Title

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Authors
Yeh, Sonia
Loughlin, Daniel H.
Shay, Carol
et al.

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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.

By Sonia Yeh, Daniel H. Loughlin, Carol Shay, and Cynthia Gage

ABSTRACT | This paper presents an analysis of the potential system-wide energy and air emissions implications of hydrogen fuel cell vehicle (H_2-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 H_2-FCV penetration by 2030. A parametric sensitivity analysis shows that H_2-FCV can become economically viable through reductions in H_2-FCV costs, increases in the costs of competing vehicle technologies, and increases in oil prices. Alternative scenarios leading to H_2-FCV penetration are shown to result in very different patterns of total system energy usage depending on the conditions driving H_2-FCV penetration. Overall, the model suggests that total CO_2 emissions changes are complex, but that CO_2 emission levels tend to decrease slightly with H_2-FCV penetration. While carbon capture and sequestration technologies with H_2 production and renewable technologies for H_2 production have the potential to achieve greater CO_2 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 H_2 PRODUCTION HISTORY AND FUTURE PATHWAYS

Hydrogen (H_2) is a versatile energy carrier, with the potential for extensive use in electricity generation, industrial, commercial, residential, and transportation sector applications. H_2 is combustible, but can also be combined with oxygen within fuel cells to create electricity. H_2 fuel can be extracted from water or through processing of carbon-rich feedstocks, such as natural gas,

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S. Yeh is with the Carolina Transportation Program, Center for Urban and Regional Studies, University of North Carolina, Chapel Hill, NC 27599-3410 USA (e-mail: sonia_yeh@unc.edu).
D. H. Loughlin, **C. Shay**, and **C. Gage** are with the National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711 USA (e-mail: loughlin.dan@epa.gov; shay.carol@epa.gov; gage.cynthia@epa.gov).

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coal, biomass, and wastes. Potential applications of H_2 in the transportation sector are currently receiving considerable attention. H_2-powered fuel cell vehicles (H_2-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 CO_2 and a myriad of pollutants from combustion, H_2-powered fuel cells emit only water vapor. For these reasons, H_2-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 H_2-FCVs presents many challenges, since it requires the parallel introduction of infrastructures for H_2 production, distribution, and refueling. Further, for H_2-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 H_2-FCV adoption.

In this context, a primary objective of the work presented here is to conduct a system-wide analysis of technological potential for H_2-FCV penetration and to examine the associated H_2 technological pathways, fuel use, and CO_2 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 H_2 production and use in the transportation sector. Our data, model assumptions, and methodologies for incorporating H_2 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 H_2-FCV adoption. Sensitivity information is used to construct several future H_2-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 CO_2 emissions implications over a wide range of conditions that yield H_2-FCV penetration. Section IV provides conclusions and Section V discusses caveats of the study and identifies future research directions.

A. H_2 Production

H_2 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 H_2, accounting for approximately 20% of global H_2 consumption. Approximately 95% of the H_2 used in the United States is manufactured via steam methane reforming (SMR) of natural gas [1]. Steam Reforming can also be applied to other H_2-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 H_2 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].

H_2 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 H_2 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 H_2 and carbon monoxide (CO). CO is removed via a CO shift reactor, and the remaining H_2 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 CO_2 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 H_2 via electrolysis is practiced in small commercial applications today. Electrolysis involves breaking water into H_2 and oxygen using electricity. Electrolysis is highly efficient, currently achieving efficiencies in the 70%–75% range. H_2 can be produced using on-site electrolysis at H_2 refueling stations, and the electricity used in producing the H_2 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 H_2 when windy conditions occur during times of off-peak demand [3], [4].

Some H_2 production technologies can be downscaled sufficiently to be placed on-board an H_2-FCV. For example, onboard H_2 production can be achieved by converting a liquid fuel (e.g., gasoline) or gaseous fuel (e.g., methanol or natural gas) to H_2. 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. H_2 Storage and Distribution

While industry has experience producing H_2, the distribution and delivery infrastructures required to support widespread H_2-FCV adoption face considerable hurdles. A major barrier is that H_2 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 H_2-FCVs unless the refueling infrastructure is convenient and H_2-FCV capital and operation costs are cost-competitive with other technologies.

Historically, H_2 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 H_2 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. H_2-Powered Vehicles

There are several technologies for powering vehicles with H_2. H_2-powered fuel cells combine oxygen from the air with H_2 from the vehicle's fuel tank to produce the electricity that powers the vehicle's electric engines. The transportation sector has already adopted H_2-FCVs, albeit on a small scale. For example, a limited number of H_2-FCV fleets, mainly buses, are currently in operation in Continental Europe, the United Kingdom, and the United States. Iceland currently has three H_2-powered fuel cell buses that are fueled by H_2 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 H_2-FCV technologies become more practical, several automakers are developing vehicles that burn H_2 directly within an internal combustion engine (H_2-ICEs) [11]. H_2-ICEs and H_2-ICE electric hybrid vehicles are expected to be considerably more efficient than conventional vehicles. H_2-ICE technologies are not included in the analyses presented in this paper.

