APPENDIX D

EMISSIONS IMPACTS ANALYSIS

Appendix D

Emissions Impacts Analysis

Air Resources Board (ARB) staff conducted a detailed analysis of the air quality benefits and impacts associated with the proposed amendments to the Clean Fuels Outlet (CFO) regulation. This document includes an overview of the greenhouse gas (GHG) emissions and criteria pollutant emissions associated with the production and distribution of hydrogen.

A. Summary of the Analysis and Results

The environmental analysis of the proposed CFO regulation identified significant decreases in the Greenhouse Gas emissions and local criteria pollutants that would result from the displacement of petroleum-based fuels by hydrogen used in fuel cell vehicles. These reductions result partly from the commercial-scale production of hydrogen with improved production efficiencies and fuel delivery methods, and penetration of large numbers of fuel cell vehicles (FCVs) in to the light duty vehicle fleet.

Modeling Scenarios and Assumptions

Two scenarios were analyzed based on the anticipated number of FCVs deployed in California. The Upper Bound Scenario, which serves as the upper limit in vehicle population, includes FCVs numbers reported by the automakers in an annual survey conducted by ARB and the California Energy Commission (discussed in Section I B of this staff report). The Lower Bound Scenario includes staff's estimate of the number of FCVs to be deployed in compliance with the Zero Emissions Vehicle (ZEV) regulation and serves as the lower limit in vehicle population. For the GHG analyses, staff assumed the existing California Low Carbon Fuel Standard (LCFS)[1] regulation reduces emissions of the gasoline baseline over time and the Pavely regulation[2] lowers the gasoline vehicle fleet-average carbon dioxide emissions. Although currently not in effect, the SB1505 regulation,[3] which will establish environmental and energy standards for hydrogen, will likely influence the "grades" of hydrogen available during the lifetime

[1] ARB, 2011a. Proposed Regulation Order "Subchapter 10. Climate Change, Article 4. Regulations to Achieve Greenhouse Gas Emission Reductions, Sub article 7. Low Carbon Fuel Standard." October 14, 2011.
[2] AB 1493, 2002. California Assembly Bill. Pavley, Fran (Assemblyman). "Vehicular emissions: greenhouse gases," Chapter 200, Statutes of 2007, July 2, 2002..
[3] SB 1505, 2006. California Senate Bill. Lowenthal, Alan (Senator). Chapter 877, Statutes of 2006, September 20, 2006.

of the CFO. A brief discussion is included in this report to evaluate the impact of its trigger.

GHG Emission Results

GHG emissions were analyzed using a life cycle analysis model called the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) that was modified for California conditions (CA-GREET). Life cycle emissions include various stages in the production of hydrogen, including the collection and processing of feedstock, the production of the fuel, and transportation and delivery of the finished fuel. GHG emissions per mile and total annual GHG reduction were evaluated for six hydrogen production options including hydrogen by central plant steam-methane reformation (SMR) with liquid delivery, central SMR with gaseous delivery, on-site SMR, on-site SMR with renewable inputs, and two different mixtures containing central and on-site production technologies.

Modeling results showed that GHG emission reductions relative to the gasoline baseline will vary depending upon when and how quickly FCVs enter the market, as well as the method(s) used for hydrogen production and delivery. If vehicles enter the market according to the Upper Bound Scenario, GHG reductions will overall be greater than the Lower Bound Scenario because, in the Upper Bound Scenario, emissions are being compared to an earlier gasoline baseline. Over time, both LCFS and LEV will drive well-to-wheel gasoline emissions down, reducing the overall GHG emissions reduction benefit.

The total GHG emissions reduction for Upper Bound Scenario ranged from approximately 0.03 to 0.8 million metric tons of carbon dioxide equivalent per year (MMTCO2e/year), based on the hydrogen production method. For the Lower Bound Scenario, the range was 0.02 to 0.7 MMTCO2e/year and the GHG reduction benefits were realized approximately three to four years later compared to the Upper Bound Scenario due to the slower growth in FCV numbers.

Hydrogen produced at a central SMR plant with liquid delivery, which is anticipated to contribute significantly to the commercialization of hydrogen, demonstrates per-mile GHG reductions in the Upper Bound Scenario of 25 to 38 percent during the span of the CFO. For the same central SMR/liquid delivery pathway, per mile GHG reductions were lower in the Lower Bound Scenario with reductions ranging from 21 to 32 percent. This shows that, if SB1505 was triggered, the central SMR/liquid delivery pathway will likely fail to meet SB1505’s 30 percent GHG reduction requirement during the span of the CFO. In the Lower Bound Scenario where the regulation is triggered later, hydrogen production will likely require more immediate improvements to achieve the 30 percent

GHG reductions required under SB1505. For hydrogen produced by other methods, per-mile GHG emissions reductions were greater, ranging from approximately 60 to 67 percent with on-site-SMR using renewable under the Upper Bound Scenario.

Criteria Pollutant Emission Results

Criteria pollutant emissions were estimated using GREET for the various stages in the production of hydrogen, including the collection and processing of feedstock, the production of the fuel, and transportation and delivery of the finished fuel. For the CFO, local criteria pollutants were evaluated at the CFO midpoint in the Upper Bound Scenario in 2020 for various pathways. Local criteria pollutants are expected to be reduced, on average, by more than 50 percent when compared to gasoline. This represents one of the most conservative reductions based on hydrogen produced by central SMR with liquid delivery. Other methods of producing hydrogen generally yield equal or greater reductions in local criteria pollutants.

Additionally, staff also evaluated the various contributions to criteria pollutants based on hydrogen production technology. For hydrogen produced by central SMR with liquid-delivery, the largest contribution to criteria pollutants was the liquefaction of the fuel followed by the production process. Fuel liquefaction contributes to over 50 percent of criteria pollutant emissions and fuel production results in over 80 percent of the particulate matter emissions. For hydrogen produced by central SMR with gaseous delivery, on site SMR, or on-site electrolysis, fuel production is the main source of local criteria pollutant emissions, followed by fuel compression. In contrast, transportation and delivery contribute minimally to the overall emissions.

Based on lifecycle results relative to gasoline, the proposed CFO regulation is expected to result in no additional adverse impacts to California's air quality due to emissions of criteria pollutants. There may be additional reductions as the technology matures.

Analysis of Greenhouse Gas Emissions Benefits

Following is a detailed discussion of the modeling protocol, calculations, assumptions and scenarios used to estimate GHG emissions associated with the production and use of hydrogen in fuel cell vehicles.

Greenhouse Gas Emissions Modeling Protocol

GHG emissions calculations were conducted using a life cycle analysis model called the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) originally developed by Argonne National Laboratory. Lifecycle analysis (LCA) is an analytical method for estimating the aggregate quantity of greenhouse gas emissions from a full fuel cycle. In general, the lifecycle analysis includes the direct effects of producing and using the fuels and indirect effects that may be associated with the particular fuel. The direct effects typically include the generation or extraction of feedstock's; the conversion of feedstock's to finished fuel or fuel blend stock; and the distribution, storage, delivery and final use of the finished fuel by the end user. Direct effects are responsible for the generation of several species of GHGs, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), volatile organic compounds (VOCs) and carbon monoxide (CO). Non-CO_2 species are adjusted to account for their global warming potential relative to carbon dioxide. Because hydrogen does not involve the conversion of food-related crops, such as corn and soybeans used for biofuels, the combined direct effects of the global warming potential of all inputs are accounted for as discussed above. Indirect effects, such as those associated with displacing production and use of food crops for fuel, are not included in the GHG value.

