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Fuel Cell Electric Vehicles: Drivers and Impacts of Adoption

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Abstract

We present scenario and parametric analyses of the US light duty vehicle (LDV) stock, simulating the evolution of the stock in order to assess the potential role and impacts of fuel cell electric vehicles (FCEVs). The analysis probes the competition of FCEVs with other LDVs and the effects of FCEV adoption on LDV fuel use and emissions. We parameterize commodity and technology prices in order to explore the sensitivities of FCEV sales and emissions to oil, natural gas, battery technology, fuel cell technology, and hydrogen production prices. We additionally explore the effects of vehicle purchasing incentives for FCEVs, identifying potential impacts and tipping points. Our analyses lead to the following conclusions: (1) In the business as usual scenario, FCEVs comprise 7% of all new LDV sales by 2050. (2) FCEV adoption will not substantially impact green house gas emissions without either policy intervention, significant increases in natural gas prices, or technology improvements that motivate low carbon hydrogen production. (3) FCEV technology cost reductions have a much greater potential for impact on FCEV sales than hydrogen fuel cost reductions. (4) FCEV purchasing incentives must be both substantial and sustained in order to motivate lasting changes to FCEV adoption.

Acknowledgment

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Preface

The analysis presented here was conducted late summer and early fall of 2015. The work was reviewed internally at Sandia and by the Fuel Cell Technologies Office. In April 2016, this manuscript was submitted for publication in a peer reviewed journal. Due to delays in the editorial process of that journal, we withdrew the paper in December 2016, without it ever having made it to review.

Given the fast pace of change of the nascent fuel cell electric vehicle market, hydrogen infrastructure construction, and federal and state energy and vehicle policy, we deemed it prudent to publish the existing work as a SAND report, rather than to try to resubmit with another journal and risk another lengthy delay to publication.

The conclusions presented here hold for the stated assumptions, most of which are unchanged in the last two years. While some of the policy questions have shifted, others remain relevant. And while the ParaChoice model is a living model undergoing continuous development, the ParaChoice model described here provides a useful framework and reference point for the simulation logic.

Nomenclature

Abbreviations	
Powertrains	
AFV	Alternative fuel vehicle
BEV	Battery electric vehicle
Conv.	Conventional
CI	Diesel-fueled compression ignition
CNG	Compressed natural gas vehicle
CNG BI	Compressed natural gas bi-fuel vehicle
EV	Electric vehicle, either BEV or PHEV
E85	Flex fuel powertrain
FFV	Flex fuel vehicle
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
PHEV	Plug-in hybrid electric vehicle
PHEVXX	PHEV with XX mi all-electric range
SI	Gasoline-fueled spark ignition
Fuels and Energy	
CNG	Compressed natural gas
BXX	Blendstock of XX% biodiesel by volume
EXX	Blendstock of XX% ethanol by volume
Elec.	Electricity
H_2	Hydrogen
NG	Natural gas
Hydrogen production pathways	
SMR	Steam methane reformation of natural gas
CElec	Centralized production via electrolysis
CCoal	Centralized production via gasification of coal
CCoal Seq.	CCoal with sequestration of carbon
CSMR	Centralized production via SMR
CSMR Seq.	CSMR with sequestration of carbon
DElec	Distributed production via electrolysis
DSMR	Distributed production via SMR
Other	
GGE	Gallon gasoline equivalent
GHG	Greenhouse gas
LDV	Light duty vehicle
VMT	Vehicle miles traveled
ZEV	Zero emission vehicle

Chapter 1

Introduction

Recent developments in the fuel cell electric vehicle (FCEV) market have prompted a need for new analyses of the impact of fuel cell technology on the composition of the US light duty vehicle stock, petroleum use, and greenhouse gas (GHG) emissions. Toyota has recently released its midsize 2016 Mirai, Hyundai is leasing the 2016 Tuscon SUV, Mercedes and BMW have been testing their FCEV models and remain publicly committed to a Hydrogen future [20], and Honda is currently advertising that its next-generation FCEV is "coming in 2016" [9]. Given the investment costs required for further FCEV technology development and the construction of dedicated hydrogen (H_2) refueling infrastructure, manufacturers (OEMs), energy companies, funding agencies, and policy makers want to know the market potential for FCEVs and how these vehicles might help or hinder the nation in achieving its national energy and emissions goals [13, 26].

However, any projections of the evolution US light duty vehicle (LDV) stock depend on energy futures, technology evolution, and future political will, all of which are highly uncertain. Sandia's ParaChoice model, a consumer choice model for US alternative energy vehicle (AEV) adoption in which key input assumptions are parameterized, is uniquely suited to address the potential role of AEVs in these uncertain futures. The recent incorporation of FCEVs into the vehicle model and six hydrogen production pathways into the fuel submodel of ParaChoice allow us to leverage this tool to explore the potential of FCEVs and hydrogen on the US vehicle stock, fuel use, and emissions. We use ParaChoice's parametric capability to explore the impacts of a wide range of energy, technology, and policy futures on the future of FCEVs, as well as to test the robustness of individual projections to uncertainties surrounding consumer choice.

In chapter 2, we outline the ParaChoice model and the incorporation of FCEVs and H_2 fuel production pathways into the model. We also provide a brief overview of our baseline assumptions and how ParaChoice handles parameterization around these assumptions. In chapters 3 and 4 we explore the role of FCEVs and the future of H_2 fuel in the baseline 'business as usual' projection and in two additional scenarios which promote low carbon H_2 production pathways. In chapter 5, we present three parametric analyses, exploring the variation in FCEV adoption in the trade spaces of different oil and NG price futures, battery and fuel cell technology evolutions, and refueling advancements leading to H_2 cost reductions. Chapter 6 explores different incentive structures for FCEVs and their potential impact on long term vehicle adoption and fuel use goals. We present the results of a global sensitivity analysis in chapter 7, identifying the most influential levers for driving or quashing FCEV adoption. In chapter 8, we use the results from the preceding chapter to construct a scenario that optimizes the adoption of FCEVs in order to explore the role they could play in the LDV stock in an ideal scenario. We conclude in chapter 9.

Chapter 2

Model description

The ParaChoice model consists of four primary sub-models: energy supply, electricity grid, fuel production, and vehicle. As shown in figure 2.1 the sub-models exchange price and demand information for commodities and fuels. Energy, electricity, and fuel prices are initialized using data from the U.S. Energy Information Administration [30, 31]. The composition of the LDV stock is initialized to 2013 values using U.S. Department of Transportation Federal Highway Administration [28] State Motor-Vehicle Registrations and model availability by powertrain from Polk and Co. [16] compiled by SRA International, Inc. Refueling station availability is initialized using data from the U.S. Department of Energy [27] and National Petroleum News Magazine [12]. At the start of the simulation, the initialized vehicle fleet is used to compute pump fuel demand for first quarter 2014. The fuel production sub-model converts this fuel demand to energy and electricity demand and passes those values to the energy and electricity sub-models respectively. Using these demand values, the energy and electricity sub-models update their prices and the electricity grid mix. The fuel production sub-model converts these new energy and electricity prices into pump-fuel prices. The vehicle sub-model evolves the vehicle stock, retiring old vehicles from the stock and simulating new vehicle sales, which are influenced by the fuel prices from the fuel production sub-model.

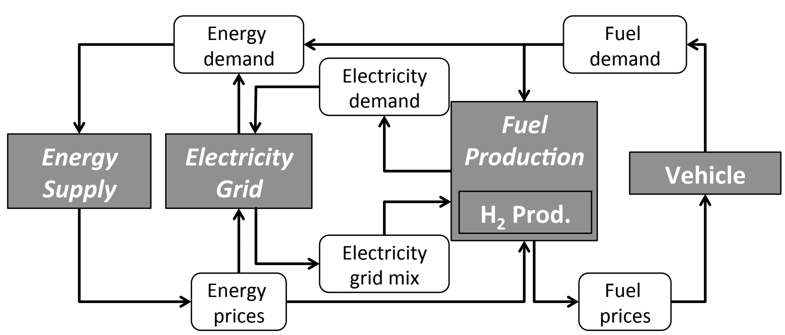


Figure 2.1. High level overview of ParaChoice model and sub-models.

The following subsections provide an overview of the ParaChoice sub-models, focusing on the recent addition of FCEVs to the vehicle sub-model and H_2 production as a sub-model within the fuel production sub-model. For a complete description of the ParaChoice model and its workings, we direct the reader to previous works [2, 3, 14].

Energy Supply

The energy supply sub-model controls the prices and supply of crude oil, coal, natural gas (NG), biomass, and zero carbon energy. Crude oil and coal are assumed to be global and national commodities respectively unaffected by LDV demand. For the baseline case, projected prices for these commodities come from the Annual Energy Outlook 2015 reference case (AEO) [31]. NG prices are also taken from AEO and vary regionally, though independently of the LDV stock. Biomass supply curves are constructed from the US Billion Ton Update analysis [25], and renewable or 'zerocarbon' energy prices are derived from the ReEDS model [21]. These commodities are segmented at the state level.

Electricity

The electricity grid sub-model captures the evolution of each state's electricity grid as old capacity is retired and new capacity is built to meet the needs of population growth. The initial grid mix is taken from the Environmental Protection Agency's eGRID database [22], and energy sources for new grid capacity are determined dynamically in response to commodity price changes in each region. Generators relying on oil, coal, or NG are retired after a default 40 years. Generators using nuclear or renewable energy are assumed not to retire, or equivalently to be replaced by generators using an identical energy source, as commissioning and decommissioning these facilities is a complex, often political, process.

Two grid mixes are considered, a base mix and a marginal mix. Biomass and zero-carbon sources supply the base demand first, and oil, coal, and NG, which are more easily scaled to demand, evenly supply any remaining base demand. The marginal mix is comprised of the grid mix after the base demand has first been supplied. Electricity prices are set by the base grid mix. However, for computing emissions, both electricity for EV charging and distributed electrolysis production of H_2 are assumed to draw upon the marginal grid mix.[1]

Fuel Production

The fuel production sub-model is a translator between the vehicle model and the energy supply and electricity sub-models. It converts the fuel and electricity demand from the vehicle stock to energy and electricity demands. Conversely, the fuel production sub-model converts energy and electricity prices into fuel prices that can then be used to inform new vehicle sales. The sub-model also tracks emissions associated with each pump fuel and any fuel mixing requirements set by the Renewable Fuel Standard (RFS) [19].[2] There are six

[1] Emissions for the other fuels and production pathways are set by the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) [33] and therefore only the price of the electricity impacts these fuels in the model. The price is set to the cost of the base mix.

[2] RFS ethanol requirements are partially met. The ethanol fraction in gasohol is increased to meet the RSF mandate not met by E85 use until either the requirement is met or the ethanol fraction in gasohol

types of pure fuels in the model which are used to produce seven different types of pump-fuel. The pure fuels are gasoline, diesel, ethanol, compressed natural gas (CNG), H_2, and electricity. The pump fuels are gasohol (a blend of gasoline and up to 10% ethanol); diesel; B20 (20% biodiesel blend); E85 (85% ethanol gasoline blend); CNG; H_2, and electricity. Because H_2 has multiple production pathways with varying commodity requirements and dynamic interactions with the energy and electricity sub-models, H_2 fuel production is handled in its own sub-model within the fuel production sub-model. The H_2 sub-model is detailed in subsection 2.

Vehicle

The vehicle sub-model tracks the LDV vehicle stock from the beginning of the simulation in 2014 to the end of the simulation in 2050. The total growth of the stock is assumed to follow population growth projections from the U.S. Census Bureau [23], and vehicles age out of the stock following vehicle survival data from the U.S. Department of Transportation National Highway Traffic Safety Administration [29].

ParaChoice models 20 powertrains including conventional gasoline spark ignition (SI), diesel compressions ignition (CI), and flex fuel spark ignition which accepts E85 as well as regular gasohol. For each of the SI, CI, and flex fuel powertrains, hybrid electric vehicle (HEV) configurations and plug in hybrid electric vehicle configurations with 10 and 40 mile all-electric ranges (PHEV10s and PHEV40s) are also modeled. The model additionally tracks full battery electric vehicles (BEVs) with 75, 100, 150, and 225 mile ranges, CNG conventional, bi-fuel, and HEV configurations, and most recently added, a FCEV. Projections for vehicle costs, battery costs, and efficiencies for these powertrains are derived from Moawad et al. [11] (Autonomie) assuming a five year delay before technology proven in the lab is commercialized [15, 32, 34]. The relative costs of select powertrains to conventional SI are given in table 2.1 for 2015 and 2050. Sales fractions by powertrain for each quarter are determined by a nested multinomial logit function, figure 2.2, which compares generalized annual vehicle costs over a (parameterized, default three year) payback for each powertrain. These costs include the vehicle sale price; fuel costs; at home recharger or NG compressor costs when applicable; inconvenience penalties for vehicle range limitations, refueling times, and refueling station scarcity; and federal and state level AEV incentives. Sales ratios determined by the logit function are then scaled by powertrain model availability, which is a fixed function of the powertrain introduction year. As the components of the generalized costs differ for different consumer driving habits, vehicle attributes, and locations, these costs are computed separately for each powertrain for each of five segments including: state; vehicle size (compact, midsize, small SUV, large SUV, pickup truck); population density (urban, suburban, rural); driver annual mileage or intensity (light, medium, intense); and dwelling type (single family with NG, single family without NG, other). While the fractions of each powertrain sold within each segment are variable, the fractions of vehicles and consumers

reaches 10%. Once the ethanol ratio reached 10%, the simulation is allowed to fall out of compliance with RFS.

within each segment are static.

