Hydrogen Internal Combustion Engine Vehicles:
A Prudent Intermediate Step or a Step in the Wrong Direction?

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Abstract

Hydrogen internal combustion engine (ICE) vehicles present much of the same promise as hydrogen fuel cell vehicles (FCVs): reduced reliance on imported oil and reduced carbon dioxide emissions. Proponents envision hydrogen ICE as a bridging technology from gasoline vehicles to hydrogen FCVs. This paper examines the hydrogen ICE technology, focusing on relevant aspects such as power, fuel economy, tank size, and the state of the technology. An economic analysis is then performed to examine the potential implications of widespread adoption of hydrogen ICE vehicles in the United States. The case for hydrogen ICE depends most on key uncertainties in the evolution of vehicle and production technology, the cost of crude oil, and the valuation of carbon dioxide emission reductions. This analysis indicates that promoting hydrogen ICE vehicles may be a sensible policy goal as a transition strategy to hydrogen FCVs, but a more prudent policy would first promote gasoline-electric hybrids.

Key Words: climate change, carbon dioxide, hydrogen, technological change, internal combustion engines, fuel cells

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1. Introduction

At the center of on-going debates regarding energy security and global climate change issues lie the difficult issues inherent in the sizable light duty vehicle transportation sector. In contrast to most other sectors, in the light duty vehicle sector there are exceedingly few economically viable substitutes to the dominant energy source: gasoline. Concerns over reliance on gasoline imports from unstable regions of the world, as well as the potential negative consequences of global climate change from gasoline's carbon dioxide emissions have motivated a vigorous policy debate on alternative pathways for the light duty vehicle transportation sector.

The advent of hybrid gasoline-electric vehicles leaves considerable opportunity for improving the fuel economy of the light duty vehicle fleet without a switch to a radical new technology. However, several technologies hold promise for powering vehicles with lower-carbon feedstocks. In particular, both hydrogen and electricity (e.g., in electric battery vehicles) can be used as *energy carriers*, in which energy can be generated from a variety of sources, including low-carbon sources, and stored as electricity or hydrogen for eventual use in powering the vehicle. For example, hydrogen can be produced through feedstocks as varied as coal gasification, natural gas steam reforming, electrolysis using solar or wind generated electricity, or direct dissociation in nuclear power production. Powering a vehicle using one of these energy carriers produces little or no tail-pipe carbon dioxide emissions (e.g., the product of hydrogen combustion with oxygen is water). This opens the possibility of running much of the transportation sector on energy derived from low-carbon sources, alleviating one of the major stumbling blocks in the way of reducing carbon dioxide emissions and oil imports.

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In the 1990s, efforts to introduce battery-electric vehicles in California largely failed, mostly due to an extremely limited range. More recent efforts have shifted to promoting hydrogen. Since 2003, President Bush's Hydrogen Fuel Initiative has received an appropriation of $150-250 million per year for hydrogen R&D (DOE 2007). In California, Governor Arnold Schwarzenegger signed an Executive Order that plans for a "Hydrogen Highways Network" to develop a hydrogen infrastructure in California (Schwarzenegger 2004). In July 2005, California Senate Bill 76 was signed, providing $6.5 million in initial funding to begin developing this infrastructure. These public policy actions underscore the importance many believe hydrogen has in the future of the transportation system.

But, there are many questions that remain unanswered concerning the economic feasibility and desirability of hydrogen in light duty vehicles. Moreover, hydrogen can be used in both fuel cell vehicles (FCVs) and hydrogen internal combustion engine (ICE) vehicles, and both technologies are currently being developed (Ford 2007). Most discussion and analysis of hydrogen has centered on the fledgling fuel cell technology due to sizeable potential fuel efficiency gains (e.g., NRC 2004). The advocates of hydrogen ICE vehicles see them as a crucial intermediate step to push the hydrogen production infrastructure forward, so it is ready for when FCVs are commercialized. However, there has been relatively little analysis of the merits of promoting hydrogen ICE vehicles as a transition step.

This paper aims to fill this gap through an analysis of the technical details and the economics of hydrogen ICE vehicles. Emphasis is placed on a comparison of hydrogen ICE light duty vehicles to the most prominent competing technologies of gasoline hybrids and hydrogen FCVs. The paper is organized as follows. Section 2 provides a brief overview of the history and technical specification of hydrogen ICE vehicles, Section 3 is a comparison of different vehicle technologies, Section 4 presents a scenario analysis of the economics of hydrogen ICEs, and Section 5 concludes.

2. Hydrogen in Internal Combustion Engines

Hydrogen-burning internal combustion engines trace their roots back to some of the very earliest developments in internal combustion engine development. Initially, gaseous fuels like hydrogen were preferred to liquid fuels like gasoline because they were considered safer to work with, due to the low pressures used for the gaseous fuels and the quick dissipation of the gases in the event of a leak. In 1807 Issac de Rivas built the first hydrogen internal combustion engine, and although the design had serious flaws, it was a more than 50 years ahead of the development of gasoline internal combustion engines (Taylor 1985). Technological advances in gasoline engines, such as the development of the carburetor (which allowed air and gasoline to be consistently mixed), eventually led to other fuels being largely passed over in favor of gasoline. Until recently, hydrogen has been relegated to niche uses, such as in experimental vehicles or in the space program.

2.1 Properties of Hydrogen

There are several important characteristics of hydrogen that greatly influence the technological development of hydrogen ICE and FCVs.

Wide Range of Flammability. Compared to nearly all other fuels, hydrogen has a wide flammability range (4-74% versus 1.4-7.6% volume in air for gasoline). This first leads to obvious concerns over the safe handling of hydrogen. But, it also implies that a wide range of fuel-air mixtures, including a *lean* mix of fuel to air, or, in other words, a fuel-air mix in which the amount of fuel is less than the stoichiometric, or chemically ideal, amount. Running an engine on a lean mix generally allows for greater fuel economy due to a more complete combustion of the fuel. In addition, it also allows for a lower combustion temperature, lowering emissions of criteria pollutants such as nitrous oxides (NO_X).[1]

Low Ignition Energy. The amount of energy needed to ignite hydrogen is on the order of a magnitude lower than that needed to ignite gasoline (0.02 MJ for hydrogen versus 0.2 MJ for gasoline). On the upside, this ensures ignition of lean mixtures and allows for prompt ignition. On the downside, it implies that there is the danger of hot gases or hot spots on the cylinder igniting the fuel, leading to issues with premature ignition and flashback (i.e., ignition after the vehicle is turned off).

[1] The combustion of hydrogen and oxygen produces water as its only product, but the combustion of hydrogen with air also produces nitrous oxides (NO_X), due to the high nitrogen content in air. Traces of carbon dioxide and carbon monoxide may also be present in emissions from seepage of engine oil.

Small Quenching Distance. Hydrogen has a small quenching distance (0.6mm for hydrogen versus 2.0mm for gasoline), which refers to the distance from the internal cylinder wall where the combustion flame extinguishes. This implies that it is more difficult to quench a hydrogen flame than the flame of most other fuels, which can increase backfire (i.e., ignition of the engine's exhaust).

High Flame Speed. Hydrogen burns with a high flame speed, allowing for hydrogen engines to more closely approach the thermodynamically ideal engine cycle (most efficient fuel-power ratio) when the stoichiometric fuel mix is used. However, when the engine is running lean to improve fuel economy, flame speed slows significantly.

High Diffusivity. Hydrogen disperses quickly into air, allowing for a more uniform fuel-air mixture, and a decreased likelihood of major safety issues from hydrogen leaks.

Low Density. The most important implication of hydrogen's low density is that without significant compression or conversion of hydrogen to a liquid, a very large volume may be necessary to store enough hydrogen to provide an adequate driving range. Low density also implies that the fuel-air mixture has low energy density, which tends to reduce the power output of the engine. Thus when a hydrogen engine is run lean, issues with inadequate power may arise (College of the Desert 2001).

2.2 Relevant Trade-offs

Based on the above unique properties of hydrogen, there are several relevant tradeoffs pertinent to the use of hydrogen in ICEs.

The first relates to a decision that for the most part has already been made: whether to use a spark-ignition engine design (e.g., most gasoline vehicles), or a compression-ignition (CI) engine design (e.g., diesel vehicles). CI engines work by compressing air in the combustion chamber, increasing its temperature above the autoignition temperature of the fuel, such that injected fuel ignites immediately and burns rapidly. This small explosion causes the gas to expand and forces the piston down, creating mechanical energy that is be used to power the vehicle. Spark-ignited engines begin combustion at a much lower temperature and pressure through the use of an ignition system that sends a high-voltage spark through a sparkplug to ignite the fuel-air mixture.