D. Emissions From the Use of H_2-FCV

When FCVs are fueled with pure H_2, they emit only water vapor as exhaust. If the energy source used to generate H_2 is a fossil fuel (or electricity derived from fossil fuels), however, emissions from the industrial and electric generation sectors occur. The introduction of H_2-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 H_2-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 H_2 production and transportation pathways [12]–[17]. For example, some studies suggest that the WTW energy use associated with a H_2-FCV is 20%–50% less than that of a conventional gasoline-powered ICE, provided the H_2 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, H_2 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 CO_2 emissions follow a pattern similar to energy use. For example, H_2-FCVs using H_2 produced from SMR of natural gas have lower system-wide CO_2 emissions than conventional vehicles. If the H_2 is produced from coal gasification (without carbon capture and sequestration), however, CO_2 emissions are expected to increase [18]. CO_2 emissions from the industrial and electric generation sectors potentially can be reduced via carbon capture and sequestration during H_2 production, provided that sequestration options prove to be practical at a large scale [2], [5], [6]. Net CO_2 emissions reduction can also be achieved by using renewable energy sources in H_2 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 H_2-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 H_2-FCVs but also on the market shares of other vehicle technologies; displacement of HEVs by H_2-FCVs would likely have very different implications than displacement of conventional ICEs. Cross-sector effects are also important. For example, the penetration of H_2-FCVs could increase the use of natural gas in H_2 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 H_2 PRODUCTION AND USE IN THE MARKAL MODEL

The H_2 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 original 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

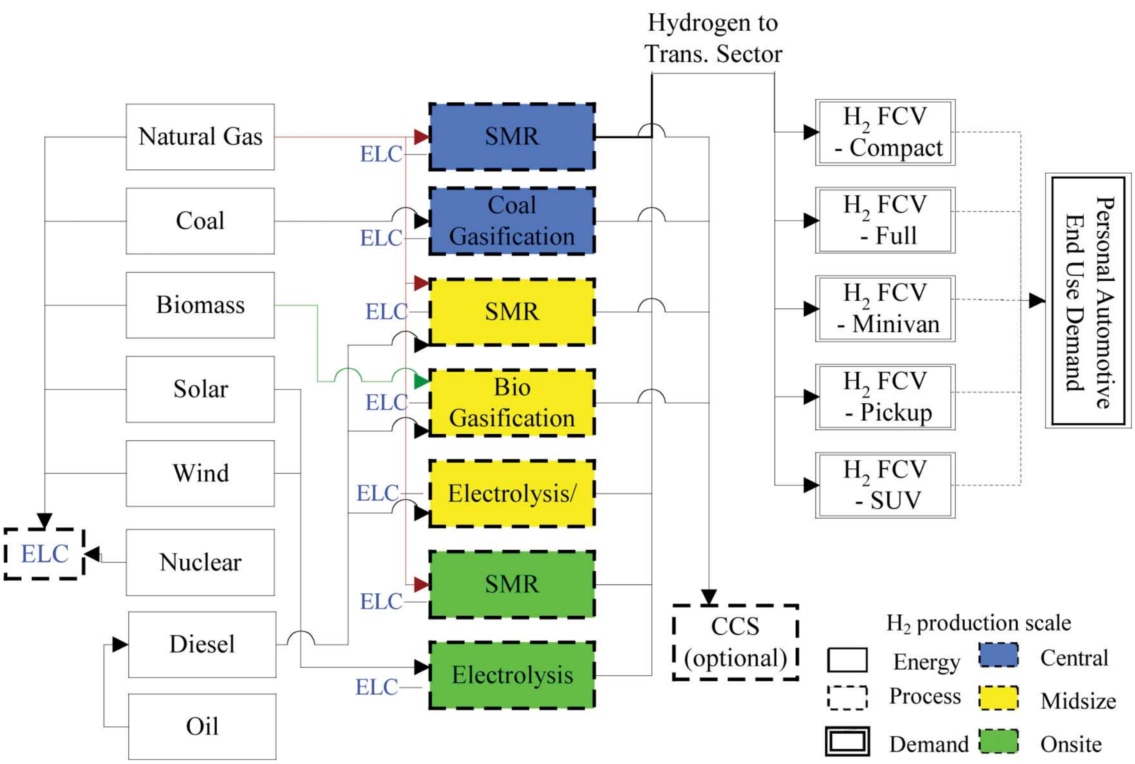

Fig. 1. *Schematic illustration of H_2 pathways. ELC represents electricity.*

Table 1 Pathways Examined in This Report

GH_2 and LH_2 stand for gaseous and liquid H_2, 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 H_2 Infrastructure Within the MARKAL Technology Database