The version of GREET used under the CFO is the same as the one used under the LCFS adjusted for California conditions. This model was initially modified by TIAX under contract to the California Energy Commission during the AB 1007 process. Changes were restricted to mostly input variables, such as electricity generation factors, transportation distances, with no changes in methodology inherent in the original GREET model. A subsequent modification was done by Life Cycle Associates, a private consulting firm, and released as California-modified GREET model (CA GREET) version 1.8b in February 2009. [4] CA GREET v1.8b served as a basis for all hydrogen pathways published in this report.

For the CFO, staff evaluated the total well-to-tank (WTT)[5] carbon intensity of hydrogen produced by various processes. These fuel pathways, shown in Table D-1, represent the total emissions contribution without considering vehicle drivetrain efficiencies in grams CO2-equivalents per megajoule (gCO2e/MJ). These values reasonably represent the GHG emissions that would occur in California as a result of hydrogen production, per unit of energy produced, and are similar to the results shown in the LCFS Initial Statement of Reason (ISOR).[6]

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[4] ARB, 2009e. Argon National Laboratory "Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model" modified by Lifecycle Associates. Feb. 2009. http://www.arb.ca.gov/fuels/lcfs/lcfs.htm

[5] ARB, 2009b. "Staff Report: Initial Statement of Reasons for Proposed Regulation to Implement the Low Carbon Fuel Standard." March 5, 2009. See Volume 1, for detailed information on lifecycle analysis, including definitions of wells-to-tank and wells-to-wheel.

[6] ARB, 2009b.

Table D-1. WTT GHG Carbon Intensity Values for Various Hydrogen Production and Delivery Pathways

Hydrogen Fuel Pathways	Carbon Intensity
Description	(gCO2e/MJ)
Hydrogen by central SMR, liquid delivered	142.18
Hydrogen by central SMR, gas delivered	101.04
Hydrogen by central SMR, pipeline delivered	98.21
Hydrogen by onsite SMR	98.21
Hydrogen by onsite SMR with 33% renewable feedstock	76.10
Hydrogen by onsite electrolysis	148.49

To complete the analysis on emissions resulting from hydrogen used as transportation fuel, the use of the fuel in the vehicle must be included. The wells-to-wheel (WTW) GHG, measured on a per mile basis, is calculated by including vehicle powertrain efficiencies reflected in the fuel consumption of fuel cell vehicles (FCVs). Equation 1 below shows the calculation of the hydrogen WTW GHG emissions used in the CFO.

$$GHG_{WTW} = \frac{(GHG_{WTT})(ED)}{FC} \qquad \text{(Equation 1)}$$

Where:

GHG_{WTT} is the WTT GHG emissions calculated by GREET, measured in gCO2e/MJ, corresponding to the pathways in Table D-1;

ED Is the energy density of hydrogen with value of 120 MJ/kg?

FC Is the fleet-averaged fuel consumption of FCVs for a given year, measured in kilograms per mile (kg/mi); and

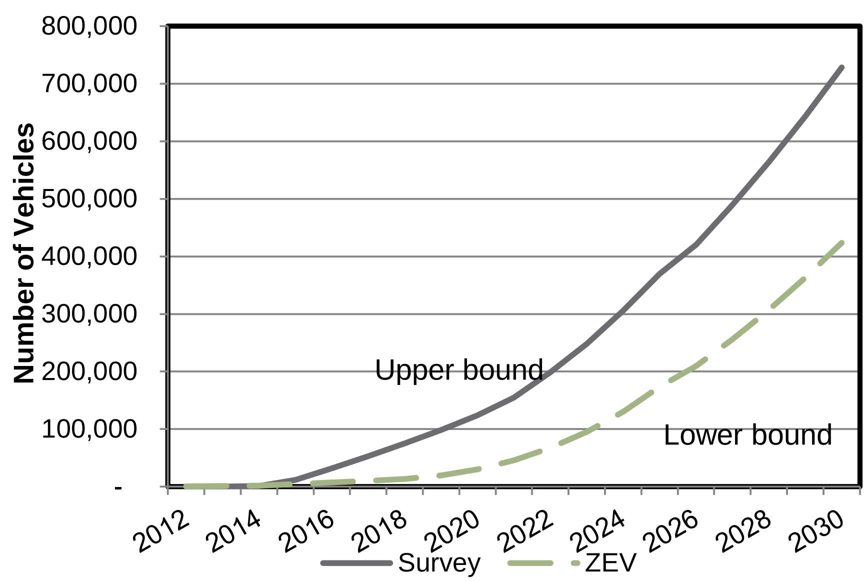
GHG_{WTW} Is the WTW GHG emission of hydrogen, measured in gCO2e/mi?

The LCFS takes a similar approach in the use of an Energy Economy Ratio (EER) that defines the miles traveled per unit energy of hydrogen FCV relative to a reference gasoline vehicle.

Estimating Hydrogen Demand by FCVs

Numbers of FCVs introduced each year, their respective per mile fuel consumption, and miles traveled each year all affect hydrogen usage by FCVs. A changing fleet-average is used for the fuel consumption value. The fleet composition of FCVs is expected to change with each year: the number of vehicles increases, new models is introduced into the fleet, and older models are retired. Staff assumed two FCV ramp-up scenarios for the GHG analyses. The first scenario, serving as the upper bound, is based on surveys conducted by ARB and the California Energy Commission in which the auto manufacturers reported 53,000 vehicles by 2017. After 2017, staff utilized a ZEV compliance scenario with high numbers of FCVs and graphical best-fit algorithms to populate the data set through 2030. The second scenario, serving as the lower bound, is based on an estimated minimum number of FCVs automakers will likely deploy to meet the ZEV mandate. Figure D-1 below shows graphically the number of total FCVs anticipated under each Upper Bound and Lower Bound scenarios for 2012 to 2030.

Figure D-1: Estimated number of FCVs 2012 to 2030



Estimating GHG Emission Reductions due to Gasoline Vehicle Displacement

In addition to evaluating GHG emissions per mile, staff also analyzed the total GHG emissions reductions resulting from displacement of gasoline vehicles by FCVs under each the Upper Bound and Lower Bound scenarios. Equation 2 defines the total GHG emissions reduction resulting from the displacement of gasoline vehicles by FCVs.

$$GHG_{red} = [(GHG_{baseline} - GHG_{WTW}) * VMT] * K \qquad \text{(Equation 2)}$$

Where:

GHG_{red} is the GHG emissions reduction resulting from the displacement of gasoline vehicles by FCVs, measured in million metric tons of carbon dioxide equivalent per year (MMTCO2e/yr);

$GHG_{baseline}$ is the per mile GHG emissions from the gasoline vehicle fleet assuming no penetration of FCVs (business as usual or baseline), measured in gCO2e/mi;

GHG_{WTW} is as defined in Equation 1;

VMT is the annual vehicle miles traveled for gasoline determined from ARB EMission FACtors (EMFAC) model 2011[7], measured in miles per year. Since FCVs are assumed to completely displace gasoline vehicles, the same gasoline VMTs are used for FCVs; and

K Is a unit conversion factor with value $\frac{1x10^{-12}\ MMTCO2e}{gCO2e}$

Assumptions at Upper Bound Scenario CFO Trigger Points

In the Upper Bound Scenario, the number of FCVs available in California is based on the automaker reported number of 53,000 by 2017, with the data extended to 2030 as discussed above. Staff estimates that the CFO regional trigger is reached when a region reaches approximately 85 percent of the total number of FCVs in California. This regional trigger is estimated to occur in 2015. The statewide trigger based on the number of FCVs reported by the automakers is estimated to occur around 2016. The CFO sunset occurs when the number of stations reaches a total of 5 percent of all gasoline stations statewide with a minimum production capacity of 400kg/day. This is estimated to occur at about 2024 when there are approximately 306,033 FCVs deployed.

