

An Integrated Assessment of the Impacts of Hydrogen Economy on Transportation, Energy Use, and Air Emissions

With the most cost-effective sources of hydrogen likely to be natural gas and coal, consideration of cross-sector fuel use and emissions impacts is essential.

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ABSTRACT | This paper presents an analysis of the potential system-wide energy and air emissions implications of hydrogen fuel cell vehicle (H₂-FCV) penetration into the U.S. light duty vehicle (LDV) fleet. The analysis uses the U.S. EPA MARKET ALlocation (MARKAL) technology database and model to simultaneously consider competition among alternative technologies and fuels, with a focus on the transportation and the electric sectors. Our modeled reference case suggests that economics alone would not yield H₂-FCV penetration by 2030. A parametric sensitivity analysis shows that H₂-FCV can become economically viable through reductions in H₂-FCV costs, increases in the costs of competing vehicle technologies, and increases in oil prices. Alternative scenarios leading to H₂-FCV penetration are shown to result in very different patterns of total system energy usage depending on the conditions driving H₂-FCV penetration. Overall, the model suggests that total CO₂ emissions changes are complex, but that CO₂ emission levels tend to decrease slightly with H₂-FCV penetration. While carbon capture and sequestration technologies with H₂ production and renewable technologies for H₂ production have the potential to achieve greater CO₂ reductions, these technologies are not economically competitive within our modeling time frame without additional drivers.

KEYWORDS | Carbon dioxide; energy modeling; greenhouse gases; light duty vehicles; Monte Carlo simulation; sensitivity analysis; transportation

ACRONYMS

AEO	Annual Energy Outlook
CG	coal gasification
CNG	compressed natural gas
ETL	endogenous technological learning
FCV	fuel cell vehicle
H ₂	hydrogen
H ₂ -FCV	hydrogen fuel cell vehicle
HEV	hybrid electric vehicle
ICE	internal combustion engine
LDV	light duty vehicles
MARKAL	MARKet ALlocation energy system model
MC	Monte Carlo
NRC	National Research Council
O&M	operation and maintenance
SMR	steam methane reforming
WTW	well-to-wheel life cycle analysis

I. OVERVIEW OF H₂ PRODUCTION HISTORY AND FUTURE PATHWAYS

Hydrogen (H₂) is a versatile energy carrier, with the potential for extensive use in electricity generation, industrial, commercial, residential, and transportation sector applications. H₂ is combustible, but can also be combined with oxygen within fuel cells to create electricity. H₂ fuel can be extracted from water or through processing of carbon-rich feedstocks, such as natural gas,

Manuscript received April 11, 2006; revised June 28, 2006.

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Digital Object Identifier: 10.1109/JPROC.2006.883719

coal, biomass, and wastes. Potential applications of H₂ in the transportation sector are currently receiving considerable attention. H₂-powered fuel cell vehicles (H₂-FCVs) are expected to be two to three times more fuel efficient than conventional gasoline-fueled internal combustion engine (ICE) vehicles. Further, unlike conventional ICEs, which emit CO₂ and a myriad of pollutants from combustion, H₂-powered fuel cells emit only water vapor. For these reasons, H₂-FCVs are often promoted as a means to decrease dependence on foreign oil and to reduce greenhouse gas emissions and urban air pollution.

The transition to widespread use of H₂-FCVs presents many challenges, since it requires the parallel introduction of infrastructures for H₂ production, distribution, and refueling. Further, for H₂-FCVs to achieve market penetration, they must be competitive with conventional and alternative technologies, requiring considerable technological advances. There also is uncertainty regarding factors such as safety and the true environmental benefits of H₂-FCV adoption.

In this context, a primary objective of the work presented here is to conduct a system-wide analysis of technological potential for H₂-FCV penetration and to examine the associated H₂ technological pathways, fuel use, and CO₂ emissions implications. This paper presents a first step in an ongoing project being carried out by the National Risk Management Research Laboratory of the U.S. Environmental Protection Agency's Office of Research and Development. The ultimate goal of the project is to evaluate the human health and environmental risks associated with future pollution emissions, accounting for future increases in energy demand and technological change.

In Section I, we provide an overview of current and expected future technologies for H₂ production and use in the transportation sector. Our data, model assumptions, and methodologies for incorporating H₂ pathways into the U.S. EPA MARKAL database and model are described in Section II. In Section III, a parametric sensitivity analysis is carried out to examine the relative importance of factors that affect H₂-FCV adoption. Sensitivity information is used to construct several future H₂-FCV penetration scenarios, each of which is analyzed to evaluate the corresponding least cost technological pathway for hydrogen production and the resulting impacts on system-wide fuel use. This is followed by a Monte Carlo simulation to generalize the energy and CO₂ emissions implications over a wide range of conditions that yield H₂-FCV penetration. Section IV provides conclusions and Section V discusses caveats of the study and identifies future research directions.

A. H₂ Production

H₂ is currently used within the United States and abroad to produce reformulated gasoline, ammonia for fertilizer, food products, and various petrochemicals. In

1999, the United States used more than 90 billion cubic meters (3.2 trillion cubic feet) of H₂, accounting for approximately 20% of global H₂ consumption. Approximately 95% of the H₂ used in the United States is manufactured via steam methane reforming (SMR) of natural gas [1]. Steam Reforming can also be applied to other H₂-rich fuels, including methanol and gasoline. The high-pressure, high-temperature SMR of natural gas technology used in many refineries is currently the least expensive large-scale method for H₂ production. The technology can be scaled down to as little as 0.1 million standard cubic feet per day (scf/day), sufficient for application at vehicle refueling stations, albeit at high cost. There is some expectation that these costs will be reduced dramatically in the near future, however [1], [2].

H₂ also can be produced using other commercially proven technologies, including gasification and water electrolysis. Since World War II and before the widespread availability of natural gas, coal gasification was the preferred method of H₂ production in the United States. This technology, which is still used in several countries (e.g., China and Europe [2]), processes coal at high temperature to produce a syngas that consists primarily of H₂ and carbon monoxide (CO). CO is removed via a CO shift reactor, and the remaining H₂ gas is purified. This process is applicable to other solid hydrocarbon feedstocks as well, such as biomass and waste. It is possible to capture and sequester CO₂ in a large scale at a reforming plant and gasification plant, though the technology has not yet been commercially applied at a large scale.

Producing H₂ via electrolysis is practiced in small commercial applications today. Electrolysis involves breaking water into H₂ and oxygen using electricity. Electrolysis is highly efficient, currently achieving efficiencies in the 70%–75% range. H₂ can be produced using on-site electrolysis at H₂ refueling stations, and the electricity used in producing the H₂ can be acquired either from the existing electric grid or any other source that generates electricity in sufficient quantity (e.g., a nuclear plant, wind farm, photovoltaic cells, or hydroelectric power plant). Because of the large amount of electricity required, electrolysis is relatively expensive compared to SMR and coal gasification. Production costs can be reduced, however, if electrolyzers are operated during off-peak hours, taking advantage of lower electricity prices. Similarly, studies suggest that siting electrolyzers at wind farms has the advantage of being able to store energy as H₂ when windy conditions occur during times of off-peak demand [3], [4].

