Assessment of Technologies To Meet a Low Carbon Fuel Standard

Supporting Information

Sonia Yeh, Ph.D.

Research Scientist

Institute of Transportation Studies

University of California, Davis, One Shields Ave., Davis, CA 95616

(530) 754-9000, Email: slyeh@ucdavis.edu

Nicholas Lutsey, Ph.D.

Postdoctoral Researcher

Institute of Transportation Studies

University of California, Davis, One Shields Ave., Davis, CA 95616

Email: nplutsey@ucdavis.edu

Nathan Parker

Ph.D. Candidate

Institute of Transportation Studies

University of California, Davis, One Shields Ave., Davis, CA 95616

Email: ncparker@ucdavis.edu

Assumptions of Carbon Intensity

Based on the California Air Resources Board Staff Report’s Initial Statement of Reasons (ISOR) (S1), we assume for this analysis that the baseline gasoline and diesel, CARBOB (California Reformulated Gasoline Blendstock for Oxygenate Blending) and ultra-low sulfur diesel (ULSD), have carbon intensity (CI) values of 95.9 and 94.7 gCO₂e/MJ, respectively, and that the carbon intensities of biofuels are 50.7 gCO₂e/MJ for advanced corn ethanol; 22.2 gCO₂e/MJ for cellulosic ethanol from forestry wastes, municipal solid waste (MSW), orchard/vineyard waste, and agricultural residue; and 15 gCO₂e/MJ for waste-derived biodiesel or renewable diesel including fatty acid to hydrocarbon (FAHC) biodiesel form waste and Fischer-Tropsch (FT) MSW. Greenhouse gas (GHG) emissions of 30, 46, 42, and 18 gCO₂e/MJ from indirect land use change are added to corn ethanol, Brazilian sugarcane ethanol, soybean biodiesel, and energy crops respectively. A complete list of CI values used in this analysis can be found in the ISOR (S1) Tables IV-20, IV-21, VI-3, and VI-4.

Figure S1. California LCFS greenhouse gas (GHG) intensity ratings (gCO₂e/MJ) for transportation fuels, adjusting for vehicle efficiency factor, the energy economy ratio (EER) (S1). Error bars represent the range of direct lifecycle emissions using different technologies/feedstocks/energy sources (S1). Although no uncertainties are reflected in this graph, the uncertainties of indirect emissions are much larger than the uncertainties of direct emissions.

As shown in Figure S1, a variety of low-GHG fuels from a wide range of feedstocks and production pathways have the potential to substitute for high-GHG gasoline and diesel. The average fuel carbon intensity (AFCI) of a regulated party is calculated as:

$$AFCI = \frac{\sum_i^n E_i \times CI_i}{\sum_i^n E_i \times EER_i} \quad (\text{Equation S1})$$

Where:

- $AFCI$ = average fuel carbon intensity value of the targeted fuel (gasoline or diesel), in gCO₂e/MJ;
 CI_i = carbon intensity value of fuel i , in gCO₂e/MJ;
 E_i = energy of fuel i , in MJ;
 EER_i = dimensionless Energy Economy Ratio (EER) of fuel i , which compares the energy efficiency of an alternative fuel vehicle to a conventional gasoline or diesel vehicle.

Bioenergy Conversion Technology Characteristics

A brief summary of biofuel conversion technologies and the assumptions of production costs and yields are given in Table S1. Further detailed information can be found in references (S2-4).

Table S1. Characteristics and assumptions of current and advanced biofuel conversion technologies. Source: (S2-4).

