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CARBON CAPTURE IN VEHICLES: A REVIEW OF GENERAL SUPPORT, AVAILABLE MECHANISMS, AND CONSUMER-ACCEPTANCE ISSUES

JOHN M. SULLIVAN
MICHAEL SIVAK

UMTRI
UNIVERSITY OF MICHIGAN
TRANSPORTATION RESEARCH INSTITUTE

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John M. Sullivan
Michael Sivak

The University of Michigan
Transportation Research Institute
Ann Arbor, Michigan 48109-2150
U.S.A.

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16. Abstract

This survey of the feasibility of introducing carbon capture and storage (CCS) into light vehicles started by reviewing the level of international support for CCS in general. While there have been encouraging signs that CCS is gaining acceptance as a means to reduce carbon emissions, the overall outlook looks somewhat mixed. Recent developments in the US, the UK, Germany, India, and China are discussed to obtain an indication of how likely it is that CCS technologies will gain acceptance in each respective country.

Fossil fuels continue to be a versatile means of energy storage, especially compared with many low-emissions alternatives. This is noted because, apart from reduced fuel consumption, CCS technology is key to reducing CO_2 emissions produced by the use of fossil fuels in transportation.

Primary focus in this review was placed on post-combustion-capture technologies because these mechanisms are most easily adapted for use with the existing fleet of internal combustion engines. Three post-combustion-capture mechanisms were described: absorption, membrane separation, and adsorption.

Considerations about the consumer's operational costs were discussed, including storage management of captured CO_2, additional energy costs to support separation and storage, discharge procedures, and vehicle maintenance costs. Models of consumer inclination to adopt new technologies were also reviewed. An important component of a consumer's motivation to adopt eco-friendly transport is perceived financial benefit. This suggests that incentives beyond reduced emissions may be required to motivate consumer adoption of vehicle-based CCS because the link between emissions and fuel consumption may change.

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Carbon capture, alternative fuels, consumer motivation, on board carbon capture

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Introduction

In 2009, transportation in the United States was responsible for emitting approximately 1,719.7 million metric tons of carbon dioxide into the atmosphere from fossil-fuel combustion (United States Environmental Protection Agency, 2011b); in the United States, the transportation sector is responsible for about 27% of all the greenhouse gas emitted in the U.S. (United States Environmental Protection Agency, 2011b). Not surprisingly, in the U.S., the transportation sector is responsible for proportionally more emissions than the worldwide estimate of about 23% (International Energy Agency, 2011), although many developing nations such as China and India are quickly catching up.

Combustion of one gallon of gasoline produces 8.9 kg of CO_2 (United States Environmental Protection Agency, 2011a). Over a year, the typical passenger vehicle (assuming 21 miles per gallon, and 12,000 annual miles) generates 5.1 metric tons of CO_2. Clearly, any effort to reduce such emissions will help address the growing accumulation of greenhouse gases in the atmosphere.

Several strategies have been used to attack the problem of transportation emissions, either by reducing or avoid the burning of fossil fuel. These include the design of more fuel-efficient internal-combustion engines (ICE), use of alternative fuels (e.g., biofuels, hydrogen, natural gas), and the development of alternative propulsion systems based on electrical power, including hybrid-electric vehicles (HEV), plug-in hybrids (PHEV), electric vehicles (EV), and hydrogen-based fuel-cell vehicles (FCV). This report examines the broad feasibility of an alternate emissions-reduction strategy, in which carbon capture and storage (CCS) methods are introduced into ICE passenger vehicles. The main focus of the report is to highlight issues that are likely to be relevant to consumers of passenger vehicles, without directly addressing issues of technical feasibility. This includes a review of the current worldwide acceptance of carbon storage methods, an exploration of the consumer's perspective with regard to the likely operational demands (e.g., maintenance, fueling), and of issues likely to drive consumer preference for this technology.

General Overview of Carbon Capture and Storage

There is general acknowledgment that fossil fuels will continue to serve as a low-cost energy resource for the foreseeable future and that, if the target global concentration of greenhouse gases set forth by the United Nations Intergovernmental Panel on Climate Change (IPCC) are to be met, some form of CCS will be required (Global CCS Institute, 2011). At this point in its development, an important step is to demonstrate the feasibility of the entire CCS processing chain, beginning with capture at the combustion site, followed by compression, transportation, and injection into a permanent storage site. To address this need, several world governments have launched CCS projects in a variety of locales. The relative success of these projects may provide an early indication of how quickly development is likely to produce a mature and workable solution, leading to the development of an infrastructure to support distributed carbon capture.

If it is initially supposed that carbon dioxide capture is feasible in light vehicles, there remains the issue of where the collected carbon dioxide will eventually be stored. Currently, carbon capture and storage methods are in a relatively early stage of proving feasibility through a series of demonstration projects. Unless these projects persuasively demonstrate that carbon dioxide can be stored safely and with long-term stability, development of the necessary infrastructure to transport carbon dioxide cheaply and efficiently to its final resting place may languish. Besides the need to demonstrate technical feasibility, commercial investment in CCS also requires legal and regulatory policies to establish clear guidelines governing aspects of the transport and storage of CO_2—for example, regulations would be needed to establish legal responsibilities related to transport (e.g., through CO_2 pipelines), injection sites, and geological monitoring. In the absence of such regulation, commercial investment would be at risk.

Level of support

Because CCS technology is thought by some to be a relaxing of the resolve to develop renewable energy resources, in some environmental advocacy circles it is not well supported. For example, Greenpeace has actively campaigned against CCS, labeling underground storage of carbon dioxide “unproven” (Greenpeace, 2007), and a "dangerous gamble" (Greenpeace, 2008). Similarly, projects involving CCS technology were not initially authorized under the Kyoto Protocol's Clean Development Mechanism (CDM). Under CDM, developed countries could be credited with Certified Emission Reductions (CERs) by investing in projects hosted by developing countries that contributed to sustainable development. CERs could then be applied toward the investing (developed) country's carbon-emissions targets. Although the CDM did not directly support CCS, another of the Kyoto Protocol's flexible mechanisms called Joint Implementation (JI) provided an alternate project-based mechanism to support CCS. Much of the support for CCS has come from private industry, interested in the use of CO_2 for enhanced oil recovery (EOR), in which CO_2 is injected into crude oil reservoirs to increase the amount of crude oil extracted, or by government funding sources wishing to address GHG emissions as well as energy dependence on foreign governments.

Some of the current worldwide CCS projects are shown in Figure 1 (Carbon Capture & Sequestration Technologies @ MIT, 2012). The majority of CCS projects are located in developed countries and in areas where there are clear storage opportunities (shown in Figure 2). Thus it seems that current carbon capture and storage technology development may be determined both by the government's will to fund development and storage availability.

Figure 1. Worldwide CCS projects. Active and pilot CCS projects are shown in yellow and blue, respectively; active storage only projects are shown in green (Carbon Capture & Sequestration Technologies @ MIT, 2012). (Map data copyright 2012 MapLink, Tele Atlas.)