A H_2 module in the U.S. EPA MARKAL database incorporates H_2 pathways and cost data provided in the recent National Research Council (NRC) report [5]. The report assumes three scales of H_2 production: central plant, midsize plant, and onsite generation at the refueling station. For each pathway, the capital cost of H_2 production technologies is calculated as the sum of the production (including compression), distribution (e.g., liquefaction, storage, pipeline cost, and liquid H_2 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 H_2 production pathway, broken down by production, distri-

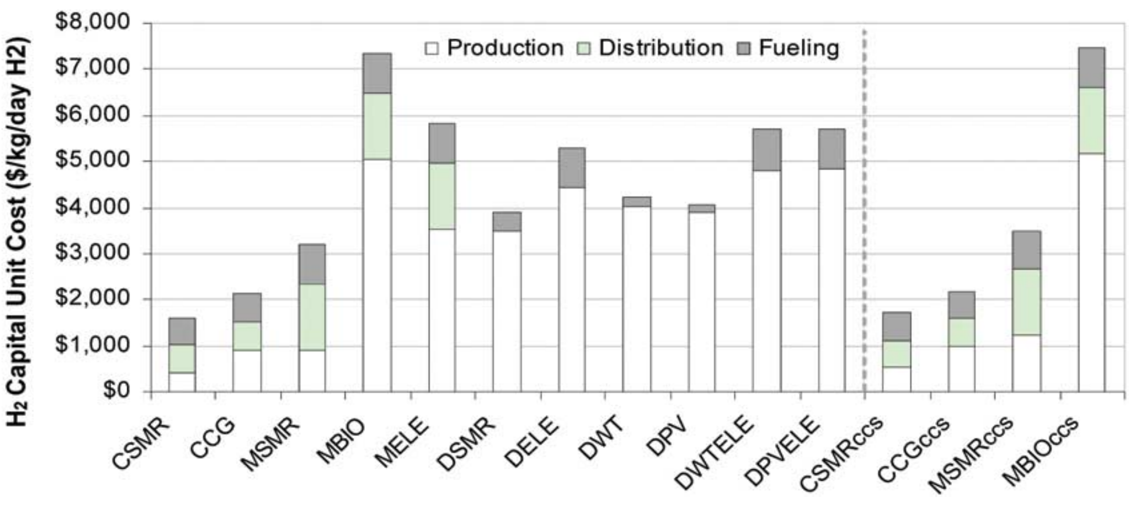

Fig. 2. ***Capital investment cost of H_2 production technologies. Each value includes the costs of production, distribution and fueling.***

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 H_2 production technologies considered, on-site generation and production from renewable sources have the highest capital costs per unit of H_2. H_2 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 H_2 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 H_2 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 H_2 production are attributed to the industrial sector.

C. Characterization of H_2-FCVs

The data for H_2-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 H_2-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 H_2-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 H_2-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 H_2 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

$$Y = ax^{-b} \tag{1}$$

where Y is the estimated average direct unit cost for the xth 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 H_2 production technologies. The maturity of each type of H_2 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 H_2 production technologies are represented with endogenous learning, while all other technologies, including H_2-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 H_2-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 H_2-FCVs, with an emphasis on characterizing H_2-FCV penetrations and system-wide CO_2 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 H_2-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 H_2-FCV penetration on energy use and CO_2 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 (SO_2) 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 CO_2 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 H_2-FCV penetration and the associated effects on CO_2 emissions. The input parameters that are examined fall into four general categories: H_2 fuel cost, the costs of competing fuels, characteristics of H_2-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 H_2 would potentially decrease the consumption level of H_2 fuel. The final price of H_2 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 H_2-FCV penetration into the light duty vehicle fleet in 2030. The results suggest that H_2-FCV penetration in the optimized solution is sensitive to H_2-FCV capital cost: a 5% decrease in H_2-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 H_2-FCV capital costs assumed in the reference case.