Reference name	Feedstock	Conversion technology	Fuel type	Size range* (million gallons / year)	Capital cost (million \$)	Annual O&M cost ⁺ (million \$ / year)	Yield (gallons fuel / ton biomass)
Current representative technologies							
Grain to ethanol - Dry Mill	Grains/starches	Enzymatic fermentation	Ethanol	5 to 100	\$13 to \$167	\$1.2 to \$16	100
Grain to ethanol - Wet Mill	Grains/starches	Separation and fermentation	Ethanol	50 to 300	\$139 to \$408	\$3.4 to \$21	89
Fatty acid to methyl ester (FAME)	Seed oil / waste oils / animal fats	Esterification	Methyl esters	1 to 80	\$3 to \$40	\$0.4 to \$17	249 to 266
Additional technologies projected to be in use by 2015 to 2025							
Lignocellulosics to ethanol - fermentation/hydrolysis (LCE fermentation/hydrolysis)	Lignocellulosic biomass	Hydrolysis and fermentation	Ethanol	20 to 100	\$61 to \$305	\$0.6 to \$18	70 to 90
Lignocellulosics to middle distillates - Fischer-Tropsch (LCMD - FT)	Lignocellulosic biomass	Gasification and Fischer-Tropsch synthesis	Middle distillates, gasoline	7 to 200	\$250 to \$4,050	-\$2.3 to -\$157	32 to 43
Lignocellulosics to gasoline - upgrading/pyrolysis (LCG - upgrading/pyrolysis)	Lignocellulosic biomass	Pyrolysis oil production and upgrading via hydrotreatment /hydrocracking	Bio-oil, diesel, gasoline	0.65 to 18.6	\$11 to \$112	\$1.4 to \$19	22 to 23
Fatty Acids to HydroCarbon - Hydrotreatment (FAHC - Hydrotreatment)	Seed oil / waste oils / animal fats	Upgrading via hydrotreatment	Renewable diesel	15 to 200	\$10 to \$37	\$2.3 to \$26	250

* Size range gives potential facility sizes expected in the 2015 time frame.

⁺ Includes co-product credit.

Biofuel Supply Curves in California and in the Western States

Quantitative assessment of resources and costs of delivery associated with each individual and applicable biomass resource, combined with Geographic Information System (GIS) modeling in conjunction with an infrastructure system cost optimization model, are used to develop biofuel supply curves using biomass feedstocks throughout California and the western US. The estimated production cost excludes local delivery costs from distribution terminals to refueling stations, market costs, and taxes. The methodologies, assumptions, and additional uncertainty analysis are described in detail in a series of reports that can be found at <http://www.westgov.org/wga/initiatives/transfuels/index.html>. The estimated biofuel resource supply curves from various feedstocks and processes in California are shown in Figure S2, which estimates the production supply curves of gasoline substitutes that involve corn-derived ethanol as well as lignocellulosic ethanol (LCE) from forest, orchard waste, agricultural residue, and municipal solid waste (MSW). Similarly, production supply curves are constructed for diesel substitutes such as fatty acid to hydrocarbon (FAHC) conversion of tallow and grease and for Fischer-Tropsch (FT) production of biomass-based diesel from municipal solid waste. The figure shows that the largest resource estimated to be available from within California is MSW, which includes mixed paper, wood wastes, and yard wastes. Corn is not found to be a significant source of biofuel resource in California, and energy crops are not estimated to be economically attractive within the state.

Figure S2. Biofuel production supply curves in California by biomass and technology type. The three lines on the far left are FAHC-tallow, FAHC-grease, and LCE-agricultural residue (from left to right). Abbreviations: LCE=lignocellulosic ethanol; FT=Fischer-Tropsch; MSW=municipal solid waste; OVW=orchard/vine waste.

The total resource supply curves for the western states are summarized in Figure S3 by biomass feedstock and in Figure S4 by biofuel type.

Figure S3. Biofuel production supply curves in the western states by biomass feedstock. Corn ethanol is off-scale and is shown in Figure S4. The two lines on the far left are FAME-soy/canola and FAHC-grease (from left to right).

Figure S4. Biofuel production supply curves in the western states by biofuel type. Abbreviations: FAHC=fatty acid to hydrocarbon; FT=Fischer-Tropsch.

Fuel Providers' Compliance Cost-Effectiveness Curves

Fuel providers' compliance cost-effectiveness curves by feedstock, as calculated based on Equation 2 in the main text, are shown in Figure S5 for biofuels from California and Figure S6 from the western states.

Figure S5. Fuel providers' biofuel GHG compliance cost-effectiveness curves from California by feedstock at gasoline fuel cost of \$2.0/gge (production cost, excluding local delivery, marketing, and taxes). Abbreviations: LCE=lignocellulosic ethanol; FAME=fatty acid to methyl esters; FAHC=fatty acid to hydrocarbon; FT=Fischer-Tropsch; MSW=municipal solid waste; OVW=orchard/vine waste; Ag=agricultural residue.

