SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

A Research Summary for Decision Makers

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Introduction: Imagining the Future of Transportation

We stand at the beginning of a revolution in transportation and energy. Over the next several decades, a convergence of growing demand, resource constraints, and environmental imperatives will reshape our energy system. These forces will change the way we travel and the kinds of vehicles we drive, and will challenge the century-long primacy of petroleum and the internal combustion engine. This transformation will unfold over many decades. But it poses urgent questions today because of the long time horizon inherent in developing new technologies and changing the energy system.

Transportation Energy Challenges

Energy supply is a critical concern for the transport sector. Global demand for mobility is growing rapidly, with the number of vehicles projected by the International Energy Agency (IEA) to triple by 2050. This is especially true in the developing world, where the number of vehicles is growing by 5 to 6 percent per year. About 97 percent of transport fuels currently come from petroleum, a large fraction of which is imported by the countries where it is used. Costs for conventional crude oil are rising, and direct substitutes for petroleum (such as unconventional oil from oil shale and tar sands) face economic, technical, and environmental challenges.

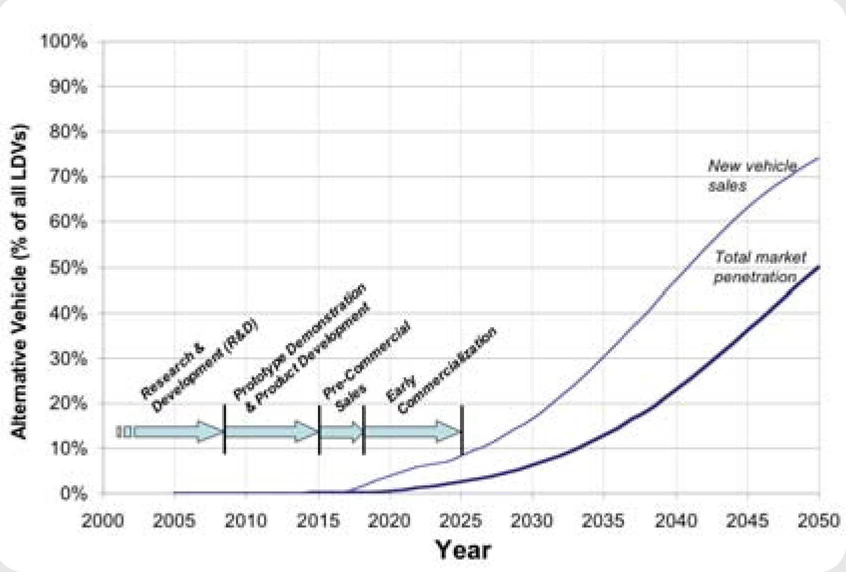
Direct combustion of fossil fuels for transportation accounts for a significant fraction of global primary energy use (19 percent), air pollutant emissions (5 to 70 percent, depending on the pollutant and region), and greenhouse gas (GHG) emissions (23 percent for 2005 on a well-to-wheels basis), according to the International Energy Agency.[1] Although improved energy efficiency in buildings or low-carbon electricity generation might offer lower-cost ways of reducing carbon emissions in the near term, decarbonizing the transport sector will be critically important to achieving the long-term, deep cuts in carbon emissions required for climate stabilization.

A host of complex resource issues complicates the path toward a sustainable transportation system. These include availability of low-carbon primary energy resources to make new transportation fuels, availability of land and water to produce these fuels, constraints on critical materials such as platinum for fuel cells or lithium for batteries, and impacts on the broader economy.

THE LONG TRANSITION

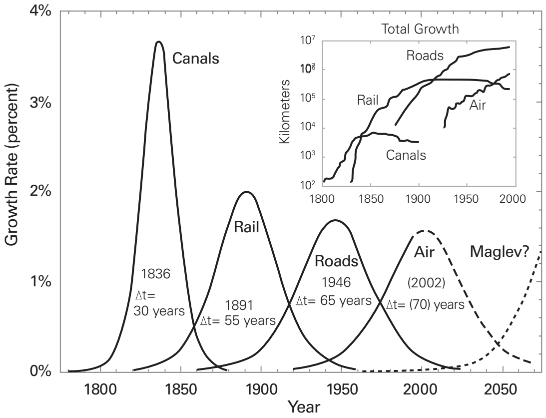
How fast can we make a transition to alternative fuels and vehicles? Transitions in the transportation sector take a long time, for several reasons.