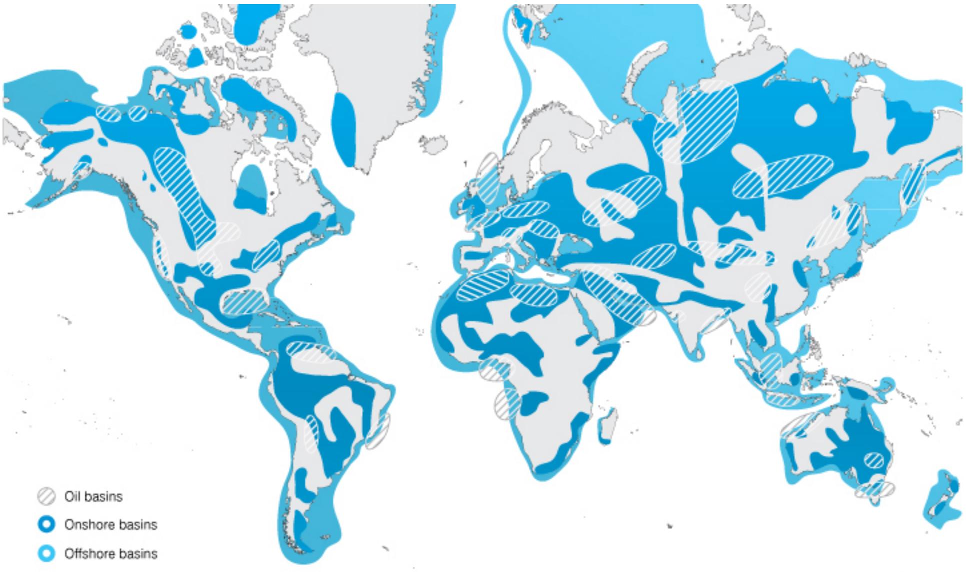

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Figure 2. Map of the world sedimentary basins with potential for carbon storage. (Figure copyright, CO2CRC.)

United Kingdom

In October 2011, a £1 billion CCS power-station project located in Longannet, Scotland was cancelled over a dispute over financing. Developers believed that the project was underfunded and would require £1.5 billion from the British government to maintain commercial viability (Gershman & Harvey, 2011). Despite this setback, the British government has resolved to support use of CCS in coal-fired power plants and appears to be prepared to relaunch its funding for CCS projects along with the U.S. partner, Summit Power. This new project, located west of Edinburgh, Scotland, appears to be another large-scale project, similar to the Longannet project, capturing carbon emissions on more than 90% of production in a commercially scaled operation. The captured CO_2 will be transported by pipeline and sequestered in a nearby offshore geologic area under the North Sea. Thus, although CCS development in the UK appears to have suffered a temporary setback, the British government appears willing to continue pursuit of CCS technologies.

Germany

On December 5, 2011 the Swedish company Vattenfall dropped plans to construct a €1.5 billion CCS pilot project in Jaenschwalde, Germany, due to the rise in public opposition to the project (Reuters, 2011). After initial approval of draft CCS legislation by the German lower house of parliament, the legislation was rejected by the upper house. Failure to resolve the concerns through mediation resulted in the withdrawal of Vattenfall. A company statement suggested that without a clear legal framework in place, the draft CCS law would be "insufficient for multi-billion investments in further development of the technology." One consequence of this development is that carbon capture technology appears unlikely to be pursued much further in Germany in the near term.

United States

In the United States, large-scale CCS projects are supported by a combination of government funding and revenue generated by the use of CO_2 in enhanced oil recovery (EOR) operations—five out of six large scale CCS power plant projects (greater than 60

MW) in the US are partially supported with revenues from EOR and substantial government support (Carbon Capture & Sequestration Technologies @ MIT, 2012). Out of 10 projects proposed over the last 10 years, four CCS projects have been cancelled. In two cases, the cancellation was a consequence of investors' reluctance to make substantial financial commitments before federal climate-change policies were clearly established. In another case, the state government rejected funding after substantial lobbying from environmental groups; in another, the cancellation occurred as a consequence of project cost and schedule challenges in the midst of the economic downturn.

Even active projects have had difficulties securing and sustaining funding and political support. In 2003, FutureGen began as a promising public-private partnership committed to producing the world's first emissions-free coal-fueled power plant. Substantial cost overruns eventually resulted in the U.S. Department of Energy withdrawing support in 2008, although a revised plan was developed in 2010, and the project was relaunched as FutureGen 2.0.

Because the large-scale power-generation projects are complex and require substantial and secure governmental funding and legislative support, these projects are difficult to support. There seems to be better support for smaller-scale research and development of carbon-sequestration technologies. For example, the National Energy Technology Laboratory (NETL) has received $70M in funding to investigate geologic-sequestration site characteristics, and to support university research and development of carbon sequestration. NETL manages the Regional Carbon Sequestration Partnership (RCSP), a partnership network investigating CCS approaches best suited to their respective regions of the country.

India

Currently, India lacks policies or legislation to directly promote development of CCS capability (Baker & McKenzie, Electric Power Research Institute, Schlumberger, & WorleyParsons, 2009; Kapila, Chalmers, Haszeldine, & Leach, 2011), nor is it seen as a immediate priority by the Indian government or industry stakeholders (Kapila et al., 2011). Without established GHG emissions targets, India may have little incentive to pursue CCS technologies. Moreover, the historic exclusion of CCS support under the Clean Development Mechanism of the Kyoto Protocol has discouraged external investment. In 2008, India developed the National Action Plan on Climate Change in recognition of the need to address the threat of climate change, as well as the need to sustain economic growth. The plan is largely focused on encouraging energy conservation by promoting, for example, more efficient urban planning, use of energy-efficient appliances, mandating limits on large energy-using industries, and enforcement of automotive fuel-economy standards (Balachandra, Ravindranath, & Ravindranath, 2010). In the most recent draft of the plan (Prime Minister's Council on Climate Change, 2012), in comments related to CCS, it is noted that "feasible technologies for this have not been developed and there are serious questions about the cost as well as the permanence of the CO_2 storage repositories." Thus, it appears that, like Germany, India remains skeptical about the long-term viability of carbon sequestration.

China

Large-scale CCS projects are currently in an early stage, although knowledge is building from a variety of pilot projects (Best & Beck, 2011). China's reliance on coal and other fossil fuels for energy production will require some form of CCS (Morse, Rai, & He, 2010), especially if China agrees to limit emissions in the future. Binding emissions targets are expected to be established in China by 2020 (Stanway, 2011). To that end, China recently ordered seven provinces and cities to establish GHG emissions caps and plans to establish an internal carbon market (Stanway, 2012).

Counter to this broad trend is the difficulty posed by the Chinese government's control over internal electrical prices. In 2008, these controls made it difficult to absorb fluctuating prices in the coal markets (Morse et al., 2010); this, in turn, suggests that the government may not be prepared to invest in CCS without some form of external support. And, since CO_2 capture reduces power-generation efficiency (in large power plants) by 20 to 30%, there may be a further disincentive to invest in CCS technologies.