Some H₂ production technologies can be downscaled sufficiently to be placed on-board an H₂-FCV. For example, onboard H₂ production can be achieved by converting a liquid fuel (e.g., gasoline) or gaseous fuel (e.g., methanol or natural gas) to H₂. In general, FCVs with on-board reforming are less efficient, more complex, and create additional safety concerns compared to those

without on-board reforming. As a result, all major automakers had suspended their development of on-board reformers by 2003 [5].

B. H₂ Storage and Distribution

While industry has experience producing H₂, the distribution and delivery infrastructures required to support widespread H₂-FCV adoption face considerable hurdles. A major barrier is that H₂ is expensive to transport, store, and distribute [1], [6]. As a result, industry may not be committed to the substantial investments that are required without sufficient consumer demand or government intervention. Similarly, consumers will not purchase H₂-FCVs unless the refueling infrastructure is convenient and H₂-FCV capital and operation costs are cost-competitive with other technologies.

Historically, H₂ transport to the chemical and aerospace industries via pipelines, road tankers, and barges has had an excellent safety record [6], [7]. Nonetheless, the high combustibility of H₂ makes safety a major issue for distribution and storage, particularly at the scale necessary to support widespread use in the transportation sector. The U.S. Department of Energy and industry are actively working to develop and implement codes, standards, and procedures that address safety concerns [8].

C. H₂-Powered Vehicles

There are several technologies for powering vehicles with H₂. H₂-powered fuel cells combine oxygen from the air with H₂ from the vehicle's fuel tank to produce the electricity that powers the vehicle's electric engines. The transportation sector has already adopted H₂-FCVs, albeit on a small scale. For example, a limited number of H₂-FCV fleets, mainly buses, are currently in operation in Continental Europe, the United Kingdom, and the United States. Iceland currently has three H₂-powered fuel cell buses that are fueled by H₂ produced overnight using electricity from hydropower [9]. More such systems are expected to be available in the next few years, including the California Hydrogen Highway Network [10]. Existing pilot studies have illustrated many of the difficulties that must be addressed before widespread FCVs adoption can be realized. These include high costs, low reliability and durability, and concerns about size, weight, and safety of the vehicles.

As a transitional step before H₂-FCV technologies become more practical, several automakers are developing vehicles that burn H₂ directly within an internal combustion engine (H₂-ICEs) [11]. H₂-ICEs and H₂-ICE electric hybrid vehicles are expected to be considerably more efficient than conventional vehicles. H₂-ICE technologies are not included in the analyses presented in this paper.

D. Emissions From the Use of H₂-FCV

When FCVs are fueled with pure H₂, they emit only water vapor as exhaust. If the energy source used to gen-

erate H₂ is a fossil fuel (or electricity derived from fossil fuels), however, emissions from the industrial and electric generation sectors occur. The introduction of H₂-FCVs thus involves a tradeoff between transportation emissions and those from other sectors, requiring a system-wide analysis to characterize overall impacts.

The most common approach for examining the system-wide energy use and emissions associated with alternative technologies is life cycle analysis, which is known as well-to-wheel (WTW) analysis when comparing the life cycle emissions of motor vehicles. WTW analysis has been applied to evaluate the implications of H₂-FCVs by considering the emissions associated with: 1) extraction and transportation of primary energy feedstocks; 2) fuel production, transportation, and distribution; and 3) fuel uses during vehicle operations. Most such analyses suggest the potential for great variations in total energy use and emissions, depending on the choice of H₂ production and transportation pathways [12]–[17]. For example, some studies suggest that the WTW energy use associated with a H₂-FCV is 20%–50% less than that of a conventional gasoline-powered ICE, provided the H₂ is produced via SMR of natural gas. There is little difference in total energy use, however, when compared to expected future gasoline and diesel hybrid electric vehicles (HEVs) [12], [14], [18], since these technologies are expected to be much more efficient than conventional vehicles. In contrast, H₂ generation via grid-based electricity is expected to increase total energy use due to the inefficiencies of electricity generation and distribution [14].

WTW analyses suggest that CO₂ emissions follow a pattern similar to energy use. For example, H₂-FCVs using H₂ produced from SMR of natural gas have lower system-wide CO₂ emissions than conventional vehicles. If the H₂ is produced from coal gasification (without carbon capture and sequestration), however, CO₂ emissions are expected to increase [18]. CO₂ emissions from the industrial and electric generation sectors potentially can be reduced via carbon capture and sequestration during H₂ production, provided that sequestration options prove to be practical at a large scale [2], [5], [6]. Net CO₂ emissions reduction can also be achieved by using renewable energy sources in H₂ production [19].

The energy system analysis presented in this paper differs from WTW analyses in several significant ways. While WTW is a straightforward supply-chain model, energy system modeling examines the economic and emissions impacts of H₂-FCVs by examining dynamic relationships with other energy-using technologies and fuels, both within and across sectors. For example, emission reductions in the transportation sector depend not only on the penetration level of H₂-FCVs but also on the market shares of other vehicle technologies; displacement of HEVs by H₂-FCVs would likely have very different implications than displacement of conventional ICEs. Cross-sector effects are also important. For example, the

penetration of H₂-FCVs could increase the use of natural gas in H₂ production. This, in turn, would increase natural gas prices, potentially leading to decreased use of natural gas and increased use of coal in the electricity generation sector. Eventually an equilibrium between fuel usage and prices among sectors would be reached, and these new changes would have implications on overall energy usage and emissions. In contrast to WTW analyses, our energy system model is designed to account for these interactions.

II. REPRESENTING H₂ PRODUCTION AND USE IN THE MARKAL MODEL

The H₂ production pathways that are examined in this paper include: 1) SMR of natural gas (referred to as SMR throughout the rest of the paper); 2) coal and biomass gasification; and 3) electrolysis using grid-based electricity, wind, and solar power. Most of these options can be employed at a central plant, midsize plant, or on-site at a refueling station. Modeled pathways, including generation and usage, are illustrated in Fig. 1.

A. Modeling Energy Systems in the U.S. EPA MARKAL Database and Model

MARKAL is a bottom-up, linear programming model that explicitly represents current and future energy system

technologies, including characteristics such as capital and operational and maintenance costs, fuel efficiency, emissions, and useful life. MARKAL accounts for this information, as well as for fuel supply and emissions constraints, in identifying the most cost-effective technological pathway to satisfy future end-use demands at the international, national, regional, state, or community level [20]. MARKAL assumes rational decision-making, with perfect information and perfect foresight, and optimizes over an entire multi-year modeling period simultaneously based on a pre-specified consumer discount rate. MARKAL is typically applied in long-term analyses, often modeling 30–50-year time horizons in 3–5-year time steps. MARKAL was originally developed by U.S. Department of Energy and the International Energy Agency for energy-system modeling and analysis in the late 1970s and is now used by over 40 countries to conduct analysis in energy planning and environmental policy formulation.