Spark-ignition engines tend to be less expensive and have lower emissions of criteria pollutants (e.g., NO_x and particular matter)[2], but have lower power at low engine speeds and a lower theoretical efficiency than CI engines. Due to hydrogen's wide range of flammability and low density, nearly all recent designs for hydrogen ICE vehicles call for CI engines (Ford 2007).[3]

A second relevant tradeoff is the type of transmission to use. Using hydrogen in a CI engine will most likely require the use of a continuous-variable transmission (CVT), as is commonly used in hybrid gasoline vehicles. The CVT may or may not be designed to be coupled with an electric battery and a separate electric motor that runs off recaptured energy from breaking. Here the tradeoff is between additional cost and improved fuel economy – although most recent hydrogen ICE designs include the battery and separate electric motor.

A third tradeoff is between power and fuel economy or emissions. Running a hydrogen engine lean reduces criteria pollutants and can improve fuel economy, but it comes at the cost of power due to the lower energy content of the fuel-air mixture. To ensure adequate power, turbo-charging, super-charging, or not running the engine lean can all be used, but are likely to come at a cost of fuel economy and possibly criteria air pollutant emissions.

A final key tradeoff is between vehicle range and the hydrogen fuel tank size. Efforts are underway to improve storage of hydrogen in fuel tanks through compression or liquification of hydrogen, but the low density of hydrogen poses challenges to engineers attempting to decrease the tank size, yet ensure adequate range for hydrogen vehicles. Moreover, the hydrogen storage systems are likely to be heavier than standard gasoline tanks, increasing vehicle weight, which can decrease fuel economy.

3. Comparison of Vehicle Technologies

Table 1 presents estimates of some of the most important characteristics of the four most relevant types of vehicles: gasoline ICE, gasoline hybrids, hydrogen ICE, and hydrogen FCVs.

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[2] Recent technological advances have been successful in lowering criteria air pollutants for CI engines, albeit with higher manufacturing costs (Kliesch and Langer 2003).

[3] Note that "diesel engine" is a general term applying to engines that work through compressed air ignition, so the CI engines described above could equally well be called diesel engines, and are often described as such. Diesel engines do not necessarily have to burn "diesel" fuel.

It must be emphasized at this point that many of these estimates, particularly on hydrogen FCVs are highly speculative due to the uncertainty in technology development, and the characteristics (e.g., size and weight) of vehicles that will be rolled out with each technology.

Hydrogen ICE vehicles tend to fall in a middle ground between the higher efficiency hydrogen fuel cell vehicles and the standard gasoline ICE vehicles. In many respects, hydrogen ICE vehicles can be thought of as diesel fuel hybrid vehicles that run off of hydrogen, rather than diesel fuel. Thus a critical difference between gasoline hybrids and hydrogen ICE vehicles is that the use of a CI engine design allows for greater engine efficiency: on the order of one third greater. Moreover, how engine efficiency varies with load and power differs between the engine types. Figure 1 provides a rough sketch of the relationship between engine efficiency and percent load for spark-ignition, compression-ignition (CI), and a single fuel cell (with equivalent output to the other engine types).

Spark-ignition engines have a maximum efficiency of 32.5% under normal conditions and at low loads have a much lower efficiency than this. Note that the additional electric engine in gasoline hybrid vehicles is highly efficient at very low percent loads, and is primarily used at low load levels, so gasoline hybrids do not suffer from this loss in efficiency at low loads as much. Compression-ignition engines tend to have a maximum efficiency rough in the range of 40%, and quickly reach efficiency levels close to the maximum efficiency at low percent loads. The greater maximum engine efficiency is in large part the reason why diesel vehicles have better fuel economy than conventional vehicles.[4]

A typical fuel cell stack can reach much higher efficiencies than either spark-ignition and CI engines, but it is important to note that as the fuel cell stack reaches maximum load, the efficiency drops precipitously, in contrast to the other engine types. The exact shape of this curve, and any quantitative estimates of fuel cell efficiency are highly speculative due to the many recent developments in fuel cell technology, but the general shape is robust (Edwards 2006).

[4] An evaluation of 24 matched pairs of diesel to gasoline light duty vehicles in Europe and the United States found that indirect-injection diesel vehicles had 24% better fuel economy on average and turbocharged, direct-injection diesel vehicles averaged 50% better fuel economy, although much of that is due to the turbocharging (Schipper, Marie-Lilliu, and Fulton 2002)

This relationship has important implications for the power delivered to fuel cell vehicles, for additional fuel cells must be added to provide adequate power for some high-intensity uses – and the fuel cell stacks are one of the most expensive components of a fuel cell vehicle. Figure 2 indicates the relationship between power train efficiency and power in one particular study. As each of the fuel cell stacks incrementally reach 100% load, efficiency begins to drop.

This relationship may reduce the possibility of fuel cell heavy duty vehicles, which need to be able to provide sufficient power at high loads. Hydrogen ICE vehicles may be more economically attractive in these markets, since to the high cost of adding more fuel cells may make fuel cell vehicles prohibitively expensive. Of course, the exact relationship between power and efficiency depends on many factors relating to the specific application.

The rough estimates of the average and maximum engine efficiency in Table 1 follow from the discussion above. Equally important as engine efficiency is the efficiency of the transmission in converting the energy generated by the engine to propulsion. Gasoline hybrids, hydrogen ICE vehicles, and hydrogen fuel cell vehicles are all assumed to use CVT and hybrid transmission technology, which has approximately 60% efficiency, as opposed to a standard transmission, which has only around a 40% efficiency. Given these estimates and an estimate of the current average fleet-wide fuel economy of standard gasoline light duty vehicles, the fuel economy of each of the vehicle types is computed.[5] These computed estimates for gasoline hybrids and hydrogen fuel cells match closely with those in NRC (2004).

Table 1 also highlights differences in engine sizeability, fuel tank size, cost of fuel, and emissions. All of these have either direct or indirect importance to the market feasibility of each vehicle type. The cost of hydrogen depends on the feedstock, as will be discussed in section 4, but there may even be a minor difference between the cost of hydrogen in ICE vehicles and fuel cell vehicles. Nearly all hydrogen fuel cells under development require very pure hydrogen to

[5] Specifically, the total vehicle efficiency for each type is first computed by multiplying the engine efficiency by the transmission efficiency. Then, for gasoline hybrids, hydrogen ICE vehicles, and hydrogen fuel cell vehicles, the current gasoline ICE fuel economy is multiplied by the ratio of each vehicle type's efficiency to the gasoline ICE vehicle efficiency. This methodology assumes that unobserved determinants of fuel economy change proportionally with vehicle efficiency.

run effectively,[6] while a hydrogen ICE vehicle would likely work with a cheaper, less pure grade of hydrogen.

Finally, Table 1 describes the current state of the technology. Gasoline hybrids have already been developed and are in the rapid market diffusion stage. On the other hand, hydrogen ICE vehicles are still for the most part on the drawing board. The few companies investing in hydrogen ICE (e.g., Ford and BMW) have made substantial progress and believe that commercialization may only be a few years away (Ford 2006). In contrast, considerable research and development effort is being focused on fuel cells today by many companies and universities, but the state of the technology is far from the market commercialization stage (Edwards 2006).

4. Economics of a Hydrogen ICE Policy

There is enormous uncertainty surrounding the advance of the hydrogen ICE technology to commercialization stage. Choices made by manufacturers about where to allocate R&D funds and how to deal with the tradeoffs inherent in hydrogen ICE vehicles will determine the final characteristics of a hydrogen ICE vehicle. Consumer preferences about the desirability of hydrogen ICE vehicles and the acceptability of hydrogen as a fuel will play an important role in the economic feasibility of the vehicles. And most importantly, the rate at which technological barriers are overcome, both on the vehicle and on the hydrogen production side, will dictate just how quickly costs drop, and thus how quickly hydrogen ICE vehicles could be economically marketable.

In light of these uncertainties, this paper follows NRC (2004) in developing four scenarios of vehicle technology adoption in order to examine the implications of policies to promote the adoption of hydrogen ICE vehicles relative to conventional gasoline vehicles, gasoline hybrid vehicles, and fuel cell vehicles. As the emphasis is on hydrogen ICE, the interested reader should be referred to NRC (2004) for more details on the implications of widespread adoption of hydrogen fuel cell vehicles. The following sections adapt the NRC (2004) economic model for analysis of hydrogen ICE vehicles.

[6] Impurities contaminate the fuel cells, reducing performance and degrading performance over time.

4.1 Scenarios of Vehicle Technology Adoption

The four scenarios are as follows: a no policy baseline scenario of gasoline hybrid adoption, a policy scenario promoting of gasoline hybrid-electric vehicles (HEVs), a policy scenario promoting hydrogen FCVs, and a policy scenario promoting hydrogen ICE vehicles. These scenarios are given in Figure 3.