Recent developments

Developments at the United Nations Framework Convention on Climate Change (UNFCCC) in Durban (2012a) have recently allowed CCS projects under the Clean Development Mechanism (CDM). The agreement includes provisions for selection of storage sites, addressing remediation of CO_2 seepage, measures to address nonpermanence, and long-term liability. While this move was heralded as a means to unlock the application of CDM benefits to drive CCS development, the European Union (EU) has resolved to purchase CERs exclusively from CDM projects located in Least Developed Countries (LDC) (Nell & Guilder, 2012). One consequence of this policy would be for the EU, as the largest buyer of CERs in the international market, to exclude China, India, Ghana, Qatar, the United Arab Emirates, and South Africa from CDM. These are the countries that are most likely to increase their use of fossil fuels to feed their increasing need for power (Nell & Guilder, 2011).

Conclusion

While there have been encouraging signs that CCS is gaining acceptance as a means to reduce carbon emissions, the overall outlook looks somewhat mixed. Attempts to establish large-scale integrated CCS projects have faltered because of cost overruns and government withdrawal of support. In the UK, this was especially apparent in the cancellation of the Longannet project. In Germany, heightened environmental concerns and lack of adequate legislative protection may have redirected focus toward alternatives to fossil-fuel use. In the United States, while there seems to be minor environmental concern about the injection of CO_2 into geologic formations for enhanced oil recovery, the cost of collection and sequestration may have weakened political resolve to address issues of climate change. Unless the U.S. enters the emissions trading market, the financial incentives to push development may be missing. India appears to be focused on energy conservation and appears unwilling to consider CCS as anything more than a potentially risky technology. China appears willing to consider CCS, but it remains to be seen how much loss in power generation efficiency it may be willing to absorb.

This review of global CCS was intended to establish a picture of what the future geographic distribution of CO_2 sequestration may look like, especially in countries where motor-vehicle use is high or rapidly expanding. If collection of CO_2 emissions from vehicles is to become commonplace, long-term storage outlets for CO_2 will be needed. At present, it seems that CCS technologies are still at too early a stage of development to make any clear forecasts.

Carbon-Collection Processes in Vehicles

Power generation is responsible for about 39% of CO_2 emissions in the United States (United States Environmental Protection Agency, 2011b). Thus, it is no surprise that carbon capture and sequestration technologies have largely focused on the power-generation industry where carbon dioxide is produced in large quantities at a single stationary site. A recent report explores the application of carbon capture to small distributed power sources where carbon dioxide might be captured directly from the exhaust stream of, for example, an automobile (Damm & Fedorov, 2008b). If such a system is indeed feasible, there are several questions regarding consumer acceptance that might arise. How will consumers view the choice between continued reliance on fossil-fuel combustion and the growing number of alternative power sources that are considered both cleaner with respect to emissions, and sustainable with respect to renewability? How will perceived need for travel range, flexibility, and operating convenience weigh against the demand for lower carbon emissions? How much CO_2 emissions reduction would offset a perceived contribution to global warming? Would tangible accumulation of carbon dioxide heighten general awareness of the hidden costs of combustion? How would the added task of offloading collected carbon dioxide affect the consumer's perception of convenience?

Why is fossil fuel combustion an attractive option?

Combustion of gasoline fuel in transportation has many advantages over alternative sources of energy for the average consumer. Gasoline has relatively high energy density (about 32 to 35 MJ/L) compared with ethanol (~21 to 24 MJ/L), compressed natural gas (CNG, 9 MJ/L compressed at 250 bar), propane (25 MJ/L compressed at 12 bar), electricity, or hydrogen (5.6 MJ/L compressed at 700 bar) (Greene, Baker, & Plotkin, 2011; Greene & Schafer, 2003; Oak Ridge National Laboratory, 2012). An average gasoline-powered vehicle can be driven more than 300 miles after a single fueling. By comparison, the travel range of the current generation of consumer electric vehicles is less than 100 miles between recharges. Range for electric vehicles is also reduced in cold operating conditions, and recharging may take between 4 and 8 hours, compared with the few minutes it takes to refuel a gasoline vehicle. From the consumer's perspective, electric vehicles require "refueling" more frequently than gasoline-powered vehicles, and the time spent recharging the vehicle effectively renders the vehicle unavailable.

Other low-emissions fuels that are maintained in a gaseous state, like compressed natural gas (CNG) or hydrogen, are more difficult to transport than gasoline. Some are gaseous at ambient temperatures and must be compressed and liquefied (e.g., hydrogen, LPG, CNG), requiring a more complex delivery infrastructure than gasoline. Use of fuels held in pressurized tanks may also be perceived as a danger should the vehicle become involved in a collision.

Finally, the cost of alternatively powered vehicles remains much higher than gasoline-powered vehicles. For example, the suggested retail price of a 2012 Chevrolet Volt is about $40K, while the 2012 Chevrolet Cruze, a comparable gasoline-powered vehicle, starts at $16,800; the average price difference between a hybrid vehicle and a gasoline-powered sibling vehicle ranges between $4,000 and $8,000—the difference between a 2012 Toyota Camry and Camry Hybrid is about $4000, the difference between a 2012 Ford Fusion and Fusion Hybrid is about $8000.

Comparison of energy sources

Gasoline and Diesel. Gasoline combustion is relatively inexpensive and versatile compared with other energy sources used in transportation. By volume, the energy density of gasoline is relatively high—about 32 to 35 megajoules per liter (MJ/L)—providing significant portability for a large amount of energy (Edwards, Larivé, & Beziat, 2011). Gasoline is a liquid, allowing precise control of the combustion process (unlike, for example, solid fuels like coal). Gasoline can be ignited at very low ambient temperatures (-45 deg F), but has a high spontaneous-ignition temperature, making it suitable for use in vehicles subject to wide variation in operating temperature.

Gasoline combustion generates about 73 grams CO_2 emissions per megajoule (g CO_2e/MJ), excluding emissions during production. By comparison, combustion of propane gas produces 65 g CO_2e/MJ; compressed natural gas (CNG), 56g CO_2e/MJ; and ethanol 71g CO_2e/MJ. Combustion of hydrogen produces no carbon emissions.

Gasoline, like all fossil fuels, is a nonrenewable resource—oil depletion estimates vary widely, but many suggest peak production will be reached in the very near term (Kjärstad & Johnsson, 2009; Miller, 2011; Sorrell, Speirs, Bentley, Brandt, & Miller, 2010). Finally, the efficiency of gasoline engines is relatively low. Estimates suggest that conventional gasoline engines use only about 14 to 26% of the fuel-energy content to propel the vehicle or power accessories (United States Department of Energy, 2012b). Engine efficiency plays a significant role in determining the ultimate emissions profile of a vehicle. For example, although combustion of diesel fuel produces similar carbon emissions to gasoline (i.e., 72.6 gCO_2e/MJ), diesel engine efficiency is higher (about 20-30%). The resulting carbon dioxide emissions produced by a diesel engine per mile of travel is typically lower than that produced by a gasoline engine, although diesel engine emissions of particulate matter (black carbon) may be even more damaging to the atmosphere (Quaas, 2011). In vehicles powered by electric motors, efficiency is about 75%.