For the GHG analysis, four representative years were evaluated: 2015 and 2016 (for the regional and statewide triggers, respectively), 2020 (a midpoint for the scenario), and 2024 (as an estimated year of regulation sunset). For each year, the number of FCVs is assumed to penetrate the gasoline pool and completely replace the VMT of the light-duty gasoline counterpart. Hydrogen GHG emissions were compared to a gasoline baseline, assuming California Reformulated Gasoline (CaRFG) with 10 percent ethanol

[7] ARB, 2011b. EMFAC is used to calculate emission rates from all motor vehicles, such as passenger cars to heavy-duty trucks, operating on highways, freeways and local roads in California.

content by volume, which is affected by the Low Carbon Fuel Standard (LCFS) regulation currently in effect for all transportation fuels in California. The LCFS is assumed to affect the amount and type of ethanol produced or imported into California with an overall effect of lowering the gasoline emissions between 2015 and 2020, when a large number of low carbon-intensity ethanol is anticipated to be available.

The GHG emissions analysis also takes into consideration SB1505, Environmental and Energy Standard for Hydrogen Production (SB 1505, Statutes of 2006, Chapter 877),[8] which is anticipated to be in effect shortly after the CFO is triggered. In the early years prior to 2016, it is assumed that some of the hydrogen produced is SB1505 compliant. As the number of commercial-scale stations increase around 2016 and beyond, it is assumed that all hydrogen produced will be SB1505 compliant. Table D-2 summarizes the key assumptions and parameters used for the GHG emissions analyses.

[8] SB 1505, 2006. California Senate Bill. Lowenthal, Alan (Senator). Chapter 877, Statutes of 2006, September 20, 2006.

Table D-2. Summary of Assumptions and Parameters Used for the GHG Emissions Analyses for the Upper Bound Scenario

Upper Bound Scenario: Assumptions				
Year	2015	2016	2020	2024
Number of FCVs	12,000	32,000	124,202	306,033
VMT Replaced by FCVs (mi)	208 million	534 million	1.9 billion	4.2 billion
FCV Fleet Fuel Consumption (gge/100 mi)	1.49	1.40	1.44	1.46
Gasoline Fleet Fuel Consumption (g/100mi)	3.46	3.40	3.21	3.02
Gasoline GHG Emissions (gCO2e/mi)	376.95	370.24	340.86	320.99
CFO and SB1505 Status	CFO regional trigger is reached. Some hydrogen produced meet SB1505 requirements.	CFO statewide trigger is reached. All hydrogen produced meet SB1505 requirements.	All hydrogen produced meet SB1505 requirements.	CFO sunset. All hydrogen produced meet SB1505 requirements.
LCFS Status	LCFS is in effect with mixture of alternative fuel-vehicle systems that result in minimum of **2.5%** carbon intensity reduction. CI of gasoline reduced to **94.1 g/MJ.**	LCFS is in effect with mixture of alternative fuel-vehicle systems that result in minimum of **3.5%** carbon intensity reduction. CI of gasoline similar to year before at **94.1 g/MJ.**	LCFS is in effect with a mixture of alternative fuel-vehicle systems remains with overall minimum **10%** carbon intensity reduction. CI of gasoline reduced to **91.7 g/MJ.**	Overall minimum **10%** carbon intensity reduction remains. CI of gasoline reduced to **91.7 g/MJ.**

Results: Upper Bound Scenario GHG Analysis

GHG emissions, in grams of carbon dioxide equivalent per mile (gCO2e/mi), were calculated for the variety of hydrogen production and delivery technologies included in

Table D-1. A total of six options (A through F below) were analyzed based on several factors including:

a) Staff's estimate of the most probable methods for the commercial-scale production and delivery of hydrogen to meet the rapid ramp-up of FCVs; and

b) Available lifecycle data at the time the report was prepared.

Each option represents the available technology that will likely be used by hydrogen suppliers in California during the course of the CFO. For instance, Option A assumes all hydrogen is produced by steam methane reformation in a central production facility and delivered to the stations in a liquid state. Option B represents a mixture in which 75 percent of the stations in California receive liquid hydrogen delivered from a central SMR plant, 20 percent is central SMR production with gaseous delivery, and 5 percent is produced by at the hydrogen station using SMR. Options B, C, and D are variations of mixtures of production technologies anticipated to be available. Option F is currently the only renewable pathway for which lifecycle analyses have been completed.[9] Additional pathways, including those that incorporate renewables, will be forthcoming under the SB1505 regulation.[10]

Option A =   100 percent Central SMR liquid delivery

Option B =   75 percent central SMR liquid delivery, 20 percent central SMR gaseous delivery, 5 percent onsite SMR

Option C =   75 percent central SMR liquid delivery, 20 percent central SMR gaseous delivery, 5 percent onsite SMR with 33 percent renewable

Option D =   40 percent by central SMR liquid delivery 60 percent central SMR gaseous delivery

Option E =   100 percent Central SMR gaseous delivery

Option F =   100 percent Onsite SMR with 33 percent renewable feedstock's

Figure D-2 shows a graph of the per mile emissions of hydrogen from 2015 to 2024 calculated for the six production options listed above. Data associated with the graph are shown in Table D-3.

Relative to gasoline, hydrogen shows a range of per-mile GHG emissions reductions

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[9] At the writing of this report, several renewable hydrogen pathways are still under development. Their omission in this report is a result of timing and does not imply non-viability of those pathways in the future. Renewable pathways will be critical in meeting requirements under the SB1505 program.

[10] Other production options such as hydrogen by central SMR delivered by pipeline and onsite electrolysis were not included due to their uncertain participation in commercial-scale production of hydrogen.

based on the method of production and the year in which the evaluation was done. Hydrogen produced by Option A (central SMR with liquid delivery) shows a 35 percent reduction in GHG emissions on a per mile basis in 2015 and the reduction decreases to 25 percent in 2024. This reduction in GHG emission benefit is primarily caused by the reduction in the carbon intensity of the baseline gasoline under the LCFS. For Option F (onsite SMR with renewables), per-mile GHG emission reductions range from 60 to 65 percent.

When looking at the GHG emissions, it is important to recognize that the percent GHG emissions reductions for hydrogen is typically greater in the early years as the gasoline fleet-averaged fuel consumption is higher and gasoline baseline emissions are higher. Over time, emission reductions decreases as both gasoline vehicle performance and GHG emissions improve. When SB1505 is activated, a 30 percent reduction in GHG emissions of hydrogen measured relative to gasoline would be required. Figure D-2 also includes lines showing the 30 percent reduction targets for each year analyzed. Between 2015 and 2024, the 30 percent reduction lines decrease as a result of the decrease in the gasoline vehicle carbon dioxide emissions due to Pavley and a decrease in the GHG emissions due to the LCFS.

