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Summary of FY17 ParaChoice Accomplishments

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1 ParaChoice FY17 Goals

As part of analysis support for FCTO, Sandia assesses the factors that influence the future of FCEVs and Hydrogen in the US vehicle fleet. Using ParaChoice, we model competition between FCEVs, conventional vehicles, and other alternative vehicle technologies in order to understand the drivers and sensitivities of adoption of FCEVs. ParaChoice leverages existing tools such as Autonomie (Moawad et al., 2016), AEO (U.S. Energy Information Administration, 2016), and the Macro System Model (Ruth et al., 2009) in order to synthesize a complete picture of the co-evolution of vehicle technology development, energy price evolution, and hydrogen production and pricing, with consumer demand for vehicles and fuel. We then assess impacts of FCEV market penetration and hydrogen use on greenhouse gas (GHG) emissions and petroleum consumption, providing context for the role of policy, technology development, infrastructure, and consumer behavior on the vehicle and fuel mix through parametric and sensitivity analyses.

In FY17, Sandia was tasked to

- Update and add detail to ParaChoice's hydrogen fuel sub-model.
- Conduct scenario analyses to understand and provide context for the market penetration potential of FCEVs, hydrogen demand, costs, and production pathways.
- Complete sensitivity analysis, varying factors including station availability, fuel cost, efficiency, or technology cost.
- Conduct parametric analyses to understand sensitivities and tipping points driving FCEV sales, emissions, and hydrogen consumption and production.
- Analyze hydrogen prices and FCEV sales in response to various coal and natural gas futures.

This last item was an addition due to the change in priorities with the incoming administration and the potential resurgence of coal as an abundant and economically viable resource. The results of each of these analyses are detailed in the sections below.

The program office also expressed an interest in exploring the impact of electricity surcharges on FCEV sales, as the present projections for electricity prices do not reflect the price of public charging infrastructure, possible grid modifications required to support increased electricity usage caused by substantial EV adoption, or increases due to recovering of the gasoline tax revenue. This analysis is presented in §7.

Last, we have additionally added a Monte Carlo uncertainty analysis tool as part of the VTO FY17 AOP. We leverage this new capability here in support of FCTO missions.

2 Model improvements

We modified and upgraded ParaChoice in FY17 in order to improve how the simulation handles Hydrogen production, pricing, and infrastructure development. In particular, we:

- Updated the Hydrogen production and pricing sub-model in ParaChoice vehicle simulation
  - removing obsolete distributed production pathways at the direction of FCTO,
  - incorporating new pricing and emissions data from the Macro System Model, overriding default energy pricing data with up-to-date AEO values,
  - and incorporating smaller station size detail for lower volume demand, when industrial Hydrogen is used to supply vehicle demand.
- Matched simulated seeding of Hydrogen station growth to the Urban Scenario from the H2USA Location Roadmap Working Group (2017), and updated ParaChoice's initial Hydrogen station data to present day from the Alternate Fuels Data Center (U.S. Department of Energy, 2016). These steps ensure consistency between DOE programs.
- Added modeling capability for parametric analysis of the market response of Hydrogen infrastructure growth to FCEV sales, independent from the infrastructure growth for other fuels.

In addition to these modeling improvements for Hydrogen handling, we incorporated new data from Moawad et al. (2016) to improve parametric analysis of FCEV technology pricing. FCEV pricing parameterization now allows for variations in on-board Hydrogen storage in addition to the fuel cell technology. Additionally, variations in the price of the battery in the FCEV are now coupled to variations in the price of the battery in other EVs so FCEV technology varies and benefits appropriately in plug-in electric vehicle (PEV) analyses.

3 Analysis of baseline FCEV sales and Hydrogen prices and production

In ParaChoice's baseline simulation, which uses Autonomie's low technology and low price uncertainty projections and only policy which has been written into law (i.e. no Clean Power Plan),[1] FCEV's grow to 4.4% of vehicle purchases by 2050. Vehicle Purchase evolution is shown in figure 1. The growth in the adoption of clean technologies, including FCEVs, is largely due to the levelization of their upfront purchase prices in Autonomie, and the growth in market availability. As shown in figure 2, the drop in Hydrogen prices also lowers the total cost of ownership of FCEVs in 2050 as compared to the present. Due to the relative efficiency of FCEVs compared to conventional vehicles, FCEVs are projected to become less costly to fuel per mile than conventional gasoline, diesel, and E85 vehicles by 2050. However infrastructure scarcity continues to remain a barrier to adoption into the future as compared to these other powertrains, especially in single family homes where PEVs have a home refueling option.