First, passenger vehicles have a relatively long lifetime (15 years average in the United States). Even if a new technology were to rapidly capture 100 percent of new vehicle sales, it would take a minimum of 15 years for the vehicle stock to turn over. In practice, adoption of new vehicle technologies occurs much more slowly; it can take 25 to 60 years for an innovation to be used in 35 percent of the on-road fleet.[2] For example, research into gasoline hybrid electric vehicles (HEVs) in the 1970s and 1980s led to a decision to commercialize in 1993, with the first vehicle becoming available for sale in 1997. HEVs still represent only about 3 percent of new car sales nationally in the U.S., 5% in California and fewer than 0.5 percent of the worldwide fleet. This slow turnover rate is also true for relatively modest technology changes such as the adoption of automatic transmissions or fuel injection. The time frame for new technologies relying on electric batteries, fuel cells, or advanced biofuels could be even longer since they all need further RD&D investment before they can be commercialized.



The steps needed to commercialize a new vehicle technology add up to a long time horizon. An alternative vehicle technology for which research and development began in 2000 might not reach 50 percent market penetration or hope to capture 75 percent of new vehicle sales until 2050. Source: Joshua M. Cunningham, Sig Gronich, and Michael A. Nicholas, Why Hydrogen and Fuel Cells Are Needed to Support California Climate Policy*, UCD-ITS-RR-08-06 (Institute of Transportation Studies, University of California, Davis, 2008).*

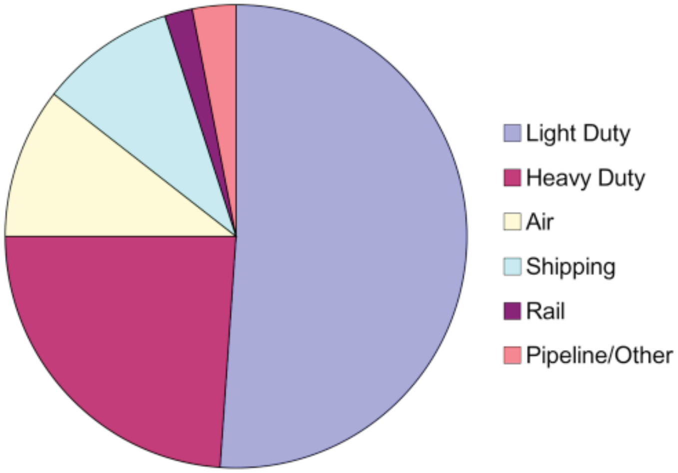
Second, changing the fuel supply infrastructure, especially if this means switching on a massive scale from liquid fuels to gaseous fuels or electrons, will require both time and a significant amount of capital. Historically, major changes in transport systems such as building canals and railroads, paving highways, and adopting gasoline cars have taken many decades to complete. Transitions will require developing new supply chains using renewable or other low-carbon sources and replacing existing fossil fuel and electricity plants. Such paradigm shifts will require close coordination among fuel suppliers, vehicle manufacturers, and policymakers.



It takes 30 to 70 years to fully implement new infrastructures, judging by historical data on the time it has taken for major U.S. transportation infrastructures to reach their peak market penetration. Source: Jesse H. Ausubel, Cesare Marchetti, Perrin Meyer, Toward Green Mobility: The Evolution of Transport, *European Review, Vol. 6, No. 2, 137-156 (1998). Posted with permission on http://phe.rockefeller.edu/green_mobility/.*

Each fuel/vehicle pathway faces its own transition challenges, which can vary with region and can slow market penetration. These include infrastructure compatibility, consumer acceptance (based on, for example, limited range or long recharging times for batteries or and limited initial infrastructure for hydrogen fuel cell vehicles), cost, availability of primary resources for fuel production, greenhouse gas emissions, and other environmental and sustainability issues (such as air pollutant emissions, and water, land, and materials use).