For each production option, the emissions increase over time as the fuel consumption of FCVs increases due to entry of larger vehicles into the fleet. An exception occurs between 2015 and 2016 when GHG emissions are reduced as a result of the decrease in FCV fuel consumption between 2015 and 2016.

Comparing across production technologies, Option A (central SMR with liquid delivery), shows the highest emissions with values ranging from 230.06 to 244.73 gCO2e/mi. Option F (on-site SMR with renewables), shows the lowest emissions with values ranging from 123.14 to 130.99 gCO2e/mi. Hydrogen produced by Option A demonstrates a 35 percent GHG emissions reduction at CFO onset. This value decreases to 25 percent at CFO sunset. For hydrogen produced by Option A, there are significant emissions associated with hydrogen liquefaction, which contributes to over 30 percent of the total GHG emissions for the production of the liquid hydrogen by central SMR.[11] Production options that have greater GHG emissions reductions include those that incorporate a greater percentage of central SMR with gaseous delivery and on site SMR pathways (Options B to F).

[11] ARB, 2009c. California Air Resources Board. Detailed California Modified GREET Pathway for Compressed Gaseous Hydrogen from North American Natural Gas, http://www.arb.ca.gov/fuels/lcfs/022709lcfs_h2.pdf

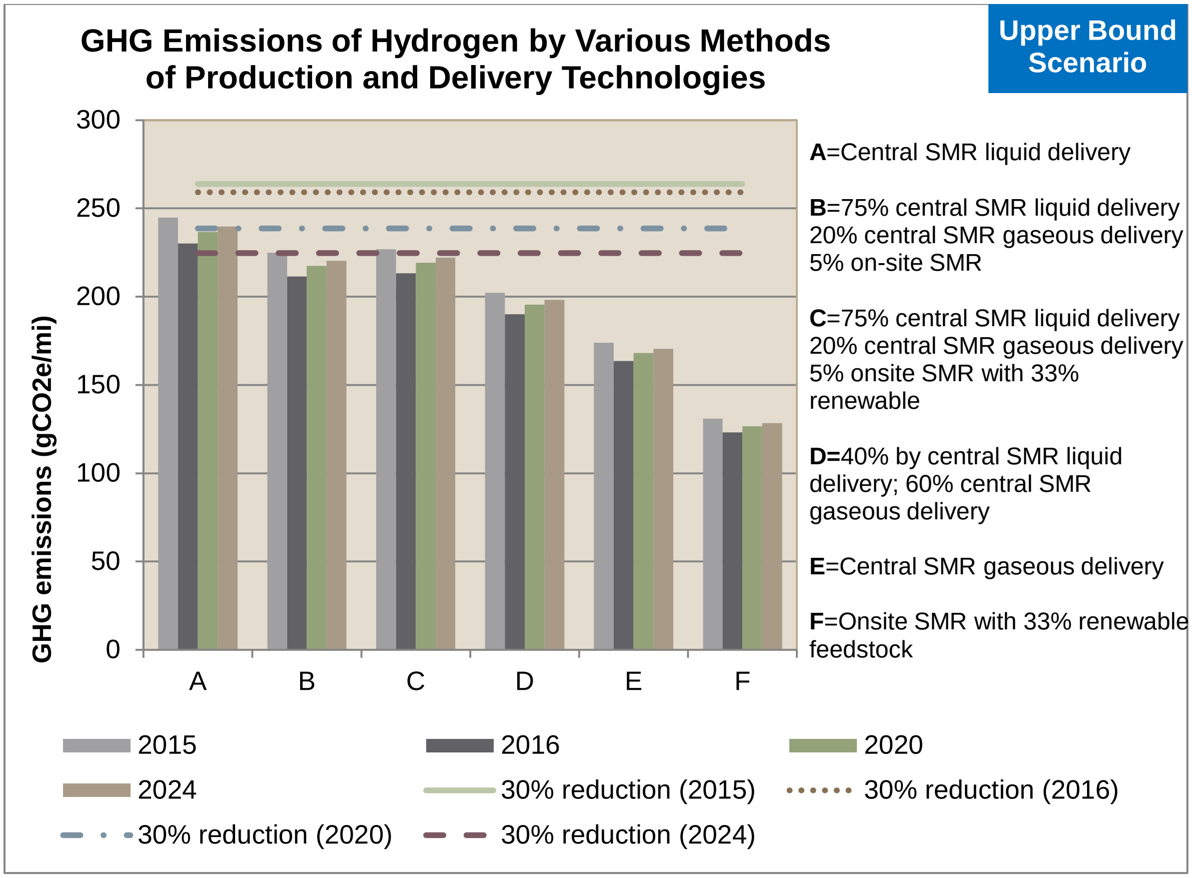


Figure D-2. Upper Bound Scenario GHG Emissions Profile of Hydrogen Produced by Various Pathways over the Lifetime of the CFO

In addition to the per-mile GHG emissions reductions, total emission reductions due to the displacement of gasoline vehicles were calculated for various hydrogen production technologies (Table D-3). For each production technology, reductions in total GHG emissions increase from 2015 to 2024 as a larger numbers of FCVs penetrate the gasoline pool. For the Option A, the total GHG emissions benefit increases from about 0.028 to 0.34 million metric tons of carbon dioxide equivalent per year (MMTCO2e/year) between 2015 and 2024. Option A represents the lower end of the emission reduction potential. If a majority of the hydrogen is produced using renewable sources, as reflected in Option F, it is likely that the GHG emission reduction could range from 0.051 MMTCO2e/year in 2015 when the CFO regional trigger is activated to about 0.80 MMTCO2e/year at CFO sunset in 2024.

Table D-3. GHG Emissions from Various Hydrogen Pathways - Upper Bound Scenario

Upper Bound Scenario		Per Mile GHG Emissions (gCO2e/mi) and (Percent Reduction)				Total GHG Emissions Reduction (MMTCO2e/year)			
Options	Years	2015	2016	2020	2024	2015	2016	2020	2024
Baseline	Gasoline	376.95	370.24	340.86	320.99	-	-	-	-
A	Central SMR liquid delivery	244.73 (35%)	230.06 (38%)	236.63 (31%)	239.74 (25%)	0.028	0.07	0.19	0.34
B	75% central SMR liquid delivery 20% central SMR gaseous delivery 5% onsite SMR with 33% renewable Average WTT CI is 130.65 g/MJ	224.88 (40%)	211.40 (43%)	217.44 (36%)	220.30 (31%)	0.032	0.08	0.23	0.42
C	75% central SMR liquid delivery 20% central SMR gaseous delivery 5% onsite SMR Average WTT CI is 131.75 g/MJ	226.78 (40%)	213.19 (42%)	219.28 (36%)	222.16 (31%)	0.031	0.08	0.22	0.41
D	40% by central SMR liquid delivery 60% central SMR gaseous delivery Average WTT CI is 117.50 g/MJ.	202.24 (46%)	190.12 (49%)	195.55 (43%)	198.12 (38%)	0.036	0.10	0.27	0.51
E	Central SMR gaseous delivery	173.92 (54%)	163.50 (56%)	168.16 (51%)	170.37 (47%)	0.042	0.11	0.32	0.63
F	Onsite SMR with 33% renewable feedstock	130.99 (65%)	123.14 (67%)	126.65 (63%)	128.32 (60%)	0.051	0.13	0.40	0.80

