gained about individual pathways, STEPS researchers used a variety of analytic approaches to develop scenarios for low-carbon transportation futures. STEPS research has shown that emerging vehicle and fuel technologies could greatly reduce GHG emissions and oil use in transportation by 2050, as part of portfolio approach. These changes will take several decades, but must start now because of the long time constants inherent in changing the energy system.[1]

Future sustainable transportation systems

- A portfolio approach is essential to meet stringent long-term goals for transportation-related GHG emissions reduction and energy security. To achieve deep reductions in GHG emissions and oil use, alternative fuels should be pursued in coordination with improved vehicle efficiency and reduced travel demand. It appears that no one fuel or pathway could meet long-term goals by itself, but combinations of improved vehicle efficiency (most likely relying on increased use of electric drivetrains), decarbonized fuels from diverse low-net-carbon primary sources, and reduced travel demand could.

- There is more than one route to deep reductions in GHGs and oil use by 2050. STEPS researchers identified several distinct "portfolio" scenarios combining multiple strategies that could reach an 80% reduction in transportation-related GHG emissions by 2050. These scenarios differ, but all are characterized by a 2050 light-duty vehicle fleet that relies on highly efficient vehicles, some degree of electrification of drivetrains, and decarbonized transportation fuels. The availability of low-carbon biofuels and the amount of travel demand reduction are "swing factors" that will impact the degree of electrification required to meet GHG reduction goals.

- Unlike today's transportation system, which is 97-percent dependent on petroleum, the transportation system in 2050 might feature a mix of different fuels that could vary by region and transport sector. For example, we might see an electrified light-duty sector and reliance on liquid fuels in the heavy-duty, air, and marine sectors.

- The relative success of several critical technologies could influence the mix of future fuels and vehicles. These include electric batteries, hydrogen fuel cells, biomass conversion technologies, carbon capture and sequestration, and renewable conversion (solar and wind to electricity or hydrogen). The long-term performance and cost of these technologies is still uncertain. This highlights the need for broad and consistent RD&D support to assure rapid progress across a broad front of crucial technologies.

Transition issues and timing

- Making a transition to a low-carbon transportation system is a complex undertaking with multiple actors: consumers, energy suppliers, vehicle manufacturers, and policymakers. Consumer behavior will have a strong influence on which types of vehicles are adopted and what type of infrastructure is needed. Some fuels, notably hydrogen, will require close stakeholder coordination to introduce fuels and vehicles together in particular locations. And most decarbonized fuels will require development of new primary supply chains that could interact with other sectors of the economy (electricity, food, land use). One of the key challenges for policymakers is mitigating the stakeholder risks inherent in introducing new technologies.

- The time required for fuel and vehicle transitions is long. Although electric vehicles and biofuels are beginning to enter the market (and hydrogen fuel cell vehicles could enter by about 2015), it will take several decades for any alternative fuel pathway to make a major difference in GHG emissions or oil use because of the time required for market penetration, vehicle stock turnover and fuel supply development.

- The transitions in vehicle fleets and energy supply systems necessary to reach low-carbon scenarios for 2050 must begin soon and progress rapidly, with rates of market penetration and change near feasible limits. To reach major market penetrations by 2050, new vehicles and fuels need support during early commercialization, as manufacturing and fuel supply systems are scaled up.

Transitions in the light duty vehicle fleet

STEPS researchers developed transition models for the U.S. light-duty vehicle sector to 2050 in support of the National Academies' assessment of the investments needed to bring hydrogen fuel cell vehicles (HFCVs) and plug-in hybrid vehicles (PHEVs) to cost competitiveness with gasoline vehicles. A variety of scenarios were explored that stressed (1) more efficient internal combustion engine technologies, (2) biofuels, (3) hydrogen and fuel cells, (4) plug-in hybrids, and (5) combinations of technologies. Dynamics and costs for vehicle technology learning and infrastructure development were included to find a break-even year when each technology becomes competitive. We also assessed the potential for GHG emissions reduction and oil displacement over time. These studies confirmed the importance of a portfolio approach to oil displacement and GHG emissions reduction. Major findings on transition costs are shown below.

- Transition costs are similar for PHEVs and HFCVs and are in the range of tens to hundreds of billions of dollars. In each case, it will take 15 to 20 years and 5 to 10 million vehicles for the new technology to break even with initial purchase and fuel supply costs for a reference gasoline car. For radically new types of vehicles like FCVs or PHEVs, there is a need to buy down the cost of the vehicle through improvements in technology and scale-up of manufacturing. (Vehicle buy-down costs are typically 80 percent of the total transition cost, and infrastructure costs 20 percent for both PHEVs and HFCVs.) For hydrogen, the fuel cost is initially high and comes down by focusing scaled-up development in lighthouse regions.

- The main transition cost issues for biofuels are to improve biorefinery technology and scale up the supply chain to the point where biofuel competes with other liquid fuels. In the United States, the total investment needed to meet the RFS standard is estimated by various studies to be $100–360 billion for biorefineries, fuel storage terminals, feedstock, and fuel transport to provide enough fuel for 30 to 60 million cars.