Compressed Natural Gas (CNG—methane). Compressed natural gas has been a popular alternative to gasoline, particularly in fleet operations. CNG produces lower carbon emissions than gasoline (56.24 g CO_2e/MJ), as well as lower-sulfur oxides, nitrogen oxides, and particulate matter. Like gasoline, CNG has a low flashpoint (-300 deg F) and a relatively high autoignition temperature (842 deg F), making it a suitable fuel across a wide range of temperatures. The cost of CNG is about half that of gasoline.

Disadvantages include the relatively low energy density of CNG, about 9 MJ/L. This means that in order to carry a comparable amount of energy as provided by gasoline, more of the vehicle's storage space is required for fuel, reducing the available space for other cargo. Although natural gas is widely used in household cooking and heating, in vehicle applications, it is compressed and held in high-pressure storage tanks (3500 psi); refueling requires special refueling connections to manage refueling under high pressure. This limits a consumer's refueling options. In half of the states in the US, there are fewer than 10 public refueling stations per state (United States Department of Energy, 2012a).

Natural gas (i.e., methane) is also a more damaging GHG contributor to global warming than carbon dioxide. Any leakage in a CNG system would produce more damaging environmental effects than CO_2 emissions—the UNFCCC estimates methane to have 21 times the global warming potential of CO_2 over a 100-year time horizon (United Nations Framework Convention on Climate Change, 2012b).

Other Gases: LPG is composed principally of propane and butane, and is popularly used where a natural-gas infrastructure or pipeline is unavailable. The energy density of LPG is 25 MJ/L: much higher than CNG, but significantly lower than gasoline. CO_2 emissions from LPG combustion are 65 g CO_2e/MJ, which is higher than CNG, but lower than gasoline.

Direct combustion of hydrogen gas has been used in limited applications since the earliest internal-combustion-engine designs. Hydrogen is also used to power fuel cells, in which hydrogen gas is used to generate electrical power through an electrochemical process. In both cases, the byproduct of the fuel consumption is water. While the low-emissions characteristic of hydrogen is attractive, use of hydrogen for combustion may be impractical. The low efficiency of internal-combustion engines compared with electric engines (14% versus 75%), coupled with the small volumetric energy density of hydrogen—at 700 bar, the energy density of hydrogen is 5.6 MJ/L—suggests that an internal-combustion engine powered exclusively by hydrogen may have an unacceptably limited range.

A key reason for hydrogen's popularity is that the supply of hydrogen is perceived as limitless, and its combustion byproduct, water, is harmless. The processes used to obtain hydrogen, however, can involve undesirable secondary costs. For example, hydrogen is commonly produced from natural gas by a process called steam reforming. An undesirable byproduct of this process is CO_2, as well as the emissions produced to generate the steam used in the reforming process.

In a "well-to-wheels" (or life-cycle) analysis by the U. S. Department of Energy (United States Department of Energy, 2005), fuel-cell electric vehicles were estimated to produce 45% and 24% less CO_2 emissions per mile than conventional ICE vehicles and hybrid-electric vehicles, respectively. This analysis factored in all emissions generated during production of the fuels. Such an analysis is reasonable, provided that fuel-production processes are somewhat standard, although for some fuels, there may be significant differences in emissions generated during the production process. Accounting for emissions in this way may also be too subtle from a consumer's perspective. For example, electric vehicles (EVs) are widely considered environmentally friendly without regard to the actual manner in which the stored electrical power was generated (Anair & Mahmassani, 2012).

Another disadvantage of hydrogen fuel is that fuel-cell technology is more sensitive to temperature extremes than gasoline-powered internal-combustion engines. For example, the operating temperature of a Polymer Electrolyte Membrane (PEM) fuel cell ranges between 50-100 deg C. Because fuel cells produce water as a byproduct of an electrochemical process, freezing temperatures pose some difficulties for fuel cells. In early designs, fuel-cell vehicles were limited to operating in above-freezing temperatures because, in subfreezing temperatures, formation of ice on the PEM would damage the membrane, and ultimately shorten the lifetime of the fuel cell.

Biofuels. Unlike most fuels, biofuels directly invite consideration about the fuel's origin—i.e., carbon from the atmosphere. To the consumer, many parts of this process are largely unseen. Current concerns about vehicle emissions, highlighted by motor-vehicle-emissions tests, are focused on the toxic byproducts of combustion—unburned fuel, nitrogen oxides and carbon monoxide—at the end-use of the fuel. A consumer might therefore judge the entire emissions impact of his or her vehicle based on end-use of the fuel. Although consumer awareness might be increased if efforts are made to publicize how the electrical power used to recharge the vehicle is generated, consumers are ordinarily unaware of the details of power generation. Similarly, consumers are also likely to be poorly acquainted with the generation of other alternative fuels.

Biofuels is one exception. The perceived virtue of biofuels is that they only burn carbon that was removed from the atmosphere; biofuels are *carbon neutral*. Combustion of this fuel simply returns it back into the atmosphere, resulting in no net increase in carbon dioxide. Thus, to see the emissions benefit in biofuels, one must consider more than what happens at combustion. It requires the knowledge that the fuel's carbon content was removed from the atmosphere by biological processes that transformed carbon dioxide in the atmosphere into the biomass from which the fuel is derived.

Recently, the carbon neutrality of biofuels has been challenged and defended in a variety of life-cycle analyses (e.g., DeCicco, 2012; Johnson, 2009; Searchinger et al., 2009). Whether biofuels are indeed carbon neutral seems to depend on numerous factors, including changes in land use, depletion of forest stocks, the energy consumed during fuel production, and whether any portion of the biomass is converted to *biochar* (i.e., the charcoal byproduct of pyrolysis of plant material) and returned to the soil (Mathews, 2008). In any case, it is unlikely that consumer opinion will be driven by the complexities of such life-cycle analyses. Most likely, biofuels will be attractive because of their similarity to fossil fuels in how they are distributed and consumed in vehicles, the size and variety of vehicle selection supporting biofuels, beliefs about the use biofuels and energy independence, and the understanding that biofuels represent a renewable energy resource.

Biofuels include all fuels derived from the biological action of carbon fixation. There are two broad classes of fuels—bioalcohols, produced by fermentation; and biodiesel, made from vegetable oil. The most common bioalcohol fuel is ethanol. The energy density of ethanol is lower than gasoline (~21 to 24 MJ/L). Thus, a vehicle cannot travel as far on one tank of ethanol as it can on one tank of gasoline. To moderate this disadvantage, ethanol is often mixed with gasoline in varying proportions, designated by a numeric suffix (for example, E5 is 5% ethanol, E10 is 10% ethanol, and so on for E15, E25, E85 and E100). The level of carbon emissions from ethanol combustion is comparable to gasoline—71.6 g CO_2e/MJ. However, as was pointed out above, carbon emitted during combustion was previously removed from the atmosphere during carbon fixation.