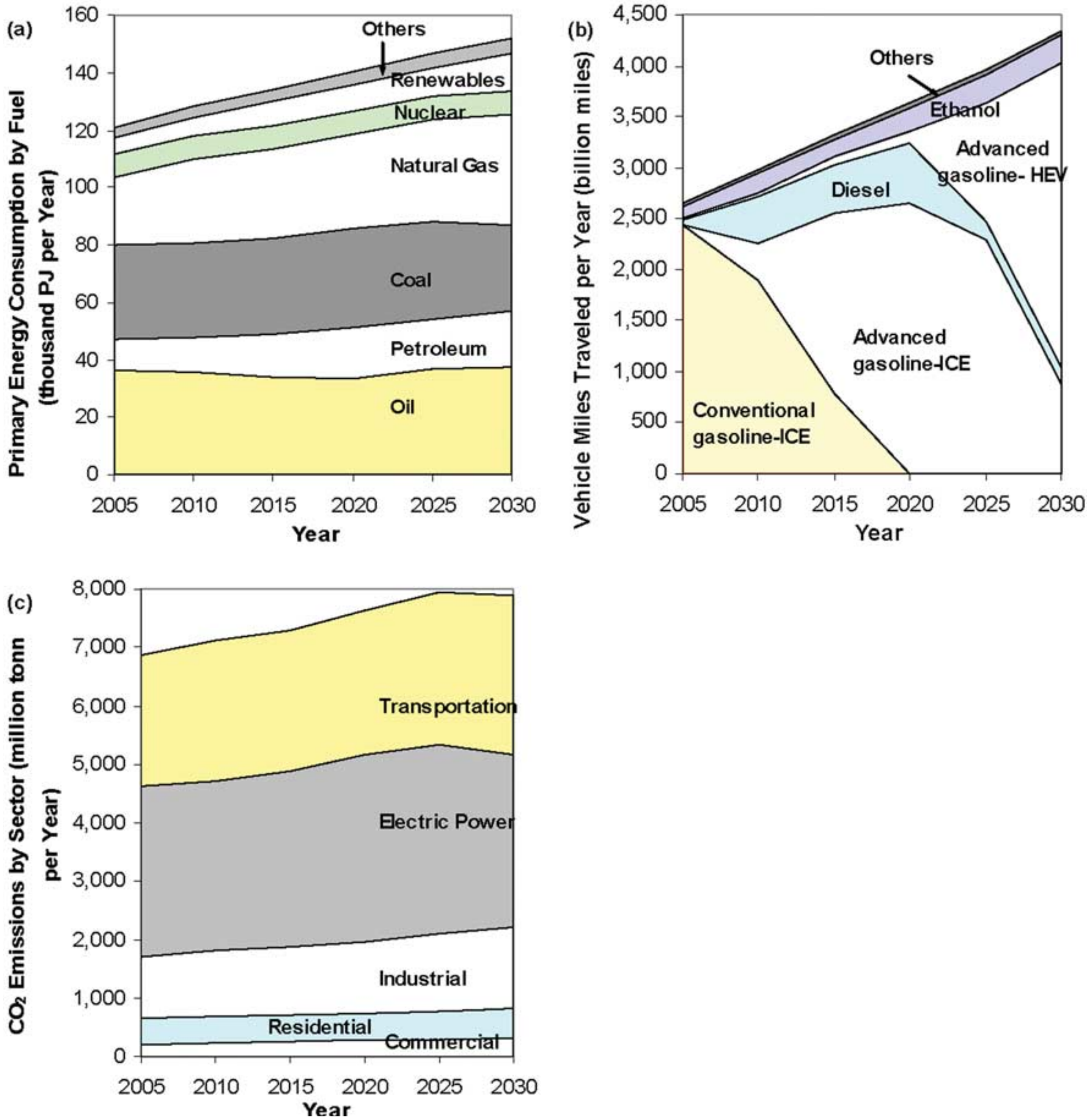

Fig. 3. ***Reference case. (a) Energy usage by sector. (b) Vehicle technology penetrations in the light duty vehicle (LDV) market. (c) Carbon dioxide emissions by sector.***

The cost of advanced gasoline-HEVs, the main competitor to H_2-FCVs, also has considerable impacts on penetration: if advanced gasoline-HEVs are only 5% more expensive than their reference values, penetration of H_2-FCVs occurs. Increases in long-term oil costs also have the potential to drive H_2-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 H_2-FCV penetration from 0% to 7% in 2030.

H_2-FCV penetration is not sensitive to the parametric changes in the other factors listed in Table 3. For example, the changes in H_2 costs did not drive H_2-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), H_2-FCV penetration is sensitive to the cost of H_2, but to a lesser degree than H_2-FCV capital cost.

Fig. 4(b) shows the response of system-wide CO_2 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 CO_2 emissions increase. On the other hand, a decrease in natural gas costs does not necessarily reduce net CO_2 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 alternative fuel (H_2 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 CO_2 emissions from these changes. Increases in advanced gasoline-HEV cost yields higher CO_2 emissions than the reference case due to increased penetration of gasoline-ICEs and H_2-FCVs at the expense of gasoline-HEVs.