Assumptions at Lower Bound Scenario CFO Trigger Points

Under the Lower Bound Scenario, staff estimated the number of FCVs that will likely be deployed by automakers to meet the requirements under the ZEV program. Under this scenario, the number of vehicles is expected to ramp up slowly in the early years between 2015 and 2020 and increases more rapidly in later years (see Lower Bound line on Figure D-1). The representative years analyzed for GHG emissions in the Lower Bound Scenario are: 2018 (regional trigger), 2020 (statewide trigger), 2023 (midpoint), and 2028 (sunset). For each year of interest, modeling parameters such as FCV and gasoline fleet fuel consumption values, and vehicle VMTs were calculated similarly as in the Upper Bound Scenario. Similarly, gasoline baseline emissions were determined with the assumption that LCFS impacts the overall mixture of ethanol available on the market, therefore, lowering the overall gasoline emissions profile over time. Key assumptions and parameters used in the determination of GHG emissions for hydrogen under the Lower Bound Scenario are summarized in Table D-4.

Table D-4. Summary of Assumptions and Parameters Used for the GHG Emissions Analyses for the Lower Bound Scenario.

Lower Bound Scenario: Assumptions				
Year	2018	2020	2023	2028
Number of FCVs	13,424	30,265	95,092	307,140
VMT Replaced by FCVs (mi)	211 million	451 million	1.3 billion	4 billion
FCV Fleet Fuel Consumption (gge/100 mi)	1.45	1.46	1.47	1.47
Gasoline Fleet Fuel Consumption (g/100 mi)	3.30	3.21	3.07	2.87
Gasoline GHG Emissions (gCO2e/mi)	350.52	340.86	326.06	305.07
CFO and SB1505 Status	CFO regional trigger is reached. Some hydrogen produced meet SB1505 requirements.	CFO statewide trigger is reached. All hydrogen produced meet SB1505 requirements.	All hydrogen produced meet SB1505 requirements.	CFO sunset. All hydrogen produced meet SB1505 requirements.

Lower Bound Scenario: Assumptions (cont'd)			
LCFS Status	LCFS is in effect with mixture of alternative fuel-vehicle systems that result in overall minimum of **6.5%** carbon intensity reduction. CI of gasoline is **91.7 g/MJ.** Assume gasoline CI remains constant onwards and LCFS standard is met through mixture of electricity, hydrogen, low-CI biofuels and other low-CI fuels.	LCFS is in effect with mixture of alternative fuel-vehicle systems that result in overall minimum of **10%** carbon intensity reduction. CI of gasoline similar to year before at **91.7 g/MJ.**	Overall minimum **10%** carbon intensity reduction remains. CI of gasoline reduced to **91.7 g/MJ.**

Results: Lower Bound Scenario GHG Analysis

As in the Upper Bound Scenario, the same six hydrogen production options were analyzed. Figure D-3 shows the GHG emissions per mile for hydrogen produced by the same pathways analyzed for the Upper Bound Scenario. GHG emissions follow the expected similar trend as those in the Upper Bound Scenario with an increase in the per mile emissions over time (decreasing percent reduction relative to gasoline). For Option A, per-mile GHG emissions range from 238.30 gCO2e/mi in 2018 to 241.29 in 2028, representing reductions between 21 and 32 percent compared to the gasoline baseline. For hydrogen produced by Option F, the emissions range from 127.54 to 129.15 gCO2e/mi – more than 60 percent reduction compared to the gasoline baseline.

In the later years, hydrogen fleet fuel consumption is typically higher as larger FCVs are introduced into pool. Simultaneously, gasoline fleet fuel carbon dioxide emissions decreases due to Pavley and the gasoline GHG emissions improve with the availability of lower carbon intensity ethanol through the LCFS. Because the years analyzed in the Lower Bound Scenario are later than those of the Upper Bound Scenario, hydrogen produced by mainly central SMR with liquid delivery (Option A) shows lower GHG emissions reduction than those in the Upper Bound Scenario. The central SMR with liquid delivery pathway demonstrate a 32 percent reduction at CFO onset and 21 percent reduction at CFO sunset. On the other hand, Options E and F (central-SMR-gaseous-delivery and onsite-SMR-with-renewables) generally exceed the 30 percent reduction. The analyses suggest that time plays a critical role in evaluating the GHG emissions of hydrogen relative to the increasingly stringent standards for conventional vehicles and fuels. Although the lower number of vehicles in the Lower Bound Scenario would allow more time for hydrogen to comply with SB1505, the SB1505 standard, once it is triggered, could be more stringent than if it had been triggered earlier.