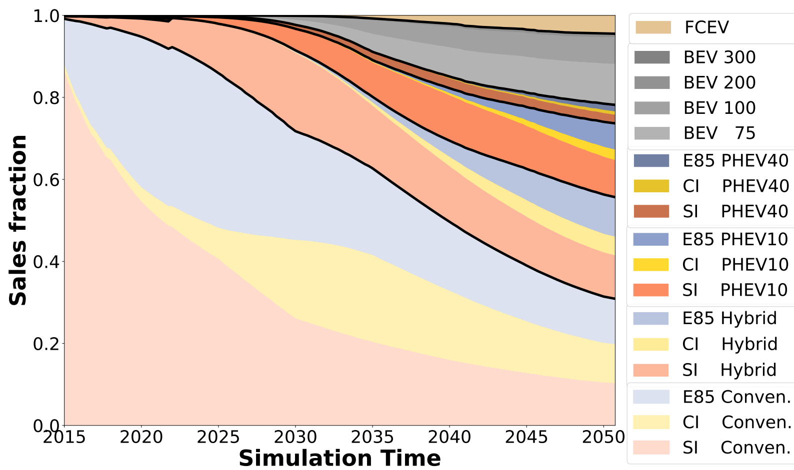
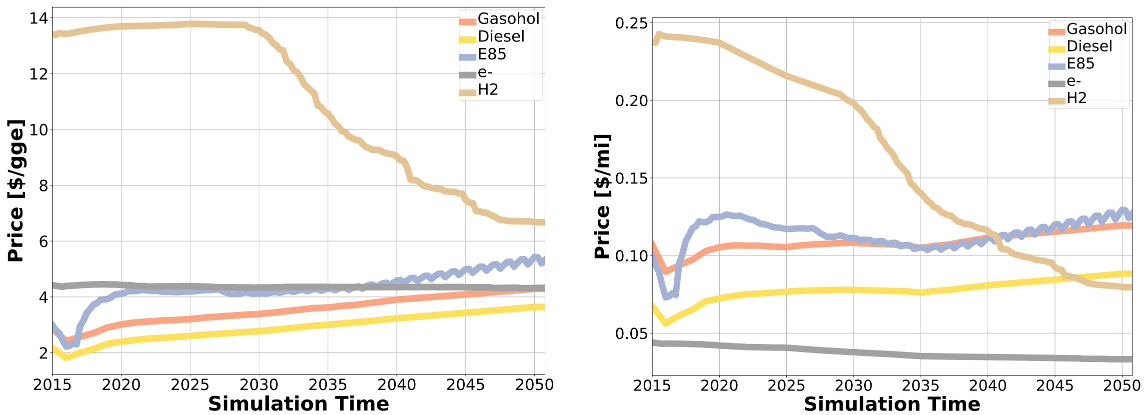


Figure 1: ParaChoice Baseline Sales Projection

As FCEV sales increase through time in the simulation, Hydrogen demand increases, delivery volumes for industrial Hydrogen increases driving down delivered prices, and eventually dedicated production of Hydrogen for vehicle use begins. This model output for Hydrogen demand as a function of simulation time is shown in figure 3. In ParaChoice's baseline simulation, natural gas is the most economically viable production pathway for

[1] ParaChoice's baseline scenario is NOT the same VTO/FCTO baseline scenario from its benefits study. Different assumptions are used for Hydrogen prices, Hydrogen station evolution, among other assumptions. The ParaChoice Baseline scenario is more conservative.



(a) Per GGE (b) Per Mile

Figure 2: ParaChoice Baseline Fuel Prices. Shown for representative midsize vehicles.

dedicated vehicle Hydrogen production once this production begins. Thus, in the states that have enough demand to transition from industrially sourced Hydrogen to dedicated Hydrogen production for vehciles, the source of the Hydrogen is still natural gas.

The breakdown of Hydrogen demand by state and production pathway in 2050 for this baseline scenario is shown in figure 4. California, Texas, the Atlantic seaboard, and the East North Central states (Michigan, Illinois, Ohio, and Indiana), have switched to dedicated Hydrogen production and dominate US Hydrogen demand.

Demand in Washington DC and possibly some of the smaller Northeastern states will likely trend slightly higher than modeled by ParaChoice, as the simulation restricts hydrogen distribution to within a state. This geographical limitation is based on the prohibitive cost of transporting Hydrogen by truck or building pipelines, and it ultimately impacts the potential hydrogen demand in a region and thus the state hydrogen price. For very geographically small states and Washington DC, the geographic restriction may not apply, and thus hydrogen prices may be lower in those states than modeled. Due to feedback, this would increase demand and lower prices even more.