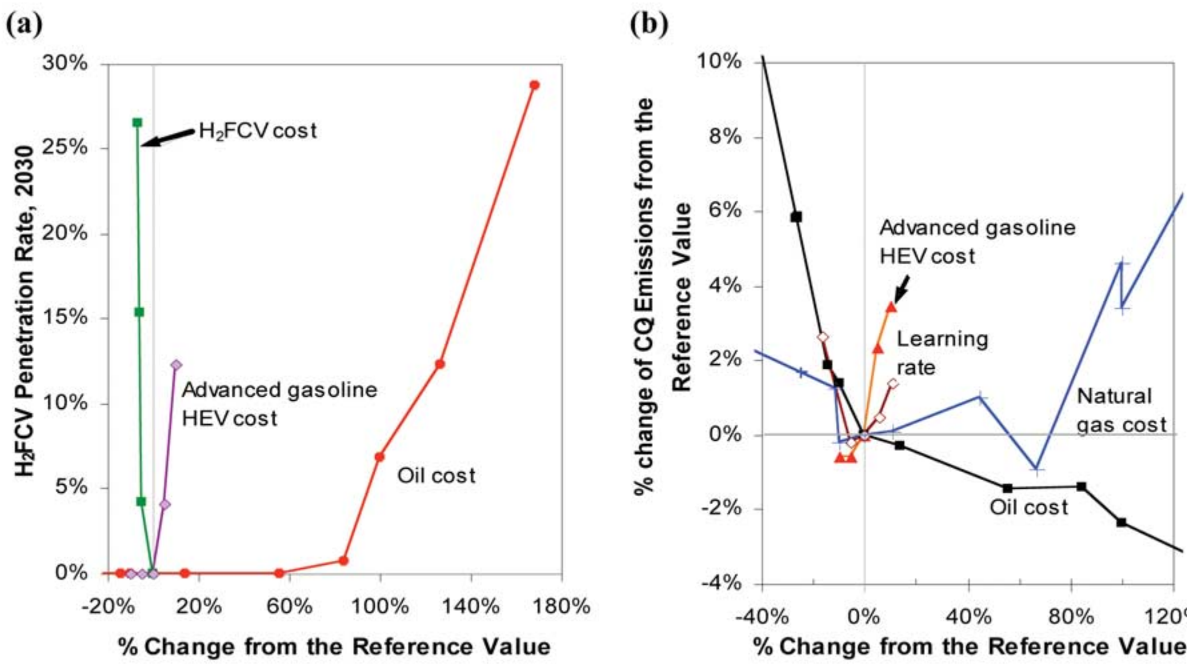

Fig. 4. ***Sensitivity analysis of input variables on: (a) H_2-FCV penetration rate in 2030 and (b) percent changes of CO_2 emissions from the reference case, 2030. The x axis captures the reference value, maximum, and minimum values of input variables as described in Table 3 (except for oil and natural gas with wider ranges).***

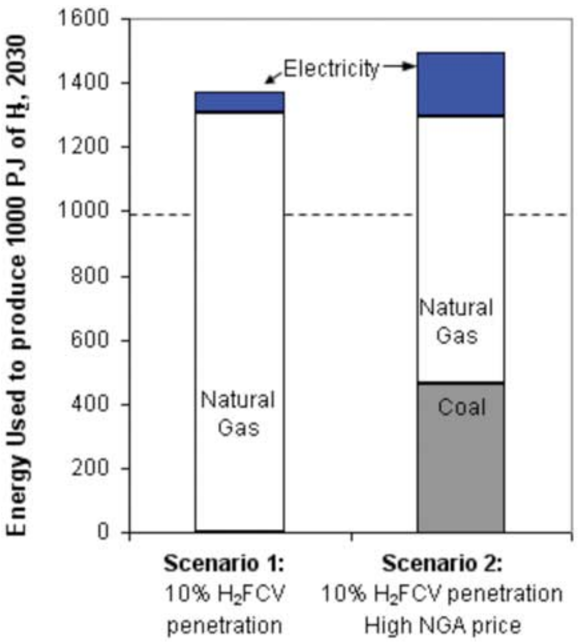

Fig. 5. *Projected energy feedstock demands to produce H_2-fuel for H_2-FCVs in two scenarios: Scenario 1: 10% H_2-FCV penetration scenario in 2030, and Scenario 2: 10% H_2-FCV penetration scenario in 2030 with high natural gas cost.*

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 H_2-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 H_2 production in Scenario 1 is via onsite SMR, as this is the least cost production option. In Scenario 2, H_2 is produced both from onsite SMR and centralized coal gasification. Since centralized coal gasification technology consumes more electricity per unit of H_2 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 H_2-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, H_2 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 H_2-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 H_2 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 H_2) 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 H_2-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 H_2-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) H_2-FCV penetration and (b) total CO_2 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 H_2-FCVs achieve some degree of penetration in only 6.4% of the five hundred realizations. H_2-FCV penetration occurs almost exclusively in the realizations that exhibit *all* of the following characteristics: relatively low H_2-FCV capital costs, medium-to-high advanced gasoline-HEV costs, and high oil costs.