Table 2.1. Incremental technology cost over conv. SI mid-size vehicles (Autonomie 2015). [2010$]

Powertrain	2015	2050
CI	2491	1186
SI HEV	3861	1466
SI PHEV10	4504	1484
SI PHEV40	10533	3305
BEV75[a]	7185	81
BEV100	9624	827
BEV150[b]	16599	2406
BEV225[c]	26446	4750
FCEV	10497	2981
CNG	2920	2545

[a] BEV100 DM vehicle with 0.75x battery cost.
[b] Average of BEV100 DM and BEV200 DM costs.
[c] BEV200 DM vehicle with 1.125x battery cost.

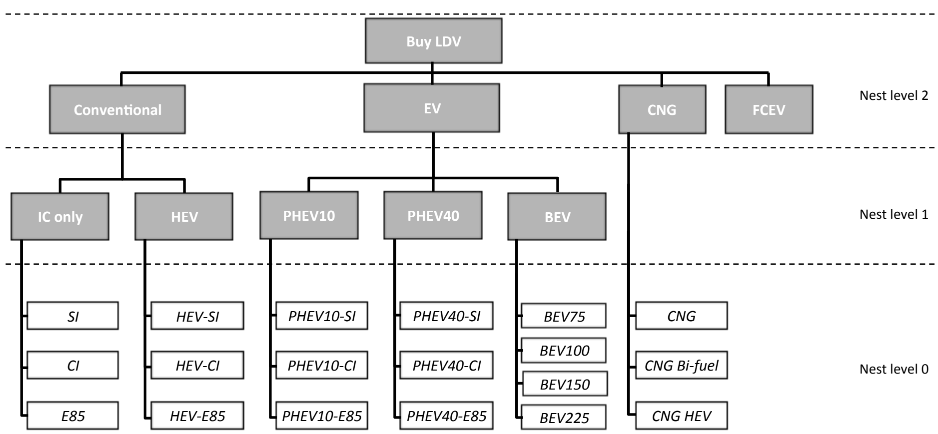


Figure 2.2. Powertrain options and vehicle choice nesting.

In addition to the assumption of model availability for all powertrains, (albeit only after a specified start year for each powertrain and with a consumer choice penalty in early introduction years for lack of model selection), we assume that manufacturers produce enough of each drivetrain to meet consumer demand. These are potential model weaknesses, as manufacturers may choose to never bring select powertrains to market (e.g. CI hybrids) or may do so only to meet compliance targets, thus producing fewer vehicles and model selections than might satisfy consumer demand. In particular, there appears to be little interest in producing mass market compact and midsize CNG vehicles.

The vehicle model tracks purchasing incentives and penalties associated with the various AEVs. At the time of conducting the modeling for this article there were no federal incentives for the purchase of FCEVs applicable to years 2015 and beyond, and thus none were included in the model.[3] State level purchasing incentives applicable to FCEVs that were active at the time of modeling were applied to these vehicles.

The penalties applicable to FCEVs are those associated with refueling time and availability of infrastructure. The refueling time penalty used in the simulation is adopted from Greene [8] and is quite small for FCEVs, as FCEVs have equivalent range to conventional vehicles and can be refueled equally quickly. The larger penalty for FCEVs is the penalty for lack of infrastructure, which is also taken from Greene [8].[4] Unlike CNGs and BEVs which have at-home refueling options for at least some of the population, or bi-fuel vehicles which benefit from the abundant conventional refueling infrastructure, FCEVs are dependent on dedicated H_2 refueling infrastructure. The penalty due to station scarcity for vehicles which cannot be refueled at one's dwelling or at gasohol stations is given by

$$\text{cost} = \delta \exp\left[-20.149\phi_f\right] \tag{2.1}$$

where the cost of zero station availability, δ, is set to \$7500, and ϕ_f is the ratio of the number of fueling stations for fuel f to the number of gasohol stations. This penalty is evaluated individually for each population density segment within each state.

According to the Alternative Fuels Data Center [27], as of January 2016, only four states, California, South Carolina, Connecticut and Massachusetts, have public H_2 refueling stations, and most states do not have any H_2 refueling infrastructure, either public or private. In states without refueling infrastructure, FCEV sales will be heavily penalized until infrastructure is built. In the simulation, infrastructure is built in response to stock growth, creating a bootstrapping issue for FCEVs where only sales can beget infrastructure but sales are unlikely until infrastructure is built. We observe this issue for FCEVs in reality as well. In order to get around this hurdle, CA has committed funding for the first 100 H_2 stations built, and has laid out a roadmap for a refueling network build out which reaches the 100 station goal by 2022 [6, 7]. We have implemented this station build out for CA in the simulation, and have included a parameter that allows implementation of similar initiatives in other states. Market driven H_2 station growth in the simulation can therefore be supplemented by this mandated infrastructure. The total number of mandated stations for each state is set to 1% of the total number of gasohol stations in the state in 2010, following CA's lead as CA had 10,100 gasohol stations in 2010 [27]. Additionally, station growth trajectories for the other states follow that for CA. Figure 2.3 shows the projected H_2 station growth in select

[3] On December 18, 2015, HR2029 retroactively extended the \$8,000 FCEV tax credit initially set to expire December 31, 2014 an additional two years [1].

[4] The infrastructure penalty sis taken from Greene [8] for all powertrains except BEVs, which are handled separately [4].

states using this state mandated growth in addition to market driven growth. In all states, the station mandated infrastructure growth ends no more than 19 years after the beginning of the mandate. At this point, market forces alone dictate infrastructure growth.

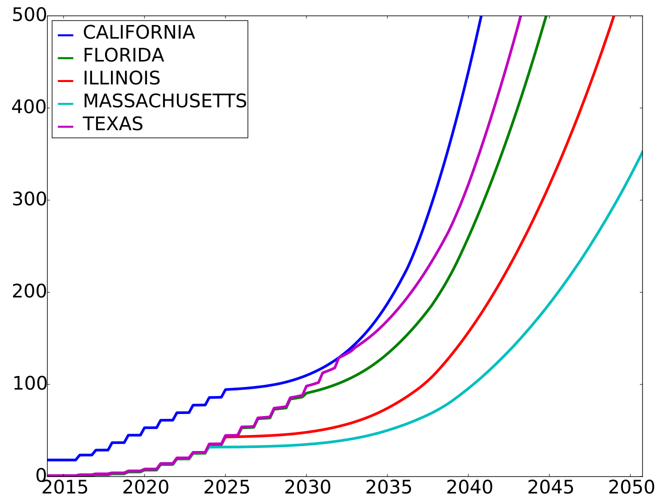


Figure 2.3. Projected H_2 station growth for selected states assuming state mandated growth akin to California's, beginning 2015.

The start year of the state mandated build out is parameterized, allowing testing of the impacts of delayed mandated infrastructure growth. In the baseline case, we assume that state mandated growth begins in 2015. However, market forces drive the majority of station growth, as shown in figure 2.3, and 2050 FCEV market share is relatively insensitive to delays in the mandate start date.

Hydrogen Production

H_2 production is a secondary sub-model within fuel production with similar interactions with the electricity and energy sub-models as the production of other fuels. For a given H_2 demand, the simulation will choose between H_2 produced for industrial purposes that is delivered to vehicle refueling stations at a markup, or between six dedicated production pathways including two distributed production pathways and four centralized production pathways. These pathways are:

- Distributed steam methane reforming of natural gas (DSMR)
- Distributed electrolysis using the marginal grid mix (DElec)
- Central steam methane reforming of natural gas with no sequestration of CO_2 (CSMR)

- Central steam methane reforming of natural gas with sequestered CO_2 (CSMR seq.)
- Central coal gasification with sequestered CO_2 (CCoal seq.)
- Central electrolysis using dedicated wind turbines (CElec)

For the centralized production pathways, H_2 is assumed to be delivered to refueling stations in gaseous form via tube truck.

Energy source requirements for these pathways are taken from the Hydrogen Macro System Model (MSM) [17, 18] which itself aggregates other DOE hydrogen models including the models falling under the Hydrogen Analysis (H2A) Project [24] and GREET [33]. National average 2015 prices for full scale H_2 production for each of these pathways are also taken from MSM simulations assuming 2015 technology, and are shown in table 2.2 with associated GHG emissions produced by the pathway. These national average prices are split into feed and non-feed costs. Feed costs are the costs directly attributable to source energy and electricity consumption in the production, delivery, and dispensing of the fuel. These costs vary regionally and evolve throughout the simulation with the changing costs of energy and electricity. Non-feed costs are the fixed construction and operation and maintenance costs associated with production, delivery, and distribution. By default, non-feed costs are static throughout the simulation, approximating no cost-reducing technological development in the production pathways. Optionally the non-feed costs for each pathway can be set to decrease by a fixed percent each year until a pre-defined fixed cost is reached for 2050. The final price for the non-feed costs is set via a multiplier, and approximates the effects of technology improvements on the cost of H_2 production. Multipliers such as these can be used to explore the scope of uncertainty in future technology and commodity prices, and are discussed thoroughly in previous works [2, 3, 14] and briefly in section 5.

Table 2.2. National average H_2 pump fuel prices and emissions for present day commodity prices and assumed full scale production.

Pathway	**2015 H_2 fuel costs (\$/kg)**[a]			**GHG**
	at pump[b]	feed	non-feed	**(kg/mi)**
DSMR	5.08	1.38	3.26	0.24
DElec.	7.32	3.46	3.41	var.[c]
CSMR	5.73	1.09	4.19	0.22
CSMR seq.	5.97	1.11	4.41	0.13
CCoal seq.	5.71	0.93	4.33	0.11
CElec	8.31	0.19[d]	7.68	0.03

[a] Assumes production at or near capacity.
[b] Includes \$0.449/kg national average fuel fees and taxes.
[c] DElec emissions vary with local marginal grid mixes.
[d] CElec uses dedicated wind turbines for electricity, not the electric grid. Feed costs are from delivery and distribution only.

The simulation dynamically chooses between H_2 production pathways based on economic evaluation, considering the impacts of any implemented carbon taxes or policy mandates. The relative cost of H_2 produced by each production pathway varies with commodity prices, H_2 demand, and possible technology improvements for the pathway. Each state is assumed to produce its own H_2 using locally priced commodities; H_2 is not imported from other states or nations.

At the beginning of the simulation, H_2 used for vehicle refueling is assumed to be sourced from industrial suppliers that sell to refueling stations at a price markup. Industrial H_2 prices are initially derived from "Hydrogen and Fuel Cells: The U.S. Market Report" [5], tables 6 and 7. We assume that industrial H_2 is produced via SMR and delivered to refueling stations at costs equal to the average of east and west coast prices in "Hydrogen and Fuel Cells: The U.S. Market Report". Any price difference between this cost and the MSM simulated price of H_2 produced via dedicated full scale CSMR is treated as a price markup due to low demand and the cost of low volume delivery. Following the Market Report, the markup decreases as H_2 demand at each station reaches 8, 24, 50, and 80 kg/day/station thresholds. We implement these low demand markups in the simulation as multipliers on the non-feed costs of H_2 production and delivery. By implementing industrial H_2 costs in this way, we allow industrial H_2 prices to vary in response to NG and local electricity prices as well as technology improvements that affect production and delivery costs. Since Hydrogen prices may have changed since "Hydrogen and Fuel Cells: The U.S. Market Report" was published in 2007, we additionally implement a scale factor for the industrial markup, allowing users to tune the price of industrial H_2 in the simulation to observed values. Current delivered H_2 prices in CA range from \$15/kg to free, depending on the station and vehicle purchase or lease agreement. We set the default markup scale to 0.3 in order to achieve an initial H_2 price of approximately \$11/kg for demand under 8kg/day/station.

As demand increases, dedicated production of H_2 for vehicle use becomes more economically viable. In the simulation, distributed production capacity can be built for any demand, though the pump-fuel price of the H_2 will be higher if the scale of production is below full capacity, assumed to be 1500 kg/day in compliance with H2A [24]. For low scale production, the non-feed costs of production are distributed over the existing demand.[5] The regional price of the pump-fuel H_2 is therefore given by:

$$\mathbb{C}_r(\$/\mathrm{kg}) = \sum_f \left(\mathbb{C}_{fr}(\$/\mathrm{GJ}) \times \mathrm{efficiency}_f \left(\mathrm{GJ}_f/\mathrm{kg}_{H_2}\right)\right) + (ds_r \times \mathbb{C}_n(\$)) + \mathbb{C}_{\mathrm{taxes}} \qquad (2.2)$$

where r is the region, f denotes the feed energy sources, 'efficiency' is the efficiency of the conversion from the feed energy source to hydrogen, and $\mathbb{C}_n$ are the non-feed costs given in table 2.2. The scale ds spreads fixed station costs over the amount of fuel actually sold. For

[5] In reality, H_2 refueling stations and distributed production can be designed and built for smaller capacities than 1,500 kg/day, thus lowering the costs of pump-fuel H_2 at lower demands. We do not consider customized station and distributed production sizing here, and thus simulated H_2 prices may be overestimated in certain low demand scenarios.

an individual station, this scale is the ratio of the full scale station capacity, 1500 kg/day, to the demand at the station. Therefore, for a region r with n_r stations and D_r total demand in the region, the average station demand scale will be given by

$$ds_r = \frac{n_r \times 1500 \text{ kg/day}}{D_r(\text{kg/day})}. \tag{2.3}$$

In each state, H_2 demand must be spread over a pre-defined minimum number of H_2 refueling stations. This distribution of demand is a reflection of the distribution of FCEV sales over the state. For example, a FCEV bought in Pittsburgh will have little impact on the demand at a refueling station in Philadelphia. The number of H_2 stations over which demand must be spread for each state is defined to be 1% of the number of gasohol stations in the state taken from National Petroleum News Magazine [12]. This requirement is in agreement with CA's commitment to fund the build out of 100 H_2 refueling stations in advance of demand. As detailed in subsection 2, we simulate similar mandated infrastructure roll-outs for the other states.