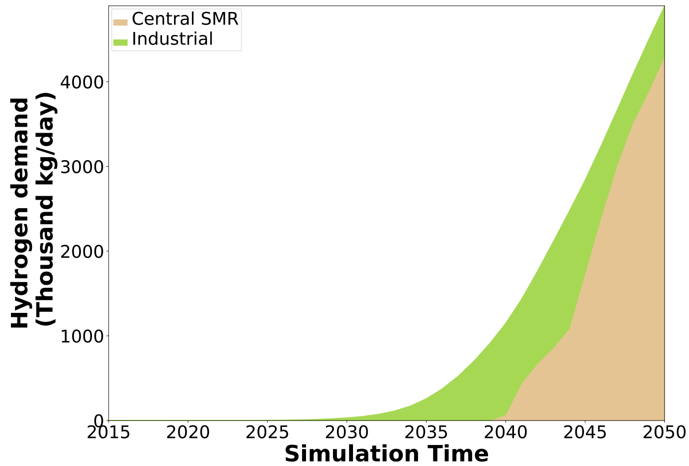


Figure 3: National Hydrogen Production

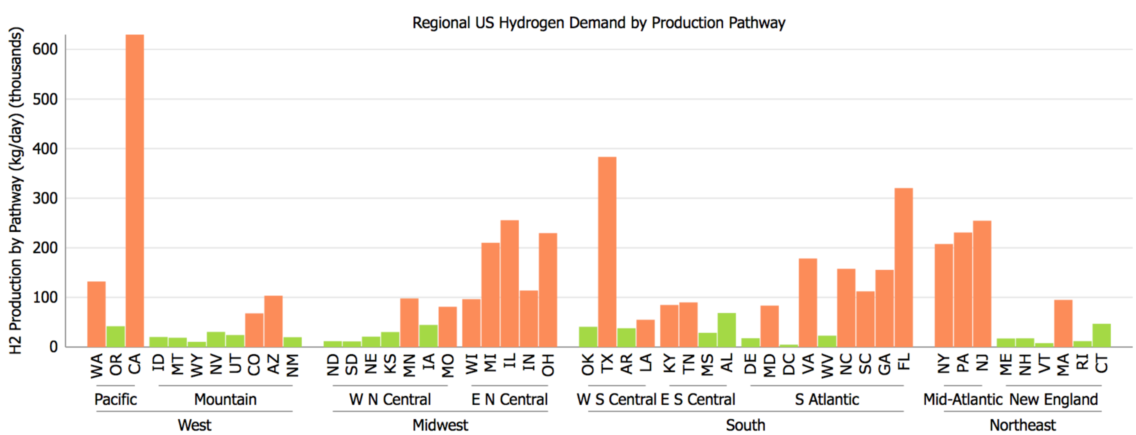


Figure 4: State Hydrogen Production in 2050. Orange bars represent states that have transitioned to dedicated Hydrogen production for vehicles. Green bars represent states that still use industrial Hydrogen to fuel vehicles.

4 Uncertainty Analysis

Many factors drive uncertainty in sales projections, and therefore uncertainty in FCEV sales is high. We quantify uncertainty in ParaChoice's projections using Monte Carlo analysis, varying the technology, energy, modeling, and behavioral (TEMB) parameters that underly the consumer choice model. Technology parameters are varied from the most optimistic case of the high technology uncertainty, high cost uncertainty in Moawad et al. (2016), around the triangular distribution center (in log space) of the low technology uncertainty, low cost uncertainty case. (The lower end of this triangular distribution is approximately the case where technology prices and efficiencies are flat from the present.) Energy prices are varied around AEO's projection in the case without the Clean Power Plan from half to double. Modeling and behavioral parameters are similarly varied. Parameter defaults and ranges for the Monte Carlo analysis are given in table 1.

Due to the uncertainties in the underlying TEMB parameters, 2050 FCEV sales are only constrained between 0.3% and 19% of purchases in 90% of scenarios, and reach 39% of purchases in the extreme. These results are shown in figure 5, alongside the uncertainties for plug-in hybrids (PHEVs) and full battery electric vehicles (BEVs). Notably, electricity surcharges for infrastructure are not assumed here, though they are explored in §7.