- Infrastructure investment costs during a transition are significant but are still relatively small compared to the investment and money flows in the current petroleum system. Maintaining and expanding the existing petroleum infrastructure is projected to cost about $1 trillion in North America alone between 2007 and 2030. Perhaps 20 percent of this capital is for building refineries and fuel transport; the remainder is for exploration and production. By contrast, the cumulative infrastructure capital costs during a 15–20 year transition to competitive hydrogen FCVs or PHEVs would be $10–20 billion (or $1,000–2,000 per vehicle served). In the United States, we estimate that building sufficient biorefinery capacity to meet the Renewable Fuel Standard over the next decade might require $100–360 billion.

4. Policy Needed to Support a Transition

We have begun to explore what kinds of policies would be needed to move toward a transportation system that is more efficient, uses lower-carbon fuels, and employs new types of vehicles. Since a portfolio approach is required and there is considerable uncertainty about the adoption, technology cost, and performance of new vehicles and fuels, one of the challenges for policy is reducing risk.

- Innovative policies will be needed if transportation and alternative fuels are to play a major role in meeting societal goals.

- Policy analyses suggest that economy-wide energy use and GHG emissions can be reduced with strong pricing policy instruments such as a tax on fuel or carbon. But in the transport sector, the evidence suggests that such an approach would not be effective, partly because consumer demand and industry supply responses to such market instruments are highly inelastic and partly because increased fuel and carbon taxes are political anathema at this time in most countries.

- A different—or at least complementary—approach is needed. This other approach might include a mix of market and regulatory policy instruments but by definition will be more fragmented and more targeted at specific technologies and activities. Specific measures could include policies to improve vehicle efficiencies (such as the CAFE standard or the vehicle GHG emission standard), to encourage the reduction of fuel carbon intensities (such as the low-carbon fuel standard), and to encourage the production and adoption of advanced vehicle technologies that both reduce fuel GHG intensity and increase vehicle efficiency (such as the zero-emission vehicle or ZEV program). Policies will almost certainly be required to mitigate stakeholder risk in the early stages of a transition to new fuels and vehicles.

- Key areas of scientific uncertainty exist about how to quantify the social and environmental impact of alternative fuels and advanced vehicles. Policy needs to acknowledge and work around these areas of uncertainty. The question is how to create a robust policy framework that reflects evolving scientific understanding and provides a stable compliance environment.

- More needs to be known about how to account for GHG emissions timing and other factors affecting measurement of GHG impacts. We need a better understanding of how to model the climate impact of land-use change and of forest management. Equally challenging are the sustainability issues associated with market-mediated effects at the system level, such as food prices, indirect land-use change (iLUC), and cumulative environmental impacts.

- So far, there has been limited experience in implementing sustainability standards over large geographical and political regions. Many technical, policy, and implementation issues remain to be tested. Continued improvement in the underlying science and models will pave the way for more effective policy in the future.

Paths Forward

We have found that there is no single transportation fuel or vehicle of the future. Just a few years ago the policy discussion about alternative fuels was framed around finding a single "silver bullet" replacement for petroleum. In light of STEPS research and other recent studies, we now believe that the future is unlikely to be a winner-take-all competition among biofuels, electricity, hydrogen, and petroleum. Instead, the path toward sustainable transportation will be paved by a long series of actions taken together across many fronts over the next decades to improve vehicle efficiency and reduce travel demand while developing new types of vehicles and building new fuel systems tapping into low-carbon primary supplies. By 2050, we will probably see a diverse mix of low-carbon fuels and efficient vehicles in different transportation sectors and regions.

A portfolio approach is essential if we want to achieve deep cuts in transportation GHG emissions and oil use by 2050. The long-term performance and cost projections for key technologies like electric batteries, fuel cells, and advanced biofuels are promising but still uncertain and it will take at least a decade bring these technologies to scale. If we down-select too soon, we run the risk of cutting needed options. This suggests that we need to nurture a range of options over the next decade or so with strong, consistent policy to improve our overall chance of long-term success. A successful portfolio strategy will require a new approach to alternative fuel policy, one that recognizes the uncertainties and long time horizon for change.[2]

Despite the uncertainties, there are clearly measures that could be taken now with a high degree of confidence to reduce GHG emissions and oil use. These include increasing the efficiency of internal combustion engine vehicles (including hybridizing drivetrains) and bringing lower-carbon biofuels into use. In parallel, we need a strong program of support to nurture emerging electric drive transportation technologies (batteries and fuel cells) so that they can be commercialized soon enough to bring deep cuts by 2050. And we need ongoing science to assess the impacts of choices with respect to GHG emissions, oil use, and water, land, air, and materials.

Fortunately, it appears that staying in the game to commercialize multiple fuel/vehicle options would have a relatively low cost compared to the money flows in the current transportation fuel system, although it is more expensive than traditional government spending on research and is risky for individual industries. It will be challenging to craft policies that can support a range of new technologies and are flexible enough to not pick winners. At the same time, we will need measures of success for different options over time, and the ability to stage public support in a timely way.