Centralized production capacity can only be built if unmet H_2 demand is greater than or equal to the capacity of the production plant, 50,000 kg/day [24], times the number of plants needed to supply H_2 to 1% of the gasohol stations in the state, consistent with the requirements for distributed refueling. As the distribution capacity of a refueling station is assumed to be 1500 kg/day, this corresponds to one production plant for approximately every 33 H_2 stations, or 3300 gasohol stations. For the majority of states, only one centralized plant is needed. For larger states such as California and Florida, three are needed. Texas requires the most central production plants with 4 plants required to serve 134 stations.

Once demand is sufficient to render either distributed or centralized production economical, the simulation will choose the lowest cost production pathway to satisfy that demand, accounting for any possible policy constraints. For each state, if there is sufficient demand for scaled distributed production but not centralized production, the simulation will only choose between distributed production methods. Once a distributed production method is selected for a state, it is the only allowed production method for that state until production at each station reaches full scale. After this initial demand is met, any additional production is assumed to be utilized at full capacity, or equivalently, to price its H_2 competitively with existing full capacity production. If unmet demand, i.e. demand increases not met by existing capacity, becomes sufficient to fully utilize centralized production pathways, the simulation can additionally select from these pathways. Distributed production capacity is assumed to retire and must be replaced after 20 years, and centralized production capacity is assumed to retire after 40 years, consistent with the assumption in H2A.

Each state's pump fuel price for H_2 and associated production emissions are computed as the weighted average of the costs and emissions of the active H_2 production pathways in that state. The non-feed H_2 costs will reflect the state of technology when each production plant was built, while the feed costs vary quarterly with commodity prices and the local price of electricity. Emissions for each pathway are set by MSM model results for all but the distributed electrolysis (DElec) pathway, which is closely tied to the simulated electricity grid. Electricity for DElec is assumed to be supplied by the marginal grid mix. This is consistent with ParaChoice's treatment of BEVs, electricity for which is also assumed to be supplied by the marginal grid mix. In the case of a carbon tax, the cost of the GHG emissions from H_2 production are computed separately for each production pathway and added to the nominal price of the pump fuel H_2 produced via that pathway. These carbon taxed prices are then used to select the most cost effective production pathways and compute the weighted average cost of the pump-fuel produced in each state.

Baseline Inputs and Parameterization

Many aspects of consumer choice modeling are uncertain. This uncertainty is inherent both in the model logic, as consumer behavior is imperfectly understood, as well as the underlying assumptions for future commodity and technology prices. While it is possible to verify the model logic to a limited degree using historical data [10], the scope of uncertainty in most parameters must be addressed in other ways. The ParaChoice model employs a parametric approach to handle uncertainty. The model uses best-available 'baseline' inputs and then parameterizes around these values, exploring thousands of potential input variations. We then use these thousands of scenarios to explore the sensitivity of results to the underlying assumptions.

For time varying input assumptions, like projections for oil price costs, we employ a multiplier approach. Rather than varying the projections for oil prices in 2030 and 2031 independently, we scale the projections for each year by a multiplier that varies from one at the beginning of the simulation to a user specified value at the end of the simulation. Depicted in figure 2.4, this multiplier approach simulates the growing scope in uncertainty for projections farther into the future. By parameterizing this multiplier, we can explore the subspace of uncertainty around the baseline projection.

In the following analyses, we explore the role of FCEVs in individual scenarios, and use parametric analysis to ascertain the impacts of uncertain futures for commodity prices, fuel cell and battery technology prices, and H_2 refueling costs and infrastructure on FCEV adoption. We also perform a global sensitivity analysis to identify the most influential levers on FCEV adoption.

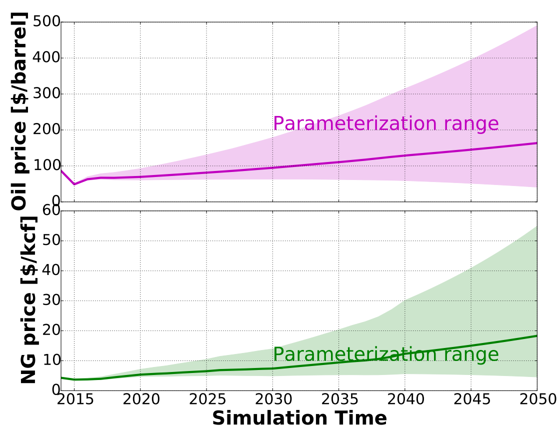


Figure 2.4. Parameteric range for evolution of oil and NG prices.

Chapter 3

Baseline Scenario

Sales and stock

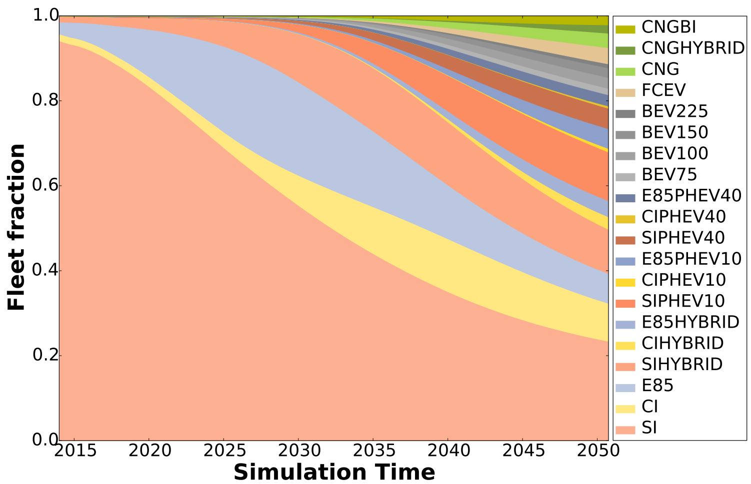


Figure 3.1. Stock projections for baseline scenario

Powertrain	% sales	% stock
SI	8.3	24.0
CI	6.5	9.5
E85	5.5	7.4
SI HEV	8.9	11.1
CI HEV	5.2	3.1
E85 HEV	4.9	2.7
SI PHEV10	13.2	12.3
CI PHEV10	2.2	0.9
E85 PHEV10	5.6	2.1
SI PHEV40	5.8	5.1
CI PHEV40	1.5	0.6
E85 PHEV40	2.5	0.9
BEV75	1.6	1.6
BEV100	2.8	2.7
BEV150	2.9	2.4
BEV225	1.3	1.0
FCEV	7.2	4.2
CNG	6.1	3.8
CNG HEV	4.9	2.2
CNG BI	2.8	2.3

Table 3.1. 2050 stock and sales

In the baseline scenario, FCEVs comprise 7.2% of new vehicle sales and 4.2% of the vehicle stock by 2050. These numbers put FCEV adoption on par with BEVs, which comprise 8.6% of 2050 sales and 7.7% of the stock. Despite these successes for zero emission vehicle (ZEV) technologies, SI, CI, E85 and non-plug-in hybrid vehicles still comprise nearly 40% of new vehicle sales, and 58% of the stock. The evolution of stock composition throughout the simulation and the projected 2050 sales and stock shares of the alternative powertrains are shown in figure 3.1 and table 3.1 respectively.

Figure 3.2 depicts generalized vehicle costs for the various powertrains over a three year payback period, revealing where FCEVs may be at an advantage or disadvantage in the

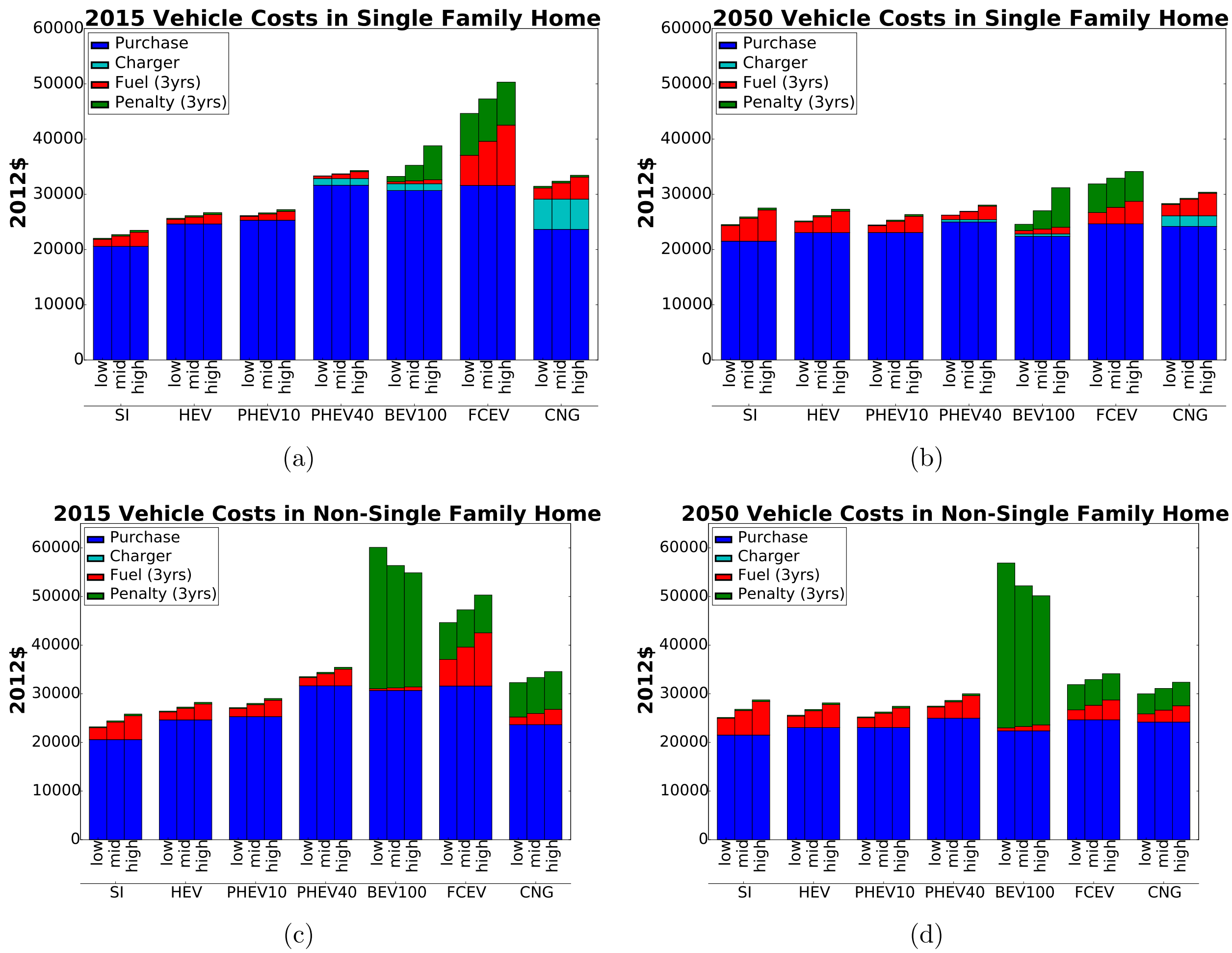


Figure 3.2. Generalized vehicle costs for different powertrains, including charger and compressor costs, fuel costs, and inconvenience penalties. Penalties are shown for heavy, medium, and light intensity drivers. Subfigures (a) and (b) show vehicle costs in 2015 (a) and 2050 (b) for vehicles kept in single family homes with potential for at home refueling of CNGs and BEVs. Subfigures (c) and (d) show 2015 and 2050 costs for vehicles in homes without at home refueling capability.

market place. In the beginning of the simulation, FCEV technology costs are high, though in line with BEV100 and PHEV40 technology costs. However, while BEVs benefit from the low cost of electricity throughout the simulation and CNG costs are on par with gasohol costs, H_2 fuel is initially very expensive. Additionally, refueling station scarcity increases the total perceived cost of FCEVs, making it the most expensive option for consumers in single family homes where at-home vehicle charging is viable. In non-single family homes, FCEVs are a more viable option than BEVs, but still compare unfavorably to HEVs and PHEV10s which can use existing gasohol refueling infrastructure, and CNGs which have lower fuel and purchasing prices. We do note that federal and state incentives, not shown in figure 3.2, will generally drive down the cost of FCEVs more so than CNGs. However, there is currently no state with incentives large enough to bridge the cost gap observed in figure 3.2.

By the end of the simulation in 2050, technology prices for the various powertrains are predicted to equalize as currently novel technologies become cheaper and SI vehicles must make cost sacrifices to meet efficiency requirements. Additionally, the adoption of FCEVs throughout the simulation increases refueling infrastructure availability and H_2 demand, lowering the 2050 price of H_2 and the penalty due to station scarcity. The combination of these three effects allows FCEVs to compete more readily against conventional vehicles and other AEVs. By 2050, FCEVs compare commensurately to BEVs, which still suffer from range associated penalties in 2050, and are also a match for CNGs which have longer refueling times and for which compressor costs offset some of the advantages to at-home refueling.