In no policy scenario, conventional vehicles begin to be more rapidly replaced by hybrids after 2018, and by 2050 90% of new vehicles in the market are hybrids. No hydrogen vehicles enter the market by 2050. When a policy is implemented to promote hybrids, conventional vehicles are replaced much faster, such that by 2026, the entire vehicle fleet is hybrid. In addition, the improvements in battery technology are assumed to spill over to hydrogen FCVs, leading to a limited diffusion of FCVs starting in 2030.

When a policy is implemented to promote hydrogen FCVs, FCVs are assumed to begin entering the market in 2015, cannibalizing the market for hybrids, and not changing the market for conventional vehicles. This is consistent with the idea that FCVs will first primarily be small cars, with many of the same intangible benefits that appeal to buyers of hybrids (e.g., new technology, quiet ride, "green"). By 2050, FCVs are assumed to have 100% of the market for new vehicles. This can be considered an optimistic scenario for FCV market diffusion, and would only be possible with major policy effort and technological breakthroughs.

With a policy to promote hydrogen ICE vehicles (dotted lines in Figure 3), hydrogen ICE vehicles begin to enter the market in 2010, consistent with the potential for rapid commercialization of the technology. Since hydrogen ICE vehicles could easily be scaled to be larger vehicles, it is assumed that they take market share from hybrids and conventional vehicles equally. By 2034, they reach nearly 50% of the market. Since hydrogen ICE vehicles are intended as a transition step FCVs, the hydrogen ICE policy scenario also assumes the same vehicle adoption of FCVs as in the FCV policy scenario. After 2034, the continued increase in FCVs begins to cut into the hydrogen ICE market, such that by 2050, there are no new hydrogen ICE vehicles on the market. This policy scenario can also be considered an optimistic scenario of hydrogen vehicle adoption.

4.2 Fuel Use

Two additional assumptions are relevant to examine the fuel use in each of these scenarios. First, Figure 4 presents the assumed new vehicle fuel economy over time for each vehicle type in the four scenarios, with the initial estimates based on those in Table 1. Second, vehicle miles traveled is assumed to continue to grow at 2.3% per year, following the NRC (2004) study.

Figure 5 presents the total gasoline and hydrogen consumption by light duty vehicles in the four scenarios. The increased efficiency of HEV in the hybrid policy scenario serves to reduce the use of gasoline relative to no policy, with about a 27% decrease in total gasoline use by 2050. In the hydrogen ICE policy scenario, the earlier adoption of hydrogen vehicles leads to large decreases in gasoline use significantly earlier than in the hydrogen FCV policy scenario and no gasoline consumption by 2050. Correspondingly, there is a greater consumption of hydrogen in the ICE scenario than the FCV scenario (18% more in 2050), due to both the earlier adoption of hydrogen vehicles and to the lower fuel economy of ICE vehicles.

4.3 Carbon Dioxide Emissions

Carbon dioxide emissions from hydrogen are determined by the fuel use and the type of hydrogen feedstock. An in-depth discussion of hydrogen feedstocks can be found in NRC (2004), and this paper uses the assumptions from the NRC analysis. The following ten types of hydrogen feedstocks are examined:

- Central station generation natural gas (CS-NG)
- Central station generation natural gas with carbon sequestration (CS-NG Seq)
- Central station generation coal (CS-Coal)
- Central station generation coal with sequestration (CS-Coal Seq)
- Distributed generation natural gas (Dist-NG)
- Mid-size generation biomass (MS-Bio)
- Mid-size generation biomass with sequestration (MS-Bio Seq)
- Distributed generation electrolysis (direct generation using electricity) (Dist-Elec)
- Distributed generation wind turbine-based electrolysis (Dist WT-Elec)
- Distributed generation solar photovoltaic-based electrolysis (Dist PV-Elec)

Each of these feedstocks has unique costs and carbon dioxide emissions, and NRC further divides each of these technologies into "current" (C) and "future" (F) versions of the technology. The attributes of the future technologies are the best estimates from the research of the NRC panel. Figure 6 presents these cost estimates for current and future technologies.

Figure 7 illustrates the carbon dioxide emissions when hydrogen is produced by various feedstocks to support the hydrogen FCV policy scenario. Figure 8 presents the same graphs for the hydrogen ICE scenario. The plots for each hydrogen feedstock are calculated as if all hydrogen were produced by each type, but any mix of different types of feedstocks can be estimated by averaging the different plots.

One message to take from Figures 7 and 8 is that a hydrogen policy is not guaranteed to reduce carbon dioxide emissions over the hybrid policy scenario. If the chosen feedstocks are distributed electric or central station coal (without sequestration), then carbon emissions would be no better with a hydrogen policy than a hybrid policy. Also important is that the reductions in carbon emissions are greater for all feedstocks in the hydrogen ICE scenario than the hydrogen FCV scenario, largely because with an ICE policy more vehicles are switched to hydrogen, and at an earlier date.

One of the more likely feedstocks, at least in the beginning, is distributed generation natural gas, and it provides significant carbon dioxide reductions (e.g., approximately 45% in 2050). However, distributed generation natural gas is one of the more expensive feedstocks, with a unit cost of the future technology around 50% greater than the unit cost of any of the centrally generated fossil fuel feedstocks. Not surprisingly, the greatest carbon dioxide reduction benefits come with the renewable feedstocks and central generation fossil fuels with sequestration. All of these fuels provide the possibility of eliminating the vast majority of the carbon dioxide emissions from the light duty vehicle sector, but these are also all more expensive feedstocks than the fossil fuel based feedstocks without sequestration, such as central-generation natural gas.

Figures 7 and 8 are based on estimates of future technologies that have not been developed yet, and most certainly would not be commercialized as quickly as hydrogen ICE vehicles are assumed to be. Using the current technologies instead of the future technologies will shift all of the plots upwards. Thus, depending on the feedstock, the hydrogen ICE policy could have greater carbon dioxide emissions than a hybrid policy.

4.4 Net Benefits

The costs of each of the policy scenarios include: the additional cost of the vehicles over the baseline vehicle cost, the cost of additional hydrogen research and development, and the cost of developing a hydrogen infrastructure in the hydrogen scenarios. The benefits of each of the policies are the value of the reduced carbon dioxide emissions the value of fuel savings due to improved fuel economy. To complete the calculation of the net benefits, several additional assumptions must be made about highly uncertain parameters: the price or valuation of carbon is assumed to be $50/ton in 2005 and rising at the rate of interest (3%), the price of a barrel of oil is assumed to be $50/barrel, and the additional vehicle costs are $2,000, $2,750, and $4,000 for hybrids, hydrogen ICE vehicles, and hydrogen FCVs respectively. The vehicle cost assumptions are based roughly on the technical details of the three technologies, while the other assumptions are just best estimates. The baseline assumed social discount rate is 3%.

To calculate the net benefits, the present discounted value (PDV) out to 2050 of the vehicle, fuel, and carbon costs are first calculated for each policy and then compared to the no policy scenario to analyze the effect of the policy in each of these categories. These policy impacts are then summed to yield the net benefits of the policy without the R&D and infrastructure costs. The PDV of the different costs out to 2050 are shown in Table 2 for a sample of some of the most relevant hydrogen feedstocks.[7] The fuel costs reflect the higher fuel economy of hydrogen ICE vehicles, and the even high fuel economy of the hydrogen FCVs. The relative carbon costs mirror the relative paths of carbon dioxide emissions shown in Figures 7 and 8.

Table 3 computes the difference between costs in the policy and no policy scenarios, providing a measure of the net benefits of the policy before R&D and infrastructure costs are included. A first point from Table 3 is that the earlier market penetration of hydrogen vehicles increases the fuel savings and carbon savings in the hydrogen ICE scenario over the hydrogen

[7] Hydrogen produced from electrolysis from solar with a grid backup is included instead of solar alone because it is more likely to be used than pure solar, due to the intermittency of solar.

FCV scenario when feedstocks such as central station natural gas and coal with sequestration are used. Thus, the total net benefits for the policy are positive in the hydrogen ICE scenario for those fossil fuel feedstocks, when they are negative in the FCV scenario. However, the size of these net benefits with current technologies is not large ($45 billion for CS-NG and $89 billion for CS-Coal with sequestration) when compared with possible R&D and infrastructure costs. With future technologies the net benefits of the ICE policy are larger: $312 billion and $478 billion. However, it is more likely that the earlier market entry of hydrogen ICE vehicles will come before the future technologies are developed.

The cost of a hydrogen infrastructure is uncertain, but a quick back of the envelope calculation provides some insight. There were 120,902 existing gasoline retail stations in the United States in 2002 (US DOC 2002). A study for the California Fuel Cell Partnership estimates the cost of a refurbishing a station for hydrogen will be $450,000, which is a reasonable mid-point between estimates in other studies (CA FCP 2001). Assuming all 120,902 stations are replaced, this indicates the cost of a hydrogen infrastructure is in the range of $54 billion, an estimate quite close the net benefit of the ICE policy with the current fossil technologies.