USES OF TRANSPORT ENERGY, 2005



Fraction of global transport energy use in 2005, Source: International Energy Agency, Transport, Energy and CO_2: Moving Towards Sustainability *(Paris, France: IEA, 2009).*

Approaches to Sustainable Transportation

Government and industry are seeking sustainable solutions for the future transportation system. Three approaches are often proposed to reduce transport-related energy use and emissions:

- **Improve efficiency.** This means shifting to more efficient modes of transport, such as from cars to mass transit (bus or rail), or from trucks to rail or ships. Further efficiency improvements could be achieved by reducing vehicle weight, streamlining, and improving designs of engines, transmissions, and drive trains, including hybridization. In the heavy-duty freight movement subsector and in aviation, there is also promise of significant efficiency improvements.
- **Replace petroleum-based fuels with low- or zero-carbon alternative fuels.** These include renewably produced biofuels, and electricity or hydrogen produced from low-carbon sources such as renewables, fossil energy with carbon capture and storage (CCS), or nuclear power. Alternative fuels have had limited success thus far in most countries, with alternative-fuel vehicles currently making up less than 1 percent of the global fleet;[3] however, the context for alternative fuels is rapidly changing and a host of policy initiatives in Europe, North America, and Asia are driving toward lower-carbon fuels and zero-emission vehicles.
- **Reduce vehicle miles traveled.** This might be achieved by encouraging greater use of carpooling, cycling, and walking, combining trips, and telecommuting. In addition, city and regional smart growth practices (planning so that people do not have to travel as far to work, shop, and socialize) could reduce GHG emissions by as much as 25 percent.[4]

The emerging consensus among transportation energy analysts is that all three approaches will be needed if we are to meet stringent societal goals for carbon reduction and energy supply security. In this book we concentrate on the prospects and challenges for large-scale development of alternative vehicles and fuels.

POLICIES DRIVING CHANGE

State and federal policy initiatives in the United States are driving toward lower-carbon fuels and zero-emission vehicles.

In California:

- The Zero-Emission Vehicle (ZEV) Regulation requires automakers to offer 7,500 pure ZEVs for sale by 2014 and 25,000 pure ZEVs by 2017. An expanded program will be proposed in 2011 for requirements through 2025.
- AB 1493 (the Pavley Act) regulates vehicle CO_2 emissions and requires a 30-percent reduction in GHG emissions by 2016. An expanded fleet program will be proposed in 2011 for requirements through 2025, as part of a broad "Clean Cars" program.
- AB 118 provides funding of $200 million per year for the establishment of alternative fuel infrastructure and vehicle rebates through 2015.
- SB 1505 requires that source-to-wheel emissions of GHG from vehicular hydrogen be reduced by 30 percent on a per-mile basis when compared to the average gasoline vehicle.
- AB 32 (the Global Warming Solutions Act) requires California's Air Resources Board to enforce a statewide GHG emissions cap reaching 1990 levels by 2020. One component of this is a GHG cap and trade program that includes transportation fuels "in the cap."
- Executive Order S-3-05 sets GHG emission reduction targets for the state, including the mandate to reduce emissions to 80 percent below 1990 levels by 2050.
- California Air Resources Board Resolution 10-49 (November 18, 2010) establishes a Low Carbon Fuel Standard to reduce the carbon intensity of California's transportation fuels by at least 10 percent by 2020.
- The proposed Clean Fuels Outlet Regulation requires that an alternative fuel supply be provided once 20,000 alternative-fuel vehicles are on the road. This regulation is under consideration by the California's Air Resources Board.
- SB 2, which was signed by Governor Jerry Brown in April 2011, solidifies the requirement for 33% of electricity production to come from renewables by 2020 (California's Renewable Electricity Standard (RPS)).