Because MARKAL is an optimization model, it is used in activities such as identifying low cost technological pathways to meet environmental goals, assessing the potential for certain technologies to penetrate the market, identifying the cost tipping points that would favor one technology or another, analyzing the cross-sector fuel use and emissions implications associated with a technological

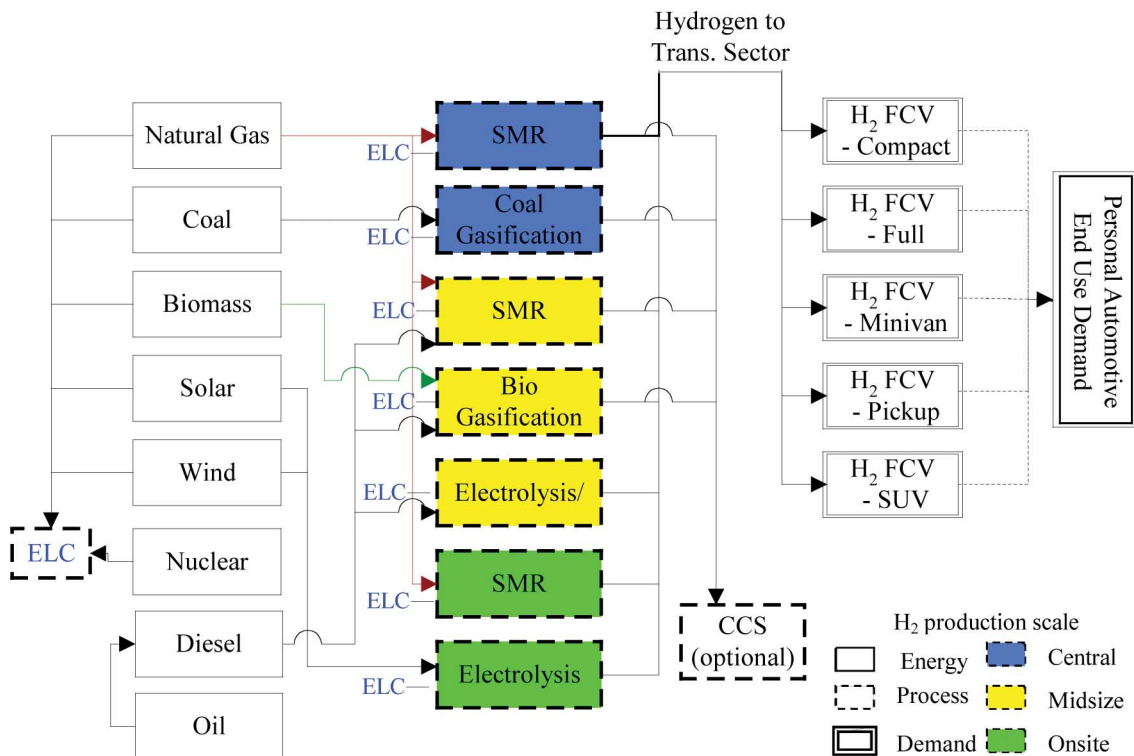


Fig. 1. Schematic illustration of H₂ pathways. ELC represents electricity.

Table 1 Pathways Examined in This Report

GH₂ and LH₂ stand for gaseous and liquid H₂, respectively. CCS in the Abbreviation column stands for carbon capture and sequestration. Source: Modified from National Research Council [5].

pathway, and evaluating specific energy system scenarios. It should be noted that MARKAL is *not* a simulation model, and its results should not be interpreted as forecasts of the future.

The MARKAL model is a framework representing a generic energy system. This framework must be populated with data specific to the particular energy system being modeled. The Atmospheric Protection Branch of EPA’s National Risk Management Research Laboratory is developing the U.S. EPA MARKAL national technology database for this purpose. The current database includes a national-scale characterization of technologies, fuels, and energy demands for the years 2000–2030, utilizing 5-year time steps. Five economic sectors are included in the U.S. EPA database: electric, transportation, industrial, residential and commercial. A detailed description of the U.S. EPA MARKAL database and model documentation is provided by U.S. EPA [21].

B. Representation of the H₂ Infrastructure Within the MARKAL Technology Database

A H₂ module in the U.S. EPA MARKAL database incorporates H₂ pathways and cost data provided in the recent National Research Council (NRC) report [5]. The report assumes three scales of H₂ production: central plant, midsize plant, and onsite generation at the refueling station. For each pathway, the capital cost of H₂ production technologies is calculated as the sum of the production (including compression), distribution (e.g., liquefaction, storage, pipeline cost, and liquid H₂ tanker cost) and dispensing costs (e.g., compression, storage, and dispensing). The production pathways are summarized in Table 1. Other detailed assumptions on the plant size, configuration, fuel transportation and storage, cost, and emissions can be found at the Appendix E of the NRC report [5].

Fig. 2 depicts the capital investment cost for each H₂ production pathway, broken down by production, distri-

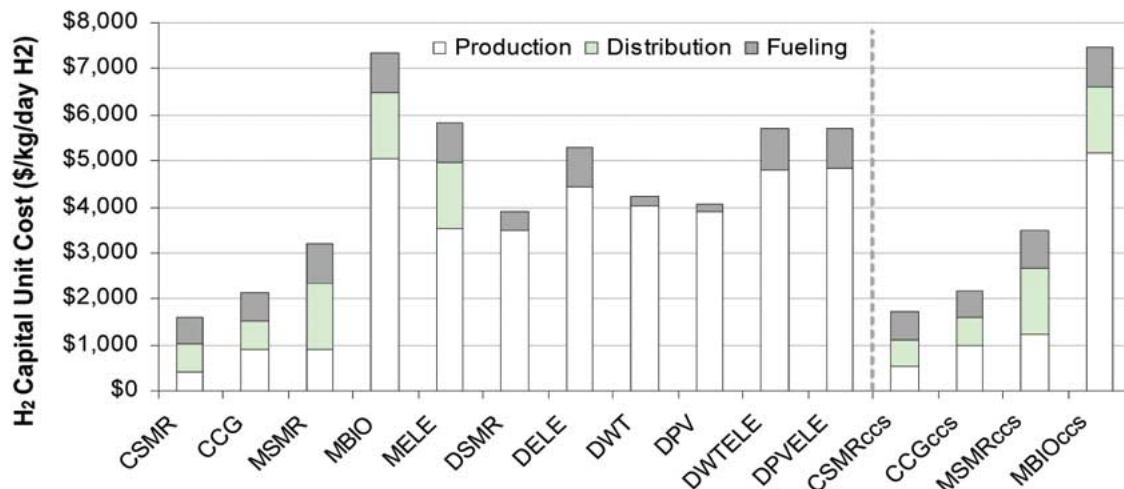


Fig. 2. Capital investment cost of H₂ production technologies. Each value includes the costs of production, distribution and fueling.

Table 2 Assumptions for Major Light Duty Passenger Vehicles

Vehicle lifetimes are assumed to be 15 years. Source: [22], [23]. The reported vehicle fuel efficiencies are adjusted by the fuel efficiency “degradation” factors from the EIA’s Annual Energy Outlook (AEO) 2004 transportation demand module that converts Environmental Protection Agency-rated fuel economy to actual “on the road” fuel economy.

bution, and fueling costs. Among the H₂ production technologies considered, on-site generation and production from renewable sources have the highest capital costs per unit of H₂. H₂ produced from natural gas and coal gasification have the lowest capital costs, even with the option of carbon capture and sequestration. The production costs of H₂ fuel depend greatly on the costs of the fuels, which will be modeled endogenously in the energy system model.

Emissions due to the use of electricity in H₂ generation and compression are calculated based on fuel inputs to electricity generation, and thus are attributed to the electricity generation sector of the model. Emissions that are directly released in H₂ production are attributed to the industrial sector.