Table 3 also indicates that the hybrid policy scenario brings in larger total net benefits than either of the hydrogen scenarios. This is notable because the hybrid policy scenario would likely have much lower R&D costs (and no infrastructure costs). Finally, Table 3 shows that distributed natural gas and the renewable feedstocks have significantly negative net benefits even before the additional infrastructure and R&D costs are accounted for – a result that emphasizes the importance of using the lowest cost feedstock for hydrogen production.

The results in Table 3 use reasonable baseline assumptions, but prove surprisingly robust in a sensitivity analysis. The results are most sensitive to the assumed oil price, for higher oil prices will increase the fuel cost of the baseline and hybrid scenarios, and increase the net benefits of the hydrogen scenarios (e.g., an $80/barrel oil price implies the net benefits of the ICE policy with a CS-NG-C feedstock would be $853 billion). Increasing the carbon price changes the carbon cost, but it has a much smaller effect, but it again increases the net benefits of the hydrogen scenarios, and particularly the hydrogen ICE scenario (e.g., a carbon price starting at $75 in 2002 implies net benefits of the ICE policy with a CS-NG-C feedstock of $162 billion).

However, the result that the hybrid scenario brings in greater net benefits has been robust to all sensitivity tests performed.

5. Conclusions

Much like hydrogen fuel cell vehicles, hydrogen ICE vehicles present a considerable promise: the chance to improve energy security and reduce carbon dioxide emissions by weaning the light duty vehicle sector off of gasoline. And much like hydrogen FCVs, there are significant barriers to the adoption of hydrogen ICE vehicles, involving both technological improvements so it is competitive with gasoline-based alternatives as well as implementing a hydrogen fueling infrastructure. Looking beyond those similarities, distinctions quickly arise due to the nature of the hydrogen ICE technology that differentiate it from fuel cell and gasoline vehicles.

The most critical differences are the power produced by the engine, the fuel economy, the fuel tank size, and the state of development of the technology. Complicating any comparison is the vast uncertainty inherent in future vehicle technologies, hydrogen ICE included. If the fuel cell technology is developed to its potential, the fuel economy advantage it has over the hydrogen ICE technology appears to present a compelling case for FCVs in the long-term. This is particularly true because the higher fuel economy allows for a smaller fuel tank size for the same range, and fuel tank size is almost certain to be a key limitation for hydrogen vehicles.

However, the issue of power may prove to be a thorn in the side of FCVs, particularly for vehicles that need the capacity to perform at high loads, since adding more fuel cell stacks can add significantly to cost of the vehicle. Buses and trucks clearly fall into this category, and light duty vehicles such as light trucks and sport-utility vehicles may also fall into it, depending on the eventual cost of fuel cells.

This leaves a quandary for the design of public policy: does a policy to promote hydrogen ICE vehicles as a transition strategy make sense? This analysis reveals four underlying points: (1) the PDV of a hybrid policy far exceeds that of a hydrogen ICE or FCV policy up to 2050, (2) if policymakers decide to invest in hydrogen anyway for the long-run benefits past 2050, then there may be a place for hydrogen ICE vehicles in the eventual fleet mix due to their lower cost and greater power, (3) if we are to promote hydrogen, the fuel savings and carbon benefits from earlier introduction of hydrogen ICE vehicles may provide large enough benefits to pay for the infrastructure and R&D costs of a hydrogen ICE policy, and (4) these benefits are contingent on the use of hydrogen generated by central station generation fossil fuels (natural gas or coal with sequestration).

These conclusions must be understood in the context of the assumptions that generated them, especially given the considerable uncertainties surrounding key components of the analysis. The four most important premises that this analysis rests on are, in order: the assumed evolution and diffusion of new vehicle technologies, the assumed decrease in cost of production of feedstock technologies (current versus future), the assumed price of crude oil, and the assumed value of carbon dioxide emission reductions. Sensitivity analyses indicate that the above conclusions are relatively robust to many other parameter combinations. Given the scenarios of vehicle adoption, the conclusions are most sensitive to oil prices and carbon benefits. Major changes in the vehicle adoption scenarios would also change the quantitative results, but cursory analysis indicates that changes within a defensible range are not likely to change the qualitative results.

Thus, if the policy goal is a long-term shift to hydrogen and the hydrogen infrastructure could be brought online quickly enough, hydrogen ICE vehicles may provide sufficient early-term fuel savings and carbon dioxide emission reductions that they may be worth promoting as a transition strategy.

Tables

Table 1. Comparison of Different Vehicle Types

	Gasoline ICE	*Gasoline Hybrid*	*H2 ICE*	*H2 Fuel Cell*
Engine Type	spark-ignition	spark-ignition & electric motor	CI (with electric motor)	fuel cell & electric motor
Average engine efficiency	~30%	~30%	~40%	~55%
Max engine efficiency	32.5%	32.5%	~40%	~65%
Transmission Type	standard	CVT/ hybrid	CVT/ likely hybrid	CVT/ likely hybrid
Transmission efficiency	~40%	~60%	~60%	~60%
Fuel Economy (mpg equival.)	21	31	41	51
Sizeability	As much power as needed, at the cost of mpg	Efficiency improvements over gas ICEs are mostly lost with increased power	Efficiency losses or higher emission control costs to increase power	Increasing power may be expensive, requiring additional FCs
Fuel Tank Size (constant range)	Moderate	Small	Large	Large; smaller than H2 ICE
Cost of Fuel	Currently low	Currently low	Currently high; but may be slightly lower than FCVs	Currently high
Criteria Pollutant Emissions	Meets emission standards	Lower than gasoline ICE	Likely low, some NO_x	Very low or none
State of technology	developed	developed, and in diffusion stage	Could be developed quickly	Earlier in the research process

Table 2. Discounted Present Value of Costs in Different Scenarios (out to 2050)												
	Vehicle Costs ($Billions)			**Fuel Costs ($Billions)**			**Carbon Costs ($Billions)**			**Total Costs ($Billions)**		
	Hydrogen FCV Emphasis	Hydrogen ICE Emphasis	Hybrid Emphasis	Hydrogen FCV Emphasis	Hydrogen ICE Emphasis	Hybrid Emphasis	Hydrogen FCV Emphasis	Hydrogen ICE Emphasis	Hybrid Emphasis	Hydrogen FCV Emphasis	Hydrogen ICE Emphasis	Hybrid Emphasis
No Policy Baseline	$638	$638	$638	$6,315	$6,315	$6,315	$1,114	$1,114	$1,114	$8,067	$8,067	$8,067
Current H_2 Technologies												
Natural Gas, CS	$983	$1,273	$1,036	$6,150	$5,869	$5,831	$1,017	$880	$1,005	$8,150	$8,022	$7,872
Coal, CS with Seq.	$983	$1,273	$1,036	$6,192	$5,982	$5,836	$952	$723	$996	$8,126	$7,978	$7,868
Natural Gas, Distributed	$983	$1,273	$1,036	$6,534	$6,914	$5,877	$1,047	$953	$1,009	$8,564	$9,141	$7,922
Electrolysis, Grid Derived	$983	$1,273	$1,036	$7,301	$9,007	$5,971	$1,104	$1,090	$1,017	$9,388	$11,370	$8,024
Electrolysis, Wind Turbine	$983	$1,273	$1,036	$8,332	$11,816	$6,097	$921	$647	$992	$10,235	$13,736	$8,125
Electrolysis, PV, Grid Backup	$983	$1,273	$1,036	$8,039	$11,018	$6,061	$1,067	$1,002	$1,012	$10,089	$13,293	$8,109
Future H_2 Technologies												
Natural Gas, CS	$983	$1,273	$1,036	$6,057	$5,615	$5,819	$1,012	$868	$1,004	$8,051	$7,755	$7,860
Coal, CS with Seq	$983	$1,273	$1,036	$6,056	$5,613	$5,819	$944	$703	$995	$7,983	$7,589	$7,850
Natural Gas, Distributed	$983	$1,273	$1,036	$6,237	$6,105	$5,841	$1,029	$908	$1,007	$8,248	$8,286	$7,884
Electrolysis, Grid Derived	$983	$1,273	$1,036	$6,637	$7,196	$5,890	$1,079	$1,029	$1,013	$8,698	$9,498	$7,939
Electrolysis, Wind Turbine	$983	$1,273	$1,036	$6,606	$7,111	$5,886	$921	$647	$992	$8,509	$9,031	$7,914
Electrolysis, PV, Grid Backup	$983	$1,273	$1,036	$6,708	$7,389	$6,061	$1,047	$953	$1,009	$8,738	$9,615	$8,106

Table 3. Discounted Present Value of Net Benefits from the Policy (before R&D and infrastructure costs)