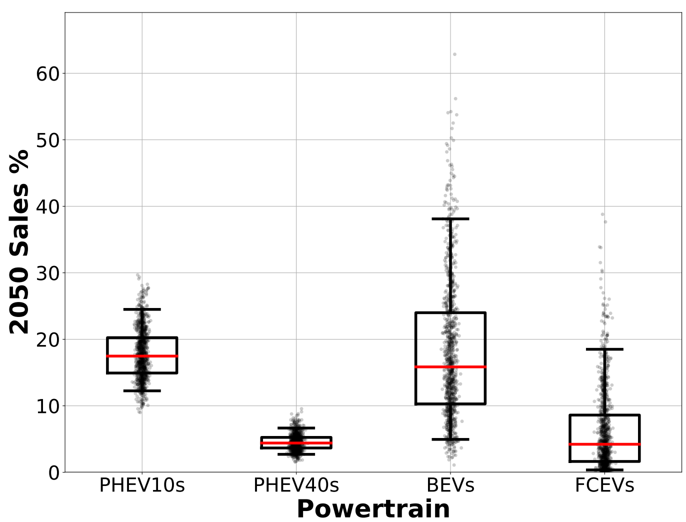


Figure 5: Uncertainty Analysis. Dots represent 1024 Monte Carlo Scenarios. Red line depict medians. Boxes contain 50% of scenarios. Whiskers contain 90% of scenarios. BEVs contain sum of all BEV powertrain sales.

Spearman correlation coefficients between the modeling parameters and FCEV sales, shown in the right hand column of table 1 show that the most sensitive drivers of fu-

Table 1: Technology, Energy, Modeling, and Behavior Parameters and 2050 FCEV Sales Sensitivity Computed with Spearman Correlation Coefficients

Parameter	Baseline	Min	Max	FCEV Sales Cor.
Energy Options				
Oil Price Multiplier[a]	1	0.5	2	0.27
Coal Price Multiplier[a]	1	0.5	2	0.05
Natural Gas Price Multiplier[a]	1	0.5	2	-0.08
Biomass Price Multiplier[a]	1	0.5	2	-0.01
Zero Carbon Energy Price Multiplier [a]	1	0.5	2	-0.04
Technology Options				
Battery Cost Multiplier[b]	1	0.5	2	-0.02
Fuel Cell Cost Multiplier[b]	1	0.5	2	-0.56
ICE Cost Multiplier[b]	1	0.8	1.25	0.08
EV Fuel Economy Multiplier[b]	1	0.67	1.5	-0.03
FCEV Fuel Economy Multiplier[b]	1	0.67	1.5	0.21
ICE Fuel Economy Multiplier[b]	1	0.75	1.33	-0.21
At-Home Charger Cost Reduction Rate	0.03	0.01	0.05	-0.03
Modeling and Behavior Options				
Multinomial Logit Exponents	[9, 12, 15]	[6, 8, 10]	[12, 16, 20]	-0.47
Vehicle Payback Period (years)	3	2	4	0.02
Penalty Sensitivity Multiplier	1	0.5	2	-0.41
BEV Infrastructure Willingness[c]	0.10	0.05	0.20	0.00
Total Vehicle Sales Rate[d]	0.067	0.05	0.09	0.05
Infrastructure Modeling Options				
H_2 Infrastructure Growth Rate (per 1k vehicles)	0.7	0.1	1.3	0.13
Other Infrastructure Growth Rate (per 1k vehicles)[e]	0.7	0.1	1.3	-0.01
Electricity Generator Lifetime (years)	40	20	60	-0.05

[a] Multiplies price projections from AEO without Clean Power Plan (U.S. Energy Information Administration, 2016).
[b] Multiplies Moawad et al. (2016) low technology uncertainty, low price uncertainty projections.
[c] For BEVs that can charge at home, this is the ratio of public (i.e. inconvenient) DC fast stations to gasoline stations at which 50% of drivers might consider using the public infrastructure rather than swapping vehicles on days when the trip length will exceed the BEV range.
[d] Sales per year as a fraction the the total vehicle stock. This is distinct from stock growth as some percent of the stock is scrapped each year. Stock growth is tied to population growth.
[e] Not including workplace charging infrastructure, which is fixed to 5% penetration.

ture FCEV sales are the FCEV technology costs (fuel cell and on-board hydrogen storage system), consumer sensitivity to vehicle cost and penalties (multinominal logit exponent and penalty sensitivity multiplier), oil prices, fuel cell vehicle on road fuel economy, and internal combustion engine (ICE) on road fuel economy. These sensitivities indicate that FCEVs will primarily benefit from their own cost reductions and efficiency gains, and are in competition with ICE vehicles more so than BEVs.