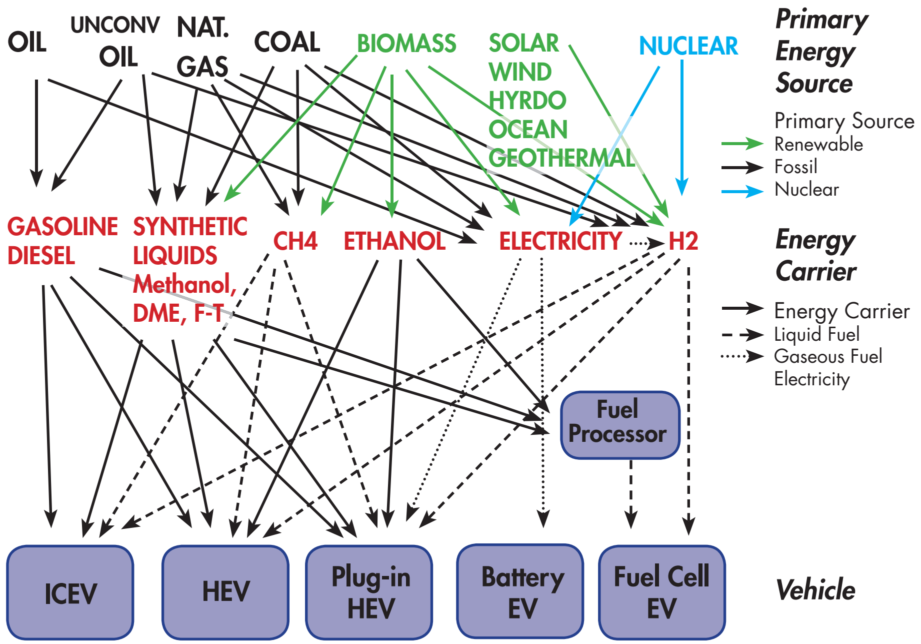
On the federal level:

- The Renewable Fuel Standard requires 36 billion gallons of biofuel by 2022.
- The Corporate Average Fuel Economy (CAFE) standard requires that new light-duty sales average 35.5 mpg by 2016. An expanded program will be proposed in 2011 for requirements through 2025. This includes both a CAFE and gCO_2/mi fleet requirement.
- Plug-in electric vehicle (PEV) and biofuel tax breaks amount to 45 cents per gallon for purchase of ethanol and up to $7,500 for purchase of a PEV.
- The U.S. Department of Energy budget includes funds for research, development, and demonstration of battery electric vehicles and smart grid technologies, and research on fuel cell vehicles and hydrogen production, delivery, and storage.
- In conjunction with the United Nations Climate Change Conference in Copenhagen in 2009, President Obama put forth a goal of reducing GHG emissions in the United States 83 percent by 2050.

Alternative Fuel and Vehicle Pathways

Although our current transportation system is based almost exclusively on petroleum and the internal combustion engine, there are many other possibilities. A variety of more efficient vehicles (including those with hybrid drive trains and fuel cells along with battery electric vehicles) and alternative fuels (including compressed natural gas, ethanol, methanol, DME, F-T diesel, electricity, and hydrogen) have been proposed to address climate change and energy security concerns.

POSSIBLE VEHICLE TYPE – FUEL SOURCE COMBINATIONS



A variety of combinations of vehicle types and fuel sources are possible to meet our transportation needs. Possible fuel/vehicle pathways are shown here, with primary energy sources at the top, energy carriers (fuels) in the middle, and vehicle options at the bottom. F-T= Fischer-Tropsch process, ICEV = internal combustion engine vehicle, HEV=hybrid electric vehicle, EV = electric vehicle.

While many of these pathways offer potential societal benefits in terms of emissions or energy security, the path forward is unclear. Much of the public discourse has been framed as winner-take-all debates among advocates for particular "silver bullet" technologies. Policy proposals and media coverage suffer from a "fuel du jour" syndrome, waves of short-lived enthusiasm for one technology after another. Given the rapidly changing technology and policy landscape, consensus is lacking about which option or options to pursue, and when and where to pursue them.