Biodiesel fuels have an energy density comparable to fossil fuel diesel—33 MJ/L. Like ethanol, biodiesel fuels are blended with conventional diesel fuels to produce various B grades of biodiesel. For example B2 is 2% biodiesel, B5 is 5% biodiesel, and so on for B20, and B100. Use of blends greater than B5 in diesel engines would generally violate a manufacturer's warranty, unless the vehicle explicitly supports them.

Biodiesel CO_2 emissions during combustion are actually higher than for fossil diesel—about 75 g/MJ for biodiesel generated by rapeseed oil, compared with 72.6 for fossil diesel.

Estimates of biofuel production in the United States suggest that it may take about 50 M acres to produce roughly half of the current US consumption of gasoline, and the production of ethanol, for example, consumes almost as much fossil-fuel energy as it replaces (Chu, 2008). Biofuels also pose the ethical dilemma of the tradeoff of food for fuel, although second generation biofuels produced from the lignocellulose in nonfood plant material—e.g., wood pulp, switchgrass, and agricultural waste—could mitigate this issue, provided the land used to cultivate this source does not directly compete with food cultivation. Finally, regardless of the crop, biomass yields may not be sufficient to meet projected levels of transportation consumption (Walker, 2009).

From the consumer's viewpoint, the similarity of biofuels to fossil fuels with respect to distribution network, operational factors, and energy density (depending on mixture and fuel type), makes the choice to switch to fuels blended with biofuels unlikely to present drivers with any specific hardships. Moreover the variety of flex-fuel vehicles (FFV), although smaller than gasoline-powered vehicles, is greater than CNG vehicles, electric, or hybrid electric vehicles. And, because these vehicles can also burn gasoline, there is more flexibility in locating fueling stations, despite the limited distribution of E85 fueling stations (i.e., fewer than 10 in 19 of the U.S. states; United States Department of Energy, 2012a).

Any carbon-capture method developed for gasoline combustion would also be adaptable for use with biofuels. The net benefit of a biofuels coupled with carbon capture could conceivably be carbon *negative*—that is, more carbon would potentially be removed from the atmosphere than is emitted during combustion.

Electric Vehicles. Key advantages of electrically powered vehicles are that they are emissions free, they use electrical motors that are more efficient than internal-combustion engines, and they can be recharged using household electrical service. Secondary advantages include the potential use of vehicle-based electrical storage as a resource to address periods of peak electrical demand on the electrical grid.

Disadvantages include the relatively low energy density of most current battery technologies (Fischer, Werber, & Schwartz, 2009). One hypothetical estimate of an advanced battery module suggests an energy density of about 1-2 MJ/L (Global Climate & Energy Project, 2006). This is significantly less than the energy density of gasoline and, despite the energy efficiency of electric motors, the range of a vehicle powered by a battery alone remains comparatively low. As discussed above, there are also potentially hidden emissions that depend on how the power stored in the vehicle's battery was generated. The vehicle's real carbon impact could be much higher than is immediately apparent to a consumer.

Consumer Relevance. From a consumer's perspective, experience with the use of fossil fuels to power vehicles establishes a benchmark against which alternatively powered vehicles are likely to be evaluated. The impetus to consider ways to mitigate carbon dioxide emissions would most likely be driven by a heightened awareness of carbon dioxide's contribution to global warming and by an understanding about the quantities typically generated during combustion. While the link between climate change and anthropogenic greenhouse gases is generally accepted in Europe, it has been contested in the popular media in the United States. The extent to which a consumer believes that there is an obligation to reduce one's individual carbon footprint will drive the decision to accept different alternative fuel solutions. With this in mind, the switch to use of biofuels may be the easiest option to adopt, provided that biofuels become more widely available. The direct cost to a consumer would be about 10% fewer miles per gallon (with E85). Such a reduction in fuel economy might easily go unnoticed by drivers amid the other sources that contribute to mileage variability—for example, cargo weight, speed, use of air conditioning, etc. (Sivak & Schoettle, 2011). And, even if biofuels are unavailable, a vehicle that is fueled by E85 can also be fueled by gasoline.

Vehicles powered by hydrogen or CNG are generally designed to burn this fuel exclusively, although some hybrid designs permit use of gasoline as a backup fuel (e.g., the BMW Hydrogen 7). In most cases, these vehicles are used in vehicle fleets in which each vehicle daily departs and returns to a central depot. While this use model fits short-distance delivery services, it may not reflect the desired operational use of an average consumer of a passenger vehicle.

Gasoline is also used as a backup fuel to extend the range in most plug-in hybrid-electric vehicle (PHEV) designs. The Chevy Volt is a *series hybrid* vehicle that uses a gasoline engine to drive an electric generator to recharge the battery that powers the electric motor; PHEV versions of the Toyota Prius are *parallel hybrids* and use either a gasoline or an electric motor to propel the vehicle. The only commercially available fully electric vehicles currently available on the U.S. consumer market are the Nissan Leaf, the Mitsubishi MiEV, and the Smart Fortwo.

Plausible in-vehicle carbon-capture mechanisms

Carbon-capture techniques are most highly developed in the power-generation industry. There, carbon capture may occur at three different points in the combustion cycle (shown in Figure 3):

1. Before combustion (*pre-combustion*)—where a fossil fuel is partially oxidized to produce *syngas* (CO and H_2O) and then *shifted* to produce CO_2 and H_2; the CO_2 is then selectively removed leaving only the hydrogen gas to support combustion. This method is most highly developed in commercial applications (Global CCS Institute, 2011).
2. After combustion (*post-combustion*)—where a mixture of carbon dioxide, oxygen, and nitrogen compounds is produced, requiring a post-combustion separation process. Post-combustion-capture methods have an advantage that they may be more easily retrofitted to existing combustion systems.
3. After removal of all but the oxygen from the combustion chamber so that the principal combustion byproduct is CO_2 (*oxyfuels*)—this simplifies post-combustion processing since the resulting byproduct is relatively pure carbon dioxide. The process eliminates the necessity of separating the CO_2 from other gases in the exhaust stream.

Besides these carbon-capture mechanisms, which are based on capture methods used in power generation, other methods have been proposed which involve use of gasoline along with light metal hydrides and carbides to trap CO_2 (Seifritz, 1993), or to separate hydrogen directly from gasoline, using only the hydrogen for combustion (Damm & Fedorov, 2008a).

If a carbon-capture process was to be implemented in automobiles, it would most likely first employ post-combustion capture, since this could be appended to the downstream management of exhaust gases without directly affecting the inputs to the internal combustion engine.