C. Characterization of H₂-FCVs

The data for H₂-FCVs and other light duty vehicles is obtained primarily from the Quality Metrics (QM) report by the U.S. Department of Energy (DOE) [22] and DeCicco *et al.* [23]. Compared with several other studies [23]–[28], assumptions in the these sources regarding future costs and efficiencies of H₂-FCVs, advanced gasoline-ICE vehicles, and advanced gasoline-HEVs are optimistic.

The vehicles considered in this analysis are light duty vehicles, including compact and full-size automobiles, minivans, sport utility vehicles, and light trucks. Parameters such as size, efficiency, lifetime, and cost for vehicle technologies in the U.S. EPA MARKAL technology database are listed in Table 2 by vehicle technology and year. The competition among technologies is based on capital costs and fixed and variable operation and maintenance (O&M) costs. The variable O&M costs largely depend on fuel efficiency and the prices of the fuels, with

fuel prices being calculated endogenously by the model based on market supply and demand. In the database, the fuel efficiencies for H₂-FCVs are, on average, three times more efficient than conventional gasoline ICE vehicles and 50% higher than advanced gasoline-HEVs in 2030. The capital costs of H₂-FCVs in 2030 are, on average, 15% and 10% higher than gasoline-ICE vehicles and advanced gasoline-HEVs, respectively.

D. Model Options and Configuration

This section describes additional modeling techniques and constraints applied within the H₂ module of the U.S. EPA MARKAL model.

Endogenous Technological Learning (ETL): Technological learning refers to the phenomenon by which the performance, productivity, and cost of a technology improves as the technology is applied and knowledge and experience accumulate. This phenomenon is recognized as one of the most important factors in driving long-term productivity increases and economic growth [29], [30]. In energy system models with ETL, learning is generally represented by a “learning curve” or “experience curve,” where the unit cost of production declines at a constant rate as experience with the technology grows [31]–[33]. Equation (1) provides a common form for a learning curve

$$Y = ax^{-b} \quad (1)$$

where Y is the estimated average direct unit cost for the x th units; a is the direct unit cost needed to make the first unit; and b ($b > 0$) is a parametric constant.

An 80% “progress ratio,” corresponding to a value of 0.32 for b , is a typical value that has been used in many

applications [30], [34], [35]. This implies that the cost of technology will be reduced to 80% of its original value for each cumulative capacity doubling. In this paper, we use a relatively conservative progress ratio of 90% for all H₂ production technologies. The maturity of each type of H₂ production technology is characterized by its current cumulative capacity, which is obtained from Suresh *et al.* [1]. We also explore the effects of varying the progress ratio in the sensitivity analysis in Section III-B. Note that in this analysis, only H₂ production technologies are represented with endogenous learning, while all other technologies, including H₂-FCVs, have exogenously specified cost data that account for the reduction of technology costs as a function of time.

Hurdle Rates in the Transportation, Residential, and Commercial Sectors: As an optimization model, MARKAL selects technology penetration by competing technologies as a function of their relative capital and O&M costs. Many technologies have lifetimes of 15 years or more. Individual consumers seldom use such long periods to evaluate technology alternatives, however. To address this issue, we use hurdle rates within the model. Hurdle rates are technology-specific discount rates that are used to change the amortization of capital costs over the lifetime of the technology. Within the transportation sector, all vehicle technologies are given a hurdle rate of 0.18, effectively resulting in the technologies being compared over an approximately 6-year time frame. Hurdle rates that differ from one technology to another can also be used to reflect consumer reluctance to accept non-conventional technologies. For example, a higher hurdle rate could be applied to a H₂-FCV compared to a conventional gasoline vehicle to force a shorter “payback” period. Differential hurdle rates are not used in this analysis.

III. APPROACH AND RESULTS

The U.S. EPA MARKAL database and model are applied to analyze the prospects and implications of the adoption of H₂-FCVs, with an emphasis on characterizing H₂-FCV penetrations and system-wide CO₂ emissions in 2030. The analysis includes the following steps: 1) specification and modeling of a reference case, to provide a baseline for comparison; 2) sensitivity analysis, to identify key uncertain variables that drive H₂-FCV penetration; 3) scenario analysis, to evaluate the impacts of optimized hydrogen pathways on energy usage; and 4) Monte Carlo simulation, to examine the impacts of H₂-FCV penetration on energy use and CO₂ emissions over a wide range of penetration scenarios. These steps are each described below.

A. Development and Evaluation of a Reference Case

The reference case represents an optimized technology pathway to meet future demands under our assumptions and should not be interpreted as a forecast of the future.

In addition, the reference case assumes that no carbon emissions constraints or carbon taxes are imposed, although sulfur dioxide (SO₂) and nitrogen oxides (NO_x) emissions from electric utilities are constrained to approximate current air quality regulations. Fig. 3(a) shows the projected energy use in the reference case. Growth in the use of renewables increases, albeit at a very slow rate. Nuclear power is assumed to remain at its year 2000 capacity.

The reference case results suggest that, in 2030, an optimal light duty vehicle mix is composed of 69% advanced gasoline-HEVs, 21% advanced gasoline-fueled vehicles, 4% diesel vehicles, 6% of ethanol vehicles, and less than 1% of CNG, electric vehicles, and LPG (liquefied petroleum gas) vehicles combined [Fig. 3(b)]. Note that the advanced gasoline-HEV represented in the model is a more advanced technology compared to the hybrid currently seen on the market today (Table 2). Overall CO₂ emissions increase from roughly 6850 tons per year in 2005 to 7900 million tonnes per year in 2030, as shown in Fig. 3(c). This increase is driven by increased demand for energy across all sectors, which more than offsets emissions reductions from energy efficiency improvements.

B. Sensitivity Analysis

Sensitivity analysis is used to identify key input variables that drive H₂-FCV penetration and the associated effects on CO₂ emissions. The input parameters that are examined fall into four general categories: H₂ fuel cost, the costs of competing fuels, characteristics of H₂-FCVs, and characteristics of competing vehicles. In addition, we look at sensitivities to learning rate and to growth in demand for light duty vehicle transportation.

Table 3 lists the inputs that are modified for the sensitivity analysis. A range of values for each input is identified. These ranges, in general, reflect the ranges of values that are observed from various reported energy modeling assumptions and projections [13], [26]–[28]. To carry out the sensitivity analysis, the inputs are modified parametrically (e.g., the value of one input is varied while holding the other inputs at their reference values). Note that the added external costs of fuels in MARKAL do not necessarily match the resulting changes in *prices* of those fuels in equilibrium, since prices are calculated endogenously. For example, raising the cost of producing H₂ would potentially decrease the consumption level of H₂ fuel. The final price of H₂ will be the partial equilibrium price calculated by the model.

Fig. 4(a) shows the relative effects of changes in each of the inputs on H₂-FCV penetration into the light duty vehicle fleet in 2030. The results suggest that H₂-FCV penetration in the optimized solution is sensitive to H₂-FCV capital cost: a 5% decrease in H₂-FCV cost yields an increase in penetration from 0% to about 4% in 2030. Note that this high sensitivity is partly an artifact of the optimistic H₂-FCV capital costs assumed in the reference case.