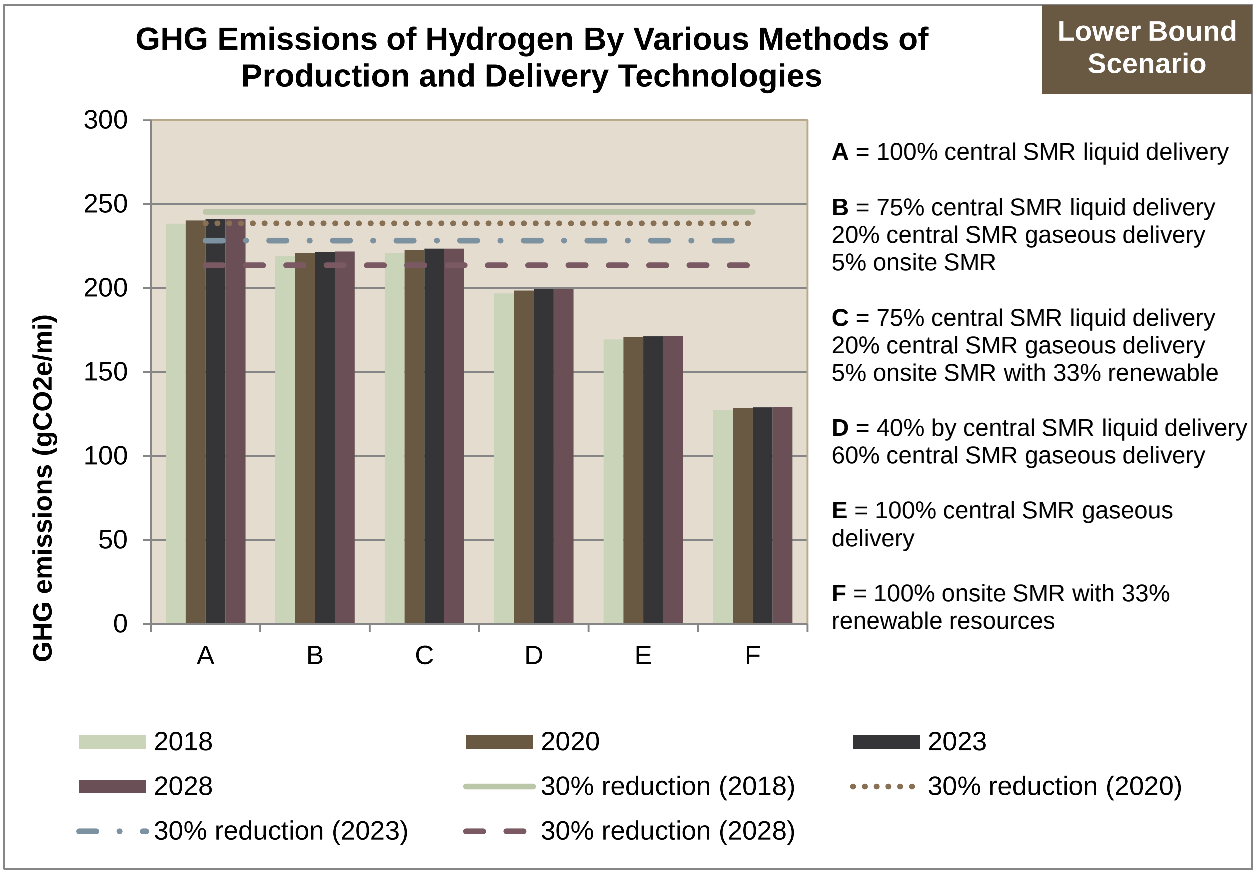


Figure D-3. Lower Bound Scenario GHG Emissions Profile of Hydrogen Produced by Various Pathways over the Lifetime of the CFO

Similar to the Upper Bound Scenario, total GHG emissions benefit was calculated assuming the number of FCVs in Lower Bound Scenario completely replace the same numbers of comparable gasoline vehicles and their associated VMT. Table D-5 summarizes the results of the GHG emission reduction over the lifetime of the CFO. For hydrogen produced by Option A, the expected GHG emission reductions at CFO sunset is about 0.25 MMT CO2e/year. If hydrogen was to be produced with renewable feedstocks, Option F demonstrates a benefit of 0.70 MMT CO2e/year at CFO sunset. This reduction at CFO sunset is about 13 percent lower than the reduction in the Upper Bound Scenario. Time and FCVs numbers are two critical factors in the reduced emissions benefits compared to the Upper Bound Scenario. With smaller numbers of FCVs in the Lower Bound Scenario, higher FCV fleet fuel consumption due to increasing vehicle sizes, and lower gasoline fleet fuel consumption in later years, GHG emissions benefits under the Lower Bound Scenario are lower overall.

Table D-5. GHG Emissions from Various Hydrogen Pathways - Lower Bound Scenario

Lower Bound Scenario		Per Mile GHG Emissions (gCO2e/mi) and (Percent Reduction)				Total GHG Emissions Reduction (MMTCO2e/year)			
Options	Years	2018	2020	2023	2028	2018	2020	2023	2028
Baseline	Gasoline	350.52	340.86	326.06	305.07	-	-	-	-
A	Central SMR liquid delivery	238.30 (32%)	240.37 (29%)	241.15 (26%)	241.29 (21%)	0.024	0.05	0.11	0.25
B	75% central SMR liquid delivery 20% central SMR gaseous delivery 5% onsite SMR with 33% renewable Average WTT CI is 130.65 g/MJ	218.97 (38%)	220.87 (35%)	221.59 (32%)	221.72 (27%)	0.028	0.05	0.14	0.33
C	75% central SMR liquid delivery 20% central SMR gaseous delivery 5% onsite SMR Average WTT CI is 131.75 g/MJ	220.82 (37%)	222.74 (35%)	223.46 (31%)	223.60 (27%)	0.027	0.05	0.14	0.32
D	40% by central SMR liquid delivery 60% central SMR gaseous delivery Average WTT CI is 117.50 g/MJ.	196.93 (44%)	198.64 (42%)	199.28 (39%)	199.40 (35%)	0.032	0.06	0.17	0.42
E	Central SMR gaseous delivery	169.35 (52%)	170.82 (50%)	171.37 (47%)	171.47 (44%)	0.038	0.08	0.20	0.53
F	Onsite SMR with 33% renewable feedstock	127.54 (64%)	128.65 (62%)	129.07 (60%)	129.15 (58%)	0.047	0.10	0.26	0.70

Analysis of Criteria Pollutant Emissions Benefits

Criteria air pollutants are regulated under U.S. EPA's National Ambient Air Quality Standards. Both the California and federal governments have adopted health-based standards for criteria pollutants including ozone, particulate matter (PM2.5 and PM10), carbon monoxide (CO), oxides of nitrogen (NOx), oxides of sulfur (SOx), and volatile organic compounds (VOC).

Criteria Pollutant Emissions Modeling Protocol

Staff performed WTW lifecycle analyses of the criteria pollutants using GREET, similar to the GHG analyses, to examine all potential air emissions from hydrogen production including those from transportation and distribution of feedstock's, the actual production of hydrogen, the transportation and distribution of the fuel (including dispensing to vehicles), and the use of the fuel in vehicles. Following the requirements established in SB1505 to mitigate local criteria pollutant emissions associated with hydrogen, this WTW evaluation includes those emissions occurring on a local level.

For the CFO, criteria pollutants for four fuel pathways were analyzed using year 2020 fuel demand associated with the midpoint of the Upper Bound Scenario, shown in Table D-6. All pathways were compared to gasoline baseline assuming California Reformulated Gasoline (CaRFG) with 10 percent ethanol content by volume.

Criteria Pollutant Emissions Modeling Results

Table D-6 shows local criteria pollutant emissions associated with the various hydrogen pathways in 2020 and percent reductions relative to the gasoline baseline. The highest criteria pollutant emissions for all hydrogen production methods are NO_x and CO; however, criteria emissions from all pathways are significantly lower than the gasoline baseline. When compared to gasoline, local criteria pollutant emissions are significantly lower, ranging from 24 percent to nearly 100 percent, depending on the hydrogen production technology and criteria pollutant evaluated.

To understand the relative significance of the criteria pollutant emissions from hydrogen, data from typical petroleum refining and industrial chemical processing were obtained for the South Coast AQMD region.[12] Data extracted from the ARB emissions almanac for 2020[13] estimates that a typical industrial process for chemicals will contribute 0.08 tons/day of NO_x and 0.14 tons/day of CO (Table D-7). Since NO_x and CO represent the

[12] The SCAQMD basin is anticipated to be the likely region for the initial deployment of a large number of FCVs and was, therefore, chosen for the comparison.
[13] ARB, 2009d. ARB Planning and Technical Support Division (PTSD) 2009 Almanac Emission Projection Data at http://www.arb.ca.gov/app/emsinv/emssumcat.php

greatest criteria pollutant emissions for hydrogen production, a comparison of these values shows that hydrogen production ranks comparable to a typical industrial process for chemicals.