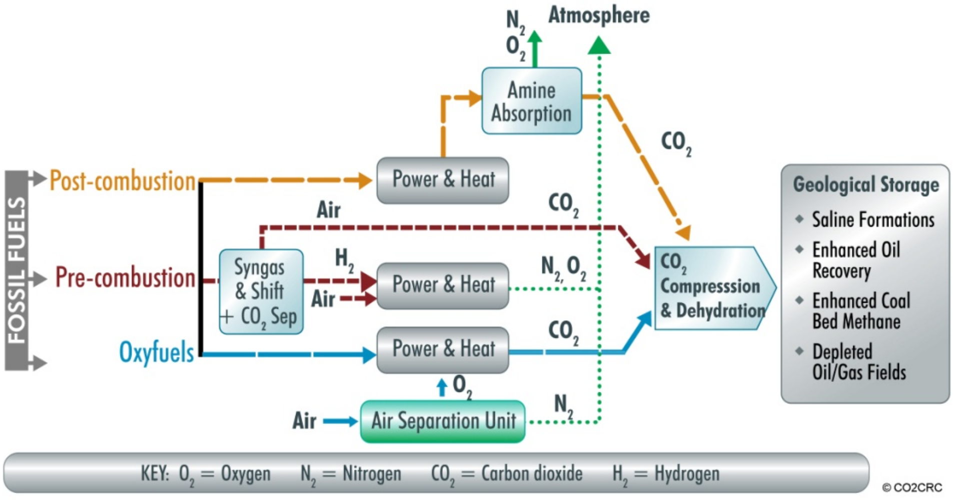

Figure 3. Carbon capture and storage. Illustrates post-combustion, pre-combustion, and oxyfuel processing (Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), 2012).

Post-combustion removal of carbon dioxide from the exhaust gas stream can be accomplished three basic ways:

1. *Absorption*. In this method, exhaust gases are first passed through a liquid medium into which the carbon dioxide selectively dissolves. A second step is required to remove the carbon dioxide from the solution. This is generally done by heating the solution to remove the carbon dioxide for capture and storage (see Figure 4). This method is commonly used for carbon capture on a small scale and is being adapted for use in large-scale coal-burning electrical-power operations (Global CCS Institute, 2011).

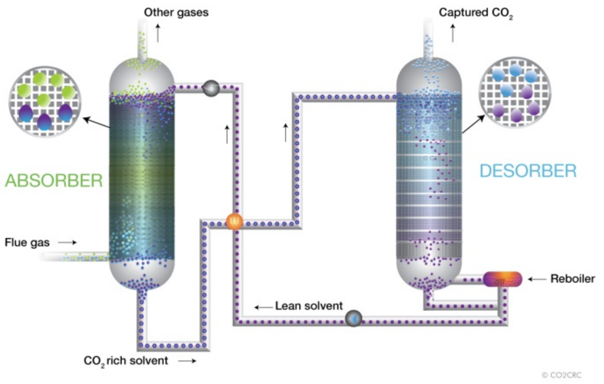

Figure 4. Carbon dioxide removal by absorption (Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), 2012).

2. *Membrane separation*. In this process, CO_2 is separated from the other exhaust gases using a semipermeable membrane that allows CO_2 to pass through more easily than other gases in the exhaust stream. The separated CO_2 is then captured for later storage. This process requires high pressure to drive the separation.

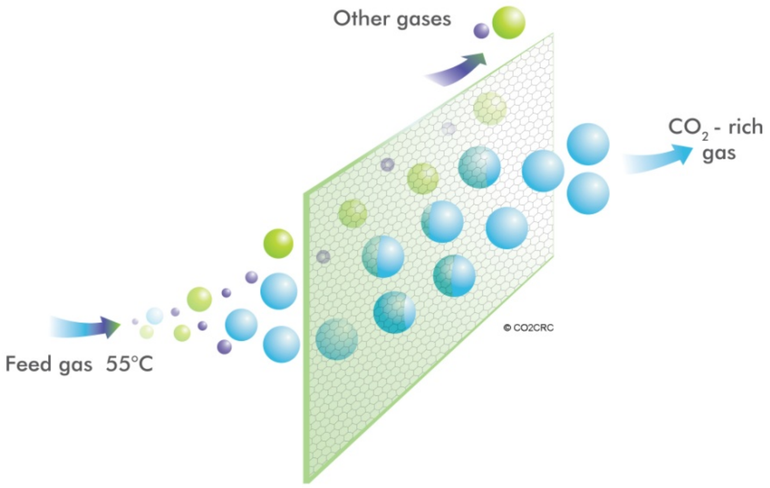

Figure 5. Carbon dioxide separation by membrane selectivity (Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), 2012).

3. *Adsorption*. In this process, CO_2 first selectively adheres to the surface of a material without forming a chemical bond while other gases pass through. This is done under either increased pressure or decreased temperature. In a second phase, the CO_2 is separated by reducing the pressure and/or increasing the temperature, allowing the CO_2 to be drawn off.

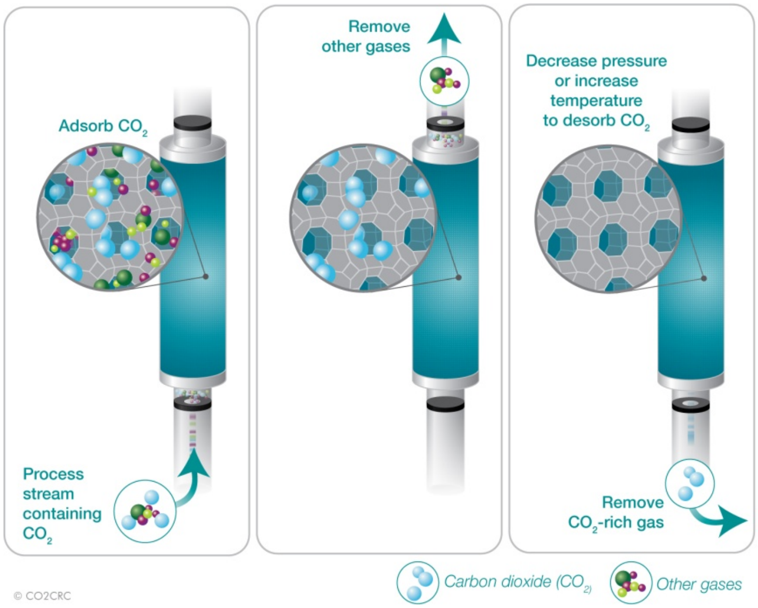

Figure 6. Carbon dioxide separation by adsorption (Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), 2012).

Transport to long-term sequestration areas

Because suitable areas for CO_2 sequestration are not available everywhere, CO_2 may need to be transported over significant distances for proper long-term storage. The most efficient means of transporting large volumes of CO_2 is by pipeline to a sequestration reservoir equipped with the necessary long-term monitoring technologies required to detect leakage. In a report to the U.S. Congress, the Congressional Research Service (Parformak & Folger, 2008) suggests that there is growing recognition in Congress that a substantial interstate network of CO_2 pipelines will be required in the future to reduce carbon emissions produced during electrical power generation. However, divergent views on pipeline requirements and cost estimates are likely to complicate the federal government’s role.