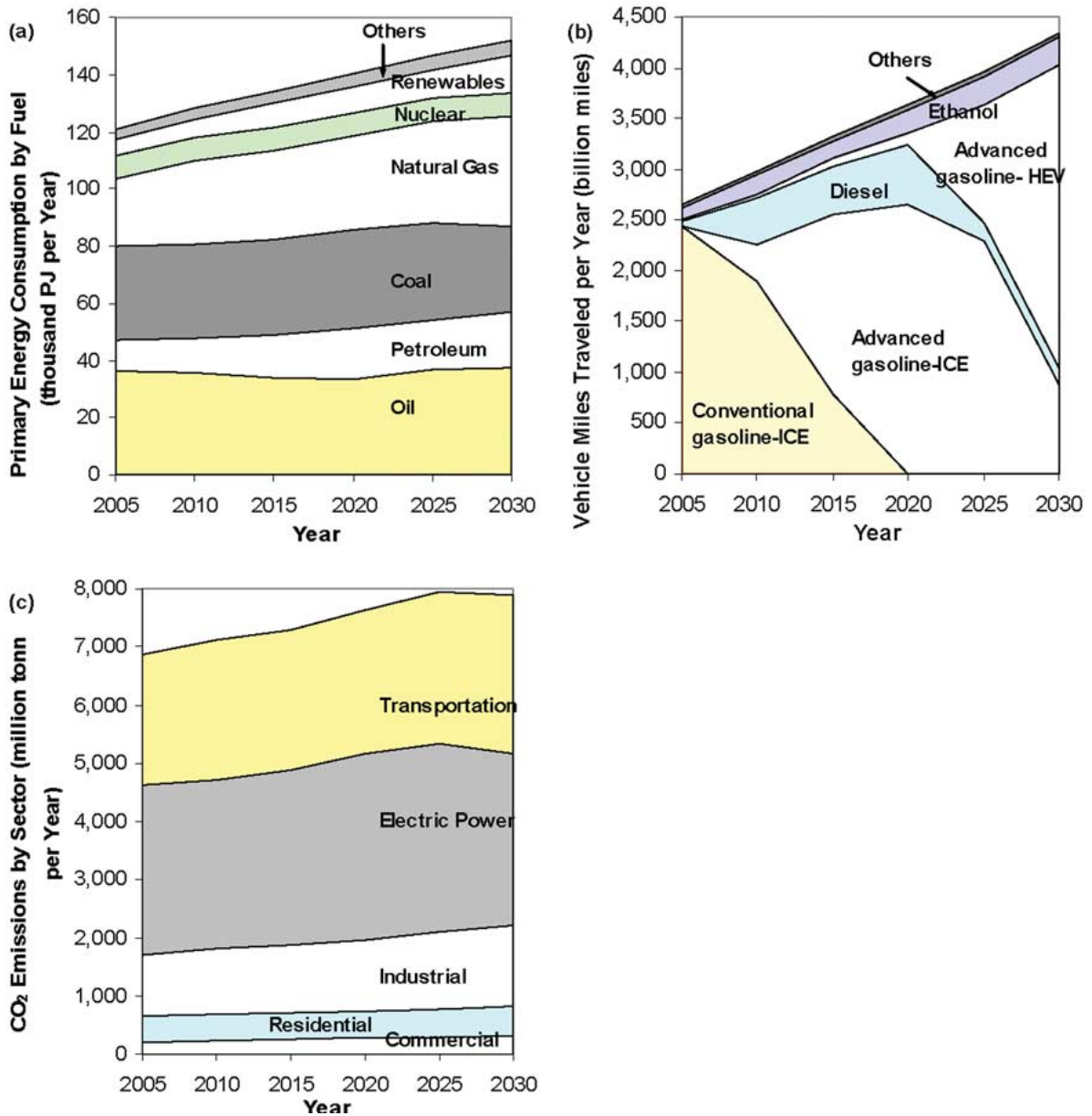


Fig. 3. Reference case. (a) Energy usage by sector. (b) Vehicle technology penetrations in the light duty vehicle (LDV) market. (c) Carbon dioxide emissions by sector.

The cost of advanced gasoline-HEVs, the main competitor to H₂-FCVs, also has considerable impacts on penetration: if advanced gasoline-HEVs are only 5% more expensive than their reference values, penetration of H₂-FCVs occurs. Increases in long-term oil costs also have the potential to drive H₂-FCV penetration, albeit at a smaller sensitivity. For example a long-term increase in the costs of oil by 100% over the reference case in 2030 yields an increase in H₂-FCV penetration from 0% to 7% in 2030.

H₂-FCV penetration is not sensitive to the parametric changes in the other factors listed in Table 3. For example, the changes in H₂ costs did not drive H₂-FCV penetration.

This is partly explained by the fact that the 18% hurdle rate is used for light duty vehicles. A hurdle rate higher than the 5% discount rate effectively increases the relative weight of capital cost to operations cost in competing one vehicle technology against another. In separate model runs using a hurdle rate of 5% (not shown), H₂-FCV penetration is sensitive to the cost of H₂, but to a lesser degree than H₂-FCV capital cost.

Fig. 4(b) shows the response of system-wide CO₂ emissions to parametric changes in the inputs in Table 3. As the cost of natural gas increases, we see fuel switching from natural gas in the electric sector to coal, oil and

Table 3 Parameters Modified in the Sensitivity and Uncertainty Analysis

The table includes the reference, minimum, and maximum values in a uniform distribution for each variable. The uncertain range for each variable covers most projections and assumptions used in the following references: [13], [26]–[28].

diesel, and renewables, resulting in net overall CO₂ emissions increase. On the other hand, a decrease in natural gas costs does not necessarily reduce net CO₂ emissions, since natural gas offsets the use of renewables in the electricity generation. Increases in oil cost change fuel consumption and technology adoption patterns in many sectors. For example, increased oil costs decrease the penetration of gasoline vehicles while increasing the penetration of al-

ternative fuel (H₂ and CNG) vehicles. High oil costs also decrease the use of oil, diesel, and coal, and increase the use of renewables and natural gas for power generation. There is a net reduction in CO₂ emissions from these changes. Increases in advanced gasoline-HEV cost yields higher CO₂ emissions than the reference case due to increased penetration of gasoline-ICEs and H₂-FCVs at the expense of gasoline-HEVs.

