

Policies for Promoting Low-Emission Vehicles and Fuels: Lessons from Recent Analyses

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Executive Summary

Since the energy crises of the 1970s the U.S. has struggled to substitute alternative energy sources for petroleum use by motor vehicles. This report reviews recent studies of a wide range of policies to promote alternative fuels and vehicles to extract insights about their impacts and effectiveness. Although the emphasis has varied over the past four decades, the motivations for replacing petroleum fuels have remained the same:

- Prevent or mitigate dangerous changes in the global climate by substituting low-carbon energy for fossil petroleum.
- Improve energy security by reducing national dependence on petroleum.
- Improve local air quality by eliminating or drastically reducing emissions from motor vehicles.

A central premise of this review is that a transition to low-GHG energy for motor vehicles is not only desirable but very likely essential to achieve the kinds of GHG emission reductions necessary to appropriately mitigate global climate change (e.g., an 80% reduction over 2005 levels by 2050).¹ Consequently, it is taken for granted that the objective of public policy is the displacement of the majority of fossil petroleum with low-GHG energy. Achieving reductions in light-duty vehicle GHG emissions of 50% to 100% by 2050 would likely require that a majority of new vehicles sold in 2050 are battery electric or hydrogen fuel cell electric vehicles (McCollum and Yang, 2009; NRC, 2013). Accomplishing such a large-scale energy transition for the public good poses new challenges for public policy (Greene et al., 2014b).

More than a decade ago, McNutt and Rodgers (2004) published a seminal assessment of alternative fuels policies from the enactment of the Alternative Motor Fuels Act of 1988 until 2003. Their findings remain valid today.

- The incumbent vehicle and fuel technology will be difficult to displace, in part because it will adapt and improve to compete with alternatives.
- Consumers make vehicle choices based almost entirely on private not social benefits.
- Scale is important in the automotive and fuel industries. Low volumes in early markets is a large financial barrier to the success of alternative fuels.
- A successful transition is likely to require disincentives for continued use of conventional fuels as well as incentives for alternatives.
- Unregulated and unsubsidized private sector investment in refueling infrastructure was inadequate to support a transition to alternative fuels.
- Coordination between the automobile and energy industries is vital.

Over the past decade, researchers have investigated consumers' attitudes and preferences toward alternative fuel vehicles (AFVs) through surveys and analyses of market transactions. Nearly all the studies attempt to estimate the impacts of the many policy measures designed to promote purchases of AFVs at local, state and national levels. On the other hand, there has been very little research that addresses the effectiveness of policies to increase the availability of alternative

¹ Studies that support this conclusion include McCollum and Yang (2009), US DOT (2010), Greene and Plotkin (2011), GEA (2012) and NRC (2013).

fuels infrastructure. While many studies have estimated the impacts of subsidies for alternative fuel vehicles, few have addressed the effectiveness of regulatory policies such as California's Zero Emission Vehicle (ZEV) mandates or credits available under the federal Corporate Average Fuel Economy (CAFE) standards.

Transitions to alternative fuels and vehicles are especially difficult because they require displacing incumbent technologies by overcoming formidable market barriers, especially:

- Lack of scale economies in the vehicle and fuel supply chains
- The need for further technological progress and learning by doing
- Consumers' lack of familiarity with and aversion to the risk of novel products
- Lack of diversity of AFV choices in vehicle markets (e.g., make, model, vehicle class)
- Lack of refueling infrastructure
- Lack of a market for alternative fuel
- Inappropriate Administrative and regulatory infrastructure (codes, standards, ordinances, etc.).

The supply and use of energy in transportation forms a socio-technical system, a network of agents, institutions, infrastructure and technologies (e.g., Markard et al., 2012). Inducing fundamental transitions in such systems entails complex and extensive changes, potentially involving all actors and components of the system.

A seminal study by the National Research Council (2013) analyzed the potential for U.S. light-duty vehicles to achieve an 80% reduction in GHG emissions by 2050. The study found that even an aggressive, well planned and supported transition would take well over 25 years to complete. Given such long time-constants for change and consequent uncertainty about future technology and market conditions, transition policies must not only be durable but adaptable (Weber & Rohrer, 2012). Without a massive increase in biofuel use, the GHG reduction goals could only be met by a transition to electric-drive vehicles powered by batteries or hydrogen fuel cells. All successful transitions to electric-drive vehicles investigated by the NRC Committee shared the following characteristics:

1. Large subsidies continue for a period of two decades, or more,
2. For a decade or more, net social benefits are negligible or negative,
3. In the long run, benefits outweigh costs by approximately an order of magnitude.

Among the market barriers AFVs face, initial purchase price is the most salient for new car buyers. The importance of providing financial incentives to encourage purchases of AFVs is the most consistent finding in the recent literature. Effective financial incentives must be large enough to gain the customer's attention. There is evidence that incentives available at the time of purchase have twice the impact of tax credits, or more. The impacts of regulatory policies such as California's Zero Emission Vehicle mandates to inducing manufacturers to subsidize alternative fuel vehicles have received inadequate attention from researchers. Non-monetary incentives, such as HOV lane access or parking privileges, can be effective as well but their effectiveness depends strongly on local conditions.

Lack of awareness, unfamiliarity and the perceived risk of purchasing a novel technology appear to be the most important non-financial barriers to AFV adoption. Surveys demonstrate that most consumers' knowledge of AFVs is minimal and often inaccurate and that many are waiting to see large numbers of AFVs on the road before they will consider purchasing one. Potential buyers are also often unaware of incentives for alternative fuel vehicle buyers. One U.S. survey found that knowledge of state and local policies promoting plug-in vehicles ranged from a low of 0.3% who were aware of incentives for home charging equipment to a high of 5.5% who were aware of vehicle purchase incentives (Krause et al., 2013, Table 1).

Lack of infrastructure is a critical obstacle to alternative fuels and vehicles. Yet the co-dependence of alternative fuel infrastructure and alternative fuel vehicles is still not well understood. Although recent experience with plug-in vehicles is producing important insights, we still don't know how best to co-evolve alternative fuel infrastructure and the alternative fuel vehicle stock. We cannot satisfactorily estimate how much of what type of infrastructure in which locations at what time will most effectively and efficiently induce a transition. Better analysis and better planning tools are needed. Nevertheless, a common finding is that refueling infrastructure must be over-provided to induce a successful transition to alternative fuels. During the early transition, infrastructure will almost certainly be under-utilized and therefore unprofitable. Direct or indirect subsidies (for example, induced by regulations) will be needed to induce an adequate level of investment.

To date, public policy in the U.S. has paid little attention to the retail **pricing of alternative fuels**, despite the fact that numerous studies of vehicle and fuel choice have demonstrated the importance of fuel price to both. The two international examples of transition to alternative fuels – Ethanol in Brazil and CNG in Argentina – both included strong policies to ensure that alternative fuels were priced competitively. If the world's economies simultaneously convert from fossil petroleum to low-carbon energy, the price of petroleum is certain to decrease. Managing the cost-competitiveness of low carbon energy poses a major challenge for the sustainable energy transition.

Institutional infrastructure is also critically important. Adapting institutions, ordinances, codes and standards to the different attributes of alternative fuel vehicles and refueling infrastructure can speed their deployment and thereby reduce their costs. When it comes to infrastructure, policy makers at local levels emphasize the importance of regulation and standardization, issues that are taken for granted with conventional fuels but that are critically important during the early stages of transition to facilitate timely deployment of alternative fuels infrastructure. Local communities have an important role to play in planning the evolution of alternative fuel infrastructure and coordinating deployment across regions.

Because of the complexity and variety of market barriers to a transition to alternative fuels, comprehensive policy strategies are more likely to be effective and economically efficient. The barriers to transition are complex and involve not only environmental externalities and other market imperfections, but network external benefits and strong positive feedbacks that can induce tipping points. Initially, transition costs such as lack of fuel availability, lack of knowledge and risk aversion by the majority of consumers, scale economies and learning by

doing are very high but decrease rapidly with annual sales volumes and cumulative production. These characteristics of system transformation argue for the superiority of comprehensive policy strategies that address all barriers simultaneously.

Finally, because the transition to low-GHG energy for motor vehicles will take several decades and the success of any one alternative is uncertain, public policy must be persistent and flexible. Policies to promote energy transition must:

1. Secure sustained public (political) support.
2. Be adaptable as technologies and markets change.

Accomplishing a large-scale energy transition for the public good is a new challenge for public policy. As more experience is gained from the ongoing market transformation process, future research will provide additional insights that will enable policy makers to refine and improve policies to promote the transition to sustainable energy for motor vehicles.

Policies for Promoting Low-Emission Vehicles and Fuels: Lessons from Recent Analyses²

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1. Introduction: Why alternative fuels?

The energy crises of the 1970s quintupled world price of oil. Ever since, the United States has struggled to substitute alternative energy sources for petroleum. Some sectors have succeeded. Petroleum supplied 18% of the energy for electricity generation in 1973 but only 4% in 1985 and about 1% today (EIA, 2016). Petroleum's share of energy use in residential and commercial buildings decreased from 18% in 1973 to 10% in 1985 and now stands at less than 5%. Meanwhile, petroleum's share of industrial and transportation energy has remained nearly constant. Industry obtained 28% of its energy from petroleum in 1973 and 26% in 2014. Transportation, which accounts for 70% of U.S. petroleum use, was 96% dependent on petroleum in 1973, 97% in 1985 and 92% in 2014. Only the mandatory blending of ethanol with gasoline keeps transportation from being 96% dependent on petroleum today (Figure 1). While some sectors have found it relatively easy to switch to alternative fuels, transportation remains overwhelmingly dependent on fossil petroleum.

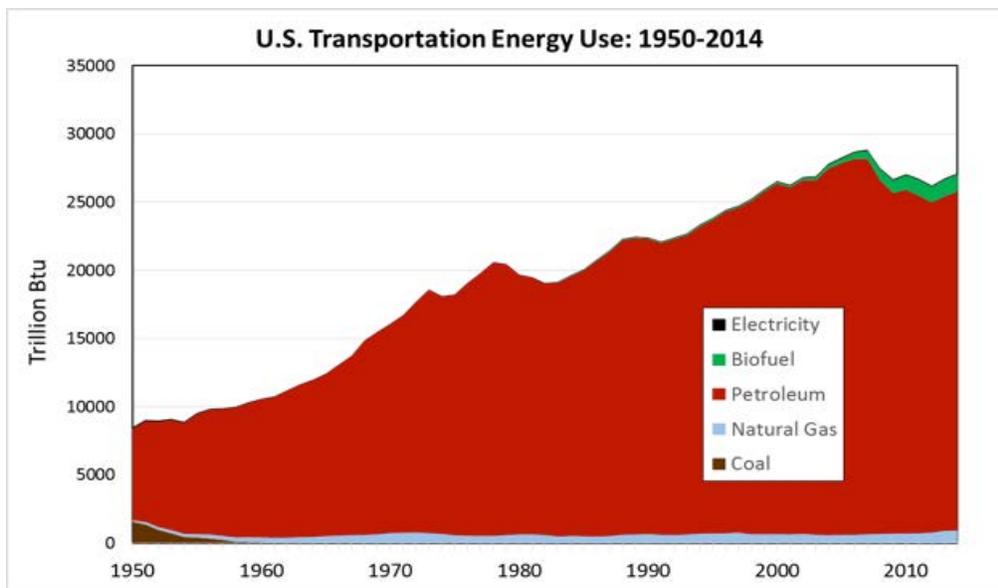


Figure 1. U.S. Transportation Energy Use by Fuel Type: 1950-2014 (EIA, 2016, MER table 2.5).

This review of recent studies of policies to promote alternative fuels aims to extract useful

² The authors gratefully acknowledge the support of this research by Argonne National Laboratory

guidance about how to effectively and efficiently accomplish a transition to low greenhouse gas (GHG), non-petroleum energy for transportation. The review is focused on passenger cars and light trucks which account for about 60% of transportation's energy use. The emphasis is on peer-reviewed literature but some studies from the gray literature are also included.

Assessment of public policies should begin with a clear statement of the objectives of those policies. Although the emphasis has varied over the past four decades, the main reasons for replacing petroleum have remained the same:

1. Prevent or mitigate dangerous changes in the global climate by substituting low-carbon energy for fossil petroleum.
2. Improve energy security by reducing national dependence on petroleum.
3. Improve local air quality by eliminating or drastically reducing emissions from motor vehicles.

A central premise of this review is that a transition to low-GHG energy for motor vehicles is not only desirable but very likely essential to achieve the kinds of GHG emission reductions necessary to appropriately mitigate global climate change (e.g., an 80% reduction over 2005 levels by 2050).³ Consequently, it is taken for granted that the objective of public policy is the displacement of the majority of fossil petroleum with low-GHG energy. Achieving reductions in light-duty vehicle GHG emissions of 50% to 100% by 2050 would likely require a majority of new vehicles sold in 2050 to be battery electric or hydrogen fuel cell electric vehicles (McCullum and Yang, 2009; NRC, 2013). Accomplishing such a large-scale energy transition for the public good poses new challenges for public policy (Greene et al., 2014b).