In those realizations that H_2-FCVs do penetrate by 2030, the mean penetration rate is close to 28% of the

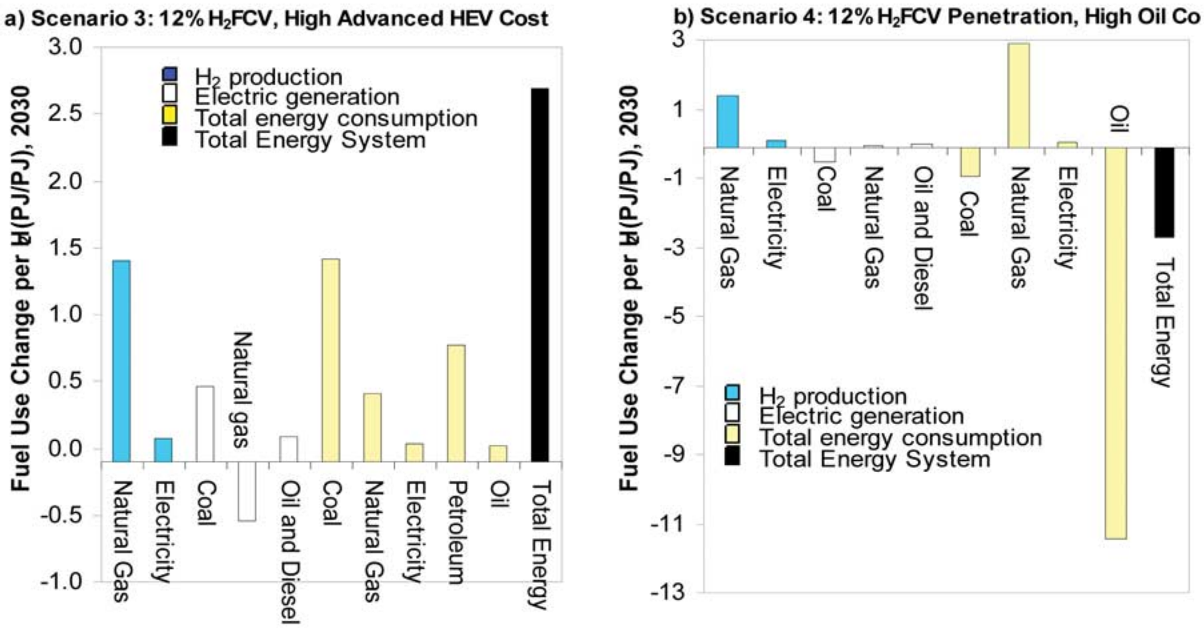

Fig. 6. ***Normalized fuel use changes from the reference case per H_2 produced (PJ/PJ) for H_2 production, sector- and system-wide energy changes in two scenarios with identical H_2-FCV penetration rate (2030) but different forcing conditions: (a) Scenario 3: high advanced gasoline-HEV cost, and (b) 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 H_2 fuel produced in 2030. These changes reflect the feedstock and electricity demands associated with producing, storing, and distributing H_2, the offset of gasoline and diesel as vehicle fuels, and the system effects