We are moving into a creative new era for the transportation energy system. As we did 100 years ago at the dawn of the automobile and oil age, we are rethinking our energy system's design and structure; new fuels and vehicles are a critical piece of the picture. This analysis and most others are reaching toward the future from the perspective of our current system. But ultimately the shape of our transportation system may be quite different as we design within the constraints of not just energy and climate but also land, water, air, and materials. Technology and policy are evolving rapidly, with decision makers facing a dynamic future playing field. Perhaps the greatest need now is for strong and consistent policies, and roadmaps and strategies showing how stakeholders can coordinate to take feasible steps toward a sustainable transportation future. STEPS has helped provide solid information and analyses to illuminate paths within the coming revolution. The ongoing challenge is putting the pieces together into realistic visions that can inspire action.

QUESTIONS FOR FUTURE RESEARCH: UNDERSTANDING TRANSITIONS TO A SUSTAINABLE TRANSPORTATION SYSTEM

STEPS researchers have identified a number of critical issues where new research is needed to understand transition paths toward a more sustainable transportation system. These are important but are not well understood and are generally not included in existing energy-economic models that guide decision making in industry and government.

Understand the underlying dynamics of transitions. In most analyses of transportation futures, many assumptions are made about the rate of adoption of new vehicles and fuels, but the underlying factors that govern transition dynamics are not well understood.

- Investigate consumer values and behavior to understand how drivers utilize new technologies and value attributes such as vehicle range and refueling time, especially during a transition.
- Examine possible commercialization pathways for critical technologies such as batteries, fuel cells, and advanced biofuels.
- Explore the roles of different stakeholders during a transition. (For example, under what conditions would automakers and energy companies coordinate to introduce new fuels? What are the pros and cons of policies to stimulate investments in energy infrastructure?)

Improve tools for modeling and technology assessment.

- Develop life-cycle analysis (LCA) tools to better understand societal costs and benefits of different fuels and vehicles during a transition. Integrate sustainability concerns to investigate whether water, land, or materials constraints will be "showstoppers" for clean transportation technologies.
- Expand LCA methodology to assess a wide range of sustainability issues—including GHG emissions, primary energy use, air pollution, energy system reliability/resilience, and water, land, and materials use—in a holistic framework.
- Study the potential interplay between new fuel/vehicle technologies and the design of the future energy system. (For example, would a smart grid and extensive use of intermittent renewables help enable electric vehicles?)
- Use optimization tools to design reliable clean-energy systems. Analyze the reliability and resilience of future renewable energy systems.
- Use geographic information systems and optimization tools to consider regional solutions for building low-cost clean-fuel supply systems.

Develop realistic scenarios and transition strategies to inform industry planning and government policy. Develop visions of the future accounting for engineering design, resource and environmental impacts, policy constraints, and what we know about consumer behavior and economics.

- Elaborate strategies for renewable-intensive transportation, expanded use of natural gas fuels, "smart growth" land use, and low-carbon options for heavy-duty trucks and air and marine transport.
- Analyze how future sustainable transportation systems vary in different regions and for different transportation applications.
- Develop region-specific transition scenarios for the United States, China, and Europe.

Analyze policy approaches for reducing GHG emissions and meeting other sustainability goals. Assess the feasibility and effectiveness of:

- Broad market instruments such as fuel and carbon taxes and cap and trade;
- Fuel policies such as a low-carbon fuel standard, fuel-specific rules, fuel infrastructure requirements, sustainability standards and requirements, and alternative methods for treating land-use change effects;
- Vehicle policies such as performance standards, feebates, and mandates; and
- Policies and actions that influence consumer purchase and use of vehicles and fuels, including social marketing, vehicle instrumentation, eco-driving, and urban land use.

Notes

1. Our findings are broadly consistent with several recent reports on low-carbon transportation futures. See: D. L. Greene and S. E. Plotkin, *Reducing Greenhouse Gas Emissions from U.S. Transportation*, report prepared for the Pew Center on Global Climate Change, February 2011; International Energy Agency (IEA), *Energy Technology Perspectives*, 2008, p. 650; International Energy Agency (IEA), Transport, Energy, and CO_2, International Energy Agency IEA/OECD, Paris; M. Grahn, J. E. Anderson, and T. J. Wallington, "Cost Effective Vehicle and Fuel Technology Choices in a Carbon-Constrained World: Insights from Global Energy Systems Modeling," Chapter 4 in *Hybrid and Electric Vehicles* (New York: Elsevier, 2010); A. Bandivadekar, K. Bodek, L. Cheah, C. Evans, T. Groode, J. Heywood, E. Kasseris, M. Kromer, and M. Weiss, *On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions* (MIT Laboratory for Energy and the Environment, 2008).

2. In the United States, alternative fuels policy over the past 30 years has suffered from the "fuel du jour" syndrome, characterized by short-lived waves of enthusiasm for one fuel after another. The result has been inconsistent "boom and bust" support. "Fuel du jour" is in tune with political desire for a "quick fix" but suffers from a fundamental mismatch between the decadal time frames for changing the transportation energy system, and much shorter political cycles. It sometimes seems that the rate of change of the transportation system (decades) is an order of magnitude longer than the political cycle (a few years), which is in turn an order of magnitude longer than the media cycle (a few weeks).