In order to determine more directly where FCEVs are in competition with the other powertrains, we compare these baseline simulation results to a simulation in which the vehicle model lacks FCEVs, but is identical in all other respects. Table 3.2 compares the 2050 sales fractions by powertrain and mileage fractions by pump fuel for the baseline scenario and this equivalent scenario without FCEVs. While FCEVs are pulling from the conventional, hybrid, and electric vehicle markets by a small amount, FCEVs seem to be primarily in competition with CNGs. CNG vehicles lose 14.8% of their 2050 sales and CNG fuel loses 13.2% of its 2050 usage when FCEVs are added to the vehicle model, and 1/3 of the FCEV market share can be attributed to lost CNG sales.

Table 3.2. Effect of FCEVs on 2050 sales and alternative fuel mileage.

2050 % Sales			
Power	**Baseline**	**no FCEVs**	$\delta(\%)$
SI	8.3	8.8	5.7
CI	6.5	6.9	5.8
E85	5.5	5.9	6.8
HEVs	19.0	20.2	5.9
PHEV10s	21.1	22.4	5.8
PHEV40s	9.8	10.4	5.8
BEVs	8.7	9.2	5.4
FCEV	7.2	0.0	
CNGs	13.8	16.2	14.8

2050 % Mileage			
Fuel	**no FCEVs**	**Baseline**	$\delta(\%)$
Gasohol	58.1	60.5	4.0
Diesel	14.3	15.0	4.7
B20	0.1	0.1	
E85	1.3	1.3	
CNG	9.9	11.4	13.2
H_2	5.1	0.0	
Elec.	11.2	11.7	4.3

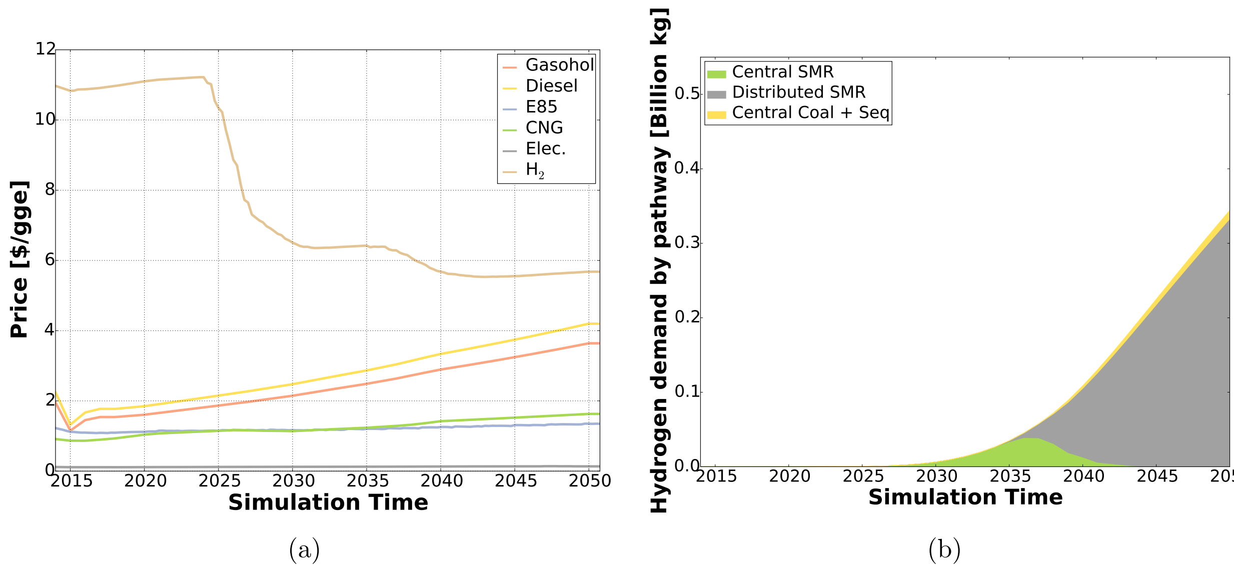


Figure 3.3. Baseline scenario H_2 pump fuel prices and production pathways. Pump fuel prices are reported in energy equivalent units and do not reflect differences in the efficiencies of various powertrains.

H_2 Fuel Costs and Production Pathways

In the baseline scenario, 2014 national average H_2 prices are set to approximately $11/kg for delivery volumes of less than 8 kg/station/day. As detailed in chapter 2, this fuel is assumed to be produced via CSMR for industrial applications and delivered to refueling stations at a markup that scales inversely with demand. Due to initial lack of demand, H_2 remains at approximately $11/kg through 2024. As can be seen in figure 3.3, simulated H_2 prices drop substantially from 2024 to 2030 following demand increases, even though the source of the pump fuel is unchanged. In 2034, demand increases sufficiently to render dedicated production economical in some states, resulting in another, more modest, price drop. This price drop extends to 2043 as the rest of the states transition and begin dedicated production at scale.

In almost all states, the lowest cost dedicated H_2 production pathway is DSMR. While economical, DSMR is a relatively carbon intense production pathway for H_2, and consequently FCEVs have negligible impact on GHG emissions in this baseline scenario; both the baseline scenario and the scenario without FCEVs result in stock average 2050 CO_2-equiv. emissions of 0.27 kg/mi. FCEVs running on H_2 produced via DSMR have a similar well-to-wheels carbon footprint as HEVs, PHEV10s, and CNGs, so displacement of these vehicles has a neutral effect on emissions if SMR is the pathway used to produce the H_2 fuel. Displacement of sales of these powertrains comprise 2/3 of the baseline FCEV sales. Moreover, the addition of FCEVs to the market only results in a modest decrease in petrol use. It is therefore apparent that FCEVs will not lower GHG emissions substantially by 2050 without either policy intervention, technological advancements in cleaner production pathways, or substantially increased FCEV adoption that significantly offsets conventional vehicle use.

Chapter 4

Reducing GHG emissions with FCEVs

Even though the baseline scenario projects that FCEVs will have limited impact on future GHG emissions, changes to 'business as usual' assumptions can effect significant changes to that outcome. Under the right circumstances, FCEVs and clean H_2 can be powerful tools for reducing stock emissions. We consider two possibilities for motivating cleaner H_2 production: a low cost electrolysis (LCE) scenario and a carbon tax scenario.

In the LCE scenario, we simulate improvements in electrolysis technology that lower the non-feed costs of both DElec and CElec substantially by 2050. We examine an idealized scenario where the non-feed costs for H_2 production via DElec are zero, and therefore the total price for pump fuel H_2 created via this pathway is simply the price of the electricity used to generate the H_2. In this scenario, we also assume that the non-feed costs of clean energy CElec fall to 70% of their 2015 values by 2050, resulting in a national average production cost of \$2.49/kg before taxes.[1]

As can be seen in figure 4.1, in the LCE scenario, the price of H_2 drops substantially in response to demand increase in 2024, similar to the baseline scenario. However, since electrolysis is less expensive, the transition to dedicated H_2 production starts earlier, in 2030, and results in a more substantial secondary drop in prices than observed for the baseline simulation. We do note that DSMR is still a less expensive production pathway than DElec in some states in this scenario. Even with no non-feed costs, the cost of DElec does reflect the cost of electricity. For states in which electricity costs are high, DSMR may still be less expensive than DElec. By 2050 in the LCE simulation, on average across the nation H_2 is both cheaper (\$4.96/kg versus \$6.09/kg) and cleaner (DElec rather than DSMR) than in the baseline scenario. This new H_2 price makes it cheaper than gasoline prices on a per mile basis in 2050; fuel for a midsize conventional SI vehicle costs \$0.16/mi while fuel for a midsize FCEV costs \$0.064/mi given projected efficiencies. Consequently, the total 2050 demand for H_2 in this scenario is 4.55×10^8 kg/year vs 3.44×10^8 kg/year in the baseline case. As depicted in figure 4.3, fleet GHG emissions drop to 0.26 CO_2-equiv. kg/mi in this

[1] CElec is assumed to use dedicated, wind generated electricity as its energy source, which is separate from grid electricity. Therefore, unlike the other pathways, it has few source feed stocks (e.g. coal, natural gas, biomass, or energy procured through the electric grid that would point back to those resources). With the exception of distribution and delivery, almost all expenses come from construction and operation and maintenance of the wind turbines and electrolysis technologies. Since delivery costs are \$1.78/kg in 2012\$ [17], the 70% reduction in non-feed costs explored here implies that hydrogen production costs are \$0.71/kg, including payback for the initial facility construction.

scenario, a 5% improvement over the baseline case.

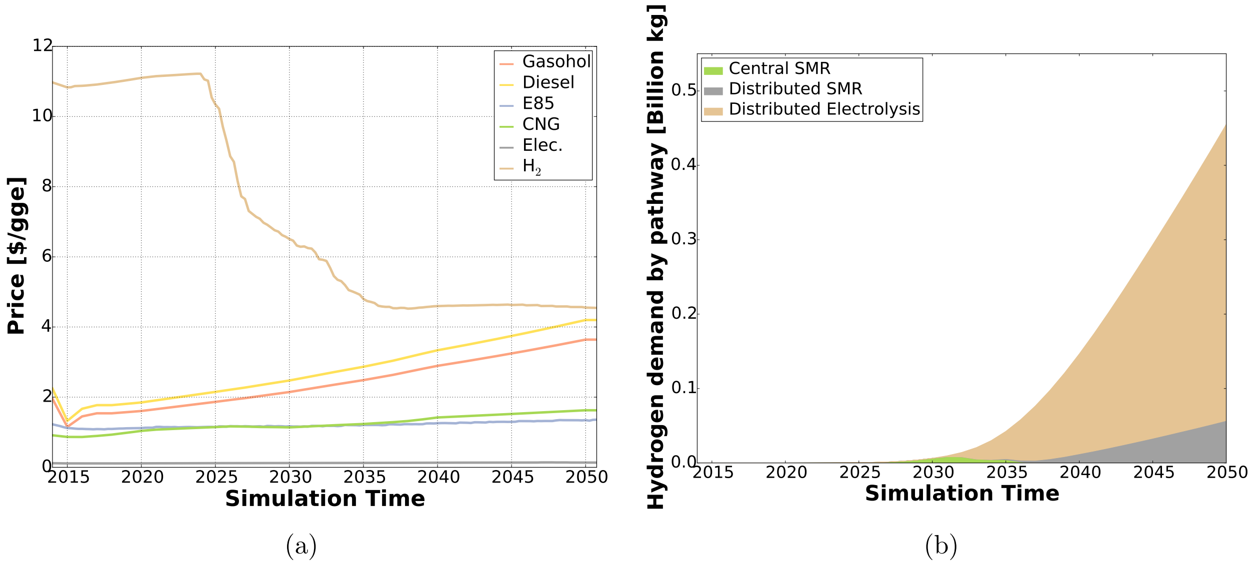
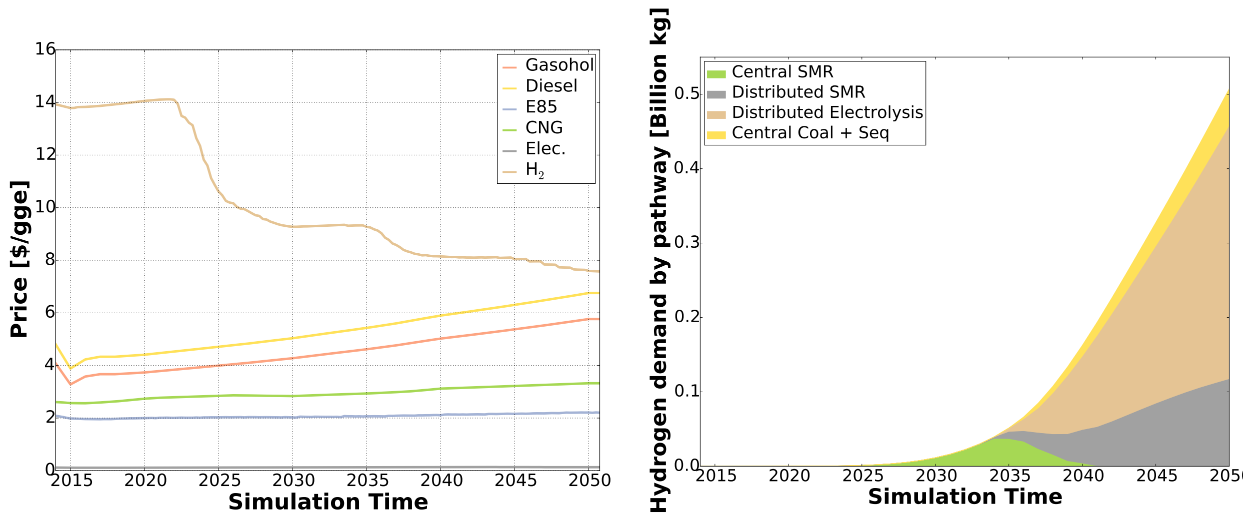


Figure 4.1. Fuel prices and H_2 production pathways for the low cost electrolysis scenario. Pump fuel prices are reported in energy equivalent units and do not reflect differences in the efficiencies of various powertrains.