Figure S6. Fuel providers' biofuel GHG compliance cost-effectiveness curves from western states by feedstock at a gasoline fuel cost of \$2.0/gge (production cost, excluding local delivery, marketing, and taxes).

VISION-CI model

The original VISION model was developed by Argonne National Laboratory (S5) and subsequently modified for California-specific data to become our VISION-CA model (S6). VISION-CI (CI standards for carbon intensity) used for this analysis is an updated version of the earlier VISION-CA model. The VISION models are vehicle-fleet turnover models that track vehicles, fuel penetration, and fleet turnover by its vintage years and allow for user-defined changes in fuel use. The rate of substitution of an existing vehicle fleet by more fuel-efficient vehicles or flex-fuel vehicles is limited by the rate of vehicle turnover and the maximum rate of introduction of new technology, which is assumed to have an S-shaped logistical function adoption curve. The model documentation can be found at the VISION model website (S5).

The reference case incorporates California's AB1493 (Pavley), which sets vehicle emission performance standard that requires a 30% reduction in GHG emissions rate from new light-duty vehicles by 2016 (S7). The E10 requirement for 10% ethanol in gasoline after 2010 is also assumed in the base case (S8). When E85 flex-fuel vehicles are introduced to utilize lower-GHG biofuels, we assume that their E85 mileage share (the percentage of time the vehicle runs on E85) will be 50% in 2020 in the LCFS compliance scenario. Ethanol, which can be derived from various agricultural and waste feedstocks, can be mixed with gasoline up to 10% by volume (E10) without any vehicle modifications, and up to 85% by volume (E85) in flex-fuel vehicles. Traditional biodiesel (fatty acid methyl ester [FAME]) from lipid feedstocks can be blended into diesel fuel up to 20% (B20) without major vehicle modifications. Advanced biomass-based diesels produced through the Fischer-Tropsch or hydrotreatment processes are expected to blend into diesel fuel without restriction. Applications for electrification span light-duty, heavy-duty, and non-road vehicles and generally include electric battery storage, electric motors, and charging equipment to allow vehicles to utilize grid-connection electricity to supplant conventional gasoline and diesel energy sources.

Total fuel use and vehicle penetration for light-duty (LDV) and heavy-duty (HDV)¹ vehicles are shown in Table S2 for the reference case and Table S3 for the portfolio scenario.

¹ Gross vehicle weight > 10,000 lbs.

Table S2. Transportation fuel use and vehicle penetration in the reference case.