	Vehicle Net Benefits ($Billions)			**Fuel Net Benefits ($Billions)**			**Carbon Net Benefits ($Billions)**			**Total Net Benefits ($Billions)**		
	Hydrogen FCV Emphasis	Hydrogen ICE Emphasis	Hybrid Emphasis	Hydrogen FCV Emphasis	Hydrogen ICE Emphasis	Hybrid Emphasis	Hydrogen FCV Emphasis	Hydrogen ICE Emphasis	Hybrid Emphasis	Hydrogen FCV Emphasis	Hydrogen ICE Emphasis	Hybrid Emphasis
Current H_2 Technologies												
Natural Gas, CS	-$345	-$635	-$398	$165	$446	$485	$97	$234	$109	-$83	$45	$195
Coal, CS with Seq.	-$345	-$635	-$398	$124	$333	$479	$162	$391	$118	-$59	$89	$199
Natural Gas, Distributed	-$345	-$635	-$398	-$218	-$599	$438	$67	$161	$105	-$497	-$1,073	$145
Electrolysis, Grid Derived	-$345	-$635	-$398	-$986	-$2,692	$344	$10	$24	$98	-$1,321	-$3,303	$44
Electrolysis, Wind Turbine	-$345	-$635	-$398	-$2,017	-$5,501	$219	$194	$467	$122	-$2,168	-$5,669	-$58
Electrolysis, PV, Grid Bk	-$345	-$635	-$398	-$1,724	-$4,703	$254	$47	$112	$102	-$2,022	-$5,226	-$42
Future H_2 Technologies												
Natural Gas, CS	-$345	-$635	-$398	$258	$701	$496	$102	$246	$110	$16	$312	$208
Coal, CS with Seq	-$345	-$635	-$398	$259	$702	$496	$170	$411	$119	$84	$478	$217
Natural Gas, Distributed	-$345	-$635	-$398	$79	$210	$474	$85	$206	$108	-$181	-$219	$183
Electrolysis, Grid Derived	-$345	-$635	-$398	-$322	-$881	$425	$35	$85	$101	-$631	-$1,431	$128
Electrolysis, Wind Turbine	-$345	-$635	-$398	-$291	-$796	$429	$194	$467	$122	-$442	-$964	$153
Electrolysis, PV, Grid Bk	-$345	-$635	-$398	-$393	-$1,074	$254	$67	$161	$105	-$671	-$1,548	-$39

Figures

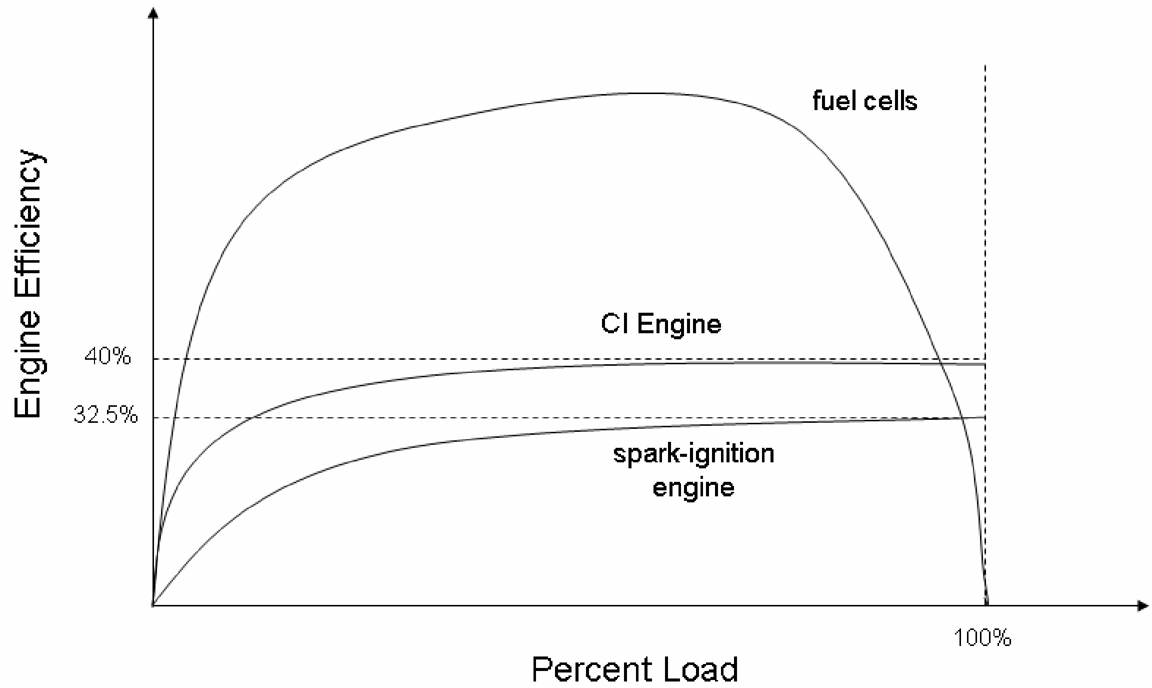


Figure 1. Engine Efficiency versus Load for Fuel Cells, Compression-ignition, and Spark-ignition Engines

Source: Edwards (2006)

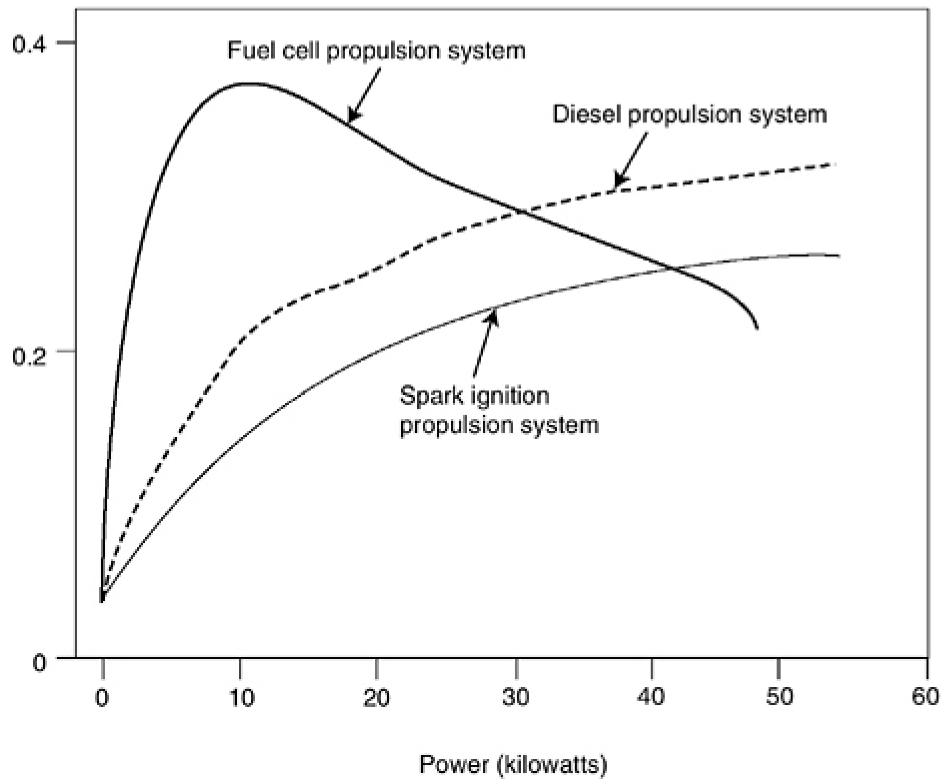
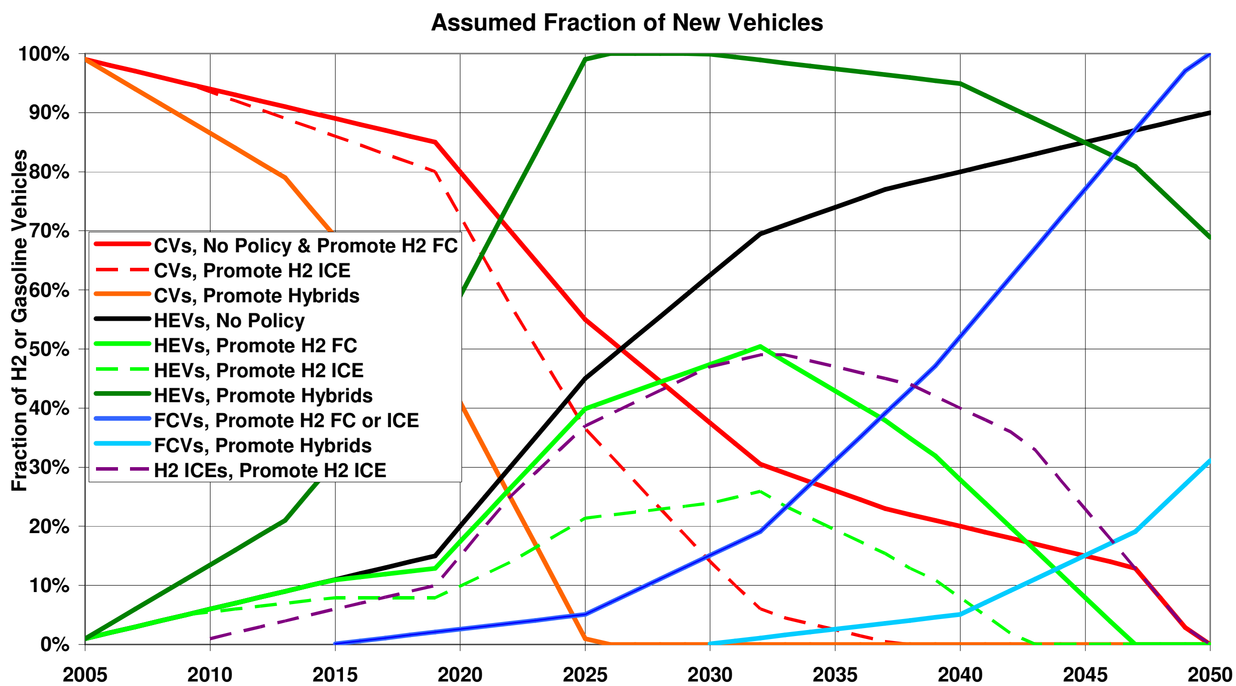