Secondary FCEV drivers include acceleration of market driven Hydrogen infrastructure growth, natural gas price reductions, which lower Hydrogen prices, and increases to ICE vehicle purchase price.

Battery costs, electric vehicle efficiency, and BEV infrastructure parameters have very little impact on FCEV sales, reinforcing that FCEVs and BEVs are complementary rather than competing petroleum displacement technologies.

5 Coal and natural gas tradespace

Commodity prices impact the price of Hydrogen produced via various pathways. Recent uncertainties in the futures of natural gas and coal prices in particular have made the future prices of Hydrogen produced via natural gas with steam methane reformation (SMR) and that produced via coal with sequestration of carbon emissions (COAL + SEQ) equally uncertain.

In figure 6 we show the results of an analysis of the projected prices of dispensed Hydrogen produced via SMR and COAL + SEQ under different commodity price futures. The prices reflect Macro System Model centralized production at 50,000 kg/day and dispensing at 1,500kg/day stations for 2015 technologies; figure 6 reflects national average levelized costs for full demand and utilization. Following the model logic implemented in ParaChoice for parameterization, futures are shown for default AEO 2016 energy price projections, and cases where natural gas and coal prices are half and twice the nominal projection by 2050.

In the default projection, SMR is the more cost competitive Hydrogen production pathway through 2050. Even if coal prices are half as expensive as nominally projected by AEO by 2050, if natural gas price projections hold, then SMR remains the more cost competitive option (national average) for producing Hydrogen out through 2050. However, if natural gas proves to be more expensive than initially projected by AEO, COAL + SEQ may overtake SMR as the most cost competitive option for producing Hydrogen.

Improvements to delivery and distributions should lower the delivered price of Hydrogen for both production pathways. Naturally, regulation on the production of cleaner Hydrogen will alter projections.

We also performed a parametric assessment of the response of Hydrogen prices and FCEV sales to coal and natural gas futures. These assessments include the impacts of Hydrogen demand on Hydrogen prices. At low volume demand, Hydrogen produced for industrial purposes is sold to vehicle stations at a markup. This industrial Hydrogen is produced via SMR and sold at 700kg/day capacity stations. As demand increases, market prices for delivered Hydrogen become more favorable, and eventually states switch to dedicated production of Hydrogen for vehicles and 1,500kg/day stations. See figures 2 - 4.

As shown in figure 7, dispensed Hydrogen prices are largely protected in futures with unexpectedly high natural gas prices or coal prices as production can channel towards the

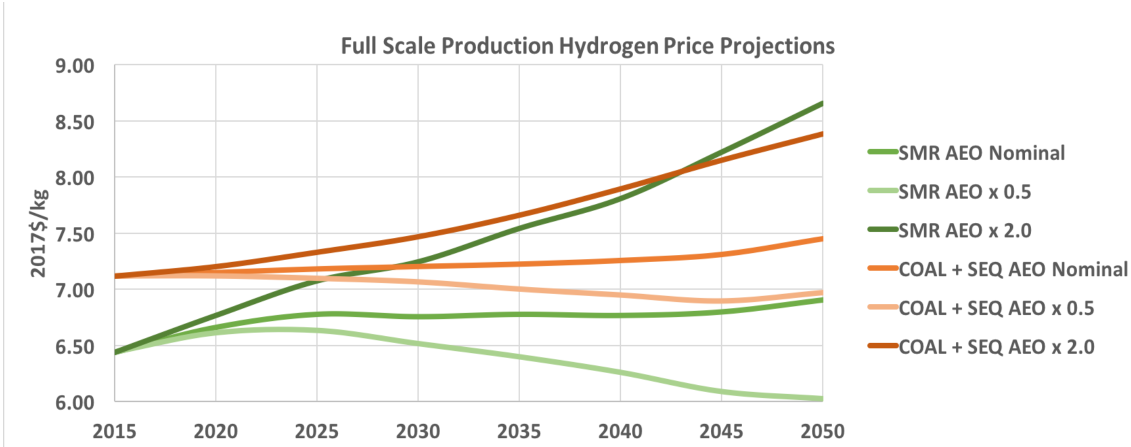


Figure 6: Hydrogen prices by pathway for different energy futures.