Following the energy crises of 1973-74 and 1979-80, serious efforts were made to replace petroleum with alternative fuels such as ethanol, biodiesel, methanol, natural gas, propane, electricity and hydrogen (see, e.g., Melton et al., 2016). Governments implemented mandates, regulatory incentives, subsidies and tax incentives for vehicle purchases and infrastructure deployment, as well as high-occupancy vehicle lane access and other non-monetary incentives to induce consumers to adopt and industry to supply alternative fuels and vehicles. Because the transportation sector remains more than 90% dependent on petroleum for energy, both in the U.S. and worldwide, it is fair to conclude that policies promoting alternative fuels have been largely unsuccessful to date.⁴ If inducing a transition to non-petroleum energy for transportation could have been accomplished quickly and easily, it would already have been done. What makes the transition so difficult for transportation?

Over the past decade, researchers have investigated consumers' attitudes and preferences toward alternative fuel vehicles (AFVs) through surveys and analyses of market transactions. Nearly all the studies attempt to estimate the impacts of the many policy measures designed to promote purchases of AFVs at local, state and national levels. On the other hand, there has been very

³ Studies that support this conclusion include McCullum and Yang (2009), US DOT (2010), Greene and Plotkin (2011), GEA (2012) and NRC (2013).

⁴ As Figure 1 shows, the most successful displacement of petroleum has been the blending of up to 10% ethanol in gasoline. However, the impacts of GHG emissions and air quality have been relatively smaller and the "transition" to gasohol is nearly invisible to the consumer since conventional vehicles can use gasohol without modification (e.g., Wang et al., 2012).

little research that addresses the effectiveness of policies to increase the availability of alternative fuels infrastructure. Many studies have estimated the impacts of subsidies for alternative fuel vehicles, but few have addressed the effectiveness of regulatory policies such as California's Zero Emission Vehicle (ZEV) mandates or credits available under the federal Corporate Average Fuel Economy (CAFE) standards. This paper reviews the recent evidence on the effectiveness of policies intended to promote adoption of alternative fuel and especially electric-drive vehicles (grid-connected and hydrogen fuel cell) and to provide refueling/recharging infrastructure. It summarizes their findings about the kinds of policy measures needed to accomplish a transition to environmentally sustainable vehicles.

The following section describes the substantial and complex natural barriers to an alternative fuel transition. Understanding the barriers to transition is critical to evaluating policies designed to overcome them. Section 3 reviews studies of monetary and non-monetary policies to promote AFV sales by reducing the costs of AFVs. Section 4 considers policies aimed at increasing consumer acceptance of AFVs by increasing consumers' knowledge and awareness of AFVs and reducing consumers' aversion to the risk of novel technology. Section 5 reviews studies of policies to increase the marketability of AFVs by reducing the cost of limited fuel availability. Section 6 is concerned with analyses of policies to reduce the price of alternative fuels. Section 7 addresses the need to adapt institutional infrastructure, such as codes, standards and ordinances, to the different attributes of alternative fuel vehicles and refueling infrastructure. Section 8 discusses the need for a comprehensive policy strategy addressing all major transition barriers. Lessons learned are summarized in section 9.

2. Barriers and Transition

More than a decade ago, McNutt and Rodgers (2004) published a seminal assessment of alternative fuels policies from the enactment of the Alternative Motor Fuels Act of 1988 until 2003. Their conclusions about the impacts of fifteen years of policies to promote alternative fuels was the following:

“The rapid growth of alternative fuel consumption promoted by stakeholders and endorsed by Congress simply did not materialize despite significant financial and policy investments.” (p. 169)

McNutt and Rodgers' key findings remain valid today.

- The incumbent vehicle and fuel technology will be difficult to displace, in part because it will adapt and improve to compete with alternatives.
- Niche markets will not grow into mass markets unless alternative vehicles and fuels offer compelling advantages to consumers. Consumers make vehicle choices based almost entirely on private benefits.
- Low energy density fuels that require more frequent refueling impose real costs on users and are an important barrier to mass market adoption.
- Scale matters a great deal in the automotive and fuel industries. Low volumes in early

markets is a large financial barrier to the success of alternative fuels.

- A successful transition is likely to require disincentives for continued use of conventional fuels as well as incentives for alternatives.⁵
- Unregulated and unsubsidized private sector investment in refueling infrastructure was very limited and ultimately inadequate. Infrastructure was rarely built in advance of market development and when it was, the financial results were disappointing.
- Coordination between the automobile and energy industries is vital.

The first four points address the difficulty of competing with the petroleum-fueled internal combustion engine, a technology that has evolved for over 100 years and that continues to improve. Transportation markets chose petroleum fuels because they have exceptionally high energy densities, are easy to store and transport, are abundant and inexpensive to produce.⁶ The sought after advantages of alternative fuels, on the other hand, are chiefly public goods. Consequently, McNutt and Rodgers' fifth point is that public policy will have to intervene to tip the scales in favor of the desired alternatives, at least during the transition period. Their final two points address the well-known chicken or egg problem: If alternative fuels are not available, consumers will not buy alternative fuel vehicles and if there are no alternative fuel vehicles on the road, fuel suppliers will be extremely reluctant to supply alternative fuels. In technical jargon, this is a case of network externalities, where building alternative fuel stations makes alternative fuel vehicles more attractive and purchasing alternative fuel vehicles makes stations more profitable. The fact that neither agent can effectively capture the benefit it confers on the other creates a natural barrier to technology transition.

Transitions to alternative fuels and vehicles are especially difficult because they require displacing incumbent technologies by overcoming formidable market barriers, especially:

- Lack of scale economies in the vehicle and fuel supply chains
- The need for further technological progress and learning by doing
- Consumers' lack of familiarity with and aversion to the risk of novel products
- Lack of diversity of AFV choices in vehicle markets (e.g., make, model, vehicle class)
- Lack of refueling infrastructure
- Lack of a market for alternative fuel
- Inappropriate administrative and regulatory infrastructure (codes, standards, ordinances, etc.)

The supply and use of energy in transportation forms a socio-technical system, a network of agents, institutions, infrastructure and technologies (e.g., Markard et al., 2012). Inducing fundamental transitions in such systems entails complex and extensive changes, potentially involving all actors and components of the system. Because of this, the challenge of inducing a sustainable energy transition is more complex and fundamentally different from the problem

⁵ Assuming there is a global effort to replace fossil carbon based transportation fuels, McNutt and Rodgers' fourth point becomes even more important. As worldwide demand for fossil fuels shrinks, there will be downward pressure on fossil fuel prices, increasing their economic attractiveness.

⁶ Since 1972, high market prices for petroleum have been caused by market disruptions and the use of market power by oil producing states. This, of course, is the main reason oil importing economies like the U.S. strive to reduce their dependence on petroleum. Nevertheless, the marginal cost of producing, transporting and refining petroleum remains low in comparison to most alternatives.

of internalizing an environmental externality. Technology transitions create direct network external benefits such as reducing the majority of consumers' aversion to the risk of novel technology, as well as indirect network externalities such as the synergy of AFVs and their refueling infrastructure. Together with scale economies and learning by doing, these positive externalities induce strong positive feedback effects that create path dependencies and possibly tipping points in the transition process (Struben and Sterman, 2008). The challenges are amplified by other market imperfections, such as the apparent undervaluing of the energy savings of advanced technologies by consumers (a.k.a., energy paradox, e.g., Gillingham et al., 2009) and the tendency for markets to generally underinvest in R&D due to the inability of private agents to capture its full benefits (Arrow, 1962). In addition, the problem of energy security is not properly classified as an externality but instead is a fundamentally different kind of market failure, namely market power, one that is not efficiently solved by taxing petroleum (Greene and Liu, 2015).

The complexity of transition barriers and the inherent nonlinearity of transition costs make simple policy solutions, such as a carbon or petroleum tax, less efficient than comprehensive strategies targeted to specific barriers. As will be illustrated below, critical components of the costs of transition are strongly nonlinear. The cost to motorists of limited fuel availability decreases exponentially as the first several stations offering alternative fuel are added (Nicholas et al., 2010). Likewise, the costs of refueling infrastructure decrease with the inverse of sales volume. The benefit of learning-by-doing decreases exponentially with increasing cumulative production and scale economies also are well approximated by an exponentially decreasing function of production volume. On the demand side, majority risk aversion to novel technology decreases with increasing market penetration, although the rate and functional form is not well understood. The strong nonlinearities in transition cost barriers imply, for example, that a relatively small investment in deploying refueling infrastructure could greatly reduce the subsidy required to sell an alternative fuel vehicle. On the other hand, subsidies or mandates to increase AFV sales not only generate scale economies and learning-by-doing that bring down vehicle costs but also increase the profitability (reduce the losses) of early refueling stations.

The complexity of the transition process favors a strategy of multiple policies targeted at specific barriers over a single simple solution. For example, California's ZEV Action Plan (Office of Governor, 2013) addresses public and private funding, includes requirements to guarantee public access, pricing transparency, signage, and support to local governments for necessary changes to requirements for siting, zoning, codes, inspections, and streamlining of permitting. It also includes facilitation of learning-by-doing and sharing best practices among governments at all levels.

Evidence that a multidimensional policy strategy targeting each of the key barriers directly is likely to be superior to less comprehensive approaches. This can be seen in the strategies of the nine countries with the highest levels of electric vehicles sales (Lutsey et al., 2015). All nine leading countries implemented the following types of policies (Figure 2):

1. Support for research and development.
2. Energy efficiency standards.

3. Public funding for public recharging infrastructure.
4. Programs to inform consumers about the benefits of PEVs.

And all but one employed

5. Vehicle purchase subsidies.
6. Carbon or fossil fuel pricing policies.

Area	Action	China	France	Germany	Japan	Netherlands	Norway	United Kingdom	United States (excl. California)	California
Global market share	Vehicle sales in 2014 (million vehicles)	22	2.2	3.3	4	0.5	0.2	2.6	14	1.7
	Vehicle manufacturing in 2014 (million vehicles)	22	1.7	5.7	10	<0.1	<0.1	1.6	11	<0.1
	Percent of 2014 global electric vehicle sales	17%	4%	4%	10%	5%	6%	5%	19%	19%
Vehicle manufacturer	Research and development support	X	X	X	X	X	X	X	X	X
	Long-term efficiency standards	X	X	X	X	X	X	X	X	X
	Incentive provisions within efficiency regulations	X	X	X		X	X	X	X	
	Cumulative sales goal	X	X	X		X	X	X	X	X
	Vehicle deployment requirements									X
	Vehicle production subsidy	X								
Consumer purchase	Vehicle purchase subsidy (tax credit)								X	
	Vehicle purchase subsidy (rebate)	X			X			X		X
	Vehicle purchase tax exemption					X	X		/	
	Vehicle fee-bate scheme		X					X		
	Government fleet vehicle purchasing preferences		X		X			X	X	X
	High fuel price and greater fuel savings		X	X		X	X	X		
Consumer use	Annual vehicle fee exemption			X	X	X	X	/	/	
	Discounted/free electric charging				X	X	X	/	/	X
	Preferential lane (e.g., bus, HOV lane) access			/		X	X		/	X
	Reduced roadway tax or tolls			X	X	X	X	X		
	Preferential parking access		/	/		/	/	/	/	/
Fuel provider, Infrastructure	Carbon pricing scheme	X	X	X	X	X	X	X	/	X
	Low carbon fuel incentive for electricity providers							/		X
	Public charging network funding	X	X	X	X	X	X	X	X	X
	Home charging equipment tax incentives		X						/	/
Consumer awareness	Public outreach activities to educate on consumer benefits	X	X	X	X	X	X	X	X	X

Based on IEA, 2015a; Jin et al, 2014; Mock & Yang 2014; NRC, 2015; OECD, 2015; OICA, 2015a, b; "X" denotes national programs; "/" signifies smaller local or regional program

Figure 2. Policies Implemented by Countries with the Greatest Plug-in Vehicle Sales in 2014 (reproduced with permission of the ICCT and the authors, Lutsey et al., 2015).

Because even a successful transition will take several decades to complete, a high degree of

uncertainty about technology and markets is inevitable. This implies that policy makers can be sure of neither success nor failure. The long time-constants for change in energy systems magnify uncertainties about future market conditions and future technologies (Gallagher et al., 2012). Replacing the petroleum-fueled internal combustion powertrains of new motor vehicles with alternatives would take a minimum of 5-10 years due to constraints on redesign and retooling. In reality, the risk to manufacturers posed by such sweeping changes to their capital-intensive production facilities means change would take much longer (NRC, 2013). Achieving a large scale transition to alternative energy vehicles requires not only selling new vehicles but replacing the existing vehicle stock. The expected lifetime of a light-duty vehicle is now approximately 15 years. As a consequence, even an aggressive, well planned and supported transition would take well over 25 years to complete (NRC, 2013). The long time-constants for change and resulting uncertainty about future technology and market conditions requires that transition policies be adaptable (Weber & Rohracher, 2012).

A seminal study by the National Research Council (2013) analyzed the potential for U.S. light-duty vehicles to achieve an 80% reduction in GHG emissions by 2050. In addition to evaluating promising vehicle and fuel technologies, the NRC committee was charged with identifying barriers and proposing policies to accomplish the GHG reduction goals.