In the carbon tax scenario, we assume baseline technology assumptions, but simulate a \$200/MT tax on carbon produced by any of the fuels. As can be seen in figure 4.2, the price for all fuels increases in this scenario. Even though H_2 has low carbon production pathways that can compete more readily with these conventional fuels in this scenario, these pathways are untenable until demand for H_2 increases sufficiently to render dedicated production for pump-fuel use economically viable. Until that point, which is not until at least 2033 in any state in this scenario, H_2 prices are substantially increased by the carbon tax since H_2 is produced via SMR, which is relatively carbon intense. However, once H_2 demand does increase sufficiently for dedicated production capacity to be built, the market largely drives production to low emission pathways and prices respond accordingly. We note that, even though DSMR production is relatively carbon intense and is therefore expensive when taxed for carbon emissions, it may still be less expensive than DElec in states for which the electric grid is highly dependent on natural gas. However, the electric grid evolves throughout the simulation to rely on cleaner energy sources, and so by 2050 much of the nation's H_2 production has transitioned to DElec. Consequently, the national average cost of H_2 is \$0.10/mi for a midsize FCEV, while gasoline costs are \$0.19/mi for a midsize conventional SI.

FCEV sales for 2050, shown in table 4.1, increase in both the LCE and carbon tax scenarios. However, in the LCE scenario conventional vehicle sales are largely unchanged from the baseline scenario, and most of the gain in FCEV sales is at the detriment of other



(a) (b)

Figure 4.2. Fuel prices and H_2 production pathways for the carbon tax scenario. Pump fuel prices are reported in energy equivalent units and do not reflect differences in the efficiencies of various powertrains.

AEVs. In contrast, in the carbon tax scenario, conventional vehicle sales drop significantly, and BEV adoption increases as well as FCEV adoption. Therefore, even though the gain in FCEV sales is slightly less in the carbon tax scenario than in the LCE scenario, the carbon tax has a more substantial impact on stock average GHG emissions, lowering them to 0.24 CO_2-equiv. kg/mi. This is a 13% improvement over the baseline scenario and a 55% improvement over 2014 emissions. GHG emissions for each of the scenarios are shown in figure 4.3.

We note that lower cost electrolysis could have a more significant impact on GHG emissions if FCEV sales were greater than the baseline scenarios might suggest. We explore the trade space of possible futures that could effect such changes on FCEV adoption in the following chapters.

Table 4.1. 2050 sales by scenario.

Power	Baseline	LCE	Carbon tax
SI	8.3	8.1	5.2
CI	6.5	6.3	4.6
E85	5.5	5.4	4.8
HEVs	19.0	18.5	16.9
PHEV10s	21.1	20.6	19.6
PHEV40s	9.8	9.5	9.9
BEVs	8.7	8.5	17.7
FCEV	7.2	9.9	9.5
CNGs	13.8	13.2	11.7

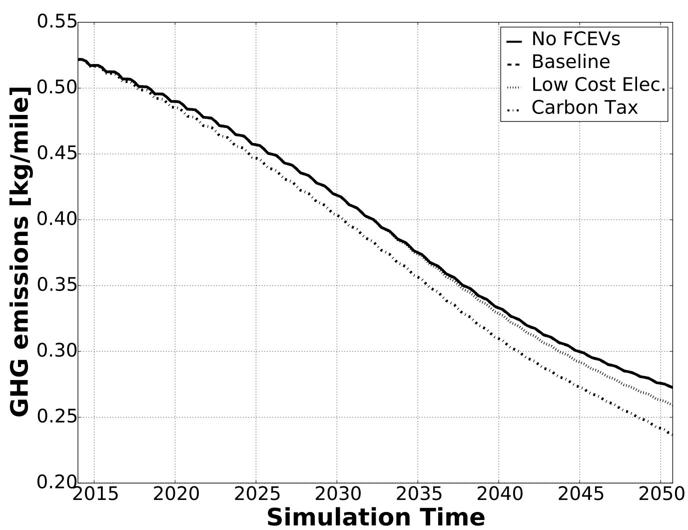


Figure 4.3. GHG emissions for the Baseline scenario, the equivalent scenario without FCEVs in the vehicle model, the LCE scenario, and the Carbon Tax scenario. The GHG emissions projected in the Baseline scenario are nearly identical to the GHG emissions projected in the scenario without FCEVs, and thus emissions from these two scenarios are indistinguishable in the figure.

Chapter 5

Parametric Analyses

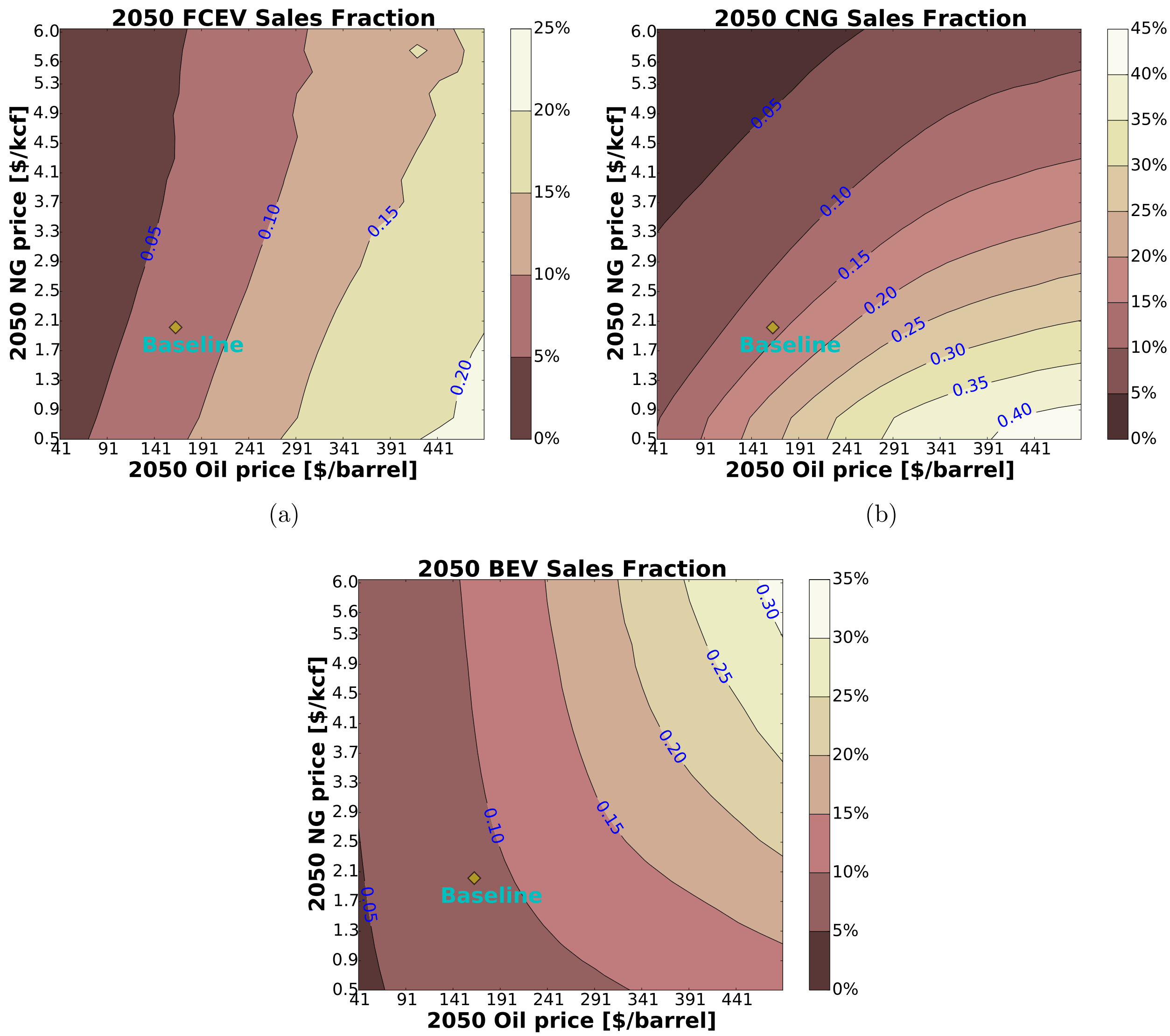
Energy Prices

Energy futures are highly uncertain and have the potentially to significantly affect AEV sales. In this chapter, we explore the trade space between oil and NG prices and the effect of these commodity price uncertainties on FCEV sales. Baseline projections for commodity prices are extrapolated from AEO [31], and place oil prices at $164/barrel and NG prices at $2.01/kcf by 2050. As detailed in chapter 2, we parameterize around these values, exploring futures where 2050 oil prices range from $41.9/barrel to $491/barrel and NG prices range from $0.50/kcf to $6.03/kcf by 2050. The responses of 2050 FCEV sales to these uncertainties in commodity price are shown in figure 5.1a. We compare the response of FCEV sales to the response to BEV and CNG sales, depicted in subfigures b and c.

Figure 5.1a shows that 2050 FCEV sales can vary from almost nothing in the extreme of low oil prices to nearly 25% in the case where oil prices are high and NG prices are low. This response to oil prices is intuitive; low oil prices lower the appeal of all AEVs, including CNGs and BEVs as shown in subfigures b and c. It is also reasonable that low NG prices would increase FCEV sales as the cheapest production pathways for H_2 are those reliant on NG SMR.[1] Conversely, when NG prices are high, both FCEVs and CNGs lose market share.

FCEV sales have a non-linear response to changes in NG prices which result in the sudden slope changes of the contours observed in figure 5.1a. This non-linearity of FCEV sales response to commodity price changes manifests most obviously in the upper right quadrant of figure 5.1a, where there is an 'island' of increased FCEV sales in a sea of lower sales fractions. In contrast CNG and BEV sales vary more fluidly in response to changes in commodity prices; CNG sales smoothly increase with high oil prices and low NG prices as expected. BEV sales uniformly benefit from both high oil and NG prices as internal combustion engines (ICEs) become less appealing. In the high NG price scenarios, BEVs benefit from the fact that electricity is produced in multiple ways, not strictly from NG. In particular, coal and natural gas produced electricity are competitively priced in the baseline scenario (barring regulatory hurdles not modeled here), so in the scenarios where NG is priced higher than expected, coal electricity production gains greater market share and keeps electricity prices low. In the case of clean energy regulation, these results might change, but

[1] If SMR were dis-incentivized in some other way, e.g. via a renewable mandate or a tax on SMR production pathways, the FCEV sales response to NG prices would change entirely.



(a) (b) (c)

Figure 5.1. Vehicle sales responses to different oil and NG price futures.

the baseline case might change as well depending on how NG is treated in the clean energy regulation.

The jaggedness of the FCEV response to commodity prices is caused by a combination of the discreteness of the H_2 production pathways, the response of H_2 production to demand, and the competition between CNGs, FCEVs, and SIs. When NG prices are high, H_2 production might switch to pathways that do not rely on NG. If the pathway does switch, the result is increased FCEV sales as FCEVs gain some of the market share which would have been held by CNGs. However, these alternate production pathways are only economically viable if H_2 demand is large enough to make dedicated production cost effective. So if NG prices are too high, the industrial H_2 supplying initial low H_2 demand will be expensive, FCEVs will be slow to gain market share, and H_2 demand may never increase sufficiently in some states to allow dedicated production to become economically viable. FCEVs will therefore lose market share. Similarly, if oil prices are too low compared to NG prices, FCEVs will be slow to gain market share over SIs, and H_2 demand may not be sufficient to allow for dedicated production in many states before 2050. So the jaggedness in the contours is caused by occurrences of 'sweet spots' in the oil and NG prices where NG prices are high enough to make non-NG H_2 production pathways more economical than SMR pathways, but the NG price isn't so high and the oil prices aren't so low that H_2 demand never gets a chance to develop.

Technology Costs

Baseline projections for battery and fuel cell technology costs are also highly uncertain. Using values from Autonomie [11], for a midsize BEV100 the 2050 battery cost is projected to be \$2983, corresponding to a price of \$114/kWh.[2] The total 2050 BEV100 vehicle cost with battery is therefore \$827 above the cost of an equivalent SI.

Similarly, the fuel cell technology in a midsize FCEV is assumed to cost \$3684 in 2050.[3] The total cost for the vehicle is therefore \$2981 above an equivalent SI.