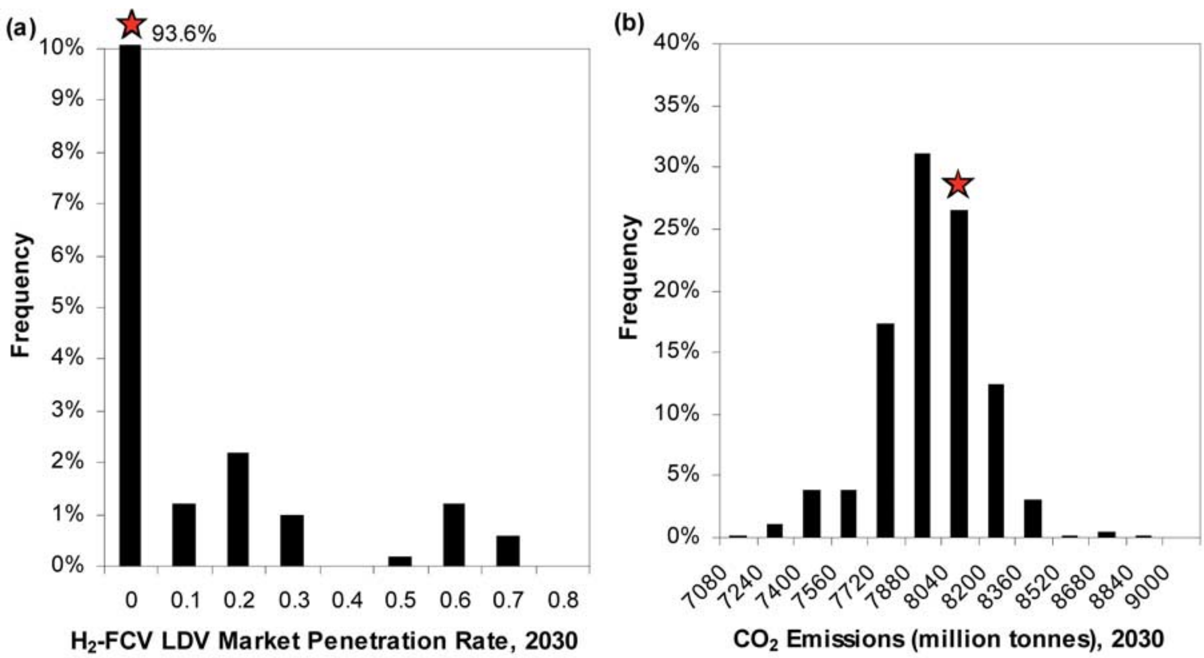

Fig. 7. ***Probabilistic distributions of the H_2-FCV penetration rate and CO_2 emissions in 2030, based on the Monte Carlo analysis of the uncertain inputs variables listed in Table 3. The star in each figure represents the bin within which the solution of the reference case is.***

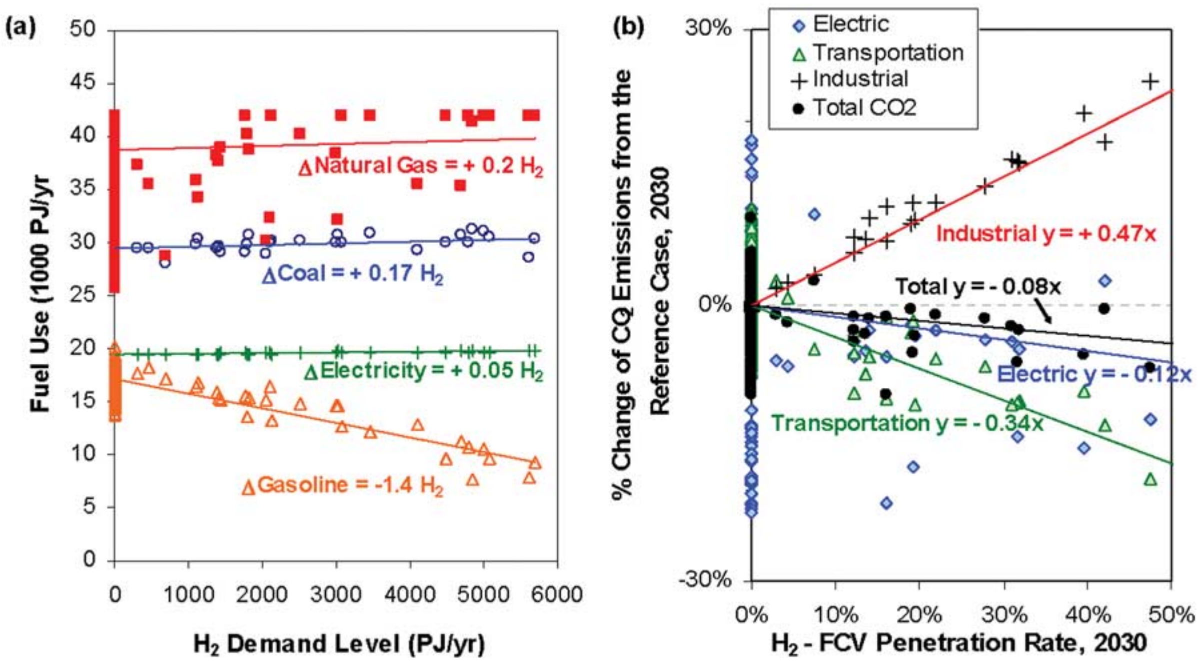

Fig. 8. ***Results from the uncertainty analysis. (a) System-wide fuel usage (right) by H_2 demand level in 2030. (b) Change of CO_2 emissions (by sector and the system total) versus H_2-FCV penetration in 2030. The regression coefficients are all statistically significant at 0.01 level.***

that result from other factors that drove H_2-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 CO_2 emissions and H_2-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 H_2 fuel occur) and transportation emissions. For example, H_2-FCV penetration tends to drive down CO_2 emissions from the transportation sector significantly, but increases CO_2 emissions from the industrial sector. The emission changes in the electric sector are much more complex, as many direct (electricity demands for H_2 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 CO_2 emission from the reference case is associated with each percent increase of H_2-FCV penetration in 2030. This trend is statistically significant. The results suggest that the penetration of H_2-FCVs is likely to have system-wide CO_2 emission slightly lower than the reference case in 2030.