The cost of CO_2 transportation is directly related to pipeline length, and this cost will contribute to regional differences in electricity prices. There is currently no federal authority governing CO_2 pipeline siting—as CO_2 pipelines increase in length they will cross more state jurisdictions, and the regulatory mechanisms governing licensing and approval will become complicated. Moreover, the involvement of many jurisdictions will likely involve more public scrutiny and possible opposition.

While CO_2 transportation costs might be reduced by situating power plants near suitable carbon-sequestration locations, power-generation costs are generally dominated by distance from electricity consumers. If it comes down to a tradeoff between long pipelines or long power lines, longer pipelines will be the preferred choice (Parformak & Folger, 2008). This might be good news for sequestration of the comparatively small quantity of CO_2 collected from vehicles relative to that collected from power plants—longer pipelines create more opportunity to tap into growing sequestration infrastructure. If carbon capture is to succeed at the vehicle level, it will require some infrastructure to collect and transport CO_2 to an appropriate storage site. It is unclear what long-term government policies will be required to support the construction and sharing of such pipelines.

Considerations about the Operational Costs of Carbon Capture

Amount of CO_2 recovered

One gallon of gasoline weighs about 2.7 kg; combustion of one gallon of gasoline produces 8.9 kg of CO_2. If all CO_2 is captured after combustion, not only will the vehicle's weight increase, but the volume required for CO_2 storage will exceed the volume displaced by gasoline. This issue can be addressed in a variety of ways, including requiring more frequent offloads of collected CO_2, allocation of more storage volume for CO_2, or reduction of the amount of CO_2 captured during the combustion of one tank of gasoline.

As an initial approximation, we might assume that storage-volume allocation for CO_2 is the same as for gasoline storage for illustration. However, it is unclear whether this is practical, or whether some method might be developed to reclaim the space vacated by the gasoline. Nevertheless, if it is assumed that the stored CO_2 can be compressed and stored in a liquid state (at about 73 bar), the resulting volume would be about three times the space required for gasoline. If the same volume is used for fuel and CO_2, this would require the vehicle operator to offload CO_2 three times per refuel with gasoline.

The second alternative, allocation of additional storage for the CO_2, would require the consumer to sacrifice vehicle storage space. To capture all of the CO_2, a volume of at least three times the size of the fuel tank might be needed to manage the storage demand.

The third option, reduction in the amount of CO_2 emissions captured, reduces the value of the environmental contribution of the carbon-capture process. For example, if only 33% of carbon emissions are captured, the resulting accumulated CO_2 might occupy the same volume as a tank of gasoline. While consumers seem to generally value low-emissions vehicles, this may be based on a broad heuristic sense that it is generally good to curb consumption of an item known to be in limited supply. Moreover, it can save money on fuel as well. It is unlikely, however, that consumers are as aware of the amount of CO_2 produced during vehicle operation. For most US consumers, awareness of vehicle emissions might stem from their experience with various jurisdictions' departments of motor vehicles (DMVs) vehicle-emissions-testing protocols. Emissions testing evaluates the amount of toxic emissions—carbon monoxide, unspent fuel, and nitrogen oxides—that exit the tailpipe. To pass an emissions test could easily suggest to a consumer that his vehicle has met an environmental benchmark and is certifiably "clean." For example, Georgia's emissions testing is administered through an organization called Georgia's Clean Air Force; most DMVs' emissions testing explicitly links vehicle emissions to air pollution. Thus, immediate concerns about CO_2 emissions may be small among consumers whose familiarity with the gas stems from its use in beverage carbonation, production of dry ice, and paintball propulsion.

Parasitic load of the in-vehicle capture process

Each of the CO_2 separation processes described earlier requires varying amounts of energy to accomplish the CO_2 separation and to store the CO_2 under pressure. Some separation processes require changes in temperature and pressure; storage of the extracted CO_2 would need to be held in a tank, under compression. Depending on the amount and area reserved for storage, this would require more or less compression, which would require additional energy. The additional energy used to support separation and storage is called the "parasitic load" and results in some reduction of operating efficiency. For example, in electrical power generation, estimates of the loss in output (i.e., energy penalty) with carbon-capture range between 15% and 35% (Page, Williamson, & Mason, 2009). Parasitic energy also depends on the percent of the carbon captured. It is unlikely that losses in a vehicle-based capture process would be quite as large as in power generation, especially if some of the energy loss due to inefficiencies in the combustion engine (e.g., heat) can be redirected toward the separation-and-capture processes. For consumers, parasitic energy cost means that a fraction of fuel energy will be consumed to support the separation and storage of CO_2. The acceptability of this cost cannot be understood unless a cost in fuel economy can also be determined so that a consumer can weigh this against the desire to reduce CO_2 emissions.

Discharge procedures for carbon capture

Assuming that CO_2 is held in on-board storage within a vehicle, procedures to offload CO_2 must also be considered. A logical approach would be to establish a discharge process that can be performed in tandem with the refueling. This would be akin to the recycling of the used engine oil during an oil change, or the exchange of a spent propane tank when a full tank is purchased. Thus, it would be optimal to discharge accumulated CO_2 at the same service station used to refuel. An efficient procedure would also allow discharge operations to occur at the same time as refueling, so that the overall duration of the operation may be no different than average refueling times. Such a tandem refuel/discharge operation would be best simplified if only one connection was required to accomplish both tasks. For example, a dual hose might be designed to send fuel on one line and remove CO_2 on the other.

It is also important that refueling operations not be restricted if the on-board CO_2 storage is full. It is likely that refueling locations will significantly outnumber discharge locations. Coupling fueling/discharge operations so that CO_2 discharge would be required before refueling would be too restrictive for consumers and perhaps deter adoption this technology. This issue suggests that reclaiming storage space vacated by fuel consumption for CO_2 storage could initially place a burden on consumers since refueling would be obstructed until the CO_2 could be discharged. That is, initially limited opportunities to discharge CO_2 should not result in a disabled vehicle, if CO_2 storage reaches capacity, nor should it restrict refueling operations. On the other hand, if there are no restrictions on refueling and vehicle operation with CO_2 storage at full capacity, the consumer incentive to collect CO_2 may be weak. That is, if collection and discharge costs additional time and money, consumers may need more direct encouragement to continue carbon collection. Depending on the consumer, encouragement may be provided by monetary reward for CO_2 discharge, or the ability to directly monitor the cumulative amount of CO_2 emissions collected.

Location of carbon-collection facilities

Planning for the introduction of a limited distribution of carbon-collection facilities is similar to planning the placement of refueling sites in an alternative-fuel network. Just as opportunities to use alternative fuels may be limited during early stages of introduction, resources to offload collected CO_2 may be similarly limited. Consumers would then need to plan to discharge more consciously than if discharge facilities were more widely available. In an analysis of the diesel refueling behavior of drivers, Sperling and Kitamura (1986) found that predictability of fuel-station location compensates for reduced fuel availability. In 56% of the cases, diesel-vehicle operators preferred fuel outlets proximate to their home, work, or school, while only 29% of gasoline-car drivers preferred outlets based on these criteria. The limited number of discharge stations will also obligate early adopters of vehicles equipped with CO_2 capture capability to devote more attention to consideration of when and how to offload CO_2. This will be true, provided that they can sustain the motivation to reduce carbon emissions. However, unlike the situation where fuel availability is limited, the consequence of failing to plan the discharge of CO_2 should not necessarily result in a disabled vehicle. A full CO_2 store may simply mean that carbon-emissions capture is temporarily disabled. With such a small penalty, it is unclear whether drivers will be well motivated to plan for CO_2 discharging. It is conceivable that without additional incentives, consumer resolve to collect CO_2 emissions may not be high.