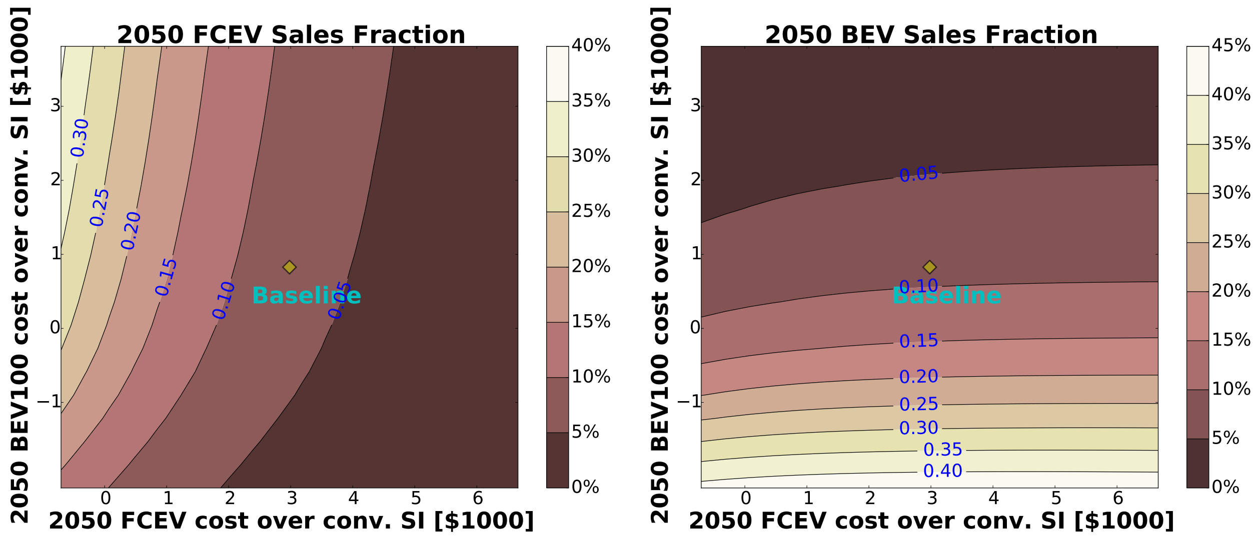
In addition to the technological uncertainty in the above values for battery and fuel cell costs, directed funding may be used to drive advancement in these ZEV technologies, rendering them less costly by 2050. In order to examine the potential impact of such funding as well as the scope of uncertainty in the baseline assumptions, we explore the response of FCEV and BEV sales to 2050 BEV100 prices between \$2156 below and \$3811 above conv. SI prices, and FCEV prices between \$703 below and \$6664 above conv. SI prices. The BEV100 price range corresponds to 2050 battery prices between \$0/kWh and \$228/kWh. The FCEV prices correspond to 2050 fuel cell technology costs between \$0/fuel cell and \$7367/fuel cell.

As shown in figure 5.2, decreases in FCEV technology costs have the potential to drastically improve FCEV market fractions. In the extreme where fuel cell technology is free, FCEV sales could be as great as 30% by 2050, despite the existing hurdles in H_2 production costs and refueling station scarcity. Interestingly, for baseline or greater fuel cell technology prices, FCEV sales are relatively insensitive to battery technology price increases. So if battery technology turns out to be more expensive than expected, FCEVs will likely not absorb most of the market share lost by BEVs unless FCEV technology improves substantially.

Similarly, BEV sales fractions are relatively independent of FCEV technology costs. Only

[2] All Autonomie prices reported in 2010\$.

[3] Autonomie provides total vehicle costs as well as battery and fuel cell specific costs. We include both the fuel cell and the battery costs for a FCEV as fuel cell technology costs.



(a) (b)

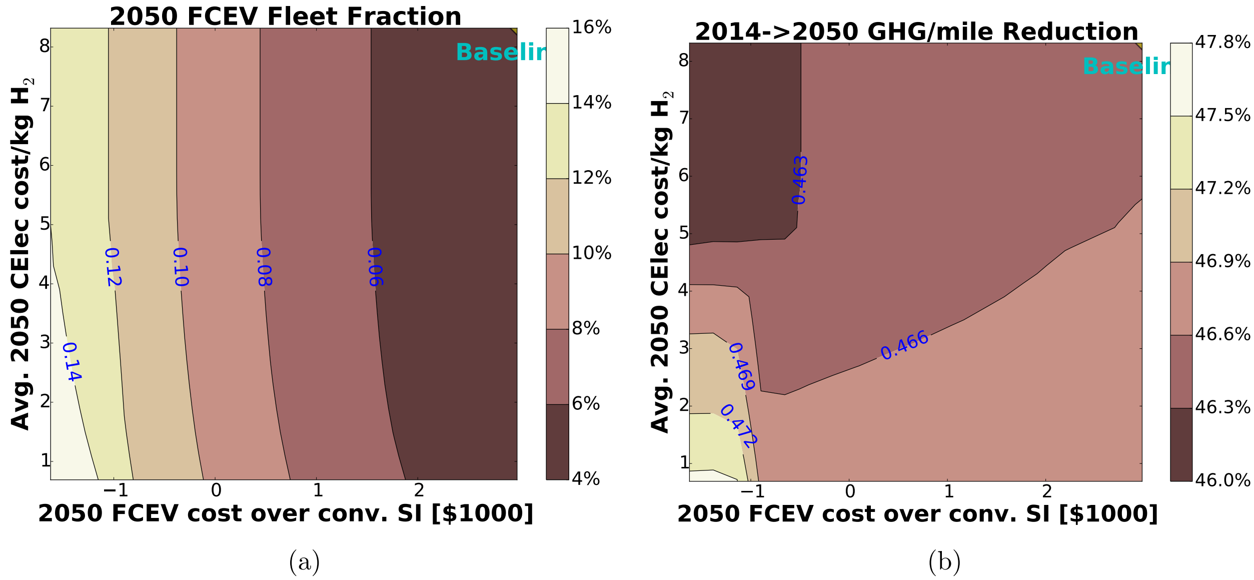
Figure 5.2. Vehicle sales responses to different technology futures.

in the extreme of low fuel cell costs does BEV market share decline in response to price pressures from FCEVs. This dynamic reflects the modest overlap of FCEV and BEV markets observed in chapter 3.

Fuel Cost

As initially shown in the low cost electrolysis scenario analysis in chapter 4, technology improvements in the H_2 production pathways can have a positive influence on FCEV stock fractions and fleet wide GHG emissions. In the baseline scenario, we assume that the non-feed costs associated with H_2 production remain fixed through 2050, and changes to H_2 prices are only driven by changes in the commodity prices and fuel demand. However, technology development is uncertain and can be influenced by directed funding, and therefore H_2 production may be less costly by 2050. We explore here in more depth the potential impacts of advancements in clean energy production pathways on FCEV adoption and GHG emissions by parameterizing the 2050 cost of H_2 produced via CElec. We juxtapose this clean H_2 cost reduction with advancements in fuel cell technology that render the vehicle less expensive. Results are shown in figure 5.3.

Exploring the subspace between the fuel cell and clean H_2 costs reveals that advancements in fuel cell technology can have a much greater impact on 2050 FCEV stock fractions than improvements in H_2 production technology. Except in the scenarios with the lowest fuel cell costs, the impact of reducing the cost of H_2 produced via CElec from its nominal \$8/kg price



(a) (b)

Figure 5.3. Response of FCEV stock and GHG emissions to improvements in fuel cell technology and clean central electrolysis (CElec). Unless CElec costs are reduced to approximately \$4/kg, more carbon intensive pathways will be more economical for H_2 fuel production and increased FCEV sales will have a neutral to negative impact on stock average GHG emissions.

to nearly \$0/kg is less than 5%.[4] In contrast, if fuel cell technology is free, the FCEV stock fraction can increase by as much as 10%.

However, while CElec costs have a small impact on FCEV adoption, they are critical for lowering FCEV emissions. If FCEV adoption is high, but clean production pathways follow baseline price projections, FCEV adoption will increase stock emissions. If the 2050 cost of CElec is not lowered by at least \$3 from the baseline projections, CElec technology improvements will have no impact on FCEV sales or stock emissions as SMR production pathways will still be the least expensive and most utilized production pathways in most states. Only if CElec becomes cheaper than the other pathways will it have the potential to impact FCEV sales and GHG emissions, albeit by a small fraction. The greatest positive impacts of CElec price reductions on GHG emissions naturally occur when FCEVs are inexpensive and abundant in the fleet.

[4]The lowest price is not exactly zero as we assume that state fuel taxes and the energy and electricity costs associated with the H_2 delivery and dispensing are unchanged.

Chapter 6

FCEV Purchasing Incentives

Since purchasing incentives will likely be necessary to move FCEVs into a dominant position in the 2050 vehicle stock, we explore ways in which such an incentive might be implemented in order to have maximum impact. The two factors we consider here are the FCEV incentive amount and the incentive end date. We assume that the incentive begins at the start of the simulation and will retain its value through the first quarter of the incentive end year.[1] We further assume baseline technology cost progression of fuel cells. Explored incentives range from \$0 to \$20,000, and end dates for the incentive range from end of 2015 to the first quarter of 2050. Vehicle sales, mileage, and station ratios are probed at the last quarter of 2050, after all incentives have ended.

Figure 6.1 shows the impacts of different incentive structures on 2050 FCEV sales, miles driven on H_2, and H_2 refueling station fractions. Figure 6.2 details the evolution of AEV sales and mileage driven by pump fuel for three of the scenarios that generate approximately the same number of 2050 FCEV sales: a \$20k incentive that extends to 2025, a \$9.5k incentive that extends to 2035, and a \$4k incentive that extends to 2045.

With large and sustained incentives, FCEVs can comprise nearly 1/4 of new vehicle sales by 2050. More modest incentives, either lower incentives extended until 2050 or larger incentives ending in the mid 2020s can still motivate substantial adoption. Notably, 2050 sales do not exceed 25% at the end of the simulation in the last quarter of 2050, even if a \$20k incentive extends into the first quarter of 2050. For all incentive structures, there exists a sharp tipping point where 2050 sales rapidly increase in response to either a small increased incentive duration or a small increased incentive value. For example, a \$10k incentive results in 10% more 2050 FCEV sales if the incentive is extended through 2035 rather than 2030.

While the 2050 mileage fraction driven on H_2 can be quite high, the largest gains in 2050 H_2 mileage fraction occur only for the simulations where the incentive extends until at least 2040, and thus for which vehicles purchased during the incentive remain part of the vehicle stock at the simulation end in 2050. For incentives expiring before 2040, the vehicle stock has largely turned over between the end of the incentive and the end of the simulation 2050, and therefore the mileage fraction driven on H_2 does not exceed 30%. These findings are

[1] Any implemented incentive would likely taper off gradually following e.g. Colorado's BEV incentive, or as FCEV sales thresholds are met following, e.g. the current federal BEV tax rebate and California's high occupancy vehicle lane incentive [26]. This analysis is a simplification in order to isolate the more long term impacts of the incentive duration.

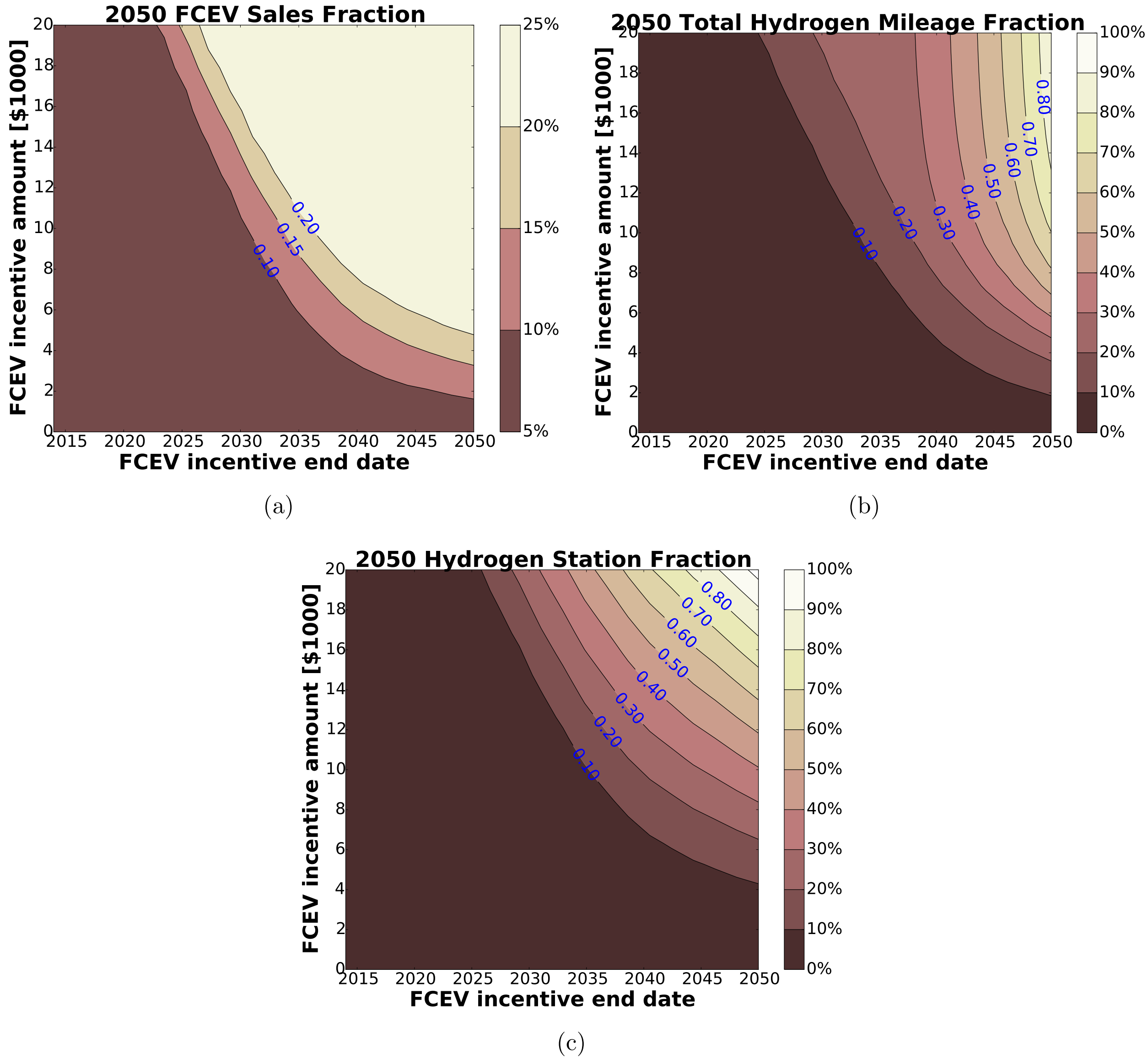


Figure 6.1. 2050 (a) FCEV adoption, (b) H_2 use, and (c) refueling station availability in response to different FCEV incentives. H_2 station fraction is computed as the ratio of H_2 and gasohol stations.

confirmed in figure 6.2, which shows that new FCEV sales drop substantially at the end of the incentives. Consequently, the fractional mileage driven on H_2 either stagnates or begins to decrease following the incentive end. One might therefore conclude that the large mileage fractions observed in in the upper right corner of figure 6.1b are also temporary and H_2 usage may decline in the 2050s as the FCEVs bought during the incentive age out of the stock.