Figure 2. Comparisons of power train efficiency of combustion engine and fuel cell systems (for a car similar to a Volkwagen Golf).

Source: Wengel and Schirrmeister (2000)



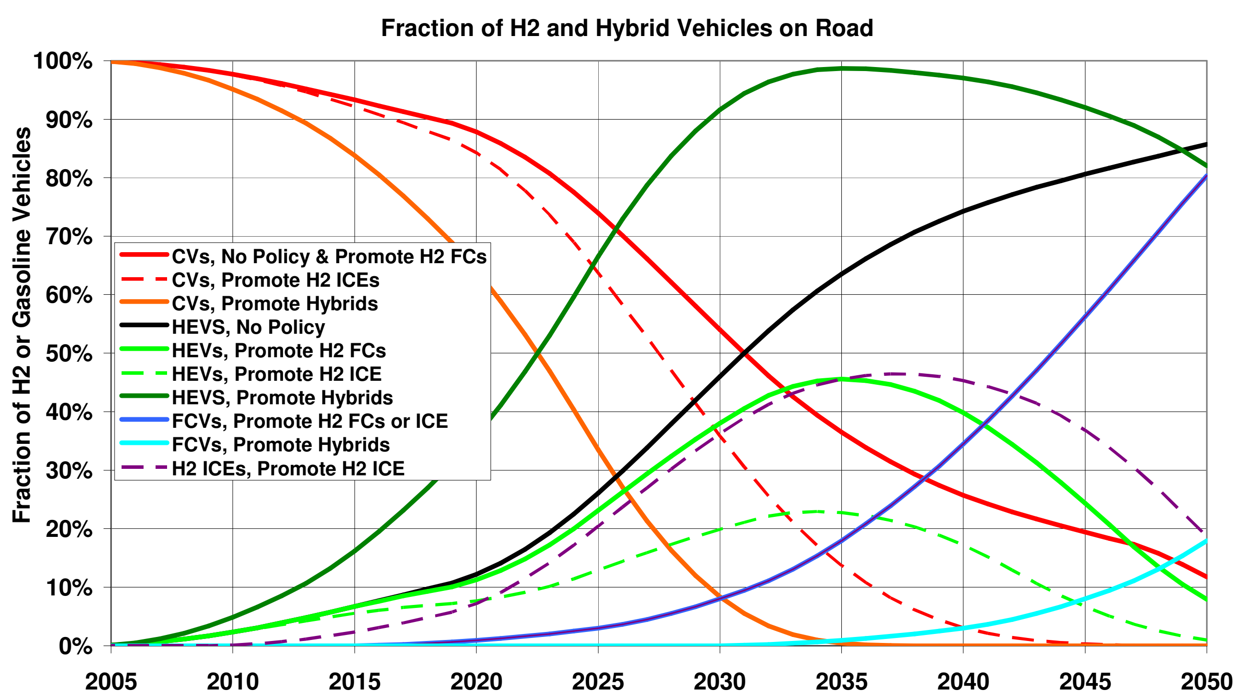


Figure 3. Scenarios of Vehicle Adoption. Top: New Vehicles; Bottom: Vehicle Fleet.

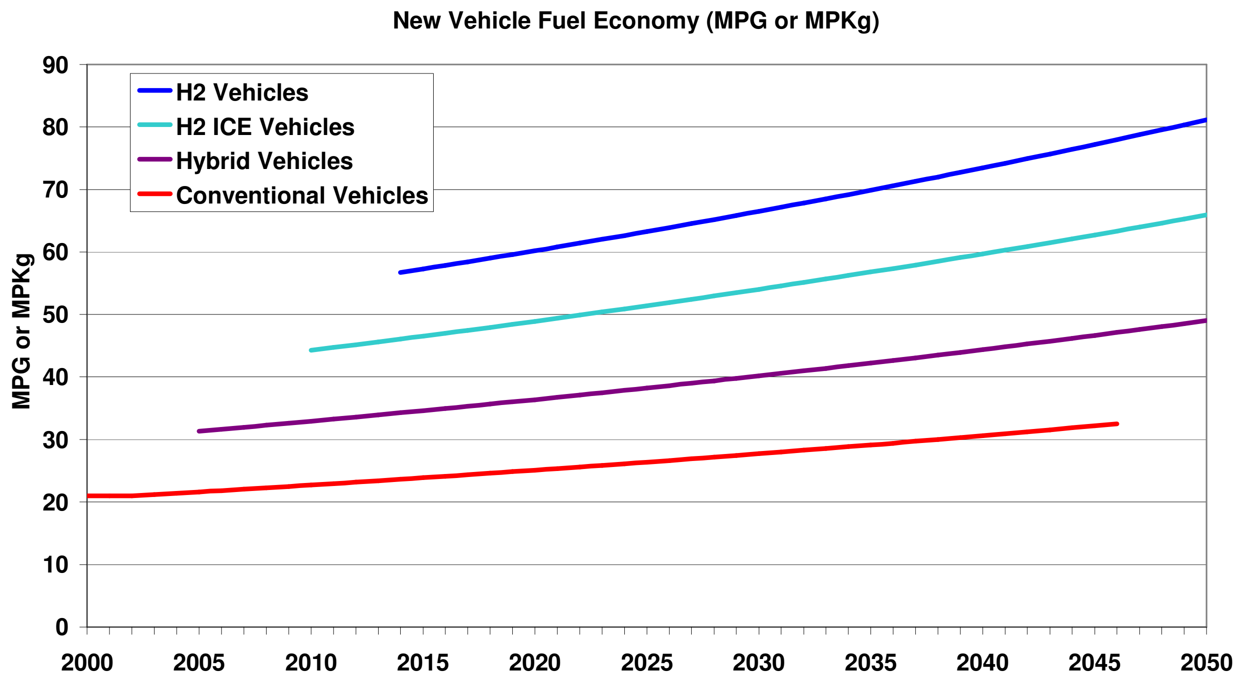
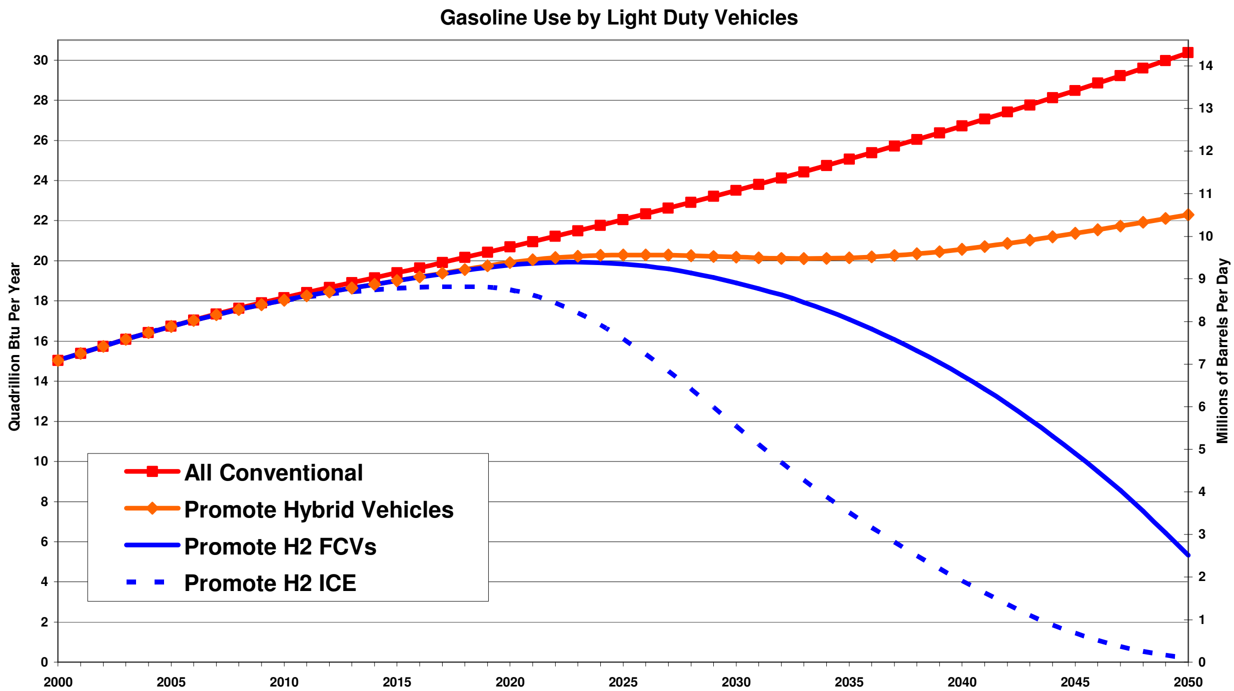