More detailed studies of the spatial distribution of driver refueling patterns seem to support these observations. For example, drivers tend to refuel in familiar places—close to home or workplace—and at the beginning or end of their trips (Kitamura & Sperling, 1987). In studies of the spatial distribution of alternative-refueling decisions, demand for refueling was related to distance traveled, with the exception of specific refueling trips to a central business area in a densely populated area (Nicholas, 2010; Nicholas & Ogden, 2006); refueling decisions were also observed to occur most frequently between home and the freeway (Nicholas, 2010). One upshot of this analysis is that stations located along a freeway may best serve initial customer demand.

Additional maintenance costs

Most vehicle operators are required to perform regular maintenance on their vehicles to ensure that the vehicle performance remains optimal. Routine maintenance items include changing out motor oil, the oil, air, and fuel filters, coolant, tire rotation, belts, etc. Automobile manufacturers establish regular maintenance intervals, typically between 3,000 and 7,500 miles. It is important that the maintenance of in-vehicle carbon-capture technologies conform to the same maintenance pattern for other vehicle components. In addition, the costs of components related to carbon capture should not exceed the customary range of other vehicle-maintenance items.

Consumer Purchase Motivations

Forecasting consumer adoption of an innovative transportation technology is a complex undertaking and involves several marketplace mechanisms. In an agent-based model (ABM) used to characterize the diffusion of alternative-fuel vehicles (AFV), Zhang, Gensler, and Garcia (2011) have modeled three key participants in this process. First, there are manufacturers, who play a role in bringing innovative products to the marketplace. This creates a technology *push* of the innovation onto consumers. Second, the consumer must desire the innovation so that some market *pull* is generated to encourage innovation. This second factor is influenced by a consumer's direct knowledge of the product and by reliance on word-of-mouth from other consumers or trusted sources. Third, the authors suggest that, especially with respect to eco-innovation in transportation, there is a significant role played by regulatory intervention that may generate some pull on the consumer side (e.g., tax deductions for low-emissions vehicle purchases) or push on the manufacturer side (e.g., Corporate Average Fuel Economy—CAFE regulations). While many low-emissions vehicle technologies are beginning to be seen in the marketplace, there remains insufficient market demand to encourage manufacturers to broaden their offerings to the level seen with gasoline-fueled vehicles. Some consider that, while the broad opinions about alternative-fuel-vehicle technologies are generally positive, significant adoption will depend on how these vehicles compare across several dimensions with respect to conventional vehicles (Shepherd, Bonsall, & Harrison, 2012).

Other consumer research suggests that a significant part of the motivation for the purchase of a low-emissions vehicle is related to perceived financial benefit: low emissions mean low fuel consumption; low fuel consumption means low fuel cost (Ozaki & Sevastyanova, 2011). Indeed, models of consumer motives to adopt a low-emissions vehicle seem to focus on the consumer's desire to offset the higher cost of a hybrid or electric vehicle with direct financial benefit (Caulfield, Farrell, & McMahon, 2010; Eggers & Eggers, 2011; Ozaki & Sevastyanova, 2011; Shepherd et al., 2012). This suggests that lowered carbon emissions may not alone present sufficient consumer incentive unless some financial benefit can be directly coupled to the collection of CO_2.

In the current marketplace, because low emissions are linked to higher fuel efficiency, consumers expect low-emissions vehicles to result in lower fuel costs. If carbon-capture technology is applied to vehicles, however, this relationship between fuel consumption and emissions is altered in a way that consumers may not readily understand. It may thus be possible to make a low-emissions vehicle that has the equivalent emissions of a hybrid vehicle, but which has the fuel economy of a heavier vehicle. Whenever a driver of a low-emissions vehicle refuels, the fuel-pump tally provides tangible and reinforcing information that there are benefits in driving a low-emissions vehicle. Unless a similarly reinforcing benefit can be made tangible when carbon dioxide is discharged from a vehicle equipped with carbon-collection technology, drivers will have little to reinforce their decision to adopt this technology. This suggests that carbon-collection incentives may be needed to support this technology. Without a widely adopted carbon-emissions policy, few incentives are likely to develop to directly support carbon collection.

One approach to creating such incentives would be to attach a “deposit” or surcharge on the price of a gallon of gasoline to cover the resulting CO_2 emissions generated during combustion, much like a deposit is charged on the cost of a beverage bottle to encourage return of the bottle for recycling. When the collected CO_2 is returned, the surcharge is then refunded back to the consumer. Similar surcharges have been considered to address the increasing amount of cell phone and e-waste refuse (Kahhat, Junbeum, Ming, Allenby, & Williams, 2008; Silveira & Chang, 2010).

Conclusions

This survey of the feasibility of introducing CCS into light vehicles initially reviewed the level of international support for CCS with the view that unless countries establish policies and infrastructure to support CCS, there may be little point in collecting CO_2. In general, it appears the CCS is still a developing technology; the expense and uncertainties of large-scale projects make it difficult to obtain financial support without governmental participation. This has been a problem in the US and the UK. Uncertainty in legislative protection has deterred private investment, particularly in Germany. India does not appear to be considering use of CCS and appears, instead, focused on improvements in fuel efficiency; China, a significant consumer of coal, appears interested in adopting CCS in coal-powered generation of electricity, but there is some uncertainty about their willingness to absorb losses in power-generation efficiency.

Fossil fuels continue to be a versatile means of energy storage, especially compared with many low-emissions alternatives. Positive attributes associated with gasoline-powered vehicles—e.g., travel range, performance across temperature ranges, fuel availability, and cost—continue to make gasoline attractive relative to many alternative fuels. This is noted because, apart from reduced fuel consumption, CCS technology is key to reducing CO_2 emissions produced by the use of fossil fuels in transportation. CCS technology can also be applied to biofuels, potentially creating a carbon-negative outcome.

Among the capture mechanisms reviewed, post-combustion technologies were given focus because these mechanisms are most likely to be readily adaptable to operate with existing internal-combustion engines. Three separation processes were described: absorption, membrane separation, and adsorption.

Considerations about operational costs from the point of view of the consumer were discussed, including storage management of captured CO_2, additional energy costs to support separation and storage, discharge procedures, and additional maintenance costs. In light of these considerations, models of consumer inclination to adopt new technologies were reviewed. In many models, consumer motivation is driven by perceived financial benefit, suggesting that incentives beyond reduced emissions may be required to motivate consumers.

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