- “Identify the barriers that might exist in transitioning to these vehicle and fuel technologies.
- Suggest policies and strategies for achieving up to 80% reduction in petroleum consumption and carbon dioxide emissions by 2050 through commercial deployment of the light-duty vehicles technologies analyzed in the study.” (NRC, 2013, p. 163)

Instead of constructing scenarios that assumed different levels of market penetration for alternative fuels and vehicles, the committee constructed a comprehensive model that predicted market outcomes as a function of economics and policies. The committee evaluated 24 scenarios in addition to a Business as Usual and a Reference case, all initially calibrated to the Energy Information Administration’s 2011 Annual Energy Outlook Reference Case. Every policy case included continued tightening of light-duty vehicle fuel economy standards through 2050, resulting in an approximate tripling of miles per gallon versus 2011. Key policies that varied by case included the following:

- Subsidies for new alternative fuel vehicles, whether by government or industry
- A system of feebates, i.e., graduated taxes on high and subsidies for low GHG vehicle technologies
- A highway user fee on energy, indexed to inflation and the average energy efficiency of all light-duty vehicles on the road
- Policies to ensure low-carbon production of electricity, hydrogen and biofuels
- Subsidies to alternative fuel infrastructure

Four of the 24 policy cases met the 80% reduction goal. One required especially optimistic assumptions about the cost and performance of fuel cell electric vehicles and another required that most of the U.S.’s potential biofuel production be used to power light duty vehicles, instead

of aircraft or heavy-duty vehicles. The remaining two cases achieving the 80% reduction goal included transitioning to both plug-in electric and fuel cell electric vehicles (NRC, 2013, table 5.29).

A key premise of the NRC (2013) analysis was that sometime after 2040, technological progress, along with economies of scale and learning-by-doing would enable both battery electric and fuel cell electric vehicles to become less expensive than comparable internal combustion engine vehicles (Figure 3). The committee estimated that stringent fuel economy standards would drive mass reduction and improvements in aerodynamic drag and rolling resistance, as well as more efficient accessory systems. These would reduce the power requirements for vehicles of comparable performance, and the costs of BEV and FCEV powertrains would scale more directly with power requirements, eventually giving those technologies a cost advantage. The Committee’s report and appendices include detailed engineering analyses demonstrating the potential for a crossover in the costs of conventional internal combustion engine and electric drive vehicles.

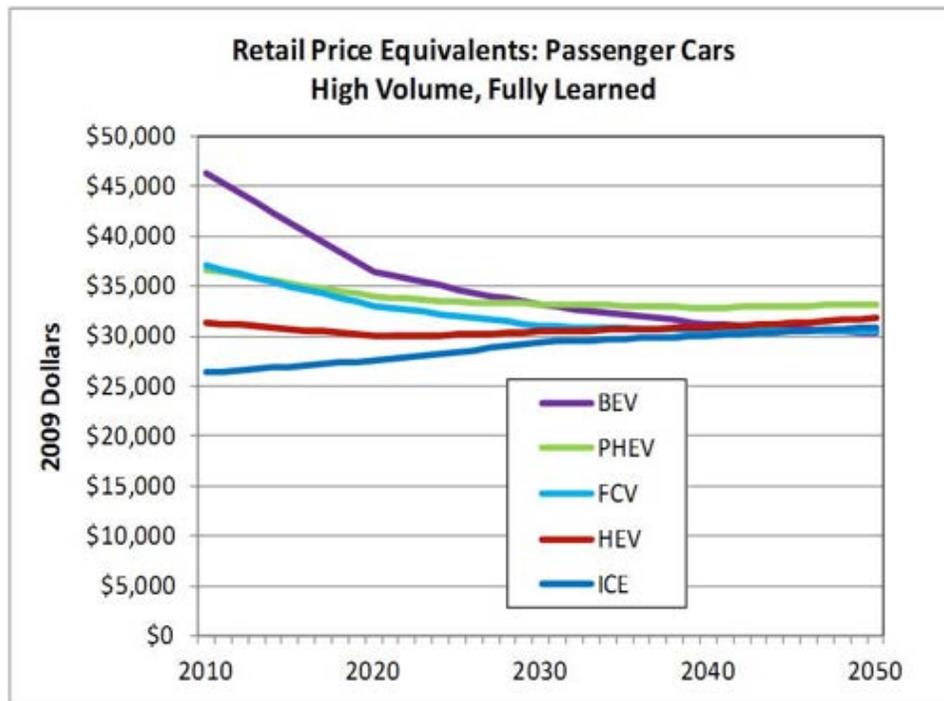


Figure 3. Estimated Retail Prices of Alternative Fuel Vehicles, Assuming High Volume, Fully Learned Production (NRC, 2013).

The NRC committee used its model to do a cost/benefit analysis of each policy case. Although the committee cautions that many aspects of the transition are not well understood, its calculations offer several insights into the nature of alternative fuel transitions. The time-discounted annual costs and benefits of a transition to plug-in and fuel cell electric vehicles with low-carbon energy production are shown in Figure 4. The calculations are conditional on the technological progress illustrated in Figure 3. The red line tracks subsidies to vehicles and fuels, the other colored lines track different social and private benefits, and the black line represents the sum of all components, i.e., net annual benefits in present value dollars. The graph illustrates

three key points about the economics of the transition:

1. Large subsidies continue for a period of two decades.
2. For a decade or more, net social benefits are negligible or negative.
3. In the long run, benefits outweigh costs by approximately one order of magnitude.

Because future technology and market conditions are uncertain and many of the transition processes are not well understood, the committee cautioned against taking the specific cost/benefit numbers at face value. However, the three points listed above held up under the committee's sensitivity analysis, assuming technological progress continued as expected.

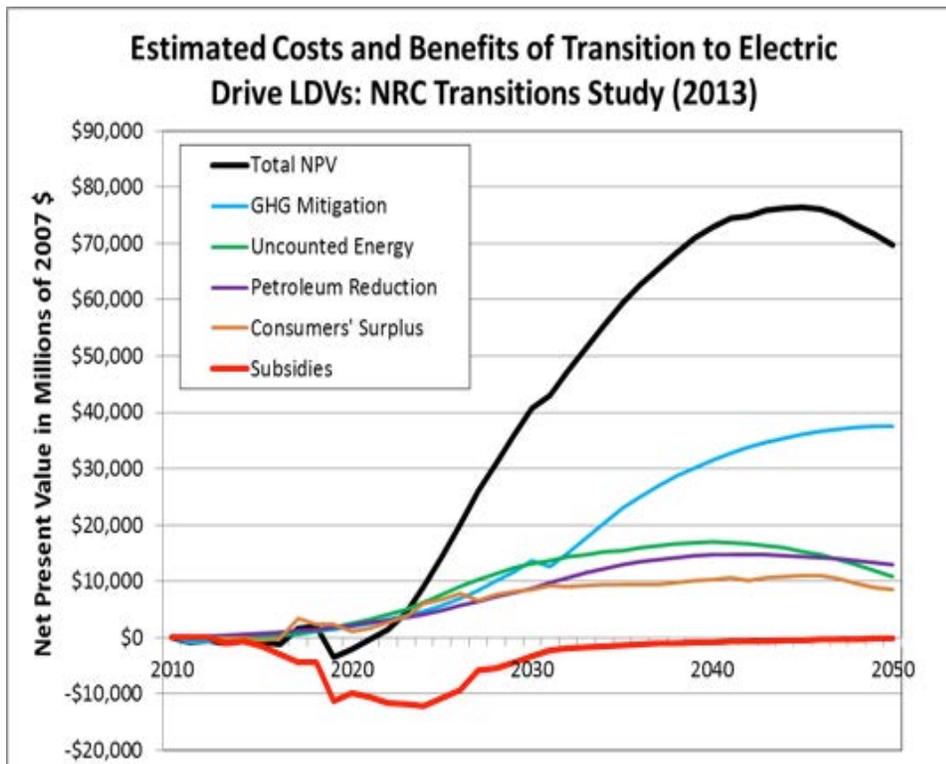


Figure 4. Estimated Costs and Benefits of Transition to Electric Drive Light-Duty Vehicles (NRC, 2013)

Greene et al. (2014a and 2014b) used the NRC model to analyze the role of California's ZEV mandates in the transition to low-GHG vehicles and fuels. The model's estimates implied that delaying the ZEV mandates by five years would reduce the total net benefits of the transition by about one-fourth. Weakening the mandates also appeared to reduce total net benefits. A Monte Carlo simulation including uncertainty in technological progress as well as economic conditions resulted in positive net present value for the transition to low-GHG vehicles and fuels in 90% of the iterations (Figure 5). On the other hand, annual net present values were almost certain to be negative until after 2020 (Greene et al., 2014b, figure 11).

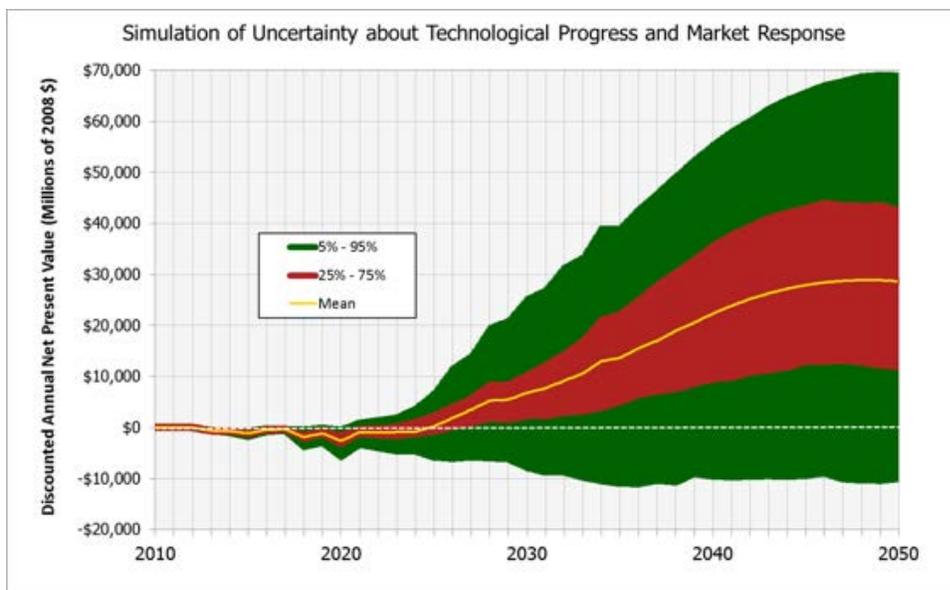


Figure 5. Distribution of Outcomes of Simulation of the Transition to Low-GHG Vehicles and Fuels (Greene et al., 2014b, Figure 11).

3. Reducing the cost of alternative fuel vehicles to consumers

Among the market barriers AFVs face, initial purchase price is the most salient for new car buyers. The importance of providing **financial incentives** to encourage purchases of AFVs is the most consistent finding in the recent literature. Recent studies confirm the finding of McNutt and Rodgers (2003) that consumers base their vehicle purchase decisions primarily on private costs and benefits. Although the motivations of AFV buyers are complex, purchase price and operating costs are consistently found to be among the most important considerations. Two conclusions stand out:

1. Financial incentives given at the time of purchase have roughly doubled the impact of income tax credits or deductions.
2. Incentives must be large enough to secure the car buyer's attention.

Many of the recent studies examine policies to promote hybrid gasoline electric vehicles because hybrids have been in the market for over a decade and consequently there is more experience to analyze. Hybrid electric vehicles (HEV) were launched in the U.S. market in 1999 and 2000, followed a decade later by mass-market introductions of the battery electric (BEV) Nissan Leaf and plug-in hybrid electric (PHEV) Chevrolet Volt in 2011. It can be argued that hybrid vehicles are not alternative fuel vehicles since all the energy to power them comes ultimately from petroleum fuel. Although this is true, it is also true that hybrid vehicles use less petroleum in part because they substitute electricity for petroleum fuel. The electricity is generated on-board the vehicle by transforming kinetic energy that would otherwise be dissipated during braking into electricity. The introduction of an important amount of electric motive power and on-board electricity storage made hybrid vehicles a novel technology. As a result, studies of policies to promote hybrid vehicles can provide insights into how to overcome the cost and consumer

acceptance barriers faced by novel vehicle technologies. Of course, the critical barrier hybrid vehicles do not face is the lack of refueling infrastructure.

The effect of federal subsidies and local supporting policies on consumers' decisions to purchase hybrid vehicles between 1999 and 2006 was investigated by Beresteanu and Li (2011) using market shares data from 22 MSAs. Subsidies were treated as price decreases rather than estimating their effects separately. However, the researchers attempted to estimate the net effect of tax deductions and credits by simulating the benefits to three income groups: less than \$50,000, \$50,000-\$100,000 and greater than \$100,000. The estimated price sensitivities implied that the lowest income group was about twice as sensitive to prices as the middle group, while the \geq \$100,000 group was one third as sensitive to prices as the middle group.⁷ The authors estimated that 20% of the sales of HEVs in 2006 were attributable to the federal income tax credit.

Subsidies available to the consumer at time of purchase appear to have a much greater impact than tax credits or deductions that must be claimed in the future. An analysis of hybrid vehicle sales in the U.S. from 2000 to 2006 concluded that a price reduction at time of sale had an order of magnitude greater impact on sales of hybrid vehicles than a tax credit (Gallagher and Muehlegger, 2011). The econometric model estimated in the study predicts that a \$1,000 state sales tax waiver for hybrid vehicles would increase sales by 45% while a \$1,000 income tax credit would increase sales by only 3% (not statistically significant). The magnitude of the difference may be due to factors not included in the model. The effect of one state's sales tax exemption could be magnified by inducing car buyers in neighboring states without such an exemption to cross state lines to purchase a hybrid vehicle. While the difference in the magnitude of the effects seems implausible, the inference that a financial incentive at time of sale would have a greater impact than a future tax credit is consistent with established behavioral principles (e.g., Khaneman, 2011) and is supported by other empirical analyses (e.g., Diamond, 2009). Based on stated preference surveys in California and Canada, Axsen et al. (2009) found that a subsidy in the form of a tax rebate available 6 months after purchase increased consumers' intentions to purchase hybrid electric vehicles by only 60% to 80% as much as an immediate reduction in purchase price.