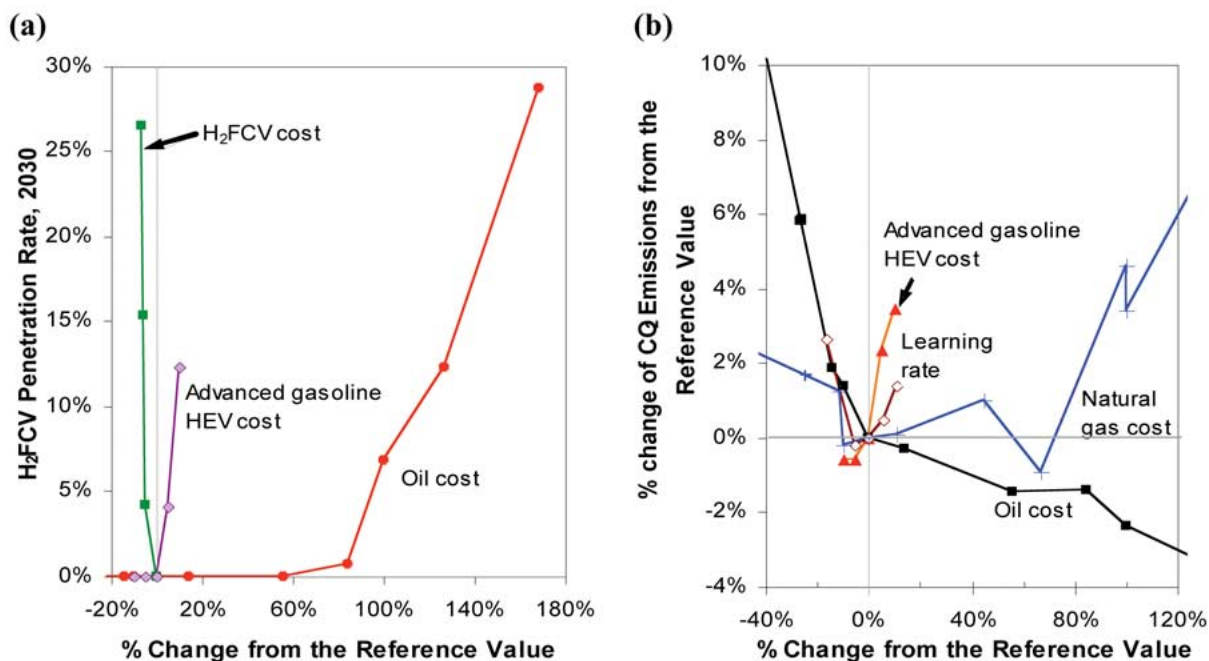


Fig. 4. Sensitivity analysis of input variables on: (a) H₂-FCV penetration rate in 2030 and (b) percent changes of CO₂ emissions from the reference case, 2030. The x axis captures the reference value, maximum, and minimum values of input variables as described in Table 3 (except for oil and natural gas with wider ranges).

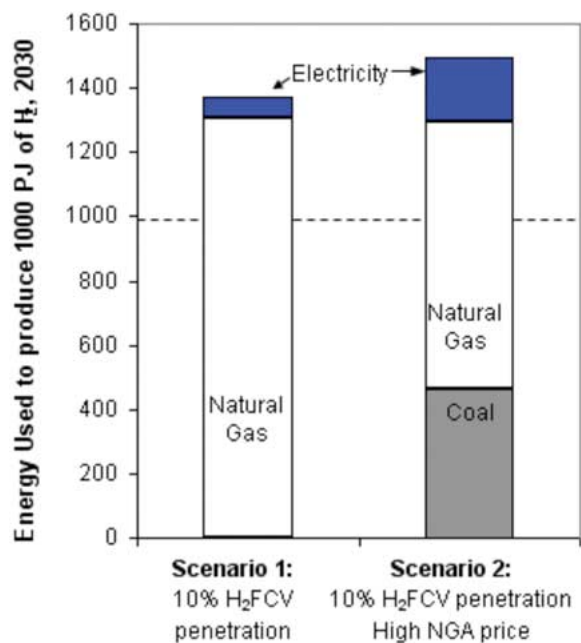


Fig. 5. Projected energy feedstock demands to produce H₂-fuel for H₂-FCVs in two scenarios: Scenario 1: 10% H₂-FCV penetration scenario in 2030, and Scenario 2: 10% H₂-FCV penetration scenario in 2030 with high natural gas cost.

C. Scenario Analysis

The results of the sensitivity analysis are used to identify two sets of alternative future scenarios. The first set includes two scenarios in which H₂-FCVs are forced to achieve a 10% penetration level in 2030. In Scenario 1, all other inputs are assumed to be the same as in the reference case. Scenario 2 is the same as Scenario 1, except future natural gas costs are assumed to be roughly twice those of the reference case.

Fig. 5 shows the energy inputs for hydrogen production in Scenarios 1 and 2. All H₂ production in Scenario 1 is via onsite SMR, as this is the least cost production option. In Scenario 2, H₂ is produced both from onsite SMR and centralized coal gasification. Since centralized coal gasification technology consumes more electricity per unit of H₂ produced, a greater amount of total system energy is consumed in the high natural gas cost scenario.

In the second set of scenarios, we do not constrain H₂-FCV penetration to attain a particular level, but instead evaluate the effect on the system of two drivers that independently yield penetrations of 12% in 2030 as presented in the earlier sensitivity analysis (Section III-B). In Scenario 3, the cost of advanced gasoline-HEVs is increased by approximately 10%, while in Scenario 4, future-year oil costs are increased by 126%. For these scenarios, Fig. 6 shows the changes in system-wide fuel use per PJ of hydrogen generated.

Fig. 6 shows very different system effects and energy consumption patterns for the two scenarios. In both, H₂ is

produced via onsite SMR, and thus consumes natural gas and electricity. In Scenario 3, high advanced gasoline-HEV cost not only induces the penetration of H₂-FCVs, but also increases the use of conventional and advanced gasoline-ICE vehicles. Though the overall demand for oil in the transportation sector decreases, the uses of oil and diesel for electric generation increases in response. Since H₂ fuel is produced via SMR of natural gas, the use of natural gas in the electric sector decreases but the use of coal increases. The total system energy use, including coal, natural gas, petroleum, oil, and renewable, increases by roughly 2% compared to the reference case for the same levels of demands in 2030.

In Scenario 4, the overall energy use shows a very different picture. High oil and petroleum costs reduce the overall use of oil and petroleum energy feedstocks, and induce the penetration of advanced gasoline-HEV vehicles and alternative-fuel (CNG and H₂) vehicles. The increased cost of oil does not have large impacts on the electric sector, however. In contrast to Scenario 3, the overall system uses less total energy to satisfy the same level of economy-wide demands compared to the reference case. The results from these four scenarios suggest that the system-wide energy impacts of H₂-FCVs are a function of the conditions by which their penetration is induced.

D. Monte Carlo Simulation and Global Sensitivity Analysis

In this section, we carry out a Monte Carlo (MC) analysis to determine if generalizations can be made about system-wide fuel use and emissions across the range of scenarios leading to H₂-FCV penetration. Monte Carlo simulation involves the propagation of distributions on a model's inputs through the model. The inputs considered are listed in Table 3. Uniform, uncorrelated distributions, bounded by the high and low values in the table, are used. Uniform distributions are selected as conservative representations of uncertainty, since more detailed statistical distributions were not readily available. Five hundred realizations of the uncertain inputs are generated using Monte Carlo (MC) sampling and fed into the U.S. EPA MARKAL model. The inputs and outputs for each realization are recorded and analyzed for the year 2030.

Fig. 7 shows histograms of (a) H₂-FCV penetration and (b) total CO₂ emissions in 2030 from all five hundred realizations of the Monte Carlo simulations. The star in each figure represents the bin within which the solution of the reference case falls. An interesting observation from the MC simulations is that H₂-FCVs achieve some degree of penetration in only 6.4% of the five hundred realizations. H₂-FCV penetration occurs almost exclusively in the realizations that exhibit *all* of the following characteristics: relatively low H₂-FCV capital costs, medium-to-high advanced gasoline-HEV costs, and high oil costs.