The three incentive scenarios depicted in figure 6.2 show that there are multiple means to achieve similar 2050 end goals. However, each incentive structure has its own costs and consequences, demonstrating that one cannot just consider one adoption metric in isolation. Table 6.1 outlines the costs of each pathway and the relative gains in total FCEVs sold before 2050, the total stock miles driven on H_2 between the beginning of the simulation and 2050, and the H_2 refueling station density at the end of the simulation. The number of FCEVs sold and stock mileage fraction are metrics for monitoring the impact of the incentive before 2050. The station density at the end of the simulation determines the infrastructure obstacles FCEVs will face moving forward from 2050.

Table 6.1. Impact of incentive structures

Incentive	**Incentive cost**	**FCEVs Sold before 2050**		**H_2 mileage before 2050**		**2050 H_2 state station frac.**
	billion	million	inc.	trillion	inc.	range
none		18.6		6.32		0.017 - 0.036
\$20k/veh. ends 2025	\$289	58.9	217%	24.4	286%	0.047 - 0.140
\$9.5k/veh. ends 2035	\$236	67.4	262%	28.7	354%	0.057 - 0.151
\$4k/veh. ends 2045	\$162	58.3	213%	22.0	286%	0.044 - 0.119

The \$4k incentive ending in 2045 is the least expensive of the three to fund, costing \$162 billion. However, the 2050 H_2 refueling station density resulting from this scenario is the smallest, implying that FCEVs may face greater challenges moving forward from 2050 than they would given other incentive structures. The \$9.5k incentive ending in 2035 costs \$236 billion, but it produces the largest impact in total FCEV sales, petroleum use reduction pre-2050, and station density at the end of the scenario. There are many metrics by which one can gauge the success or impact per dollar of an FCEV incentive program. This analysis demonstrates that the metric for success must be carefully chosen and incentive structures optimized accordingly.

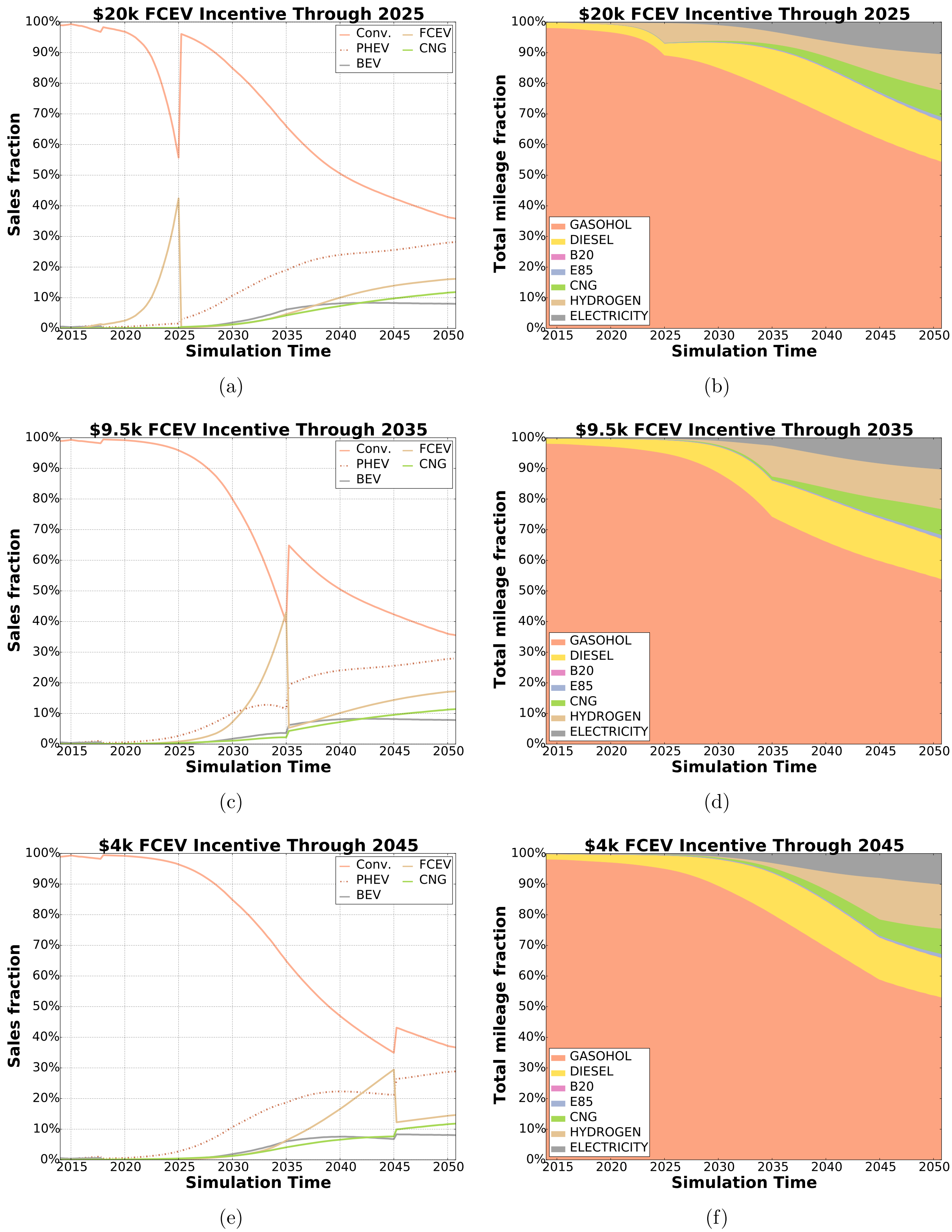


Figure 6.2. Evolution of sales and fuel usage for different FCEV incentive structures.

Chapter 7

Global Sensitivity Analysis

In order to verify the model behavior and determine the most significant drivers of FCEV adoption, we perform a global sensitivity analysis of the key input assumptions on output metrics of interest including 2050 stock fractions of FCEVs, BEVs, and ICEs. SI, CI, E85, and HEV versions of the same are all included in this ICE category. We sample input triangular distributions 3,000 times in a Monte Carlo simulation with Latin hypercube sampling and use the simulation results to compute Spearman rank correlation coefficients between the input parameters and the output metrics. The magnitude of the correlation coefficient reflects the statistical association between the variation of an input parameter and variations in the output metric. Coefficient values of 1 or -1 respectively represent perfect positive or negative correlation between the input parameters and output metrics.

The results of the sensitivity analysis are shown in table 7.1. The input parameters and the baseline, minimum, and maximum values for these parameters are shown in the left four columns of the table. The correlation coefficients between each input parameter and 2050 FCEV, BEV, and ICE stock fractions are given in the rightmost three table columns. Parameters are sorted by type and then by influence on 2050 FCEV stock fractions.

The most influential parameters on FCEV stock fractions are ICE efficiency, ICE prices, and oil costs; the vehicle choice function exponent; fuel cell and DElec technology costs; the consumer payback period and penalty multipliers; battery costs; and the vehicle sales rate.

As oil prices decrease, ICE efficiency improves, or ICE prices drop, conventional vehicles become more attractive and sales fractions of FCEVs and BEVs decrease, resulting in strong negative correlations. FCEV and BEV stock fractions also decrease in response to increases in the penalty multiplier. This multiplier weighs the consumer tolerance of inconvenience penalties, assigning these penalties greater costs as the multiplier increases. As FCEV, BEV, and CNG sales are the technologies most negatively impacted by infrastructure and range penalties, it is only natural that stock fractions of these vehicles correlate negatively with increases in this multiplier.

FCEV stock fractions correlate negatively with the vehicle choice exponent, as larger exponents increase the value of the dollar and assign greater sales fractions to the vehicles with the lowest generalized costs. Since FCEVs are relatively expensive, their sales are hindered when greater value is assigned to the dollar. In contrast, BEVs in single family homes are quite inexpensive once the federal tax credit is factored into the total vehicle

Table 7.1. Baseline, minimum, and maximum values for sensitivity analysis parameters. Also shown are Spearman rank correlation coefficients for outputs (columns) with respect to inputs (rows). Output metrics are measured at simulation end, 2050.

Parameter	Baseline	Min	Max	2050 fleet response FCEV	BEV	ICE
Choice functions						
Vehicle choice logit exponent	[9,12,15]	[6,8,10]	[12,16,20]	-0.35	0.16	-0.14
Fuel choice logit exponent	18	6	20	0.02	-0.03	0.03
Consumer attitudes						
Consumer payback period (years)	3	2	11	-0.18	0.34	-0.36
Penalty mult	1	0	1.5	-0.12	-0.25	0.24
Charging station ratio for 1/2 of pop. to consider public charging	0.1	0.01	0.2	0.13	-0.29	0.14
Bi-fuel usage at \$0.10/gge premium	0.395	0.3	0.49	0.03	0.04	-0.08
Policy						
Carbon price (\$/MT CO_2-equiv)	0	0	500	-0.05	0.41	-0.31
Start year of state mandated H_2 station growth	2015	2015	2040	-0.04	0.03	-0.02
Commodity prices						
Oil price mult	1	0.25	3	0.16	0.18	-0.29
NG price mult	1	0.25	3	-0.14	0.04	0.08
Zero-carbon energy price mult	1	0.25	3	-0.14	-0.02	0.05
Biomass energy price mult	1	0.25	3	-0.04	0.02	-0.03
Coal price mult	1	0.25	3	0.00	0.00	0.01
Vehicle technology						
ICE powertrain eff mult	1	0.6	3	-0.43	-0.41	0.50
Fuel cell cost mult	1	0	2	-0.31	0.03	0.07
ICE vehicle cost mult	1	0.9	1.5	0.30	0.27	-0.22
Battery cost mult	1	0	2	0.20	-0.23	0.10
H_2 technology						
DElec non-feed cost mult	1	0	1	-0.21	0.05	-0.01
DSMR non-feed cost mult	1	0	1	-0.08	0.05	-0.01
CElec non-feed cost mult	1	0.25	3	-0.02	-0.01	0.00
CSMR non-feed cost mult	1	0	1	-0.01	0.01	-0.01
Low demand H_2 price markup mult	0.3	0.01	0.6	-0.02	-0.01	0.02
Other						
Vehicle sales rate (%)	6.7	5	9	0.12	0.12	-0.38
Electricity generator lifespan (years)	40	20	60	-0.09	-0.01	0.02
New stations / 1000 vehicles	0.7	0	1.75	0.00	0.23	-0.16
CNG tech cost reduction rate	0.03	0	0.4	0.00	-0.07	0.04

cost. BEV stock fractions therefore correlate positively with the vehicle choice exponent. Last, there is a negative correlation between the choice exponent and ICE stock fractions. As technology advances, many alternative powertrains become more cost advantageous than conventional vehicles for many drivers. In particular, by 2050 the total generalized cost of a

SI PHEV10 vehicle is less than the total generalized cost of a conventional SI vehicle for the average driver, even in absence of incentives. Thus ICE stock fractions correlate negatively with the vehicle choice exponent.

Unsurprisingly, FCEVs respond positively to decreases in fuel cell and H_2 costs and increases in battery costs. As distributed H_2 production pathways are more economically viable than centralized production pathways in most scenarios, the effects of technology improvements on these pathways have the greatest impact on sales.

Interestingly, FCEV sales decrease in response to consumer consideration of longer payback periods. Even though refueling FCEVs can be much less expensive than refueling ICEs by 2050, this price differential is contingent on H_2 demand and not guaranteed. In contrast, H_2 is always quite expensive in early years compared to the other fuels. By increasing the consumer payback period, the effects of fuel prices and recurring incentives and penalties are amplified, rendering FCEVs unattractive compared to conventional vehicles. The result is a slower start for FCEV adoption and an overall negative impact on 2050 fleet fraction. In contrast, BEV stock fractions benefit from an increased consumer payback period. Electricity prices are inexpensive in comparison to gasoline prices in almost all scenarios, so increasing the consumer payback period amplifies the value of plug-in vehicles. While the inconvenience penalty for BEVs due to BEVs' range limitations and long refueling times are also amplified by the extended consumer payback period, these penalties can be much smaller, especially in the limit of low battery prices where longer range BEVs become less expensive.

Last, the vehicle sales rate correlates with increased FCEV and BEV stock fractions in 2050, as increased vehicle turnover allows greater penetration of new technologies.