The impacts of state incentives for the purchase of BEVs and PHEVs from 2008 to 2014 were analyzed by means of regression analysis (Narassimham and Johnson, 2014; Clinton et al., 2015). Both studies found a statistically significant effect of monetary incentives on BEV sales, ranging from 3-4% for a \$1,000 increase in a tax credit. Clinton et al. (2015) found that monetary incentives did not increase sales of Tesla BEVs, but when Teslas were excluded from the sample, the estimated effect of the \$1,000 increase in tax credit was much larger, boosting sales by 7%. Narassimham and Johnson (2014), however, found no statistically significant effect of state subsidies on PHEV sales.

DeShazo et al. (2014) explored ways of designing financial incentives to improve both cost-effectiveness and distributive equity across income groups. They calibrated a model of vehicle

⁷ Prices and incomes are in 2006 dollars.

choice using stated preference data obtained in a survey of 1,261 California new car buyers and used the model to simulate the impacts of a variety of rebate policies. They found that policies that imposed a cap on the maximum price of a PEV eligible to receive a rebate and policies that provided higher rebates to lower income PEV buyers were uniformly superior to a single rebate offered to all PEV buyers. The finding strongly depends on the greater sensitivity to price of lower income car buyers.

Complex rules and procedures also reduce the value of subsidies to consumers. Cahill et al. (2015) emphasized the negative effect of buyers' uncertainty about their eligibility for federal and California state tax credits. The relative complexity of the federal tax credit created by the Energy Policy Act of 2005 (it phased out gradually after a manufacturer sold 60,000 vehicles in one quarter and varied depending on the degree of hybridization) limited its effectiveness. In addition, the fact that it could only be claimed in the future in the process of paying one's taxes further reduced its salience in consumers' vehicle purchase decision making.

Analyzing monthly hybrid vehicle make and model sales data from 2000-2010, Jenn et al. (2013) found that the incentives created by the Energy Policy Act of 2005 increased hybrid vehicle sales by 3% to 20% (depending on model formulation). They also found that the size of the incentive mattered: only hybrid vehicles receiving an incentive of more than \$1,000 showed any statistically significant impact. This result suggests that salience may be a key factor: policies must be large enough to get car buyers' attention. Unlike the previous studies, Jenn et al. (2013) attempted to correct for the generally increasing trend of hybrid vehicle sales over time due to market diffusion processes by including the previous period's hybrid vehicle sales as an explanatory variable.

A major reason for the effectiveness of subsidies for hybrid vehicles appears to be the fact that consumers received the full benefit of such subsidies, instead of having to share them with manufacturers and dealers. In general, subsidies are divided between consumers and firms as a function of the price elasticities of supply and demand. The less demand responds to price, the greater the share of the subsidy that goes to the consumer. The more supply responds to price, the greater the share to the consumer. A detailed study of individual transaction prices for Toyota Priuses sold between 2002 and 2007 found that essentially all of the benefits of tax subsidies went to consumers (Sallee, 2011). The finding that essentially all of the subsidy went to consumers is surprising because Priuses were generally in short supply during the time period of the study and demand for specific makes and models of vehicles is usually very price-sensitive. The study's author argues that Toyota did not raise the price of the Prius to capture some of the tax benefit in the belief that this would damage the prospects for future sales.

Policy evaluations from outside North America generally reinforce the findings of North American studies. This is despite the fact that fuel prices and vehicle taxes are typically much higher in the EU and Japan, where most studies have been conducted. A cross-sectional analysis of PEV penetration rates in 30 countries in 2012 found that the size of financial incentives provided by the central government and the number of recharging stations per 100,000 residents were the only factors related to PEV market share that were statistically significant at the 0.05 level or better (Sierzchula et al, 2014). Comparing fiscal incentives for electric vehicles

across 11 countries, Mock and Yang (2014) also found a strong relationship between the size of fiscal incentives and both EV and PHEV market shares. However, neither incentives nor infrastructure alone were sufficient to predict a high PEV market share; both were required to be present. Socio-economic factors such as income, education levels, urban population densities or an index of national environmentalism were not statistically significant. The number of PEV models available to purchase was also not statistically significant. Even when controlling for incentives and charging infrastructure, there was substantial unexplained variability across countries, which the authors attribute to the specific forms of policies as well as other country-specific factors. For example, the government of Belgium offered among the highest subsidies but had among the lowest PEV market shares. The authors attributed this, in part, to the high percentage of company cars in Belgium and the fact that Belgium's subsidies were available only to households and not fleet owners and operators. The authors note that the presence of both strong incentives and substantial infrastructure reflects strong national and local interest in and commitment to PEVs, which is likely an important unmeasured factor in their market success.

Exemption from vehicle taxes, free parking and bus lane access were found to have the greatest value to potential purchasers of alternative fuel vehicles in a German stated preference survey. Because respondents don't actually pay to realize their preferences in such surveys, values of non-monetary attributes can be overstated relative to purchase price. Still, the surveys are useful for revealing attitudes and the relative importance of vehicle attributes. Consumers who paid less than 20,000 euros for their vehicles expressed a willingness to pay about 1,250 euros for an increase of 150 km in vehicle range for a non-BEV and almost twice as much for the same increase in range for a BEV. Respondents who paid more than 20,000 euros for their vehicles were willing to pay about twice as much. An increase in fuel availability of 1% was valued at between 45 and 92 euros by the two groups. Unfortunately, the analysis did not estimate different willingness to pay values for different vehicle technologies, nor did the value of fuel availability vary with the current level of fuel availability.

Deloitte (2011) conducted a global survey between November 2010 and May 2011 in 17 countries. The findings from this survey showed that consumers would not be willing to pay a premium for EVs over gasoline cars. The potential consumers' expected sales price of EVs ranged from \$20k to \$30k. In a study of EU incentives, Gass et al. (2014) concluded that both CO₂ and purchase taxes, which increase the costs of ICEs relative to electric vehicles, have to be prohibitive to make electric cars competitive. However, introducing such levels of taxes was not considered politically feasible. In contrast, an up-front price support system (e.g. direct financial support, exemption from registration tax, bonus/malus system) was more favorably received by the public than taxation.

The costs of vehicles to consumers can also be affected by regulation. California requires manufacturers marketing vehicles in the state to sell a quota of Zero Emission Vehicles (ZEV).⁸ There is little doubt that the ZEV mandates induce manufacturers to subsidize ZEVs. Five of the seven leading cities in EV deployment are in states that have adopted California's Zero Emission Vehicle program. Manufacturers offer more makes and models of electric vehicles in these states

⁸ The California ZEV mandates are complex and allow some flexibility in how the standards may be met.

and target them with marketing to increase sales and earn required ZEV credits (Lutsey et al., 2015).

The Corporate Average Fuel Economy and GHG standards offer special credits for alternative fuel vehicles. For the purpose of compliance with the standards, the fuel economy of alternative fuel vehicles is computed counting only the petroleum content of the fuel the vehicle is designed to use. The precise formulas differ for flex-fuel and dual-fuel vehicles, plug-in hybrid electric vehicles and dedicated alternative fuel vehicles.⁹ The GHG regulations currently assign ZEVs a rating of 0 grams/mile. However, upstream emissions will be counted once manufacturers' production of ZEVs exceeds specified levels. Although the Environmental Protection Agency (EPA) and Department of Transportation (DOT) assumed 0% BEVs and FCEVs and 2% PHEVs in 2025 in their joint rulemaking, the National Research Council's assessment of the standards concluded that actual market penetrations would be larger due, in part, to the incentives provided. Past credits for flex-fuel vehicles have been shown to be largely responsible for the production and sale of millions of flex-fuel ethanol vehicles (Rubin et al., 2009).

In summary, monetary incentives that reduce the price of an AFV help overcome the most important barrier to AFV sales. As Jenn et al. (2013) concluded, incentives are most effective when the amount provided is large enough to gain the customer's attention. In addition, incentives available to the vehicle purchaser at the time of sale have approximately twice the impact of tax credits or tax deductions that must be claimed and received at a later date. Incentives available to manufacturers in regulatory standards such as the ZEV mandates or CAFE/GHG standards induce manufacturers to subsidize vehicles to consumers. However, subsidies alone are not as effective as subsidies combined with policies to increase the supply of alternative fuels.

4. Consumer acceptance

Lack of awareness, unfamiliarity and the perceived risk of purchasing a novel technology appear to be the most important non-financial barriers to AFV adoption. Surveys demonstrate that most consumers' knowledge of AFVs is minimal and often inaccurate and that many are waiting to see large numbers of AFVs on the road before they will consider purchasing one. Because of this, policy makers emphasize information and education as a key component of public policy, and maximizing the opportunities for consumers to experience an AFV first hand as a critical element of early market development. For the same reason, early adopters, the minority of consumers who are attracted to novel and advanced technology, play a critical role in the diffusion process because much smaller subsidies are needed to induce them to purchase AFVs. Their experience then helps break down the mainstream consumers' aversion to the risk of novel technology. Several studies have found that individuals concerned about climate change and oil dependence are more likely to be early adopters of AFVs. On the other hand, the same individuals do not want to pay more for an AFV than they would pay for a conventional vehicle. Non-monetary policies that encourage or reward early adopters can also be effective. In this regard, non-financial policies such as HOV-lane access, free parking and free PEV charging, not

⁹ The rules are complex and changing. A concise review can be found in NRC (2015) pp. 350-355.

only have value in their own right, but serve as positive reinforcement for choices that improve the general welfare.

Lack of knowledge and unfamiliarity with AFVs appear to be a major barrier to consumer acceptance. A survey of over 2,000 adult drivers in 21 U.S. cities found that most respondents had a high degree of misperception about PEVs and more than 70% underestimated the fuel cost savings of battery and plug-in hybrid electric vehicles (Krause et al., 2013). A comprehensive survey of new car buyers in Canada found that the overwhelming majority of “mainstream” car buyers did not know how HEVs, PHEVs or BEVs were refueled (Axsen et al., 2015). For example, only 18% knew that the Toyota Prius hybrid used only gasoline as fuel. Most mainstream consumers were unaware that PHEVs even existed.

Krause et al. (2013) also found that consumers were profoundly unaware of state and local incentives for purchasing a PEV. Knowledge of state and local policies ranged from a low of 0.3% who were aware of incentives for home charging equipment to a high of 5.5% who were aware of vehicle purchase incentives (Krause et al., 2013, table 1). On the other hand, four out of five respondents indicated that the existence of such incentives would make them more likely to purchase a PEV.

The majority’s aversion to the risk of novel technologies is a major barrier to AFV sales. Axsen et al. (2009) estimated the combined effects of limited market penetration and limited make and model availability of HEVs in a stated preference survey of Californian and Canadian households. Survey respondents were asked to compare a scenario of only a 0.17% HEV market share (HEVs available as only small cars and small SUVs, and limited experience with HEVs by friends and neighbors) to a scenario in which HEVs had achieved a 50% market share and were available across all makes and models. Axsen et al. (2009) estimated that respondents would be willing to pay \$1,500 more for an HEV in the second scenario in which HEVs were commonplace. The amount is small compared with other estimates of the aversion of the majority of consumers to novel vehicle technology (e.g., NRC, 2013b) and the value of make and model diversity (NRC, 2013b; Axsen et al., 2015) and may be due to respondents’ difficulty envisioning the hypothetical scenarios in a meaningful way. In modeling transitions to low-GHG vehicles, Greene et al. (2014b) found majority risk aversion to be one of the greatest barriers to market acceptance of BEVs and FCEVs.

How consumers’ environmental beliefs and attitudes affect their vehicles purchases was explored in a series of focus groups in Sacramento, California (Flamm and Agrawal, 2001). Participants cited the following reasons for not considering “sustainable” vehicles:

- Too expensive
- Lack desired features
- Unfamiliarity of technology
- Lack of supporting infrastructure
- Scale of environmental problems renders individual action ineffective

Increasing consumers' familiarity with and confidence in novel vehicle technology is important. While most respondents to Krupa et al.'s (2014) survey of U.S. attitudes towards PHEVs said that others' experiences and the opinions of friends and neighbors would have little impact on their likelihood of purchasing a PHEV, the majority said at least 18% of vehicles on the road would need to be PHEVs before they would consider buying one. Krupa et al. (2014) attributed this discrepancy to lack of awareness, unwillingness to admit the importance of social influences and failure to consider the novelty of PHEVs when responding to the first set of questions. Based on a detailed analysis of documented interactions between households participating in a PHEV demonstration project and their social networks, Axsen and Kurani (2011) found that interpersonal influences played an important role in individuals' assessments of PHEVs. The closer the relationship between individuals, the stronger the influence was.

A potentially important finding confirmed in several studies is that individuals most concerned about environmental and energy issues are not willing to pay substantially more for a low-emission, alternative fuel vehicle, yet they are much more likely to be early adopters of those vehicles. Krupa et al. (2014) found that even among individuals selected for their pro-environmental attitudes, only one in ten said they considered environmental impacts when making their most recent vehicle purchase. While this may seem to be a discouraging result with respect to mass market acceptance of sustainable vehicles, the one in ten whose purchases are influenced by environmental concerns may be critically important in the process of early market development.