LDV transportation fuel use (Quads/yr) ²											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Gasoline	1.99	2.02	2.04	2.06	2.06	2.05	2.03	2.03	2.00	1.97	1.89
Ethanol	0.14	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Diesel	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.05
Electricity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Compressed natural gas (CNG)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrogen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	2.16	2.20	2.22	2.25	2.25	2.24	2.22	2.22	2.20	2.16	2.09
LDV fleet market share (%), based on VISION-CI model											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Conventional gasoline and gasoline hybrid vehicle	95.2%	94.3%	93.3%	92.2%	91.0%	89.6%	88.1%	86.5%	84.9%	83.2%	81.5%
Battery electric vehicle	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E85 flex-fuel vehicle	3.1%	3.9%	4.8%	5.9%	7.1%	8.3%	9.7%	11.0%	12.5%	13.9%	15.3%
Diesel vehicle	1.6%	1.7%	1.7%	1.8%	1.9%	2.0%	2.1%	2.2%	2.4%	2.6%	2.8%
Compressed natural gas vehicle	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Plug-in hybrid vehicle	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%
Plug-in hybrid diesel vehicle	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Hydrogen fuel cell vehicle	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Sum	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
HDV transportation fuel use (Quads/yr)											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Gasoline	0.031	0.031	0.032	0.032	0.032	0.033	0.033	0.034	0.034	0.035	0.035
Ethanol	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.003
Diesel	0.432	0.443	0.455	0.468	0.483	0.499	0.512	0.525	0.537	0.549	0.559
liquefied petroleum gas (LPG)	0.008	0.008	0.008	0.009	0.009	0.009	0.010	0.010	0.010	0.010	0.010
CNG	0.013	0.013	0.014	0.014	0.014	0.015	0.015	0.015	0.016	0.016	0.016
Total	0.49	0.50	0.51	0.53	0.54	0.56	0.57	0.59	0.60	0.61	0.62
HDV fleet market share (%), based on VISION-CI model											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Gasoline trucks	17.3%	16.8%	16.7%	16.5%	16.7%	16.8%	16.5%	16.4%	16.6%	16.9%	16.8%
Diesel trucks	51.2%	52.1%	52.8%	53.6%	54.4%	55.0%	54.5%	54.5%	54.6%	54.5%	54.5%
LPG trucks	11.3%	11.2%	11.0%	10.8%	10.4%	10.2%	10.4%	10.5%	10.4%	10.3%	10.4%
CNG trucks	20.1%	19.9%	19.5%	19.1%	18.5%	18.1%	18.5%	18.6%	18.4%	18.3%	18.3%
Total on-road transportation fuel use (billion gasoline gallon equivalent per year, BGGE/yr)											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
CARBOB	17.83	18.10	18.30	18.49	18.46	18.37	18.21	18.21	17.97	17.65	16.96
Ethanol	1.30	1.32	1.34	1.36	1.36	1.37	1.37	1.36	1.36	1.35	1.35
CA ULSD	4.06	4.16	4.27	4.40	4.54	4.69	4.82	4.95	5.07	5.20	5.32
Biodiesel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electricity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
LPG	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.09
CNG	0.13	0.14	0.14	0.14	0.15	0.15	0.15	0.16	0.16	0.16	0.17
Hydrogen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	23.39	23.79	24.13	24.46	24.59	24.66	24.63	24.77	24.66	24.46	23.90

² 1.0 Quad = One quadrillion Btu (10¹⁵ Btu) = 1.055 exajoules (EJ), or approximately 172 million barrels of oil equivalent.

Table S3. Transportation fuel use and vehicle penetration in the portfolio scenario.

LDV transportation fuel use (Quads/yr)											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Gasoline	1.98	2.01	2.02	2.02	2.00	1.96	1.91	1.91	1.85	1.79	1.65
Ethanol	0.14	0.15	0.16	0.16	0.17	0.18	0.20	0.21	0.23	0.25	0.28
Diesel	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.05
Electricity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
CNG	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Hydrogen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	2.16	2.19	2.21	2.22	2.21	2.18	2.15	2.18	2.14	2.10	2.00
LDV fleet market share (%), based on VISION-CI model											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Conventional gasoline and gasoline hybrid vehicle	94.8%	93.7%	92.4%	90.8%	88.9%	86.7%	84.4%	81.9%	79.3%	76.6%	73.8%
Battery electric vehicle	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%	0.2%
E85 flex-fuel vehicle*	3.4%	4.4%	5.6%	7.0%	8.6%	10.5%	12.4%	14.4%	16.5%	18.4%	20.3%
Diesel vehicle	1.6%	1.7%	1.7%	1.8%	1.9%	2.0%	2.1%	2.2%	2.4%	2.6%	2.8%
Compressed natural gas vehicle	0.1%	0.1%	0.1%	0.1%	0.2%	0.2%	0.2%	0.3%	0.3%	0.4%	0.5%
Plug-in hybrid vehicle	0.0%	0.1%	0.2%	0.2%	0.3%	0.5%	0.7%	0.9%	1.2%	1.6%	2.1%
Plug-in hybrid diesel vehicle	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Hydrogen fuel cell vehicle	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Sum	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
HDV transportation fuel use (Quads/yr)											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Gasoline	0.031	0.031	0.032	0.032	0.032	0.033	0.033	0.034	0.034	0.035	0.035
Ethanol	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.003
Diesel	0.432	0.443	0.455	0.468	0.483	0.499	0.512	0.525	0.537	0.549	0.559
LPG	0.008	0.008	0.009	0.009	0.009	0.010	0.010	0.010	0.010	0.011	0.011
CNG	0.014	0.014	0.015	0.016	0.016	0.017	0.018	0.019	0.019	0.020	0.021
Total	0.49	0.50	0.51	0.53	0.54	0.56	0.58	0.59	0.60	0.62	0.63
HDV fleet market share (%), based on VISION-CI model											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Gasoline	16.7%	16.1%	15.9%	15.7%	15.8%	15.8%	15.5%	15.3%	15.4%	15.6%	15.4%
Diesel	49.4%	49.9%	50.4%	50.8%	51.4%	51.7%	50.9%	50.6%	50.5%	50.2%	49.9%
LPG	10.9%	10.8%	10.5%	10.2%	9.8%	9.6%	9.7%	9.7%	9.6%	9.5%	9.5%
CNG	23.0%	23.3%	23.3%	23.3%	23.0%	22.9%	23.9%	24.4%	24.5%	24.7%	25.2%
Total on-road transportation fuel use (BGGE/yr)											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
CARBOB	17.80	18.00	18.09	18.12	17.89	17.58	17.16	17.17	16.66	16.09	14.87
Ethanol	1.30	1.34	1.40	1.47	1.55	1.65	1.77	1.92	2.08	2.27	2.48
CA ULSD	4.06	4.11	4.16	4.22	4.29	4.37	4.43	4.48	4.52	4.56	4.60
Biodiesel	0.00	0.06	0.12	0.18	0.25	0.32	0.39	0.47	0.55	0.64	0.73
Electricity	0.00	0.01	0.01	0.02	0.02	0.03	0.04	0.05	0.07	0.09	0.11
LPG	0.07	0.07	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.10
CNG	0.14	0.15	0.00	0.00	0.00	0.19	0.16	0.16	0.17	0.18	0.29
Hydrogen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	23.37	23.74	23.86	24.09	24.08	24.23	24.04	24.34	24.14	23.92	23.18