In those realizations that H₂-FCVs do penetrate by 2030, the mean penetration rate is close to 28% of the

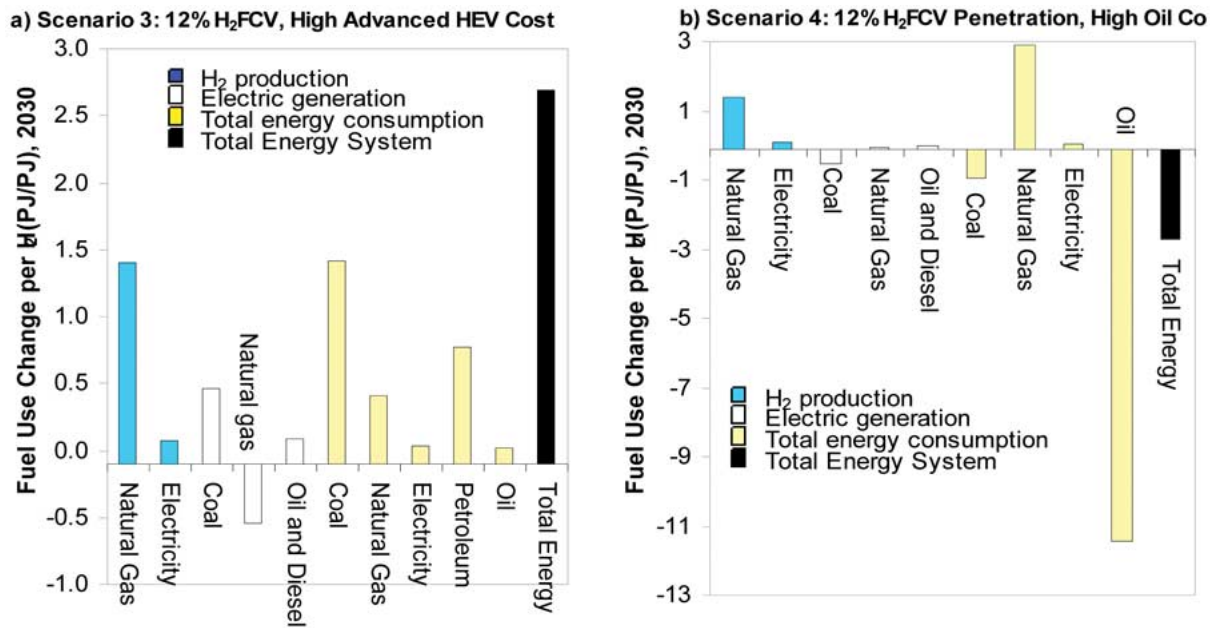


Fig. 6. Normalized fuel use changes from the reference case per H₂ produced (PJ/P) for H₂ production, sector- and system-wide energy changes in two scenarios with identical H₂-FCV penetration rate (2030) but different forcing conditions: (a) Scenario 3: high advanced gasoline-HEV cost, and (b) Scenario 4: high oil and petroleum cost. Note that the two graphs are on different scales.

LDV market in 2030. Fig. 8(a) shows the system-wide fuel use changes for select fuels with respect to the quantity of H₂ fuel produced in 2030. These changes

reflect the feedstock and electricity demands associated with producing, storing, and distributing H₂, the offset of gasoline and diesel as vehicle fuels, and the system effects

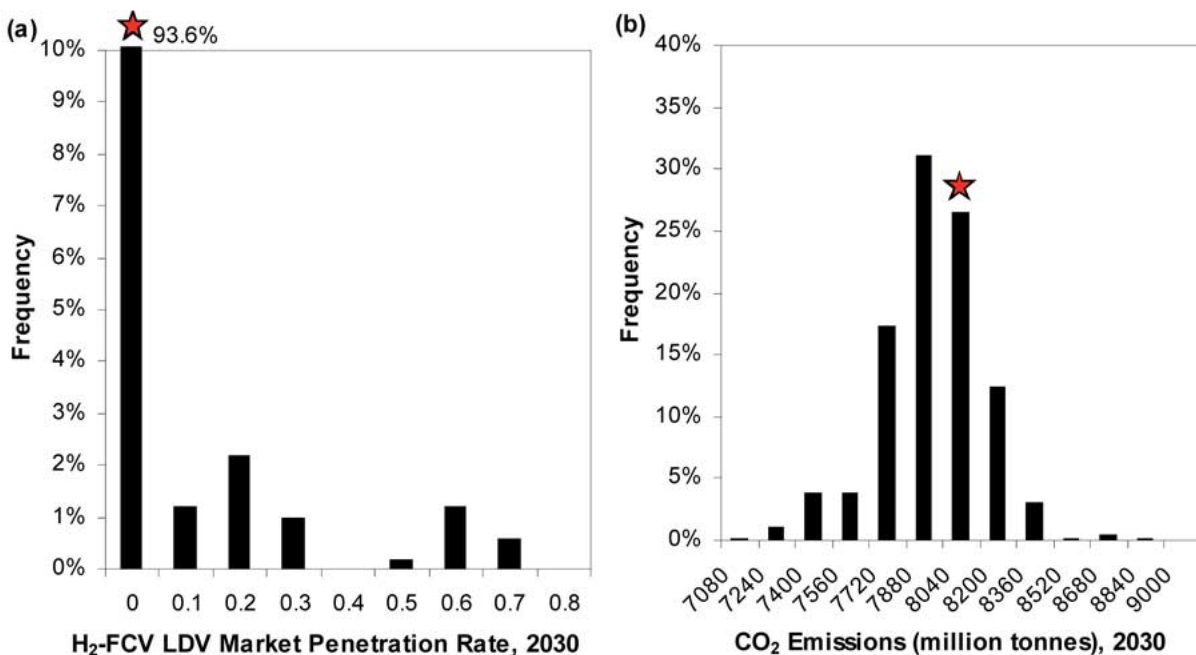


Fig. 7. Probabilistic distributions of the H₂-FCV penetration rate and CO₂ emissions in 2030, based on the Monte Carlo analysis of the uncertain inputs variables listed in Table 3. The star in each figure represents the bin within which the solution of the reference case is.