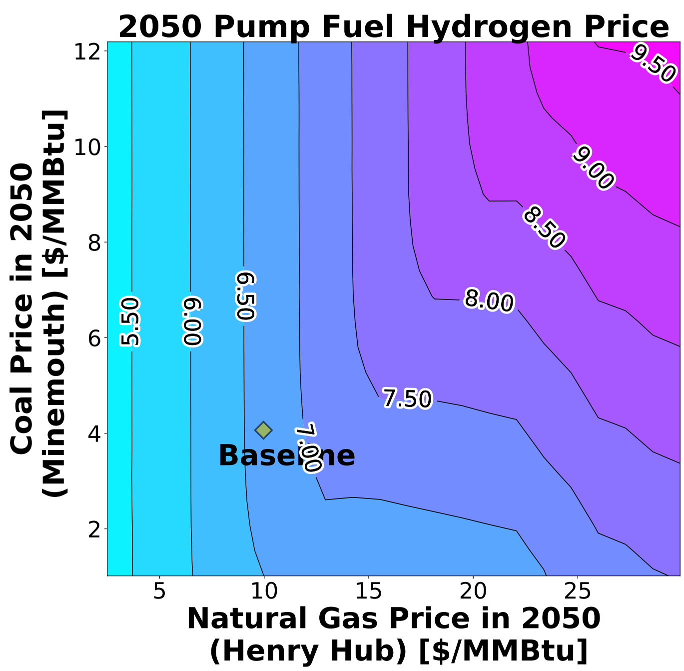


Figure 7: Commodity Price Impact on Hydrogen Prices

lower cost pathway if either commodity price trends higher than expected. Only in the case where both commodity prices are high will the price of Hydrogen rise significantly.

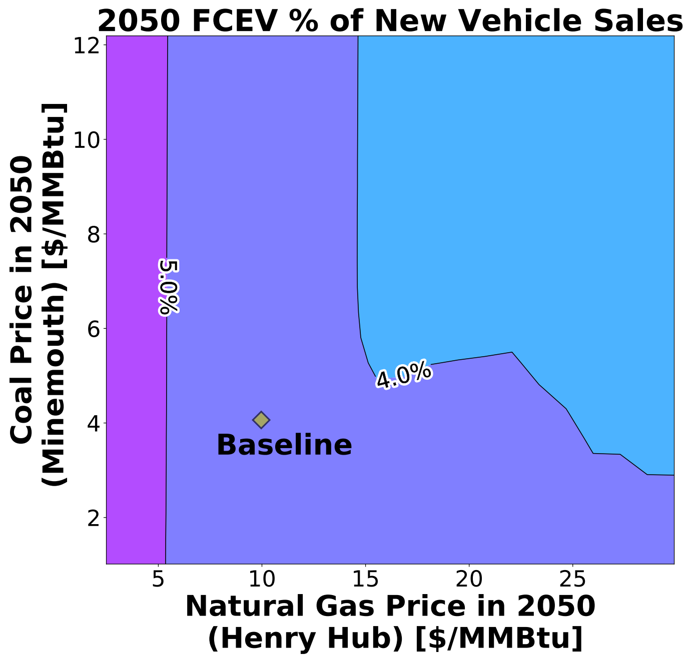


Figure 8: Commodity Price Impact on FCEV Sales

However, in the case where natural gas prices are much larger than expected, industrial Hydrogen prices will rise, leading to slower initial growth of the FCEV market. This slowed growth will create a negative feedback effect wherein it will take longer for states to build up sufficient Hydrogen demand to justify dedicated Hydrogen production for vehicle use. Only with this transition from reliance on industrial Hydrogen to dedicated production can consumers access Hydrogen sourced from other, potentially less expensive pathways, here COAL + SEQ.

Figure 8 shows the impact of commodity prices on FCEV sales directly. FCEV sales are only modestly impacted by coal and natural gas prices, as follows from the sensitivity analysis in §3. FCEV sales generally follow the same trend as Hydrogen prices, however there is a slight increase FCEV sales as a function of natural gas price from $15/MMBtu to ∼$22/MMBtu in 2050. Natural gas is used to make gasoline, so increases in natural gas prices also increase gasoline prices, improving all alternate energy vehicle sales. This is very likely the cause of the modest trend seen here, where the Hydrogen price impact is largely flat.

6 Hydrogen station growth analysis

Within ParaChoice, Hydrogen infrastructure is implemented in three stages.

1. From the start of the simulation in 2015 until the present date in 2017, data from the Alternative Fuels Data Center are used to accurately place stations when they are built.