Chapter 8

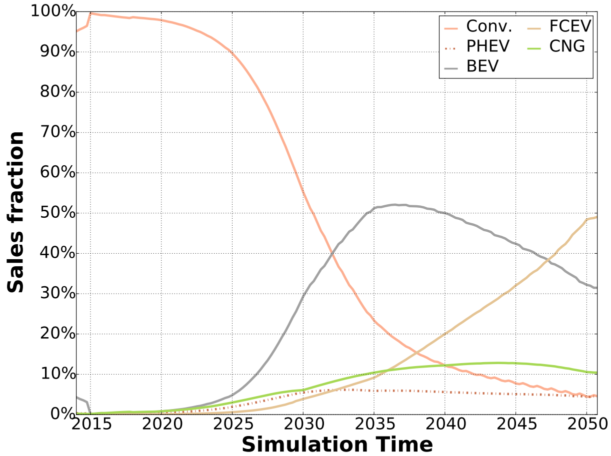
FCEV Utopia

Based on the sensitivities discussed in the previous chapter, we explore a 'utopia' scenario for FCEVs and clean H_2 to see the potential impact of FCEVs on GHG emissions and the 2050 vehicle stock. In this utopia scenario, industrial H_2 is sold to consumers without any low demand markup; the fixed costs for distributed and centralized electrolysis hydrogen production are 0 by 2050; fuel cell technology is free by 2050; the vehicle sales rate is 9% so the stock can transition to new technologies quickly; and the penalty multiplier is 0, removing all consumer concern about sparse refueling infrastructure.

While this utopia scenario targets FCEVs, no parameters are changed in such a way as to hinder the growth of electric vehicle or CNG technologies. Battery costs are fixed to their baseline values, as is the consumer payback period. ICE efficiencies and costs remain constant, though we do assume that oil prices increase to $328/barrel.

The impact of this FCEV utopia can be seen in figure 8.1. In this scenario, FCEVs play an ever increasing role in the LDV fleet, reaching 10% of sales by 2035 and comprising 29.6% of the stock and 49.1% of new vehicle sales and by the end of the simulation. Due in large part to the substantial role of DElec and CElec in H_2 production and the efficiency of FCEVs, GHG emissions plummet to 0.081kg CO_2-equiv. per mile by the end of the simulation, an 85% reduction over 2014 emissions and a 70% improvement over the baseline scenario's projected 2050 emissions.

Because many of the parameters that benefit FCEVs benefit EVs, EVs also play a substantial role in the stock in the FCEV utopia scenario. BEVs comprise 40.4% of the 2050 vehicle stock and 31.5% of new vehicle sales. Once again, we observe that BEVs and FCEVs are mostly harmonious technologies, each appealing to its own segment of the market.



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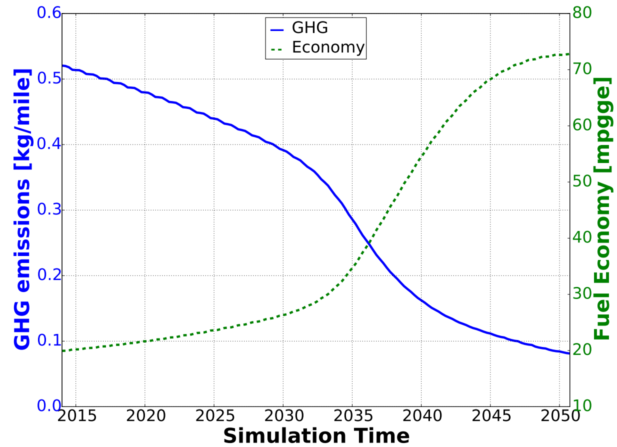

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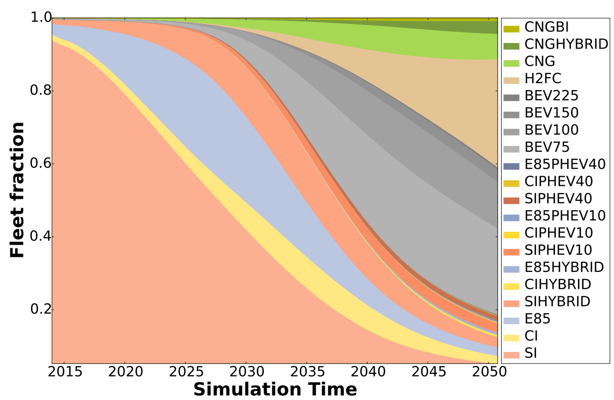

(c)

Figure 8.1. Impacts on vehicle sales, stock, and emissions in an FCEV utopia scenario.

Chapter 9

Conclusion and Policy Implications

FCEVs have the potential to play a substantial role in the future of the LDV stock. FCEVs appeal to many of the same consumers as CNGs, but displace petroleum consumption as well. The magnitude of FCEV market share, which vehicles FCEVs displace, and the net impact of these vehicles on GHG emissions depend on many factors explored throughout this work. We summarize our findings here:

- In the baseline scenario, FCEVs comprise 7.2% of 2050 vehicle sales and 4.2% of the vehicle fleet in 2050. In comparison, BEVs comprise 8.6% of sales and 7.7% of the fleet in this same scenario. However, baseline market conditions make distributed steam methane reformation of natural gas the most economical H_2 production pathway in most states, limiting FCEVs' ability to reduce GHG emissions.

- If technological advancements lower the costs of electrolysis, distributed electrolysis will become the dominant production pathway in most states, lowering stock average emissions 5% from the baseline scenario. A carbon tax can effect even greater GHG reductions as it motivates vehicle electrification as well as FCEV adoption.

- While higher natural gas prices will generally decrease FCEV adoption rates, this effect is less substantial than the impact of natural gas prices on CNG vehicles. FCEV sales have a complex relationship with natural gas prices as dedicated H_2 production may or may not rely on this resource depending on both commodity prices and the scale of demand for H_2.

- Fuel cell technology advancements have significant potential to increase FCEV sales. In the extreme limit where fuel cells are free by 2050, 2050 FCEV sales fractions can reach upward of 35%, despite infrastructure scarcity and initially expensive H_2 costs. Moreover, these sales are not at the detriment of BEV sales, indicating that these two ZEV technologies serve largely complementary markets.

- Substantial price reductions in clean H_2 production only increase FCEV adoption marginally compared to cost reductions in fuel cell technology. However, the promotion of clean production pathways is necessary in order to convert FCEV adoption into reduced GHG emissions. If SMR is the dominant H_2 production pathway, substantial FCEV sales can have a negative effect on GHG emissions.

- FCEV purchasing incentives have the potential to increase 2050 FCEV sales by a factor of three over the baseline scenario, but only if these incentives are substantial and sustained. A $20k incentive lasting until 2025 and costing $289 billion, a $9.5k incentive lasting until 2035 and costing $236 billion, and a $4k incentive lasting until 2045 and costing $162 billion all lead to 2050 FCEV sales of approximately 20%. However, each incentive has its own effect on petroleum consumption pre-2050 and on the vehicle stock moving forward from 2050. The cumulative impacts of these incentives, not just their short term effects on FCEV adoption, must be weighed and balanced against costs.

References

[1] 114th U. S. Congress. H. R. 2029, December 2015.

[2] Garrett E. Barter, David Reichmuth, Jessica Westbrook, Leonard A. Malczynski, Todd H. West, Dawn K. Manley, Katherine D. Guzman, and Donna M. Edwards. Parametric analysis of technology and policy tradeoffs for conventional and electric light-duty vehicles. *Energy Policy*, 46(0):473 – 488, 2012.

[3] Garrett E. Barter, David Reichmuth, Todd H. West, and Dawn K. Manley. The future adoption and benefit of electric vehicles: a parametric assessment. *SAE Int. J. Alt. Power*, 6(1), 2013. doi: 10.4271/2013-01-0502.

[4] Garrett E. Barter, Mike A. Tamor, Dawn K. Manley, and Todd H. West. The implications of modeling range and infrastructure barriers to battery electric vehicle adoption. *Transportation Research Record Journal of the Transportation Research Board*, (2502): 80–88, September 2015. doi: 10.3141/2502-10.

[5] G. Bromaghim, K. Gibeault, J. Serfass, P. Serfass, E. Wagner, and the National Hydrogen Association. Hydrogen and Fuel Cells: The U.S. Market Report. Technical report, Technology Transition Corporation, March 2010. Prepared by the Technology Transition Corporation for the National hydrogen Association.

[6] California Fuel Cell Partnership. A california road map, the commercialization of hydrogen fuel cell vehicles. Technical report, West Sacramento, CA, July 2014.

[7] Joe Gagliano. State commits funding for first 100 hydrogen stations. *California Fuel Cell Partnership Blog*, November 2013.

[8] David L. Greene. TAFV Alternative Fuels and Vehicle Choice Model Documentation. Technical Report TM-2001/134, Oak Ridge National Laboratory, Oak Ridge, TN, 2001.

[9] Honda. FCX Clarity, 2015. http://automobiles.honda.com/fcx-clarity/. Accessed 2015-10-27.

[10] Rebecca S. Levinson, Dawn K. Manley, and Todd H. West. History v. Simulation: An analysis of the drivers of alternative energy vehicle sales, 2015. Manuscript submitted for publication.

[11] A. Moawad, P. Sharer, and A. Rousseau. *Light-Duty Vehicle Fuel Consumption Displacement Potential up to 2045*. Argonne National Laboratory, Argonne, IL, April 2014.

[12] National Petroleum News Magazine. NPN Marketfacts 2012, October 2012. Table "2012 NPN Station Count (a)".

[13] Office of the Press Secretary. FACT SHEET: U.S. Reports its 2025 Emissions Target to the UNFCCC. *Statements and Releases*, March 2015.

[14] Meghan B. Peterson, Garrett E. Barter, Todd H. West, and Dawn K. Manley. A parametric study of light-duty natural gas vehicle competitiveness in the united states through 2050. *Applied Energy*, 125:206–217, 2014. doi: http://dx.doi.org/10.1016/j.apenergy.2014.03.062.

[15] S. Plotkin, T. Stephens, and W. McManus. Vehicle technology deployment pathways: An examination of timing and investment constraints. *Transportation Energy Futures Report Series*, March 2013. doi: DOE/GO-102013-3708.

[16] R.L. Polk and Co. U.S. Vehicle Registration Data MY 2005-2016, January 2015. Compiled by SRA International, Inc.

[17] Mark Ruth, Victor Diakov, Tim Sa, Mike Goldsby, Karen Genung, Ryan Hoseley, Ashley Smith, and Elvin Yuzugullu. Hydrogen macro system model user guide, version 1.2.1. Technical Report NREL/TP-6A1-44799, National Renewable Energy Laboratory, July 2009.

[18] Mark Ruth, Melissa Laffen, and Thomas A. Timbario. Hydrogen pathways: Cost, well-to-wheels energy use, and emissions for the current technology status of seven hydrogen production, delivery, and distribution scenarios. Technical Report NREL/TP-6A1-46612, National Renewable Energy Laboratory, September 2009.

[19] Randy Schnepf and Brent D. Yacobucci. Renewable fuel standard (RFS): Overview and issues. Technical report, Congressional Research Service, 2012.

[20] Sarah Shelton. Mercedes' and BMW's Future Emphasizes Fuel Cell Vehicles Over Battery Electric Cars. *HybridCARS*, August 2015.

[21] Walter Short, Patrick Sullivan, Trieu Mai, Matthew Mowers, Caroline Uriarte, Nate Blair, Donna Heimiller, and Andrew Martinez. Regional energy deployment system (reeds). Technical Report NREL/TP-6A20-46534, Golden, CO, November 2011.

[22] TranSystems. The emissions & generation resource integrated database for 2012 (egrid2012): Technical support document. Technical report, U.S. Environmental Protection Agency, Washington, DC, April 2012.

[23] U.S. Census Bureau. 2010 census of population and housing. Technical report, 2010.

[24] U.S. Department of Energy. DOE H2A Analysis. http://www.hydrogen.energy.gov/h2a_analysis.html. Accessed 2015-10-27.

[25] U.S. Department of Energy. *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry.* Number ORNL/TM-2011/224. R. D. Perlack and B. J. Stokes (Leads) Oak Ridge National Laboratory, Oak RIdge, TN, 2011.

[26] U.S. Department of Energy. *Federal and State Laws and Incentives*, February 2011. URL http://www.afdc.energy.gov/laws/.

[27] U.S. Department of Energy. *Alternative Fueling Station Counts by State*, 2015. URL http://www.afdc.energy.gov/ fuels/ stations_counts.html. Accessed 2015-10-28.

[28] U.S. Department of Transportation Federal Highway Administration. Highway statistics 2014, state motor-vehicle registrations. Technical Report MV-1, MV-9, 2014.

[29] U.S. Department of Transportation National Highway Traffic Safety Administration. Vehicle survivability and travel mileage schedules. Technical Report DOT HS 809 952, Washington, DC, January 2006.

[30] U.S. Energy Information Administration. *Electric Power Annual 2012*. Washington, DC, December 2013.

[31] U.S. Energy Information Administration. *Annual Energy Outlook 2015: with Projections to 2040*. U.S. Department of Energy, April 2015.

[32] U.S. Environmental Protection Agency. Light-duty automotive technology, carbon dioxide emissions, and fuel economy trends: 1975 through 2014. Technical Report 420-S-14-001, Washington, DC, 2014.

[33] M. Wang. *GREET 1 2012 rev1*. Argonne National Laboratory, Argonne, IL, 2012. http://greet.es.anl.gov.

[34] S. Zoepf and J. Heywood. Characterizations of deployment rates in automotive technology. *AE Int. J. Passeng. Cars - Electron. Electr. Syst.*, 121, 2012. doi: 10.4271/2012-01-1057.

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