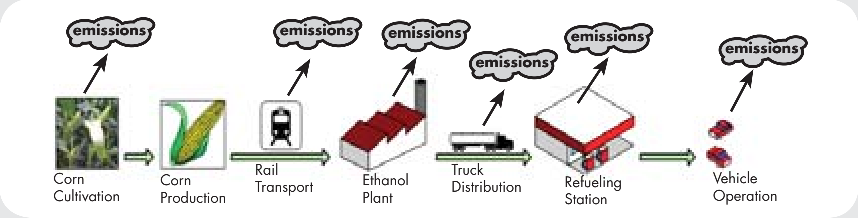
Scope of This Book: Sustainable Transportation Energy Pathways

The purpose of this book is to help inform decision makers in industry and government about the potential costs and benefits of different fuel/vehicle pathways, and to illuminate viable transition strategies toward a sustainable transportation future. We draw heavily on insights gained from the Sustainable Transportation Energy Pathways (STEPS) research program at the University of California, Davis. STEPS began in 2007, with a goal of performing robust, impartial comparative analyses of different fuel/vehicle pathways drawing on engineering, economics, environmental science, and consumer behavior. An interdisciplinary team of 15 Ph.D.-level researchers and 25 graduate students was formed, with support coming from 22 diverse sponsoring organizations, each of which contributes to the STEPS consortium.

WHAT IS SUSTAINABLE TRANSPORTATION?

Energy sustainability has been defined as "providing for the ability of future generations to supply a set (or basket) of energy services to meet their demands without diminishing the potential for future environmental, economic and social well-being."[5] Sustainability is not necessarily a static concept or an end state: for transportation, "future well-being" could mean providing mobility to growing numbers of people.

How do we define and measure sustainability for transportation? Life-cycle analysis (LCA) is a powerful method for evaluating and comparing fuel/vehicle pathways with respect to a set of sustainability metrics. These could include primary energy use, greenhouse gas emissions, air pollutant emissions, water use, land use, materials requirements, and other factors that might be harder to quantify such as reliability and resiliency. The life cycle of a product encompasses all of the physical and economic processes involved directly or indirectly in its life, from extracting the raw materials used to make it to recycling the product at the end of its life. Life-cycle analysis for transportation analyzes all the steps in producing and using fuels: resource extraction and transport, production of the fuel, fuel delivery to refueling stations, and use in vehicles. (Sometimes the energy and materials used to make vehicles are also included in the life cycle, but these tend to be significantly lower than fuel cycle energy use and emissions.) Emissions, energy use, and other factors can be estimated at each step and added up to give a "well-to-wheels" total.



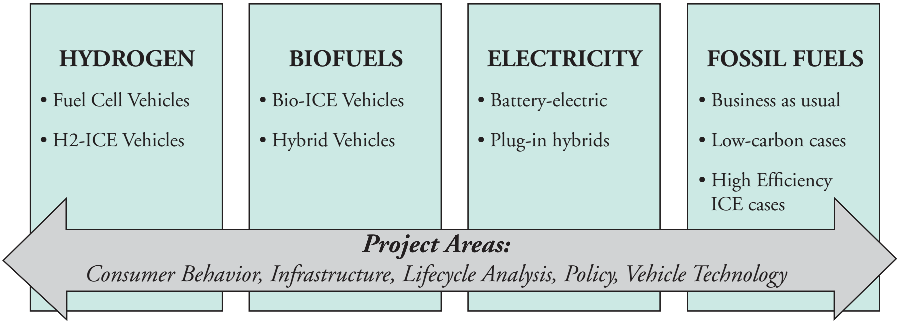
A fuel life-cycle analysis traces a fuel pathway from well to wheels. The corn ethanol pathway is shown here as an example. Source: M. A. Delucchi, Lifecycle Analyses of Biofuels *(Institute of Transportation Studies, University of California, Davis, 2006), UCD-ITS-RR-06-08.*

LCA can also be used as a basis for estimating the societal costs of different fuel/vehicle pathways including externalities, such as health damage from air pollution, climate impacts of greenhouse gas emissions, and economic costs of oil insecurity. When these costs are added to the direct cost of owning and operating the vehicle, low-emission options become more competitive with conventional fuels.[6]