Figure 4. Average Fuel Economy Assumptions for Conventional, Hybrid, Hydrogen ICE, and Hydrogen FC Vehicles.



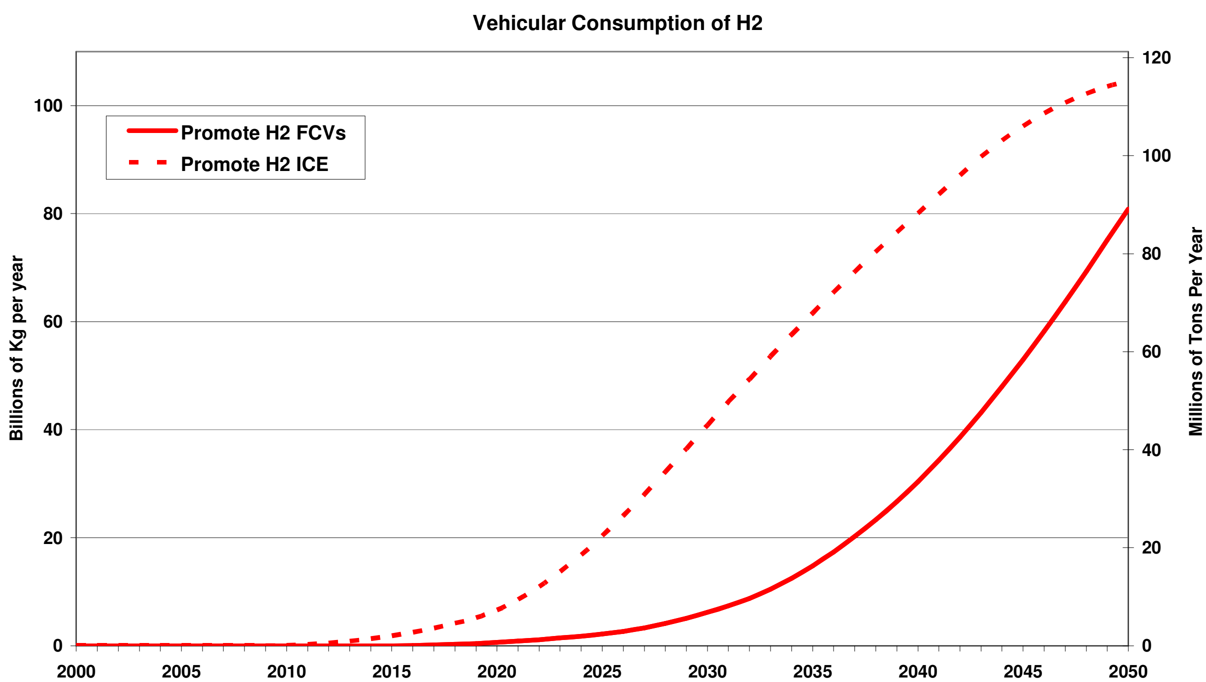


Figure 5. Gasoline Use by Light Duty Vehicles in the Four Scenarios and Hydrogen Use in the Hydrogen Scenarios.

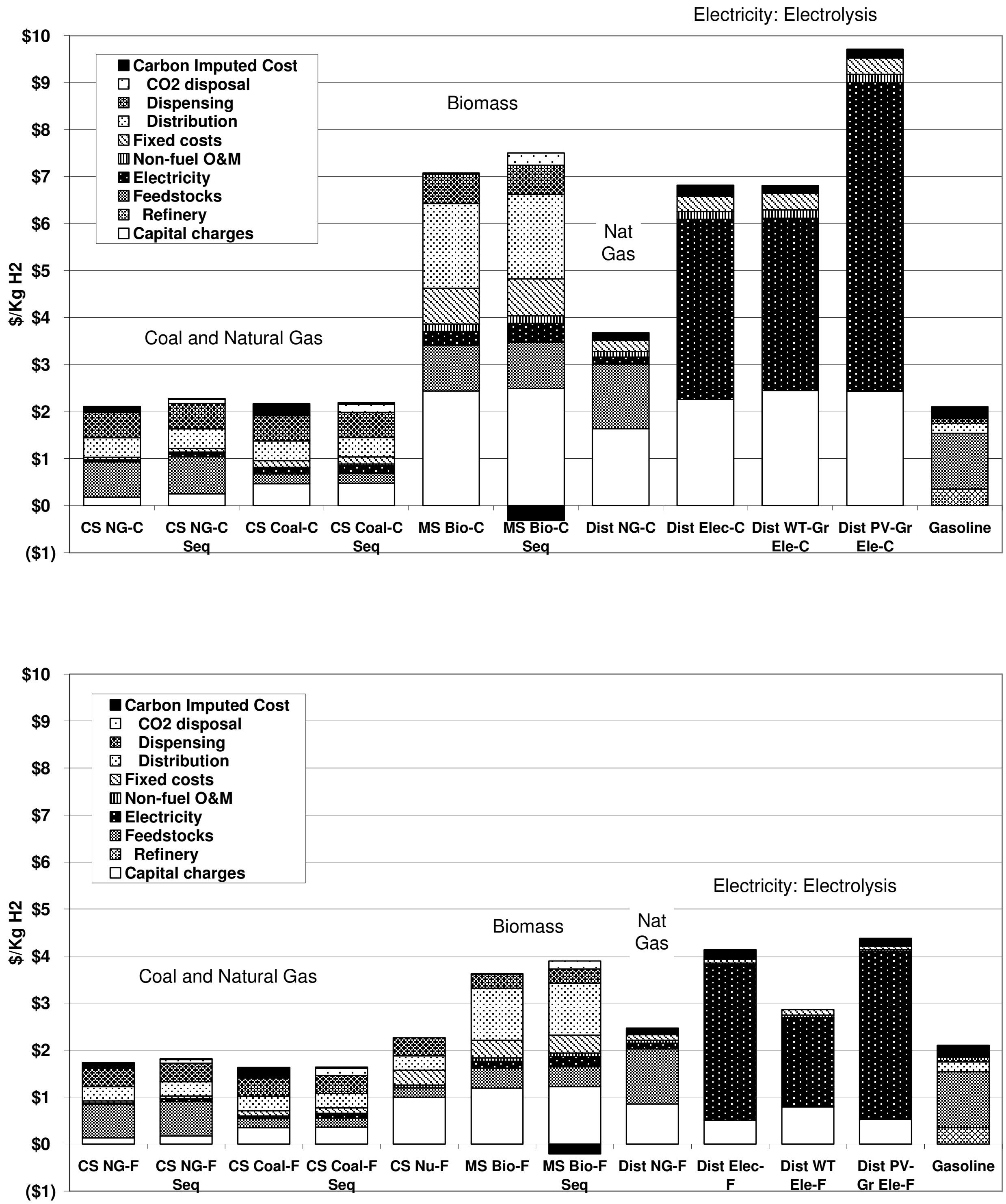


Figure 6. Hydrogen Cost Estimates. Top: Current Technologies; Bottom: Future Technologies.