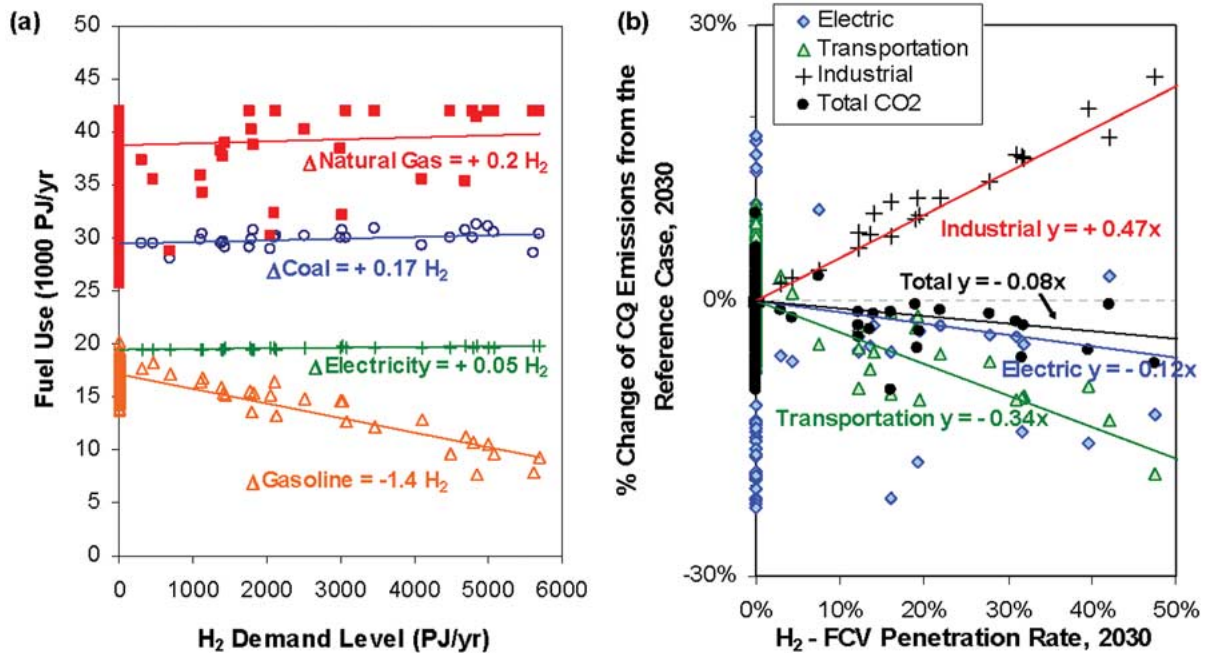


Fig. 8. Results from the uncertainty analysis. (a) System-wide fuel usage (right) by H₂ demand level in 2030. (b) Change of CO₂ emissions (by sector and the system total) versus H₂-FCV penetration in 2030. The regression coefficients are all statistically significant at 0.01 level.

that result from other factors that drove H₂-FCV penetration, such as high oil costs. These values take into account both direct and indirect fuel use, as well as fuel switching in all sectors.

Fig. 8(b) evaluates relationships between CO₂ emissions and H₂-FCV penetration from the MC results. Despite the noise introduced by random sampling, the trends are apparent for industrial emissions (where emissions from energy feedstock to produce H₂ fuel occur) and transportation emissions. For example, H₂-FCV penetration tends to drive down CO₂ emissions from the transportation sector significantly, but increases CO₂ emissions from the industrial sector. The emission changes in the electric sector are much more complex, as many direct (electricity demands for H₂ production, transportation, storage, and dispensing) and indirect factors (fuel-switching and constraints on air pollutant emissions) all play a role. The net result shows that a -0.08% change of total CO₂ emission from the reference case is associated with each percent increase of H₂-FCV penetration in 2030. This trend is statistically significant. The results suggest that the penetration of H₂-FCVs is likely to have system-wide CO₂ emission slightly lower than the reference case in 2030.

IV. CONCLUSION

Widespread adoption of H₂-FCVs has been promoted as being of strategic importance in the pursuit of a low-emission, sustainable energy system. Realizing such a goal will require significant cost and performance improve-

ments in production, storage, conversion, transportation, end-use technologies, reliability, and safety. Our modeling suggests that, based on the technological potential of future vehicles, economic considerations, and assumptions on H₂ production and end-use technologies, advanced gasoline-HEVs would be the dominant vehicle technology from 2020 to the end of our modeling period. Further, with our reference case assumptions, H₂-FCVs are not expected to penetrate the light duty vehicle market driven by economics alone until at least beyond 2030.

Through sensitivity runs involving changes to various technology assumptions and costs of various fuels, we found that, within the range of inputs examined in this paper, the cost of H₂-FCVs, cost of advanced gasoline-HEVs, and cost of oil affect the future penetration rate of H₂-FCVs to various degrees.

Central coal gasification and on-site SMR are estimated to be the dominant technology choices to produce H₂ fuel for transportation use in the solutions of our optimization model. The cost of on-site SMR will be high initially, but is estimated to improve quickly through technological learning after significant technology deployment. Our modeling suggests that H₂-FCV penetration significantly reduces gasoline, oil, and petroleum consumption; however, the change in total system-wide energy consumption is dependent on the conditions driving H₂-FCV penetration.

These results also inform the discussion regarding whether a H₂ economy yields an increase in national energy security, since the most cost-effective H₂ pathways examined reduce, but do not eliminate, the dependence on

fossil fuel imports such as natural gas. According to the Energy Information Administration [36], 30% of the natural gas projected to be used in the United States in 2025 will be imported. Estimated gas reserves worldwide are relatively large compared to oil and widely scattered around the world, though 58% are reported to be located in Russia, Iran, and Qatar [37].

The results also provide insight into the question of whether H₂-FCVs have the potential to greatly reduce greenhouse gas emissions. The results show that H₂-FCV penetration tends to reduce CO₂ emissions from transportation, but increase industrial CO₂ emissions where emissions from energy feedstock to produce H₂ fuel occur. While there is a small net decrease in CO₂ emissions with H₂-FCV penetration, our results suggest that unless H₂ is produced from renewables, nuclear power, or technologies with carbon capture and sequestration, the CO₂ reduction potential will be minor. The potential role of these technologies in achieving emissions reductions will be explored in the future.

V. CAVEATS AND FUTURE RESEARCH

MARKAL provides a systematic mechanism for examining within- and cross-sector competition of technologies and fuels. As MARKAL is an optimization model, readers should keep in mind that the results of this paper are not intended to *forecast* the future, but rather to identify possible pathways that most cost-effectively lead to an H₂ transportation economy, allowing examination of economic barriers and tradeoffs, as well as the cross-sector impacts on energy and CO₂ emissions. Also, in the configuration used in this study, MARKAL does not capture either elasticities of energy demands in response to changes in prices or changes in macroeconomic outputs such as gross domestic product and labor-versus-capital tradeoffs. Most models that include these details are not able to capture

the level of technological detail represented in MARKAL. While there are modeling tradeoffs when selecting one model over another, MARKAL's strengths are well-suited to the analysis presented here.

One of the arguments for H₂-FCVs is that they would have a great potential to reduce ambient concentrations of urban air pollution such as NO_x, ozone, particulate matter, and toxics (for example, see Jacobson, Colella *et al.* [38]). Whether such reductions would occur would depend on the pathways by which H₂ is produced and the system dynamics with the rest of the energy system. Our ongoing research is examining the tradeoffs in air quality between reducing mobile vehicle emissions and emissions from electricity generation and H₂ production. In addition, the potential role of advanced nuclear technologies, wind, and solar energy to generate H₂ and potential reductions of air quality is being examined. ■

Acknowledgment

S. Yeh expresses her thanks to the U.S. Environmental Protection Agency for funding the research described herein through a postdoctoral program administered by the Oak Ridge Institute for Science and Education interagency agreement with the U.S. Department of Energy. It has been subjected to the Agency's peer and administrative review and has been cleared for publication. The views and opinions of authors expressed herein do not necessarily state or reflect those of the EPA or DOE, or any agency thereof. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. The authors acknowledge the intellectual and technical support by the team members at the Atmospheric Protection Branch, NRMRL, including J. DeCarolis, T. Johnson, and E. Wilson and E. Wright (formerly of EPA). The authors alone remain responsible for the final content of this paper.

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