But while LCA is a very useful tool, LCA alone can't define sustainability. Deciding on the acceptable limits for different LCA metrics (for example, allowable well-to-wheels GHG emissions) is a difficult task. Besides, complex social and economic factors come into play when trying to formulate a practical (and enforceable) definition of sustainability. While carbon storage, biodiversity, soil conservation, water use, water quality, and air pollution are amenable to LCA, the socioeconomic principles of welfare of local communities, land-rights issues, and labor welfare are not. Furthermore, sustainability impacts from market-mediated or macroeconomic effects—including indirect land-use change (iLUC), food price, and food availability—can be very important but are hard to measure and predict. Such effects become important when energy and environmental policies affect prices, which in turn affect consumption and hence output, which then changes emissions. (For example, U.S. biofuel policy led to use of the corn crop for fuel ethanol, which caused a spike in Mexico's corn-based food prices.)

Several authors[7] have suggested developing a "sustainability index" incorporating multiple criteria. This work is still nascent, in part because it is difficult to value different attributes on the same scale, and valuation depends on cultural and political norms. In this book, we discuss sustainability based on LCA and cost-benefit concepts, while recognizing this is a major simplification. Our underlying assumption is that pathways that score well on many sustainability metrics are likely to be attractive.

STEPS research is organized around four fuel pathways: hydrogen, biofuels, electricity, and fossil fuels. We have explored technical aspects, cost, market issues, environmental implications, and transition issues for each individual pathway. STEPS research is also organized by thread or project area, allowing us to compare fuels with each other along multiple dimensions—with respect to consumer behavior, infrastructure requirements, well-to-wheels energy use and emissions, policy, and vehicle technology. This allows us to develop integrative scenarios to address goals like reducing greenhouse gas emissions or oil dependency.



Sustainable Transportation Energy Pathways (STEPS) research is organized by energy pathway, with comparative analysis in project areas.

Analyzing single-fuel pathways gave us a strong basis for comparing different fuels and developing scenarios about how the various fuel/vehicle pathways might be integrated to meet societal goals. The STEPS research has flowed naturally from single pathway analyses to robust comparison of fuel pathways to integrative scenarios and transition analyses for future vehicles and fuels, and increasingly to case studies that inform carbon and alternative fuel policies in California, the United States, and beyond. It addresses these four "big picture" questions that the parts of this book are organized around:

1. **What do individual fuel/vehicle pathways look like?** We characterize individual fuel/vehicle pathways, with chapters on biofuels, electricity, and hydrogen. We explore technical aspects, costs, market issues, environmental implications, and transition issues for each pathway. Our interdisciplinary approach enables us to describe each pathway with depth and sophistication from multiple perspectives.

2. **How do these pathways compare?** Building on single-pathway analyses, we compare different fuel/vehicle pathways with respect to vehicle technology and costs, infrastructure issues, and well-to-wheels environmental impacts. We have done this on an impartial, self-consistent basis, across many dimensions. This allows us to understand when different fuel/vehicle options might be available and how the costs and benefits compare.

3. **How could we combine pathways and approaches to meet societal goals for carbon reduction, energy security, and such?** Drawing on the insights in Parts 1 and 2, we have developed integrative scenarios for reaching societal and policy goals (for example, 80 percent reduction in GHG emissions by 2050). We have studied transition issues as well as interactions between, for example, electricity and transportation. We have found that "silver bullet" solutions won't reach long-term goals and that a portfolio approach is needed, incorporating both near-term and long-term technologies and changes in behavior.

4. **What policy measures and tools are needed to encourage progress toward sustainable transportation?** We discuss policies and strategies for developing a sustainable transportation system, as well as measurement challenges that must be addressed in order for analysts to be able to predict the full impact of potential policies.

Perhaps the single most important insight from the STEPS research is that a portfolio approach will give us the best chance of meeting stringent goals for a sustainable transportation future. Given the uncertainties and the long timelines, it is critical to nurture a portfolio of key technologies toward commercialization. All our work in characterizing pathways and comparing them flows toward this conclusion.

We invite you to explore intriguing pathways, to compare options, and to synthesize these insights into your own vision for the future of transportation.