*Several major automakers have plans to increase their E85 vehicle sales to 50% of their new vehicle sales by model year 2014. See (S9-11).

Based on Equation S1, the trajectories of AFCI-gasoline (the average carbon intensity values of gasoline and gasoline-substitutes) and AFCI-diesel (the average carbon intensity values of diesel and diesel-substitutes) for the reference case and the portfolio scenario are shown in Figure S7.

Figure S7. Trajectories of AFCI-gasoline and AFCI-diesel for the reference case, and the portfolio scenario that meets the 10% AFCI reduction goals.

National LCFS Analysis

Tables S4 and S5 show the first-order estimates of fuel use and CO₂e emissions, and the amount of emission reduction required to achieve a 10% APCI reduction target if the US adopts a California-like LCFS. Table S4 is based on the Annual Energy Outlook 2009 reference case (*S12*), and Table S5 assumes that the RFS target mandated in the Energy Independence and Security Act (EISA) will be fully met. Instead of meeting separate APCI-gasoline and APCI-diesel targets, the following calculations are based on the compliance of one APCI target since over-compliance credits can be traded between the two targets. Table S5 shows that the implementation of the federal biofuel target mandated in the Energy Independence and Security Act (*S13*) would reduce the average transport-fuel carbon intensity by 3.3% by 2020 and 4.5% by 2022.

Table S4. Estimates of fuel use and CO₂e emission reduction required to achieve a 10% APCI reduction target based on the Annual Energy Outlook 2009 projections (*S12*).

Fuel type	Transportation fuel use (BGGE/yr)											CI (2010)	CI (2020)	EER
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020			
Gasoline	140.5	143.9	143.6	142.6	141.3	139.4	137.3	135.6	133.7	132.5	131.0	95.9	95.9	1
Ethanol	10.5	10.7	10.7	10.6	10.5	10.8	11.2	11.5	12.1	12.9	13.9	99.4	64.0*	1
Diesel	62.1	63.6	65.3	66.5	66.8	67.0	67.5	68.2	69.0	69.6	70.4	94.7	94.7	1
Biodiesel	0.9	1.0	1.3	1.6	1.8	2.1	2.3	2.6	2.9	3.1	3.4	48.0	48.0	1
Electricity	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	164.4	164.4	3
LPG	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	77.3	77.3	1
CNG	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.6	0.6	67.7	67.7	1
Hydrogen	0.0	0.0	0.001	0.001	0.001	0.002	0.003	0.004	0.006	0.008	0.009	98.3	98.3	2.3
Jet Fuel (kerosene & naphtha)	26.5	25.9	26.0	26.1	26.5	26.9	27.3	27.8	28.6	29.2	29.9	86.4	86.4	1
Aviation Gasoline	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	85.0	85.0	1
Total	241.4	246.1	247.8	248.3	247.9	247.2	246.8	246.9	247.4	248.6	249.8			

*Based on the GHG emission reduction targets specified in the EISA.