Concern about environmental and energy issues is strongly related to interest in advanced technology vehicles. Survey respondents expressing concern about climate change were 44 times more likely to be willing to consider purchasing a PHEV and those who considered energy independence important were 71 times more likely (Krupa et al., 2014). Axsen and Kurani (2013) found that early adopters of PEVs were more pro-technology and pro-environment than other consumers. Carley et al. (2013) found that individuals who express the greatest interest in EVs, the "early adopters," are likely to be highly educated, environmentally-sensitive individuals who believe it is important to reduce dependence on foreign oil and who already own a conventional hybrid vehicle. Similar results were found in a survey of Canadian early adopters (Axsen et al., 2015). These findings echo those of a U.S. internet survey of attitudes towards alternative fuel vehicles conducted in 2010 (Nixon and Saphores, 2011). That study found that beliefs about greenhouse gases and concerns about oil imports significantly increased preferences for AFVs, especially with respect to the most novel technologies, hydrogen fuel cell vehicles and battery electric vehicles. It appears that concerns about environmental and energy issues tend to counterbalance aversion to the risk of novel technologies but that this group of early adopters does not believe they should have to pay more for choosing vehicles that help solve those societal problems.

Non-monetary incentives have also been found to promote AFV sales, but their effectiveness has sometimes proven difficult to detect by statistical analyses at the national or state level. The key inference seems to be that non-financial incentives such as HOV access or parking privileges are location specific and dependent on the severity of the problem they alleviate. Jin et al. (2014) analyzed the impacts of the following financial and non-financial incentives offered by states on

the PEV purchases:

- Vehicle purchase subsidy
- License fee reduction
- Annual fee reduction
- Home charger subsidy
- Public charger availability
- HOV lane access
- Free parking
- Exemption from emissions testing

The researchers monetized all benefits and used stepwise regression analysis to test the relationship between benefits and PEV sales. They found that while the monetized benefits to BEV purchasers correlated significantly with state BEV sales, the same was not true for PHEV sales. Their model implied that increasing total monetized benefits by 10% would increase BEV sales by about 2%. Four policy variables were statistically significant: vehicle subsidies, HOV access, exemption from emissions testing, and annual fee reduction. Public charger availability, home charger subsidies, license fee exemption and free parking did not appear to have a strong effect. Recalling that Krause et al. (2013) found that public knowledge of such policies ranged from 0.3% to 5.5%, depending on the policy, it seems that lack of knowledge could easily account for their lack of a statistically significant impact on sales. Beresteanu and Li (2011) represented the presence of state and local supporting policies by a (0,1) variable and included policies as different as HOV lane access, as well as sales, excise and income tax incentives. The presence of local support was estimated to be worth \$200 in equivalent purchase price reduction to the lowest income group, over \$1,000 to the middle income group and about \$10,000 to the highest income group.

In California, a hybrid vehicle with an HOV lane sticker could be sold for between \$1,200 and \$4,000 more than an equivalent vehicle without a sticker (Blanco, 2009; Woodyard, 2007). A 2013 survey of California plug-in vehicle owners found that 57% of plug-in Prius buyers, 34% of Chevy Volt purchasers and 38% of Leaf owners cited the HOV sticker as their primary motivation for purchasing a plug-in vehicle (Tal and Nicholas, 2014). Offering High-Occupancy Vehicle lane access to hybrid vehicle owners, without the necessity of forming a car pool, has been found to increase hybrid vehicle sales, but only in certain states. Gallagher and Muehlegger (2001) found that the offer of HOV access increased hybrid vehicle sales in Virginia but none of the other 5 states that offered it as an incentive. Using data for the same time period (2000-2006), Diamond (2009) found that HOV access increased the sales of the Prius, Honda Civic Hybrid and Ford Escape Hybrid (the three vehicles included in the analysis). However, the effect was strongest when Virginia was the only state offering an HOV incentive. Non-financial incentives other than HOV access did not show a statistically significant relationship to hybrid vehicle sales. Analyzing state data from 2008 to 2014, Narassimham and Johnson (2014) found statistically significant relationships between HOV access and both PHEV and BEV sales. However, in a similar analysis of state level BEV sales, Clinton et al. (2015) did not find a statistically significant effect of HOV lane access.

Kelley (2015) analyzed the implication of HOV lane access for the early adopters of natural gas vehicles in Los Angeles, CA. While HOV lane access was found to be an important incentive for Los Angeles-based commuters to consider a transition to CNG vehicles, Kelley observed that this may not be the case for potential early adopters in other markets that do not have as many people who participate in long distance commutes. Cities similar to Los Angeles can pursue these same types of incentives to encourage adoption of AFVs, but stronger tax incentives for vehicle purchasers, exemption from congestion pricing, and fuel subsidies may be more effective for cities with higher population and employment densities and fewer freeways compared to Los Angeles.

The role of new car dealers in the market for alternative fuel vehicles has received inadequate attention. Cahill, et al. (2015) found that purchasers of plug-in vehicles rated the dealer purchase experience much lower than buyers of conventional vehicles. Tesla dealers were a notable exception. Dealers frequently lacked adequate knowledge of their PEV products and often felt that the financial incentives to sell PEVs did not justify the extra effort required. Sales personnel generally perceived that selling a PEV required more time than selling a conventional vehicle. However, data collected by Cahill et al. (2015) on profits per PEV and customer time spent in the dealership per sale did not support the dealers' perceptions. This suggests that training for sales personnel could improve the sales experience for potential PEV buyers and increase sales volumes.

In summary, consumers' unfamiliarity with and aversion to the risk of novel vehicle technologies are major barriers to alternative fuel vehicle sales. Lack of awareness of incentives to purchase them exacerbates the problem. In addition to efforts to promote public awareness, non-monetary incentives tailored to local circumstances can confer tangible benefits on early adopters and serve as positive reinforcement of socially beneficial behavior. Although those who feel strongly about the environment and energy security are far more likely to be early adopters of AFVs, they do not expect or intend to pay more for them. Concern about energy and the environment appears to "buy down" risk aversion rather than increase willingness to pay for AFVs.

5. Reducing refueling costs: fuel availability

As McNutt and Rodgers (2004) concluded, lack of infrastructure is a critical obstacle to alternative fuels and vehicles. Yet the co-dependence of alternative fuel infrastructure and alternative fuel vehicles is still not well understood. In the U.S., this is called the "chicken or egg" problem; which comes first? In Japan, they refer to it as the "flowers and bees" phenomenon (Tanaka and Furukawa, 2015), which better reflects the synergistic network benefits each generates for the other. Recent experience with plug-in vehicles is producing important insights. Yet we still don't know how best to co-evolve alternative fuel infrastructure (flowers) and the alternative fuel vehicle stock (bees). We lack a clear understanding of how much of what type of infrastructure in which locations at what time will most effectively and efficiently induce a transition. Better analysis and better planning tools are needed.

Gnann and Plötz (2015) reviewed models of the market diffusion of AFVs and their infrastructure. They found a consensus that there has to be a minimum level of infrastructure

for first users to adopt AFVs: availability equivalent to 15 - 20% of that of conventional fuels. This conclusion echoes earlier work by Sperling and Kurani (1987) and Greene (1998), who concluded that fuel availability concerns did not become a relatively minor issue until the number of alternative fuel stations reached 10% - 20% of the number of gasoline stations. A recent study of E85 choice by flex-fuel vehicle owners found that station availability was a serious impediment to E85 until station availability reached about 10% of that of gasoline (Liu and Greene, 2015). A seminal study by Nicholas et al. (2004) estimated the impact on motorists' access time of removing refueling stations from the gasoline refueling network in Sacramento, California. The results proved that the fundamental quantifiable cost of limited fuel availability declined exponentially with the number of (well located) stations (Figure 6).

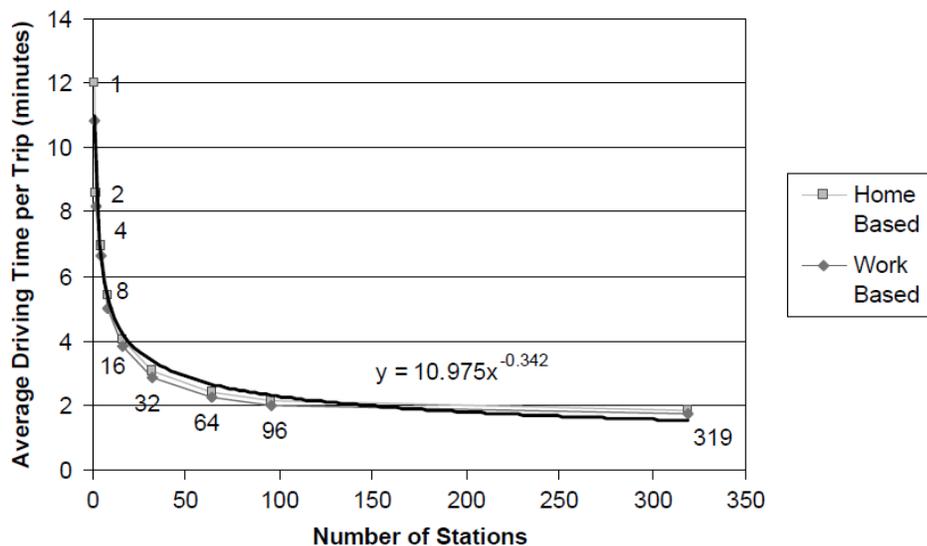


Figure 6. Effect of station availability on time required to access fuel (Nicholas et al., 2004).

The importance of infrastructure to AFV purchase decisions varies greatly by vehicle technology. Recharging infrastructure is less critical to market acceptance of PEVs than it is for FCEVs and other dedicated alternative fuel vehicles with no opportunity for recharging at a home base. BEV owners consider recharging infrastructure important but it is a less important factor in the purchase decision if home charging is available. Public recharging infrastructure is perceived as even less important by PHEV buyers. A Canadian study of interest in purchasing a PEV found a weak but statistically significant relationship between awareness of public recharging opportunities and interest in PEVs (Bailey et al., 2015). Likewise, Axsen et al. (2015) found that awareness of public recharging infrastructure had a weak to non-existent relationship to interest in PEVs among Canadian car buyers. Narassimham and Johnson (2014) found a statistically significant relationship between charging infrastructure availability at the state level and both BEV and PHEV sales. However, Clinton et al. (2015) using similar data found no consistent, statistically significant relationship between infrastructure availability and BEV sales.

Evidence of the importance of charging infrastructure was found in a study of the Norwegian BEV market. Mersky et al. (2016) found that given the strong financial incentives available to all Norwegian car buyers, access to charging infrastructure, nearness to a major city and income

had the greatest impacts on BEV sales. A statistical analysis of plug-in vehicle sales in the U.S. from 2011 to 2013 found that the number of public charging stations had a strong effect on PEV sales (Li et al., 2015). While the magnitude of the effect depended strongly on model formulation and estimation methods, the number of local charging stations was statistically significant in all models estimated. Li et al. (2015) also found a strong statistically significant relationship between the local stock of PEVs and the number of charging stations, illustrating the indirect network effects (positive feedbacks) between infrastructure and alternative fuel vehicle sales.

U.S. data indicate that 75-80% of PEV charging is done at home (INEL, 2014). The ability to charge at home is almost a prerequisite for PEV purchase in the U.S. (e.g., Krupa et al., 2014). Public recharging adds value by extending the range of BEVs and increasing the energy cost savings of PHEVs, but ability to charge at home is far more important. The perception that public recharging infrastructure is less important to potential PHEV than BEV customers may reflect a lack of understanding of the economics of PHEV energy use. Dong and Lin (2012) analyzed the value of public recharging networks to PHEVs with 10, 20 and 40-mile all-electric ranges. They found that public charging networks of any extent saved PHEV-20 vehicles more on fuel costs than PHEV-40 vehicles. Furthermore, PHEVs can often obtain greater economic benefits from extended electric range enabled by public recharging than BEVs can (Dong and Lin, 2012).

For hydrogen fuel cell vehicles, however, public refueling infrastructure is clearly essential. Because most consumers have not experienced an environment in which opportunities to refuel are very scarce or because studies including fuel availability are almost entirely based on stated preferences, the literature has not yet satisfactorily measured the importance of policies to increase fuel availability at low levels of availability. One nationwide survey found equivalent price penalties for hydrogen fuel availability from 10% down to 1% ranged from \$4,250 to \$16,000 per vehicle (Melaina et al., 2013). Clustering stations within an urban area reduces the cost of limited fuel availability substantially for respondents living in the vicinity of the stations (Ogden and Nicholas, 2010). Clustering not only makes access more convenient in the local area but creates options in case any station goes out of service. Lack of fuel availability is a greater concern for risk-averse majority consumers than for early adopters. Research indicates that actual users of AFVs have less difficulty finding refueling stations than they thought prior to AFV purchase. Still, perceived availability prior to purchase remains an important factor for most AFVs.

The greatest obstacle to alternative refueling infrastructure is the lack of an adequate return to capital during the early stages of transition. Absent policy interventions, early investors cannot capture the value to potential vehicle purchasers of increased fuel availability. The levels of availability necessary to satisfy even early adopters are likely to produce years of under-utilization of refueling infrastructure. This can be a show stopper for investors who typically require a 3-5 year payback to justify a capital investment in a refueling station (IPHE, 2010). Costs per unit of fuel dispensed fall rapidly with increasing utilization (e.g., Figure 7) but the time required to build up a large enough fleet of AFVs to reach economical levels of utilization

discourages investment (Eckerle and Garderet, 2012; Brown et al., 2013; Ogden and Nicholas, 2011).