2. Following this historically accurate infrastructure placement, stations are seeded into urban areas of states in early simulation years in order to stimulate initial incentivized FCEV market growth.

3. Once the number of seeded hydrogen stations per state reaches ∼1% of the number of gasoline stations, the seeding stops, and infrastructure must grow endogenously in response to market demand from FCEVs.

Example FCEV growth patterns are shown in figure 9. We seed 1,600 stations nationally by 2024 similar to H2USA's 1,800 by 2025 in their Urban Markets scenario. Stations built due to market driven feedback at 0.7 Hydrogen stations per 1,000 vehicles sold (Yeh, 2007)[2] far exceed the seeded station numbers by 2050.

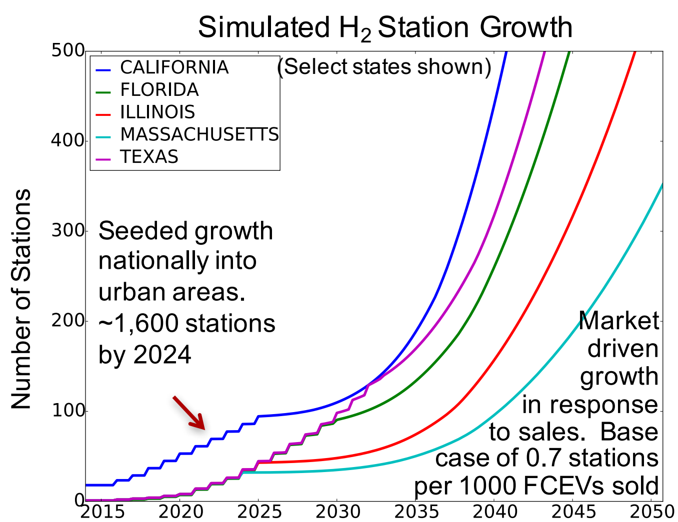


Figure 9: Station Growth Seeding and Market-Driven Station Growth

In order to determine the impact of incentivized or suppressed market driven Hydrogen station growth, we performed a parametric assessment of the impact of the Hydrogen

[2]0.7 is also the number of gasoline stations in the US divided by the number of LDVs.

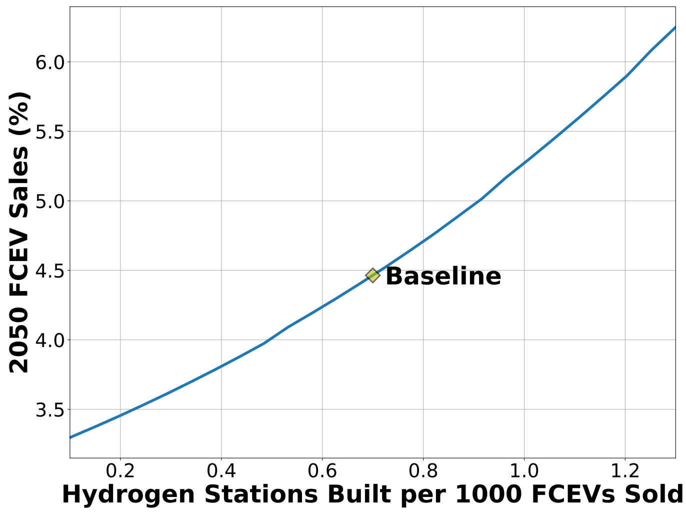


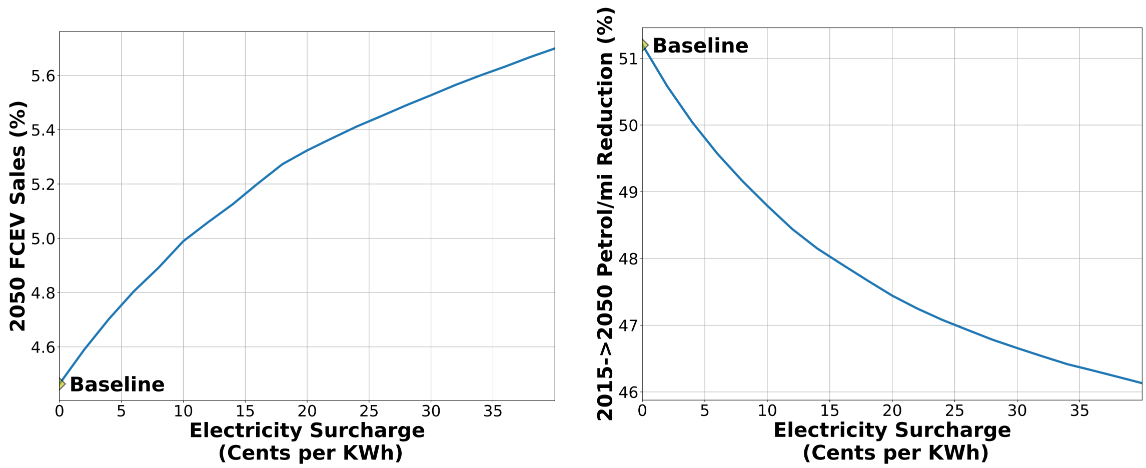
Figure 10: FCEV Sales Response to Infrastructure Growth