Table D-6. Criteria Pollutants from Various Hydrogen Production Methods and Percent Reductions Relative to Gasoline Baseline

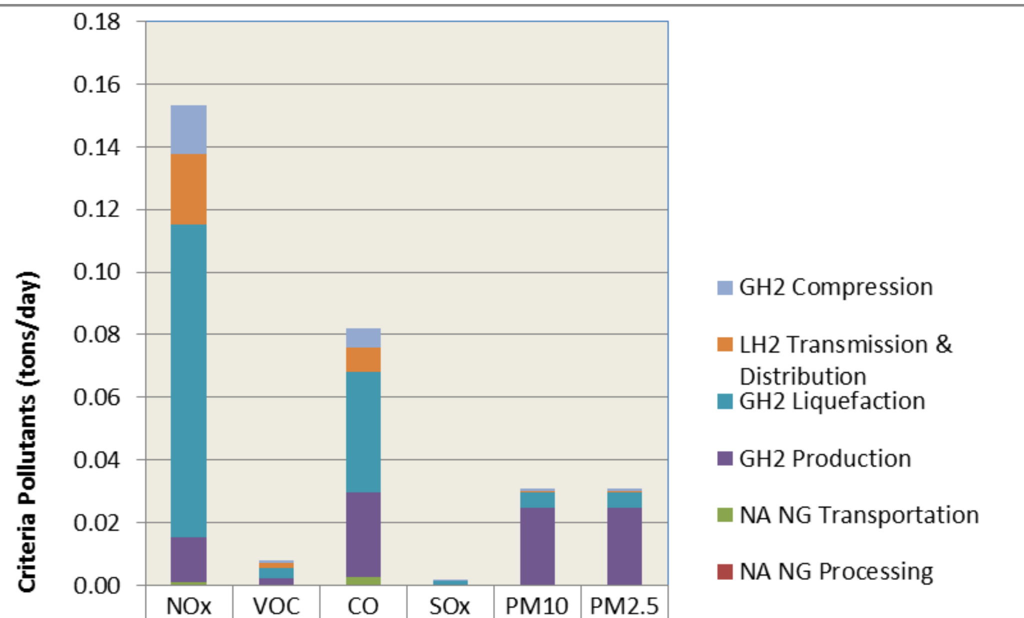
Hydrogen Criteria Pollutants Emissions (tons/day) and Percent Reduction Relative to Baseline						
	NO_x	**VOC**	**CO**	**SO_x**	**PM10**	**PM2.5**
Gasoline (baseline)	0.47	0.23	0.24	0.15	0.15	0.06
Hydrogen by central SMR, liquid delivered	0.15 (67%)	0.0078 (97%)	0.082 (66%)	0.0018 (99%)	0.031 (80%)	0.031 (45%)
Hydrogen by central SMR, gas delivered	0.068 (86%)	0.0089 (96%)	0.041 (83%)	0.0042 (97%)	0.028 (82%)	0.027 (52%)
Hydrogen by onsite SMR	0.057 (88%)	0.0065 (97%)	0.036 (85%)	0.0 (100%)	0.026 (83%)	0.026 (54%)
Hydrogen by onsite electrolysis	0.36 (24%)	0.013 (94%)	0.14 (43%)	0.0037 (98%)	0.017 (89%)	0.017 (70%)

Table D-7. Estimated Criteria Pollutant Emissions for SCAQMD in 2020 from Petroleum Refining and Industrial Chemical Processing

Estimated 2020 Average Criteria Pollutants Emissions in South Coast AQMD (tons/day)[14]						
	NOx	VOC	CO	SOx	PM10	PM2.5
Petroleum Refining	4.32	4.58	8.83	6.53	2.46	2.06
Industrial processes - Chemical	0.08	11.16	0.14	1.07	0.76	0.66

[14] Ibid.

Figures D-4a through D-4d show criteria pollutant emissions from various stages of the hydrogen production process. For hydrogen produced by central SMR with liquid delivery, fuel liquefaction contributes to over 50 percent of the NOx, VOC, CO, and SOx emissions. For particulate matter (PM10 and PM2.5), fuel production contributes to over 80 percent of the emissions. In contrast, fuel delivery only contributes to about one percent of the particulate matter emissions.

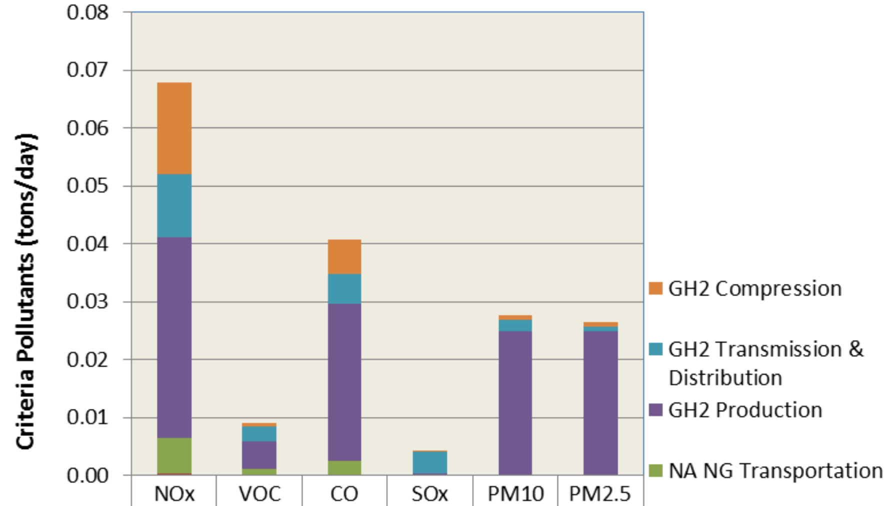


	NOx	VOC	CO	SOx	PM10	PM2.5
GH2 Compression	0.0157	0.0006	0.0061	0.0002	0.0007	0.0007
LH2 Transmission & Distribution	0.0225	0.0016	0.0076	0.0003	0.0004	0.0004
GH2 Liquefaction	0.0996	0.0036	0.0385	0.0010	0.0047	0.0047
GH2 Production	0.0143	0.0019	0.0272	0.0003	0.0247	0.0247
NA NG Transportation	0.0008	0.0001	0.0024	0.0000	0.0001	0.0001
NA NG Processing	0.0002	0.0000	0.0001	0.0000	0.0000	0.0000
NA NG Recovery	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000

Figure D-4a. Criteria Pollutants – Hydrogen by Central SMR with Liquid Delivery

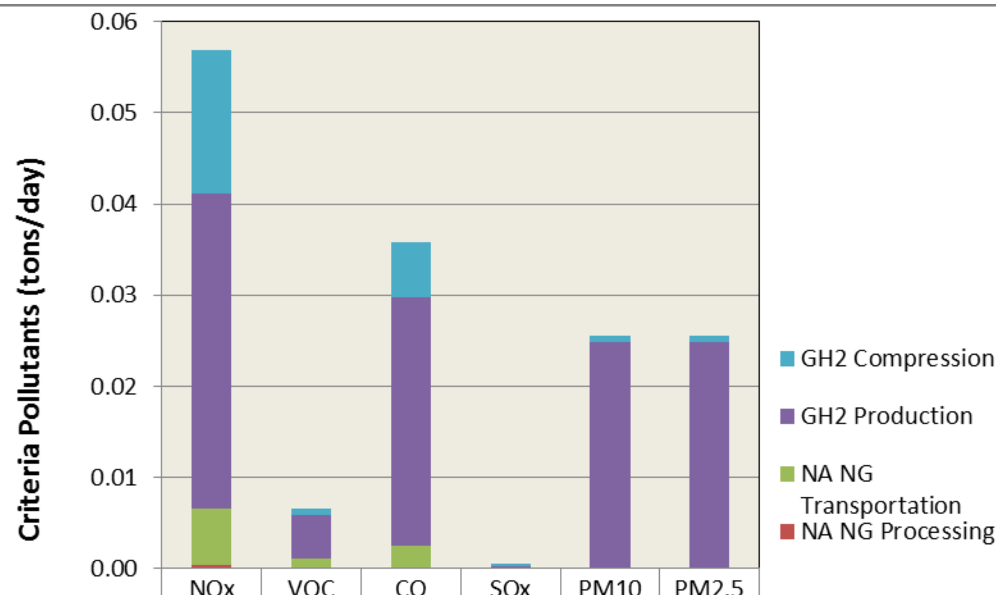
For hydrogen produced by central SMR with gaseous delivery, the greatest impact on overall criteria pollutants emissions is the fuel production process, which is estimated to contribute to over 50 percent each of the NOx, VOC, and CO, and about 90 percent of the particulate matter emissions. Fuel compression shows a slight impact of 23 percent for NOx, 15 percent for CO, less than 7 percent for all other criteria pollutants.