IV. CONCLUSION

Widespread adoption of H_2-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 improvements 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 H_2 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, H_2-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 H_2-FCVs, cost of advanced gasoline-HEVs, and cost of oil affect the future penetration rate of H_2-FCVs to various degrees.

Central coal gasification and on-site SMR are estimated to be the dominant technology choices to produce H_2 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 H_2-FCV penetration significantly reduces gasoline, oil, and petroleum consumption; however, the change in total system-wide energy consumption is dependent on the conditions driving H_2-FCV penetration.

These results also inform the discussion regarding whether a H_2 economy yields an increase in national energy security, since the most cost-effective H_2 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 H_2-FCVs have the potential to greatly reduce greenhouse gas emissions. The results show that H_2-FCV penetration tends to reduce CO_2 emissions from transportation, but increase industrial CO_2 emissions where emissions from energy feedstock to produce H_2 fuel occur. While there is a small net decrease in CO_2 emissions with H_2-FCV penetration, our results suggest that unless H_2 is produced from renewables, nuclear power, or technologies with carbon capture and sequestration, the CO_2 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 H_2 transportation economy, allowing examination of economic barriers and tradeoffs, as well as the cross-sector impacts on energy and CO_2 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 H_2-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 H_2 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 H_2 production. In addition, the potential role of advanced nuclear technologies, wind, and solar energy to generate H_2 and potential reductions of air quality is being examined. ■

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ABOUT THE AUTHORS

Sonia Yeh received the M.S. degree with a concentration in environmental health and risk management from the School of Public Health, Harvard University, Cambridge, MA, in 1997 and the Ph.D. degree in engineering and public policy from Carnegie Mellon University, Pittsburgh, PA, in 2001.

She was the Oak Ridge Institute for Science and Education Fellow with the National Risk Management Research Laboratory, U.S. Environmental Protection Agency. She is currently the Research Director for the Carolina Transportation Program at the University of North Carolina, Chapel Hill. She holds an Adjunct Assistant Professor appointment in the Department of Engineering and Public Policy, Carnegie Mellon University. Her collaboration work at Carnegie Mellon focuses on environmental technology innovations and the relationship to government actions. Her research interests primarily focus on energy and environmental assessment, especially the effects of technological, economic, and social changes on future energy demand, air emissions, and environmental outcomes. Much of her work has involved applying tools such as risk analysis, decision analysis, and uncertainty analysis to policy issues that intersect with energy, transportation, environment, and public health.

Daniel H. Loughlin received the B.S. degree in civil and environmental engineering from Duke University, Durham, NC, and the M.S. and Ph.D. degrees from North Carolina State University, Raleigh.

He is an Environmental Scientist with the U.S. Environmental Protection Agency's Office of Research and Development (ORD), Research Triangle Park, NC. He is a member of ORD's Integrated Systems Analysis Workgroup, a modeling team that uses the MARKAL model and other tools to evaluate the impacts of energy-related scenarios on pollutant emissions, air quality, and health impacts. His specialty area is environmental systems analysis, a multidisciplinary field involving the study of complex systems through the integration and application of techniques from areas such as decision analysis, operations research, sensitivity and uncertainty analysis, statistics, data mining, high-performance computing, modeling, and economics.

Carol Shay received the B.S. degree in textile chemistry from North Carolina State University, Raleigh.

She is an environmental scientist with the Environmental Protection Agency, Research Triangle Park, NC. Ms. Shay serves as the database manager for the EPA's National MARKAL Database, a research project of the Integrated Systems Analysis Workgroup (ISA-W), a part of the Atmospheric Protection Branch in EPA's Office of Research and Development. Her work involves using the MARKAL model to assess future technological change and the effects of such change on the environment.

Cynthia Gage received the Ph.D. degree in chemical engineering from the University of Texas, Austin.

She joined the Office of Research and Development (ORD) of the U.S. Environmental Protection Agency, Research Triangle Park, NC, in 1989. She is currently a Senior Research Engineer with ORD. She participated in EPA's evaluations of alternative refrigerants and technologies for ozone-depleting substances. For the last six years, she has participated in EPA's air quality assessment under the national Climate Change Science Program (formerly USGCRP). She is Team Leader of the Integrated Systems Analysis Workgroup which contributes to ORD's global climate change and air quality assessment activities. Her technical contributions to the workgroup include MARKAL database development and scenario analyses with an initial focus on hybrid and hydrogen-fuel cell technologies for passenger vehicles. She also serves as a member of the Transportation Research Board's Transportation Energy Committee.

In 1997, Dr. Gage was a recipient of an EPA Bronze Medal for her research contributions to new chemical alternatives for the protection of stratospheric ozone.