station growth parameter. Results are shown in figure 10. Parametric variation of Hydrogen infrastructure response to sales shows that 2050 FCEV sales may increase by 50% if 1.3 stations are built per 1,000 FCEVs sold rather than the 'business as usual' 0.7. The response of FCEV sales to Hydrogen station growth is super-linear as there is a positive feedback between infrastructure abundance and new vehicle sales. Infrastructure is one of the limiting factors for FCEV sales compared to the other AEVs, even into 2050. So measures that improve infrastructure growth, even in 2050, will likely have a positive impact on sales.

7 Electricity price impacts

The analyses in the previous sections have all been conducted assuming that the price for electricity used in EVs will be the residential price for electricity (which varies by state). While the electric grid and thus commercial, industrial, and residential electricity prices vary with changes in commodity prices in ParaChoice, the baseline electricity prices and commodity prices are based on AEO data and projections, which may not fully account for increased grid requirements due to the projected EV adoption in this model. Moreover, electricity prices do not incorporate the cost of public electric vehicle charging infrastructure (though home level 2 charger costs are included in the model for BEVs and longer range PHEVs).

It is therefore quite possible that EV drivers will be charged a higher rate in the future for their electricity than estimated in baseline projections. Thus, we analyze here the projected changes to FCEV sales if EV drivers are subject to a surcharge on electricity prices in order to pay for grid upgrades and public infrastructure, similar to the price added to Hydrogen and other fuels to pay for distribution and refueling infrastructure. Results are shown in figure 11.



(a) FCEV Sales

(b) Petrol Use

Figure 11: Impact of Electricity Price Surcharge on FCEV Sales and Fleet-Wide Petroleum Use

Figure 11a shows that, if an electricity surcharge is imposed on electricity used to power EVs, FCEV sales will increase over the baseline case, but only modestly. For 10¢/kWh surcharge, which doubles the residential price of electricity in most states, FCEV sales in 2050 increase by half a percent. In order to reach a full percent increase in purchases, that surcharge would need to triple.

Figure 11b shows the corresponding impact of this surcharge on petrol use. Unfortunately the increase in electricity costs creates a much greater case for petrol consumption for consumers than FCEV adoption. This corroborates the findings in §4 that FCEVs and BEVs are complimentary technologies more so than competing ones. The loss in sales of one does not necessarily create sales in another.

8 Conclusions

Leveraging modeling upgrades made in FY17, we were able to conduct new analyses with ParaChoice and update analyses made in previous years finding:

- FCEVs have a role to play in the future LDV fleet as a petroleum alternative, alongside PEVs.
- The magnitude of the market share of FCEVs in the future fleet is highly uncertain, ranging from 0.3% to 19% of 2050 purchases in 90% of Monte Carlo scenarios.
- Major drivers of FCEV purchases are FCEV technology costs, FCEV efficiency, oil prices, and efficiency of competing conventional vehicles.
- Vehicular Hydrogen demand is projected to increase substantially, to upwards of 4 million kg/day by 2050 in the baseline case.
- If projections for natural gas prices hold, the most likely production pathway for Hydrogen, barring string policy incentives for alternative production pathways, is natural gas SMR.
- If natural gas proves to be more expensive than currently projected, Hydrogen prices may remain low as coal gasification plus sequestration may remain an economical alternative.
- Infrastructure scarcity will remain a barrier for FCEVs into 2050. 2050 FCEV sales may increase by half if 1.3 stations are built per 1,000 FCEVs sold rather than the 'business as usual' 0.7.
- FCEV purchases may increase slightly if the price of electricity is increased to reflect the cost of charging infrastructure and grid enhancements. However, as FCEVs and PEVs largely serve complementary rather than competing markets, petroleum use increases substantially as electricity prices increase.

9 Acknowledgements

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