For hydrogen produced on site either by SMR or electrolysis, the greatest overall contribution to criteria pollutants is the fuel production process, with impact ranging from 60 to 96 percent.



	NOx	VOC	CO	SOx	PM10	PM2.5
GH2 Compression	0.01572	0.00057	0.00607	0.00016	0.00074	0.00074
GH2 Transmission & Distribution	0.01099	0.00245	0.00499	0.00377	0.00198	0.00093
GH2 Production	0.03458	0.00486	0.02723	0.00029	0.02469	0.02469
NA NG Transportation	0.00621	0.00099	0.00236	0.00001	0.00013	0.00013
NA NG Processing	0.00021	0.00001	0.00008	0.00000	0.00001	0.00001
NA NG Recovery	0.00012	0.00007	0.00004	0.00000	0.00000	0.00000

Figure D-4b. Criteria Pollutants – Hydrogen by Central SMR with Gaseous Delivery



	NOx	VOC	CO	SOx	PM10	PM2.5
GH2 Compression	0.01572	0.00057	0.00607	0.00016	0.00074	0.00074
GH2 Production	0.03458	0.00486	0.02723	0.00029	0.02469	0.02469
NA NG Transportation	0.00621	0.00099	0.00236	0.00001	0.00013	0.00013
NA NG Processing	0.00021	0.00001	0.00008	0.00000	0.00001	0.00001
NA NG Recovery	0.00012	0.00007	0.00004	0.00000	0.00000	0.00000

Figure D-4c. Criteria Pollutants – Hydrogen by On-Site SMR

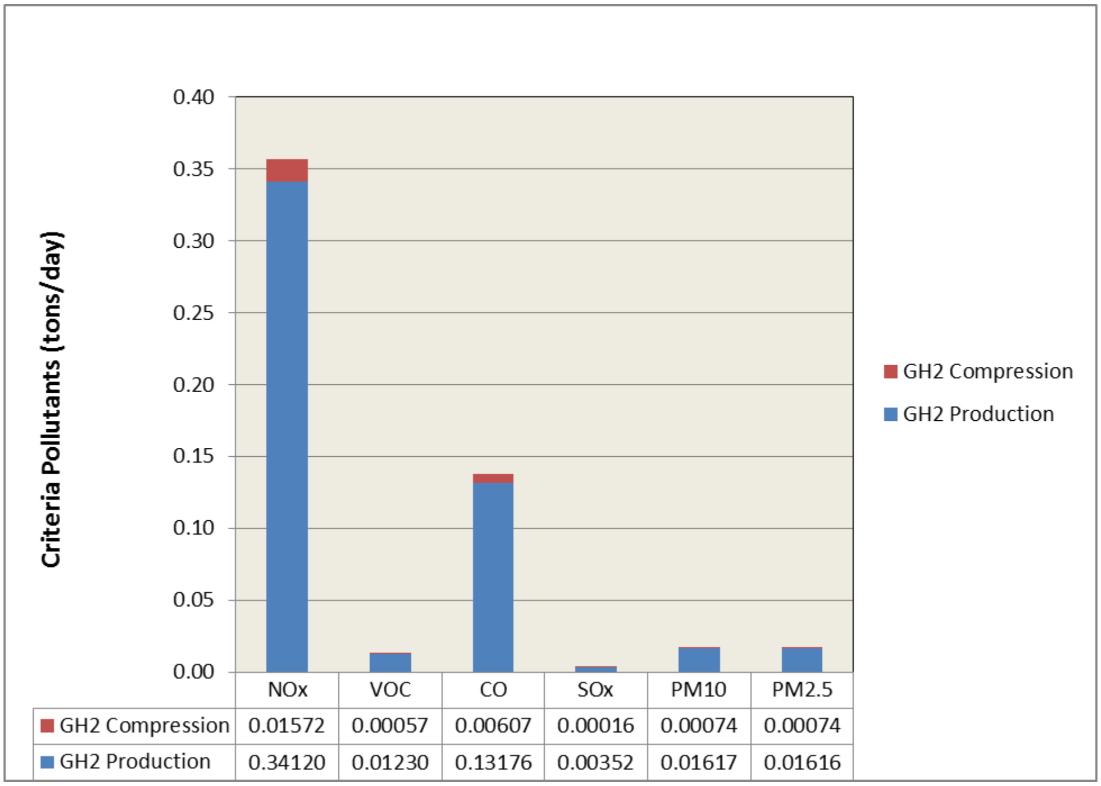


Figure D-4d. Criteria Pollutants – Hydrogen by On-Site Electrolysis

Criteria Pollutant Emissions during Station Permitting

Under State law, the air pollution control and air quality management districts (local districts) have the primary responsibility for controlling air pollution from non-vehicular sources, including stationary sources such as hydrogen production facilities.[15] Each local district has a program designed to address new stationary sources of air pollution. For most local districts, these programs are referred to as new source review (NSR) programs.[16] NSR programs provide mechanisms to: (1) reduce emission increases up-front through the use of clean technology; and (2) achieve no net increases in emissions of nonattainment pollutants or their precursors for all new or modified sources that exceed particular emission thresholds. This is accomplished through two major requirements in each district NSR rule: best available control technology (BACT)[17] and offsets. The local air districts also develop rules to reduce emissions from specific sources and govern the overall permitting process. Local districts enforce their local rules and prepare air quality plans to achieve ambient air quality standards.

[15] Health and Safety Code section 39002.
[16] See, e.g., Bay Area Air Quality Management District Regulations 2-1 through 2-6. A few local districts, because of their federal attainment status for certain pollutants, implement a Prevention of Significant Deterioration (PSD) program.
[17] In California, BACT is synonymous with the federal term Lowest Achievable Emission Rate (LAER) for nonattainment area permit requirements.

In addition to meeting local district NSR rules, new hydrogen production facilities must meet California Environmental Quality Act (CEQA)[18] requirements as part of the permitting process. As these facilities are industrial facilities, an environmental impact report (EIR) must be prepared. To comply with CEQA requirements, the EIR must identify any significant environmental impacts, identify feasible alternatives, and incorporate feasible mitigation measures to minimize the significant adverse environmental impacts identified in the environmental impacts analysis. CEQA prohibits the adoption of projects as originally proposed if they have significant adverse environmental impacts, and feasible alternatives or mitigation measures are available to reduce or eliminate such impacts (except if specific overriding considerations are identified that outweigh the potential adverse consequences of any unmitigated impacts).

[18] Public Resources Code section 21000 et seq.