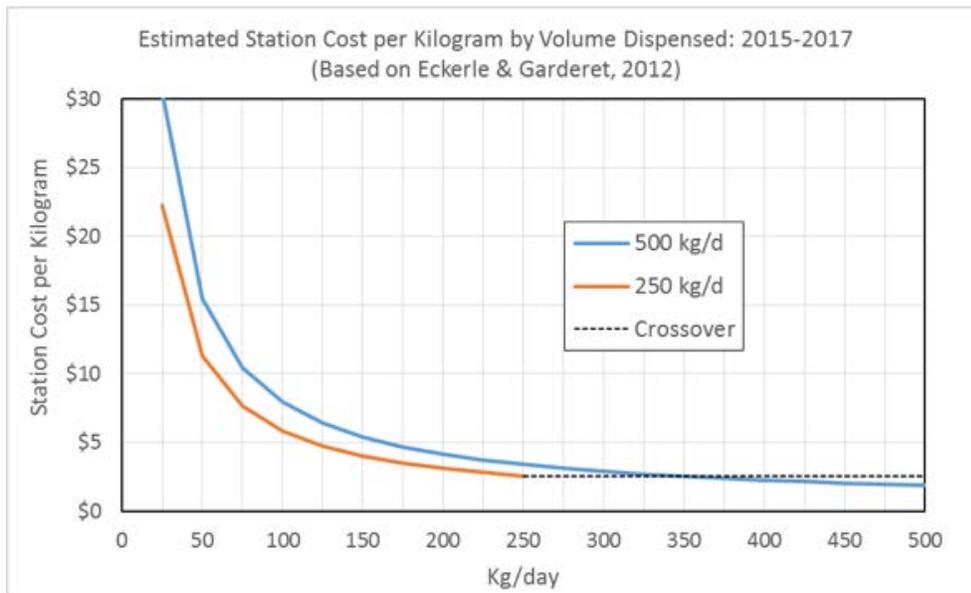


Figure 7. Estimated Hydrogen Refueling Station Cost by Daily Volume Dispensed: 2015-2017.

The combination of low financial returns to an EVSE or hydrogen fueling project due to initially low utilization and great uncertainty about future revenue streams makes alternative fuels infrastructure unattractive to investors (Eckerle and Garderet, 2012; Brown et al., 2013; Botsford, 2012). On the other hand, the NRC Committee on Overcoming Barriers to Deployment of Plug-in Electric Vehicles concluded that utilities able to capture the entire residential electricity consumption of PEV owners appeared to have the only known viable business model for installing public recharging infrastructure (NRC, 2015).

EVSE infrastructure has been deployed widely instead of intensively targeting limited geographical areas. The result, at least initially, has been very low average utilization rates (Green et al., 2014; Russo, 2015). In some locations, however, demand for chargers has occasionally exceeded supply, creating conflicts that highlight the need for commonly accepted usage protocols (Richtel, 2015). The value to a potential BEV owner of the existing recharging networks in 25 U.S. cities was estimated by Lutsey et al. (2015) using a method based on daily travel distributions and an assumed cost per day that an EV's range would be insufficient to satisfy a day's travel distance. Expanding the recharging infrastructure effectively increased daily EV range thereby increasing the number of travel days an EV could accommodate. The networks in Portland, San Francisco and Seattle were estimated to add \$1,000 to \$2,000 to the value of an EV for a typical car buyer. The remaining cities' recharging infrastructure added less than \$1,000 in the value of extended use down to about \$100 per EV. Optimally locating charging stations can increase their value to EV owners and increase electrified vehicle use too. Shahraki et al. (2015) analyzed the vehicle itineraries of 11,280 taxis equipped with GPS monitoring devices in Beijing, China where there are currently 40 existing public charging stations. If all the stations were DC fast chargers, the study found that optimally locating the

stations could increase electrified VMT by 88%.

Thirty-one thousand public and private PEV charging stations comprise the vast majority of the 40,000 alternative fuel stations in the U.S. (Figure 8) (AFDC, 2016). Funded equally by the ARRA and private sources, the EV Project deployed more than 12,000 Level 2 chargers for residential and public use and over 100 DC fast-chargers. Considering only venues that averaged more than three charging events per week and were publicly available, the median number of charging events for Level 2 sites during the period from September 1, 2012 to December 31, 2013, ranged from four to seven events per week (INL, 2014). This is despite the fact that a number of sites had multiple chargers. In addition, the distribution of site-average charging frequencies was skewed: most sites had even less usage. The most highly utilized DC fast chargers were located in Seattle and San Francisco, not surprisingly among the top five metropolitan areas in sales of the Nissan Leaf (INL, 2015). The most highly utilized sites were located along major commuter routes within the metropolitan areas and many were located near high-tech employers.

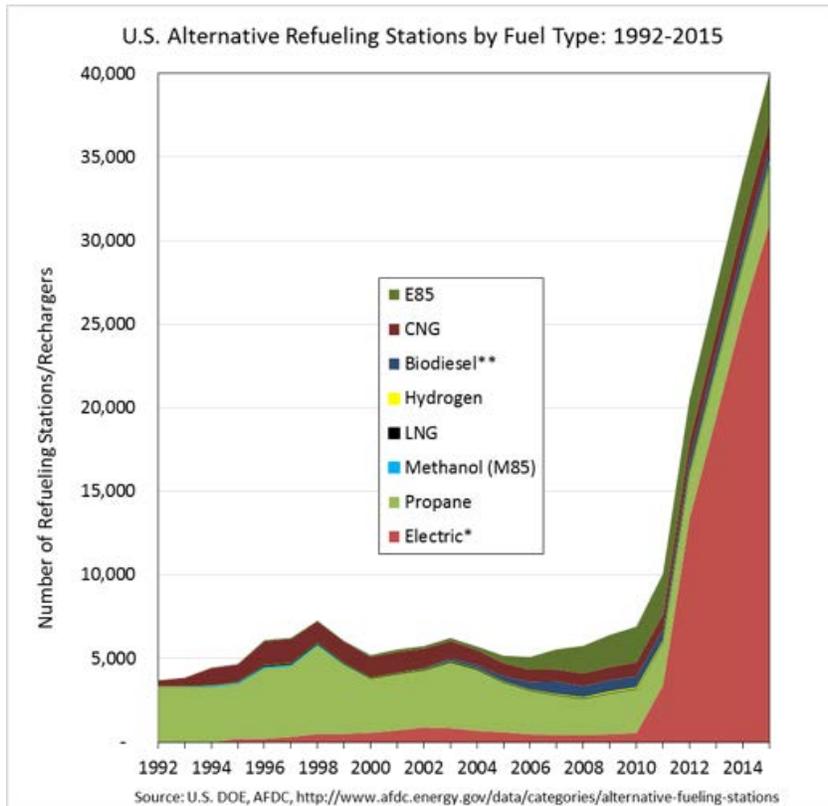


Figure 8. U.S. Alternative Refueling Stations by Fuel Type: 1992-2015 (AFDC, 2016).

The pervasive underutilization of rechargers across the U.S. apparently led the NRC Committee on EV Barriers to recommend that the federal government refrain from further direct investment in public charging infrastructure until the relationship between its provision and PEV adoption and use could be better understood (NRC, 2015). The simulation studies cited above indicate that even an optimal deployment of refueling infrastructure for alternative fuel vehicles is likely to be underutilized for many years. How much infrastructure is needed to optimally stimulate

AFV sales and how much underutilization is appropriate during the early transition is not well understood. Nevertheless, underutilization, per se, is not evidence of suboptimal provision of alternative fuels infrastructure.

Although publicly accessible hydrogen refueling infrastructure has only just begun to be available, its reliability could be a major issue for early hydrogen refueling stations. The first U.S. station certified to sell hydrogen by the kilogram to the public at Cal State LA's Hydrogen Research and Fueling Facility experienced a series of reliability issues (Edelstein, 2015). While this is not surprising for the very first public station, it does highlight the need to ensure reliability in the availability of alternative fuels, especially when station counts are low and alternative refueling sites may be far away. In response, the California Air Resources Board and Energy Commission have implemented a program to methodically test each station before allowing it to open to the public, using a mobile testing station developed by the U.S. Department of Energy specifically for that purpose (Johnson, 2015).

Studies have concluded that diffusion of PEVs could be accelerated by targeting subsidies and other policies toward geographic areas where early adopters are most concentrated and social benefits are greatest (Skerlos and Winebrake, 2010; Green et al., 2014). Geographically targeted policies could avoid or de-emphasize regions where pollutant emission from electricity generation are most damaging at present (Yuksel and Michalek, in review; Reid and Spence, 2016). Locations of PEV charging stations in California, Oregon and Washington relative to demographic groups most likely to purchase PEVs were analyzed by Reid and Spence, (2016). They found that, "...the public PEV charging stations do not appear to be located according to likely-PEV consumer demographics." Targeting infrastructure and incentives may raise equity concerns, however, an issue that has so far not received attention from researchers.

Federal and State policies provide substantial support for alternative fuels infrastructure. Unfortunately, little attention has been given by researchers to analyzing the effectiveness of these policies. As mentioned in the introduction, the ARRA provided \$400 million for vehicle electrification and increased the alternative fuels infrastructure tax credit to 50% or \$50,000 per installation, whichever was smaller. The RFS II requirements to sell renewable fuels and California's Low-Carbon Fuels Standard (LCFS) also generate incentives for suppliers to ensure that the necessary infrastructure is deployed. Other policies, such as the Federal Transportation Law (MAP-21), provide funding for state and metropolitan planning organizations to support EVSE and hydrogen infrastructure under the Congestion Mitigation and Air Quality Improvement (CMAQ) program. The Department of Energy's Clean Cities Program provides financial and technical assistance, as well as a peer support network for those seeking to adopt alternative fuel vehicles and deploy supporting infrastructure (Clean Cities, 2016). California's Zero Emission Vehicle (ZEV) program and ARFVTP include policies to ensure the expansion of infrastructure to support plug-in and hydrogen fuel cell vehicles.

The State of California has committed more than \$2 billion to be spent between 2014 and 2023 to incentivize purchases of clean and low-carbon vehicles and construction of the refueling infrastructure necessary to support the introduction of zero emission vehicles (Campbell, 2013). The California Energy Commission's Alternative and Renewable Fuel and Vehicle Technology

Program (ARFVTP) provides financial incentives for businesses, vehicle and technology manufacturers, workforce training partners, fleet owners, consumers and academic institutions to develop and deploy alternative and renewable fuels and advanced transportation technologies (CEC, 2016). The ARFVTP distributes up to \$100 million each year in grants supporting purchases of vehicles and implementation of infrastructure. A comprehensive evaluation of the ARFVTP program is currently being carried out for the CEC by Rand but unfortunately no reports had been published at the time of writing this report.

Regulatory mandates have played a key role in the deployment of alternative fuel infrastructure. Motor vehicle manufacturers subject to ZEV mandates have allied with energy companies and electricity producers, refueling station and charging equipment manufacturers, station operators and charging network providers as key stakeholders in alternative fuels infrastructure. Vehicle manufacturers are motivated by a long-term desire to ensure a sustainable vehicle market but more immediately by regulations requiring reductions in GHG emissions or sales of zero emission vehicles. By requiring manufacturers to sell ZEVs, California's ZEV program creates an incentive for the manufacturers to help ensure the availability of supporting recharging/refueling infrastructure. For example, Toyota reportedly provided in excess of \$7 million in financial backing to FirstElement Fuel in support of the startup company's successful bids to secure \$27.6 million from the state of California to construct and operate hydrogen refueling stations (Ohnsman, 2014). Charging network providers are often supported in part by vehicle manufacturers or electricity producers. Recently, BMW and Nissan announced a plan to provide public DC fast-charging at 120 locations in 19 states, continuing the companies' past efforts to expand recharging infrastructure. Similar alliances of automobile manufacturers or electricity producers, or both, to support charging networks are responsible for most of the public charging network development in Northern Europe (Ninh et al., 2014). Similarly, Tesla and Nissan have invested in substantial networks of DC fast-charging stations (NRC, 2015).

Innovative financial approaches have been proposed as a means of overcoming barriers to investment in alternative fuels infrastructure (Dougherty and Nigro, 2013). Among the possibilities are leasing rather than purchasing infrastructure, thereby shifting much of the risk from the lessee to the lessor who may have a greater tolerance for risk, easier access to capital or a greater interest in the success of the fuel. Another option is performance contracting, whereby infrastructure may be sold to a fleet operator with a guarantee of cost savings sufficient to finance the cost of the project. Green banks, which use public funds to leverage private financing of infrastructure are still another option for sharing risk. In principle, these strategies which shift the burden of risk to agents more willing to accept it or provide indirect subsidies to investors should help to increase the deployment of alternative fuels infrastructure. Rigorous evaluations of their effectiveness in alternative fuels markets are lacking, however.