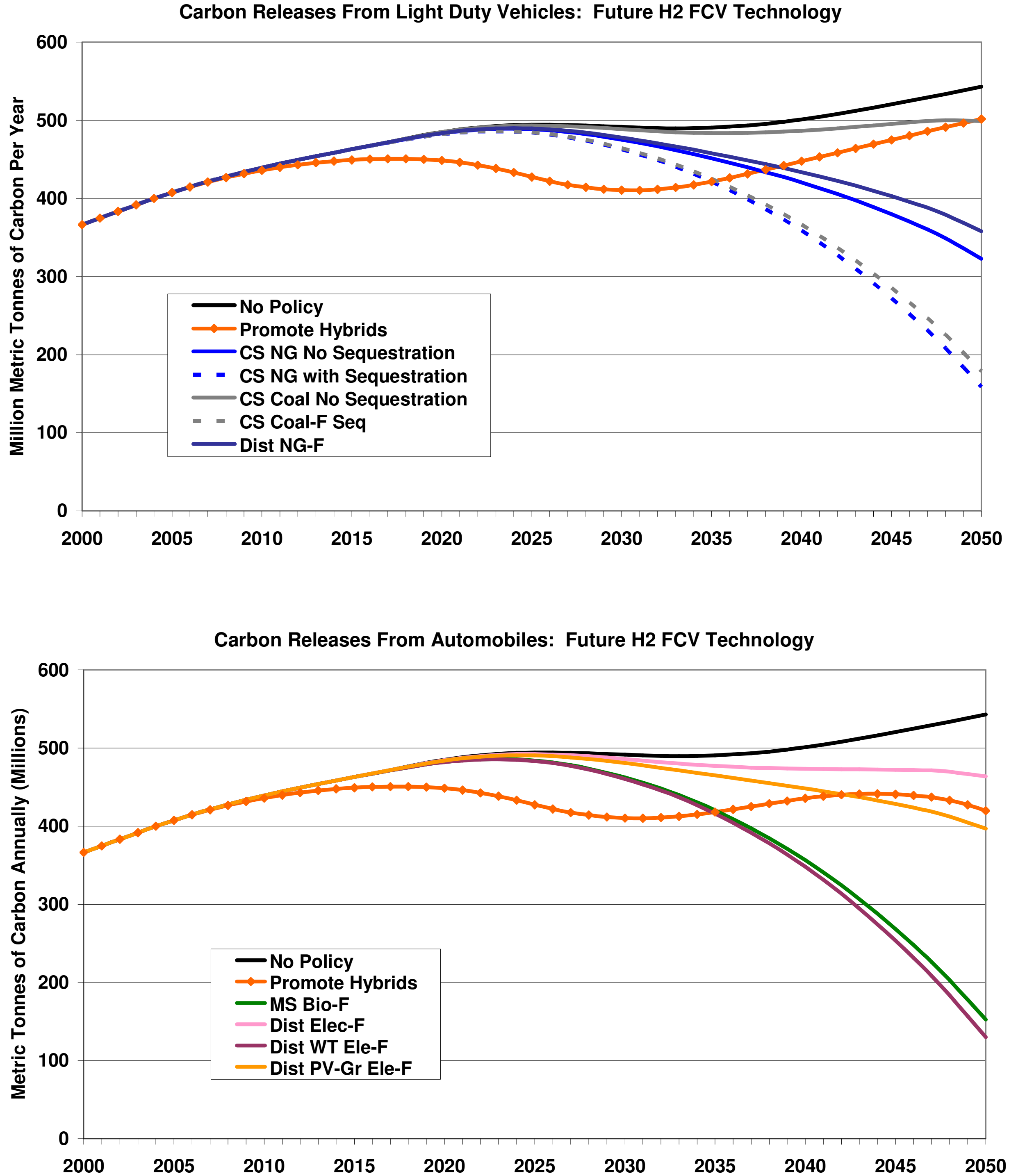
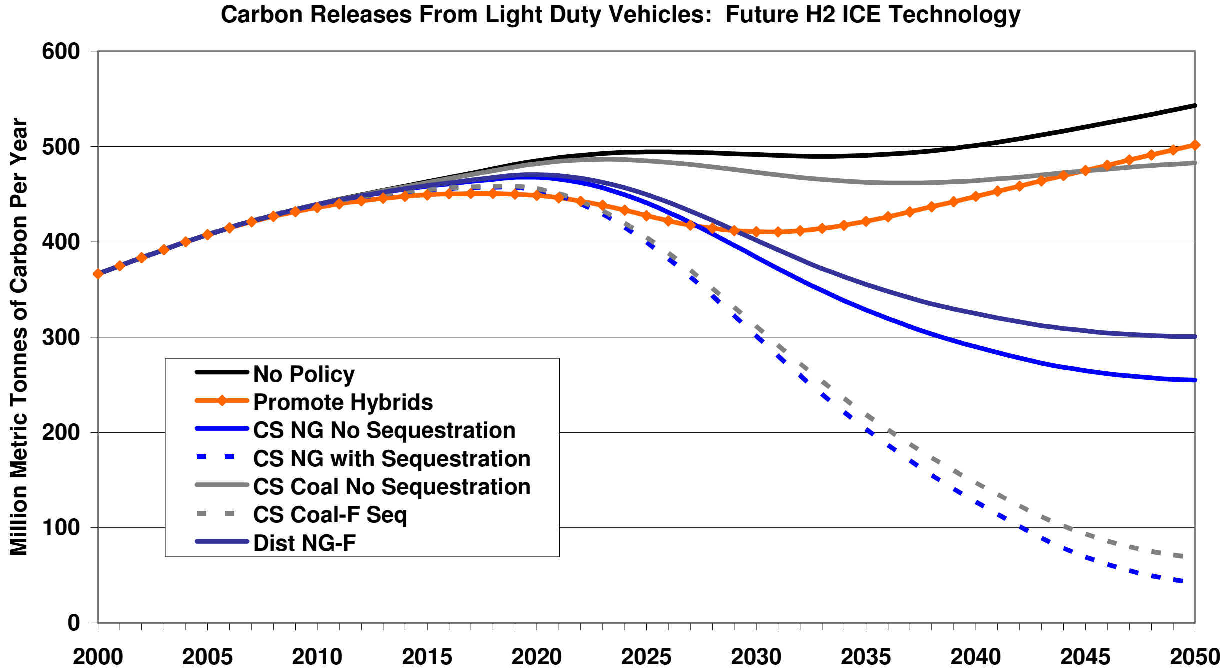


Figure 7. Carbon Dioxide Emissions for Various Feedstocks in the Hydrogen FCV policy scenario (Future Technologies)



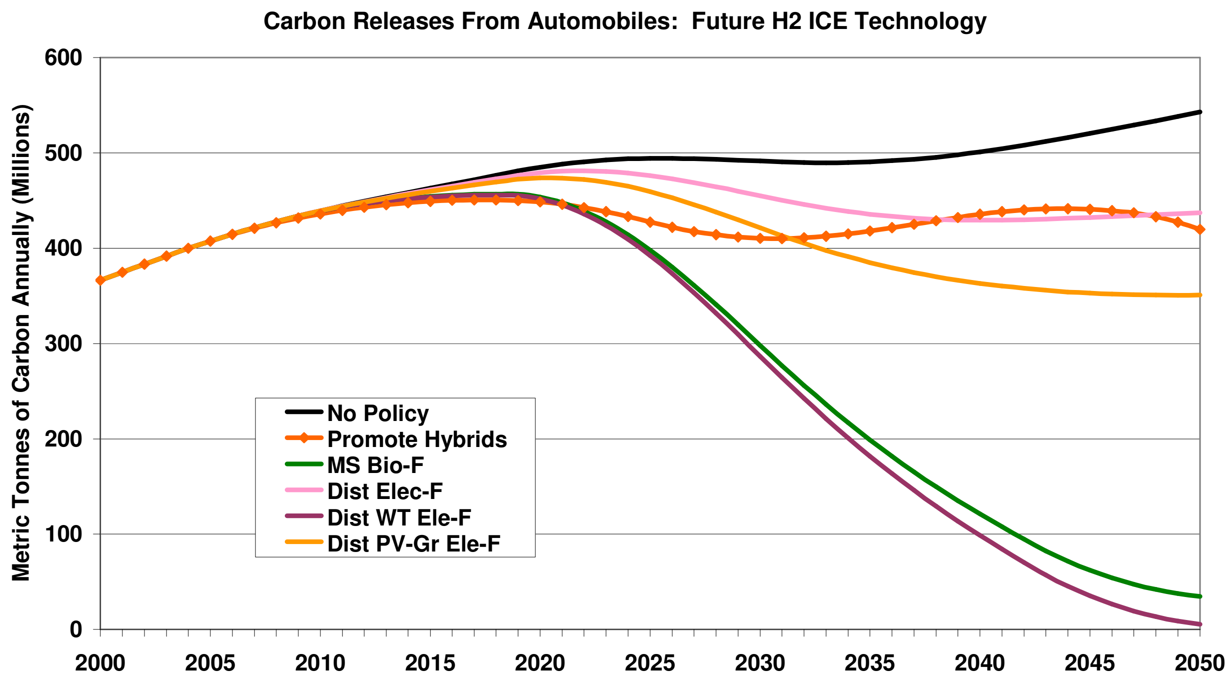


Figure 8. Carbon Dioxide Emissions for Various Feedstocks in the Hydrogen ICE policy scenario Feedstocks (Future Technologies)

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