Notes

1. International Energy Agency (IEA), *Energy Technology Perspectives*, 2008, p. 650.
2. M. A. Kromer and J. B. Heywood, *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet*, LEFF 2007-02 RP (Sloan Automotive Laboratory, MIT Laboratory for Energy and the Environment, May 2007), http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/kromer_electric_powertrains.pdf.
3. Exceptions: in Brazil, around 50 percent of transport fuel (by energy content) is ethanol derived from sugar cane; in Sweden, imported ethanol is being encouraged; in India, Pakistan, and Argentina, compressed natural gas (CNG) is widely used; and in the United States, ethanol derived from corn is currently blended with gasoline up to 10 percent by volume in some regions and accounts for 3 percent of U.S. transport energy use, according to the U.S. Energy Information Administration's *Annual Energy Outlook 2009*.
4. A. M. Eaken and D. B. Goldstein, "Quantifying the Third Leg: The Potential for Smart Growth to Reduce Greenhouse Gas Emissions," Proceedings from the 2008 ACEEE Summer Study on Energy Efficiency in Buildings (American Council for an Energy-Efficient Economy, 2008).
5. A. Löschel, J. Johnston, M. A. Delucchi, T. N. Demayo, D. L. Gautier, D. L. Greene, J. Ogden, S. Rayner, and E. Worrell, "Stocks, Flows, and Prospects of Energy," chapter 22 in *Linkages of Sustainability*, ed. T. E. Graedel and E. van der Voet (MIT Press, 2009), http://pubs.its.ucdavis.edu/publication_detail.php?id=13584.
6. See M. A. Delucchi, *A Conceptual Framework for Estimating Bioenergy-Related Land-Use Change and Its Impacts over Time*, UCD-ITS-RR-09-45 (Institute of Transportation Studies, University of California, Davis, 2009); D. Greene, P. Leiby, and D. Bowman, *Integrated Analysis of Market Transformation Scenarios with HyTrans,* ORNL/TM-2007/094 (Oak Ridge National Laboratory, 2007); J. Ogden, R. H. Williams, and E. D. Larson, "A Societal Lifecycle Cost Comparison of Cars with Alternative Fuels/Engines," *Energy Policy* 32 (January 2004): 7-27, http://pubs.its.ucdavis.edu/publication_detail.php?id=; A. Rabl and J. V. Spadaro, "Public Health Impact of Air Pollution and Implications for the Energy System," *Annual Review of Energy and the Environment* 25 (2000): 601–27; J. V. Spadaro, A. Rabl, E. Jourdaint, and P. Coussy, "External Costs of Air Pollution: Case Study and Results for Transport between Paris and Lyon," *International Journal of Vehicle Design* 20 (1998): 274–82; Y. Sun, J. Ogden, and M. A. Delucchi, "Societal Lifetime Cost of Hydrogen Fuel Cell Vehicles," accepted for publication in the *International Journal of Hydrogen Energy* 2010; C. E. Thomas, "Fuel Cell and Battery Electric Vehicles Compared," *International Journal of Hydrogen Energy* 34 (2009): 6005–20.
7. These authors include D. L. McCollum, G. Gould, and D. L. Greene, *Greenhouse Gas Emissions from Aviation and Marine Transportation: Mitigation Potential and Policies*, UCD-ITS-RP-10-01 (Institute of Transportation Studies, University of California, Davis, 2010), http://pubs.its.ucdavis.edu/publication_detail.php?id=1363; and R. Zah, M. Faist, J. Reinhard, and D. Birchmeier, "Standardized and Simplified Life-Cycle Assessment (LCA) as a Driver for More Sustainable Biofuels," *Journal of Cleaner Production* 17, Supplement 1 (2009): S102–S105; S. Yeh, D. A. Sumner, S. R. Kaffka, J. M. Ogden, and B. M. Jenkins, *Implementing Performance-Based Sustainability Requirements for the Low Carbon Fuel Standard—Key Design Elements and Policy Considerations*, UCD-ITS-RR-09-42 (Institute of Transportation Studies, University of California, Davis, 2009).