In order to better understand the issue of deploying recharging/refueling infrastructures for AFVs, the Organization for Economic Co-operation and Development's International Futures Program (IFP) organized a workshop in November 2012 with the theme "Developing Infrastructure for Alternative Transport Fuels and Power-trains to 2020/2030/2050: A cross country assessment of early stages of implementation" (Stevens and Scheib, 2013). The workshop identified several strategies to governments and industry to reduce the risks inherent in

AFV infrastructure development. For example, to reduce the risk of investing in infrastructure, the French Environmental and Energy Agency ADEME created the “Ville de demain” (city of tomorrow) project that covers 50% of the costs for normal and fast charging points for BEVs and 30% of costs for rapid charge points, provided the chargers are made available to the public. In Norway, government co-funding of the charging infrastructure network provides up to 45% of the cost of a faster charger. As of 2012, the UK had provided a 30 million pound matching funding for recharging infrastructure to local consortia consisting of business and other public partners. Transferring the economic risk of AFV infrastructure deployment to a third party is another strategy used within certain segments of the supply chain. In Norway, private companies, especially those in the energy industry, are assuming responsibility for the ownership and operation of some of the fast charging infrastructure. The government maintains a role by requiring a viable long-term business proposal from these companies as a condition for government approval of a contribution to the funding. Retaining the economic risk of AFV infrastructure development would appear to be a strategy for industrial players. General Electric is installing its own recharging stations to supply the many thousand electric vehicles it plans to purchase. Car rental companies (such as Hertz in London) are setting up their own networks of charging stations to supply their growing fleets of EVs. And European utilities are beginning to integrate downstream operations in infrastructure installation and management (Stevens and Schieb 2013).

The European Commission drafted a directive on the deployment of alternative fuels infrastructure which was adopted on October 22, 2014 (TML, 2015). It requires Member States to adopt national policy frameworks for the market development of alternative fuels and their infrastructure and to submit these plans by November 2016. It sets binding targets for the build-up of alternative fuel infrastructure, including common technical specifications. It also defines how fuels must be labeled at refueling stations. An assessment of these plans is underway but no reports were available at the time of writing.

In summary, although lack of refueling infrastructure hinders sales of PEVs and is essential to FCEV sales, there has been little analysis of the effectiveness of policies promoting AFV infrastructure. An efficient transition to alternative fuels almost certainly requires over-provision of infrastructure relative to demand during the early stages of transition. While excess infrastructure is necessary to accelerate sales of AFVs, it also makes investments in alternative fuels infrastructure uneconomical for private investors. As the NRC’s (2013) seminal analysis indicates, the social return on investment in the transition to alternative fuels and vehicles is likely to be negative for at least a decade, even though the long-run benefits may exceed excess costs by an order of magnitude. Existing studies have demonstrated that alternative fuels infrastructure must be subsidized during the early stages of transition to low-GHG vehicles and energy sources. Unfortunately, our current understanding and ability to model transition processes is not adequate to estimate the efficient level of overinvestment during the early stages of transition. This is undoubtedly the greatest gap in the existing literature.

6. Reducing refueling costs: the price of fuel

To date, public policy in the U.S. has paid little attention to the retail pricing of alternative fuels despite the fact that numerous studies of vehicle and fuel choice have demonstrated the importance of fuel price to both. Price was the most important factor in the market success of natural gas as a light-duty vehicle fuel in Argentina (Collantes and Melaina, 2011). The Argentine government provided funding for the first three CNG refueling stations but afterwards adopted a policy of creating a favorable environment for private investment by implementing necessary codes, standards and regulations, but chiefly by regulating the price of CNG to be only 30% to 40% of the price of gasoline. The success of Brazil's PROALCOHOL program illustrates the importance of both sustained policy commitment to alternative fuels and of managing fuel prices during the transition. In the U.S. it took more than a decade of government subsidies to ethanol producers and vehicle purchasers, a commitment to ethanol on the part of vehicle manufacturers (a key factor was the development of the flex-fuel vehicle which replaced dedicated ethanol vehicles), and the substitution of ethanol for premium gasoline pumps nationwide (Goldemberg, 2006). Ethanol prices were initially over \$100/barrel of oil equivalent in 1980 but gradually declined to levels competitive with relatively low-cost gasoline by the year 2000. Among the policies used to manage the transition were low interest loans to ethanol producers, guaranteed purchases by the state oil company and price controls on gasoline and ethanol (Lovins, et al., 2005). While electricity is almost always and everywhere cheaper than gasoline, especially on a per vehicle mile basis, managing the price of hydrogen during the early stages of transition could be essential.

Economic factors such as fuel costs weigh more heavily in most consumers' purchase decisions than environmental attitudes, although in the early period of market development such factors as interest in novel technology, aversion to the risk of unproven technologies, diversity of product choices and availability of infrastructure are also critically important (Collantes and Eggert, 2014). A survey of U.S. consumers' intentions to purchase PHEVs (Krupa et al., 2014) found that the three factors most frequently mentioned as increasing consumers' comfort levels with PHEVs were large fuel cost savings (86%), at-home recharging (83%) and a large tax rebate (82%). The cost of electricity has not posed a serious problem for EV sales because the cost of electricity per vehicle mile has been lower than the cost of gasoline per mile for consumers. On the other hand, providers of public charging services have had to compete with home charging, which has made it difficult for them to price electricity so as to recover the full cost of providing and maintaining recharging infrastructure. But this has not been the case for the earliest hydrogen vehicles. Hyundai, the first manufacturer to offer a hydrogen fuel cell vehicle to the public, bundled vehicle leases with free hydrogen to avoid the possibility that car buyers would react negatively to potentially high or volatile hydrogen prices (Edelstein, 2015).

Given the fuel economy advantage of hybrid vehicles, it is no surprise that studies consistently find that higher gasoline prices increase hybrid vehicle sales. Studies differ, however, in their estimation of the strength of the impact. If one assumes that \$1 in sales tax reduction at time of sale is equal to \$1 present value, then Gallagher and Muehlegger's (2011) estimates imply that consumers value \$1/year in fuel cost savings at \$3.88 present value, equivalent to requiring a less than 4-year simple payback period. This is almost exactly half of the present value of fuel

savings discounted at 10% per year over the 15-year life of a typical vehicle. Analyzing the sales of three leading hybrid vehicles over the same time period (2000-2006), Diamond (2009) found that a 10% increase in the price of gasoline would increase hybrid vehicle sales by 72% to 93%. This result seems implausibly large, however, and is based solely on difference among states and not over time. It seems likely that gasoline prices are aliasing other state-specific factors omitted from the model. Diamond's (2009) estimate of the effect of gasoline prices over time, pooling the state data, is only 1/3 as large. Even this estimate may be inflated, however, since gasoline prices were generally increasing over the time period as were hybrid vehicle sales. Again, gasoline prices may be aliasing time-dependent factors omitted from the model, especially consumers' familiarity with hybrid vehicles. Deloitte's (2011) global survey of consumer attitudes toward EVs found that if the price of a gallon of gas in the U.S. rose to \$5, the percentage of respondents who indicate they would be interested in EVs would rise dramatically. Egbue and Long (2012) calculated that at \$5.42/gallon of gasoline EVs would be economically competitive with conventional vehicles if \$7,500 tax credits were still available.

In general, consumers do not appear to be willing to pay the full, lifetime discounted present value for fuel savings. While 86% of U.S. consumers stated that potential fuel cost savings would be important to their likelihood of purchasing a PHEV, they also implied that their willingness to pay for fuel savings was far less than their full discounted present value (Krupa et al., 2014). The 28% of respondents who said they would definitely consider purchasing a compact PHEV like the Chevy Volt were only willing to pay \$1,858 upfront for a promised \$500 per year in fuel savings (a 3.7-year payback). The majority, who were not interested in a compact PHEV, stated they would pay only \$800 in additional upfront cost (a 1.6-year payback).

In summary, not only the availability but the price of an alternative fuel is critical to its success. Although consumers tend to undervalue the future fuel savings that can be obtained with an AFV, the same does not appear to apply to excess fuel costs. Policies to maintain the cost-competitiveness of alternative fuels during the transition period have received little attention in the literature. This is unfortunate given the importance of fuel costs to customer satisfaction and the volatility and unpredictability of the prices of petroleum fuels (Figure 9). If the world's economies simultaneously convert from fossil petroleum to low-carbon energy, the price of petroleum is certain to decrease. Managing the cost-competitiveness of low carbon energy poses a major challenge for the sustainable energy transition.

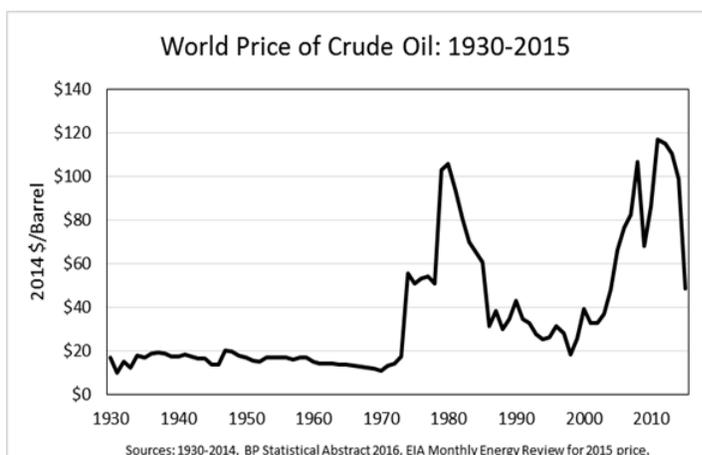


Figure 9. World Price of Crude Oil: 1930-2015

7. Institutional infrastructure

Adapting institutions, ordinances, codes and standards to the different attributes of alternative fuel vehicles and refueling infrastructure can speed their deployment and thereby reduce their costs. When it comes to infrastructure, policy makers at local levels emphasize the importance of regulation and standardization, issues that are taken for granted with conventional fuels but that are critically important during the early stages of transition to facilitate timely deployment of alternative fuels infrastructure. Local communities rarely offer subsidies or rebates for purchase of PEVs or deployment of infrastructure, however, several communities reported that waiving or reducing EVSE permitting fees and streamlining permitting procedures or offering real estate or sales tax incentives for EVSE infrastructure were effective low-cost incentives for promoting PEVs (Langford and Cherry, 2013).

Communities have an important role to play in planning the evolution of EVSE infrastructure and coordinating deployment across regions. The Department of Energy Clean Cities' (2015) EV Readiness project awarded 16 communities grants to help plan and prepare for EVs and supporting infrastructure (Langford and Cherry, 2013). Key areas requiring planning coordination cited in a US DOE study were:

- Insuring interoperability of equipment and software across regions
- Requiring EV compatibility in building codes
- Siting analysis balancing workplace and other public charging opportunities
- Creating charging opportunities for multi-unit dwellings
- Insuring compliance with requirements of the Americans with Disabilities Act.

A consistent theme of the projects was the need for coordination of planning and regulation across national, regional, state and local agencies. Recommendations to promote coordination included:

- Developing a consistent state planning toolkit for local governments and agencies
- Creating local coordinating councils
- Holding one-day workshops with local leaders
- Creating a panel of experts at the state level to assist localities
- Implementing a comprehensive program of education and outreach for the public and governments.

An expert workshop of local policy makers evaluated policy options to support adoption of electric vehicles in European cities (Bakker and Trip, 2013). Policies ranked highly by municipal decision makers focused on infrastructure and awareness: 1) standardization of recharging infrastructure and requirements for EV readiness, 2) political leadership, information for businesses and consumers, and facilitation of personal experiences with EVs, 3) special privileges for EV users (free parking, bus and taxi lane access, toll and congestion fee exemptions). Municipal policy-makers also stressed the importance of coordination among cities to facilitate intercity travel and to ensure compatibility.

8. A system of policies to transform an energy system

The barriers to alternative fuels are substantial and complex. They include strong positive feedback effects, market and institutional inadequacies, network externalities between vehicle and fuel markets and substantial uncertainty about technological and market conditions decades into the future:

- Lack of scale economies in the vehicle and fuel supply chains
- The need for further technological progress and learning by doing
- Consumers' lack of familiarity with and aversion to the risk of novel products
- Lack of diversity of choice in vehicle markets (e.g., make, model, vehicle class)
- Lack of refueling infrastructure
- Lack of a market for alternative fuel
- Inappropriate Administrative and regulatory infrastructure (codes, standards, ordinances, etc.)
- Uncertain rates of technological change and future energy prices.

The supply and use of energy by motor vehicles comprises a socio-technical system, a network of interacting agents, institutions, infrastructure and technologies (e.g., Markard et al., 2012). Fundamentally transforming such systems requires complex and extensive changes involving all agents and components of the system. Given this, it is not surprising that U.S. and international studies indicate that governments achieving the greatest success deploying AFVs have pursued several different policies targeted at individual barriers, simultaneously. Different barriers call for different solutions. Policies must also address each of the key stakeholders in the transition process:

- Vehicle purchasers and operators, individuals, private and government fleets,
- Vehicle manufacturers and dealers,
- Fuel producers and distributors and retailers,
- Governments at all levels from municipal to federal.

Although it would be possible to overcome market resistance with a very large subsidy, it is undoubtedly more efficient to use a range of policies targeted to each of the major barriers. To a great extent, this is because the different costs of transition tend to be very high to begin with but decline rapidly (at a decreasing rate) as progress toward transition is made. The costs of lack of fuel availability decline rapidly towards 10% - 20% of current gasoline availability, then very slowly thereafter (Figure 6). Similarly, infrastructure costs per unit of energy delivered to a vehicle decrease with the inverse of capacity utilization (Figure 7). Scale economies and learning by doing also decline exponentially with production volume and cumulative production and apparently the lack of diversity of make and model choices, and majority risk aversion, do as well. For all these reasons, policies aimed at achieving rapid initial cost reductions in each barrier would seem to be superior to attempting to overcome all barriers with a single general policy, such as a tax on carbon or a vehicle subsidy or mandate.

Analyses of multi-dimensional policy strategies are rare but seem to support the assertion that multiple policies have the greatest impacts. The factors contributing to PEV sales in seven

leading markets were analyzed by Vergis et al. (2014). In terms of PEV market share, Norway (14%), Netherlands and California (both about 4%), were far ahead of Japan, France, the U.S. and Germany (all less than 1%). All seven markets were supported by a wide range of policies, including financial and non-financial incentives, government support for research, development and demonstration, public information, support for charging infrastructure and support from local and regional governments. The three leading markets generally offered the largest incentives and the most comprehensive policy support.

The market shares of electric vehicles in 21 U.S. cities are plotted against the number of policy actions taken to promote those vehicles in Figure 10 (Lutsey et al., 2015). The size of each bubble indicates the intensity of deployment of charging infrastructure. Five of the seven leading cities in EV deployment are in states that have adopted California’s Zero Emission Vehicle mandate. Although there is an obvious correlation between market success and both the number of policies implemented and the number of chargers, there is also a great deal of variability. Moreover, the mix of policies selected by each city also varies. The market’s receptivity, the mix of policies implemented and the intensity of policy execution matter as much as the number of policies implemented. No single action, whether subsidy, mandate, infrastructure investment or promotional activity, seems to explain the successes of the leading cities.

“California cities’ electric vehicle consumers are benefiting from state vehicle and fuel policy, long-term commitment to consumer incentives, and implementation of city-level promotion actions, and their electric vehicle uptake is consistently higher than the U.S. average. Seattle has a mix of incentives, utility action, and charging infrastructure and has 3 times the U.S. average electric vehicle deployment. Atlanta’s electric vehicle market has benefited from subsidies and carpool lane access; its battery electric vehicle sales were more than 8 times the U.S. average. Portland, with the most extensive electric charging network and extensive planning and outreach, is seeing 3 times the average U.S. battery electric vehicle sales, without subsidies.” (Lutsey, et al., 2015, p. vi)

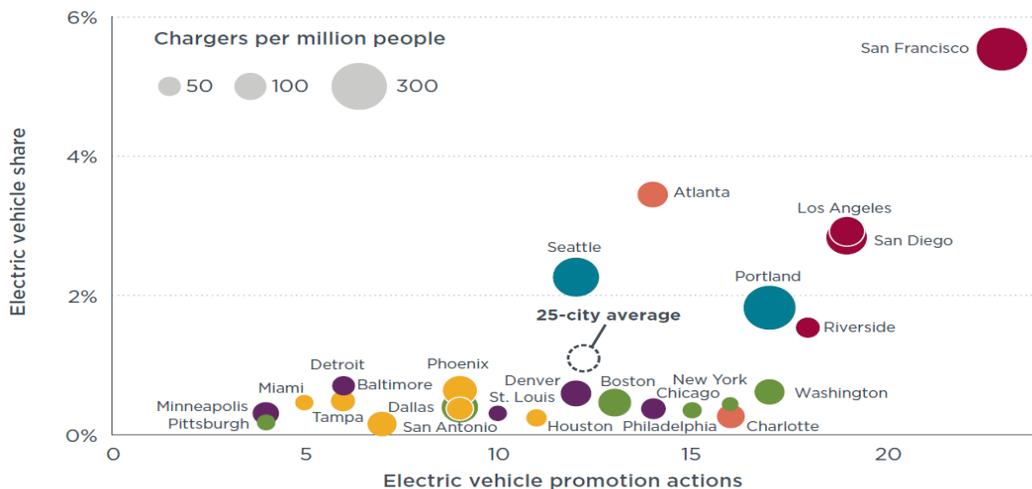


Figure 10. Electric vehicle market share, promotion actions and charging infrastructure in 25 U.S. metropolitan areas. (Lutsey et al., 2015, Figure ES-1)

That multiple factors are important in the market success of BEVs and PHEVs was also confirmed by Vergis and Chen (2015) in an analysis of state market shares of plug-in vehicles in 2013. The price of gasoline and the extent of charging infrastructure were found to most strongly correlate with state BEV market shares. Almost as important and nearly equal in importance were consumer awareness (internet searches for BEVs), educational attainment, temperatures (warmer favors BEVs), population density and the price of electricity, the only factor negatively correlated with state BEV market shares. PHEV market shares were most strongly correlated with the number of PHEV makes and models available and the number of supporting policies and incentives. Other statistically significant correlates were the existence of purchase incentives and the strength of environmentalism in the state.

The National Research Council's Committee on Alternative Vehicles and Fuels' (NRC, 2013) attempted to model the transition process, including all of the transition barriers described above. The study produced many useful insights despite the fact that, as the Committee acknowledged, many of the transition processes and parameters are poorly understood. It concluded that a transition beginning in 2015, backed by strong and sustained policy support, could accomplish a self-sustaining transition by 2050, provided that technological advances made battery electric and hydrogen fuel cell vehicles cheaper than comparable internal combustion engine vehicles by about 2040. However, the analysis found that the costs of the transition would likely exceed the benefits for at least a decade or two. That is, the net social benefits of the transition, including social as well as private costs and benefits, would be negative for 10 to 20 years. Despite this, the study's cost/benefit analysis estimated that by 2050 the present value of benefits would exceed the excess transition costs by an order of magnitude. As the NRC Committee noted, all these results are dependent on the study's many assumptions about technological progress and economic conditions and should be interpreted with caution. The transition to low-GHG energy will be a complex, multi-decadal process whose outcome is uncertain but whose benefits are likely to greatly exceed its cost.

If the problem of accomplishing a transition to alternative fuel vehicles were solely a matter of the external cost of GHG emissions, levying a tax on GHG emissions by all fuels equal to the marginal damage cost of the emissions would be an effective and efficient solution. Moreover, "leveling the playing field" with a uniform tax and letting the market choose the winner is not only equitable but avoids giving political decision making a central role (e.g., DeCicco, 2015). The simplicity and elegance of this solution is so great that one is tempted to overlook the complexities of energy transitions catalogued above. The problem with this prescription is that it fails to address the very high but transitory market barriers to alternative fuels, as well as the complexity of the barriers to a large-scale transition in the energy system and the strong positive feedback effects generated during the transition process. Consequently, it virtually assures that the winner will be the incumbent technology.

Over fifty years ago, the Nobel Prize-winning economist Ronald Coase (1960) pointed out that the general measure of the merit of a policy, including those that address environmental externalities, is cost/benefit analysis: How much better or worse is the world with the policy than without it? Cost/benefit analysis is especially appropriate when there are negative and positive externalities, other kinds of market failures, further complicated by large uncertainties and strong

positive feedback effects creating the possibility of tipping points. The NRC Committee on Transitions to Alternative Vehicles and Fuels (2013) used cost/benefit analysis for evaluating alternative technologies and policies for reducing GHG emissions from light-duty vehicles by 80% by 2050. Their analysis found that even a relatively high tax on carbon would not be sufficient to induce a transition but that a suite of strong but temporary policies could, and that the expected benefits of the transition would likely exceed the costs by an order of magnitude.

9. Concluding observations

The existing literature on policies to promote a transition to low carbon fuels does not yet provide enough information to objectively rank policies and policy strategies by their efficiency and effectiveness. Nonetheless, the past decade and a half of research reinforces all of McNutt and Rodgers' (2004) conclusions and offers several new insights derived from recent experience with hybrid, plug-in and fuel cell vehicles.

The importance of providing substantial and sustained financial incentives to **reduce the costs of AFVs** to consumers is the most consistent finding in the literature. AFVs face a variety of market barriers and initial purchase price is perhaps the most salient for new car buyers. Although the motivations of AFV buyers are complex, purchase price and operating costs are generally the most important considerations. Studies indicate that financial incentives given at the time of purchase have two to ten times the impact of income tax credits or deductions and that subsidies should be large relative to the incremental cost of an alternative fuel vehicle to ensure salience in consumers' vehicle choice decisions. Financial incentives should be designed to be readily understandable by consumers and their availability should be well publicized. Government subsidies are not the only means of inducing AFV sales. Although the strategy is unique in the world, California's ZEV mandates have played a critical role in early market transformation by inducing manufacturers not only to research, design and offer ZEVs, but also to subsidize their sale and the deployment of supporting recharging and refueling infrastructure.

Lack of awareness, unfamiliarity and the perceived risk of purchasing a novel technology appear to be the most important non-financial barriers to AFV adoption. Surveys demonstrate that most consumers' knowledge of AFVs is minimal and often inaccurate and that many are waiting to see large numbers of AFVs on the road before they will consider purchasing one. Because of this, successful AFV policies generally include information and education as key components. Maximizing the opportunities for consumers to experience an AFV first hand can also accelerate early market development. By the same token, early adopters, the minority of consumers who are attracted to novel and advanced technology, play a critical role in the diffusion process. Surveys indicate that individuals concerned about climate change and energy security are far more likely to be early adopters than others, yet don't expect to pay more for vehicles that help achieve the same societal goals. Subsidies are still needed. Even so, non-financial policies such as HOV-lane access, free parking, and free PEV charging, when local circumstances are favorable, have value in their own right but serve as positive reinforcement for early adopters.

Most findings about the importance of **recharging and refueling infrastructure** to AFV sales come chiefly from stated preference surveys and model simulations, rather than market experience. Statistical analyses of PEV sales are not unanimous but generally indicate that charging infrastructure promotes PEV sales. In general, it appears that public recharging infrastructure is beneficial to adoption of BEVs but not absolutely critical, and is somewhat less important to potential PHEV than BEV customers. This may reflect a lack of understanding of the economics of PHEVs which can often obtain greater economic benefits from extended electric range than BEVs. For hydrogen fuel cell vehicles, however, refueling infrastructure is clearly essential. Because most consumers have not experienced an environment in which opportunities to refuel are very scarce or because studies including fuel availability are almost entirely based on stated preferences, the literature has not yet satisfactorily measured the importance of policies to increase fuel availability at low levels of availability. A small number of stations may be adequate to initiate sales to the most innovative consumers, especially if the stations are geographically clustered. However, achieving mass market success will almost certainly require that alternative fuel availability exceed 20% of that of gasoline today, or greater. It is critically important to better understand the role of infrastructure in promoting AFV sales, so that appropriate policies can be implemented to induce an efficient coevolution of vehicles and fuels. Underutilization of infrastructure in the early transition appears to be inevitable. Yet it is also almost certainly necessary to encourage the growth of the stock of AFVs. How much infrastructure, of what kind, where and when continues to be a conundrum.

Reducing the price of alternative fuels is also critically important. Consumers expect alternative fuels to be competitive with the price of gasoline. The two examples of successful alternative fuel transitions cited above, ethanol in Brazil and CNG in Argentina, both included policies to ensure a competitive price advantage for the alternative fuels. Ensuring competitive pricing is challenging because the early stages of transition appear to require excess investment in refueling infrastructure and therefore low utilization rates for AFV refueling stations. By far the most important barrier to the deployment of alternative fuels infrastructure is the difficulty of achieving profitability during the early stages of transition when demand is very limited but motorists' expect 10% to 20% of the availability of conventional fuels. Direct public subsidies, investment tax credits and public/private partnerships (driven by regulatory mandates) have all been tried with some degree of success. Comparative analyses of the effectiveness of these policies are generally lacking.

Policy makers at local levels emphasize the importance of developing appropriate codes and standards for alternative fuels and increasing public awareness (e.g., through public information but also standardized signage), issues that are taken for granted with conventional fuels but that are critically important during the early stages of transition. The importance of consistent and efficient permitting processes, codes and standards at the local, state and regional levels is an important part of transforming the fuel system. While the evidence for the importance of an efficient administrative infrastructure comes mainly from expert focus groups and workshops, the testimony seems compelling.

Because of the complexity and variety of market barriers to a transition to alternative fuels, comprehensive policy strategies are more likely to be effective and economically efficient.

The barriers to transition are complex and involve not only environmental externalities and other market imperfections, but network external benefits and strong positive feedbacks that can induce tipping points. Initially, transition costs such as lack of fuel availability, lack of knowledge and risk aversion by the majority of consumers, scale economies and learning by doing are very high but decrease rapidly with annual sales volumes and cumulative production. These characteristics of system transformation argue for the superiority of comprehensive policy strategies that address all barriers simultaneously. Cross-national and regional analyses tend to support this conclusion as well.

Finally, because the transition to low-GHG energy for motor vehicles will take several decades and the success of any one alternative is uncertain, public policy must be persistent and flexible. Documenting the cycles of exaggerated promotion (“hype”) and abandonment that accompanied the failure of past efforts to promote alternative fuels Melton et al. (2016), indict past public policies for two kinds of failures:

1. Directionality failure: the lack of consistent vision, policy and funding
2. Reflexivity failure: the inability to deal with uncertainty.

The authors identify two additional, important attributes that policies to promote energy transition should possess:

3. They should be able to enjoy sustained public (political) support.
4. They should adapt as technologies and markets change.

Accomplishing a large-scale energy transition for the public good is a new challenge for public policy. As more experience is gained from the ongoing market transformation process, future research will provide additional insights that will enable policy makers to refine and improve policies to promote the transition to sustainable energy for motor vehicles.

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