APCI 2010 (baseline fuels include all transport fuels in 2010): 94.3 gCO₂e/MJ

APCI 2020: 91.8 gCO₂e/MJ

Total CO₂e emissions in 2010 = 2727 million tonnes

Total CO₂e emissions in 2020 = 2747 million tonnes

2020 APCI goal: 84.9 (10% reduction from the baseline)

2020 CO₂e emissions if 10% APCI goal is met = 2535 million tonnes

LCFS CO₂e emission reduction from 2020 reference case = 211 million tonnes

Table S5. Estimates of fuel use and CO₂e emissions if the biofuel target mandated in the Energy Independence and Security Act (EISA) is assumed to be fully met.

Fuel type	Transportation fuel use (BGGE/yr)														CI (2010)	CI (2022)	EER
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022				
Gasoline	142.9	146.1	145.0	143.2	140.9	138.0	135.6	133.3	131.0	129.6	127.8	125.3	123.5	95.9	95.9	1	
Conventional biofuel	8.0	8.4	8.9	9.3	9.7	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	99.4	76.7 [#]	1	
Cellulosic biofuel	0.1	0.2	0.3	0.7	1.2	2.0	2.9	3.7	4.7	5.7	7.1	9.1	10.8	38.4	38.4 [*]	1	
Diesel	62.1	63.6	65.3	66.5	66.8	67.0	67.5	68.2	69.0	69.6	70.4	71.0	71.4	94.7	94.7	1	
Biomass based biodiesel	0.9	1.0	1.3	1.6	1.8	2.1	2.3	2.6	2.9	3.1	3.4	3.6	4.1	47.95	48.0 ⁺	1	
Electricity	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	164.4	164.4	3	
LPG	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	77.3	77.3	1	
CNG	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.6	67.7	67.7	1	
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	98.3	98.3	2.3	
Jet Fuel (kerosene & naphtha)	26.5	25.9	26.0	26.1	26.5	26.9	27.3	27.8	28.6	29.2	29.9	30.5	31.0	86.4	86.4	1	
Aviation Gasoline	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	85.0	85.0	1	
Total	241.4	246.1	247.8	248.3	247.9	247.2	246.8	246.9	247.4	248.6	249.8	250.9	252.2				

[#] Assume to have 20% lower life-cycle GHG emissions than gasoline. ^{*} Must have 60% lower life-cycle GHG emissions than gasoline. ⁺ Must have 50% fewer life-cycle GHG emissions than gasoline.

AFCI 2010 (baseline fuels include all transport fuels in 2010): 94.3 gCO₂e/MJ

AFCI 2020: 91.4 gCO₂e/MJ (3.1% reduction from AFCI 2010)

AFCI 2022: 90.1 gCO₂e/MJ (4.4% reduction from AFCI 2010)

The carbon intensities of jet fuel and aviation gasoline are based on Table A-29 of EPA, US Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2006

(http://epa.gov/climatechange/emissions/downloads/08_CR.pdf) and adjusted for lifecycle emissions, assuming upstream emissions account for about 20% of total GHG emissions from petroleum (Table S6).

Table S6. Estimates of lifecycle carbon intensities for jet fuel and aviation gasoline.

	Carbon content (gCO ₂ e/MJ), HHV	Carbon content (gCO ₂ e/MJ), LHV	Estimated lifecycle emissions (gCO ₂ e/MJ), LHV (assuming 20% emissions are from upstream)
Aviation gasoline	65.6	70.9	85.1
Jet fuel (kerosene and naphtha)	67.2	72.0	86.4

References

- S1. CARB. *Staff Report: Proposed Regulation to Implement the Low Carbon Fuel Standard - Initial Statement of Reasons Volume 1: Staff Report*; California Air Resources Board: 2009. Available from http://www.arb.ca.gov/fuels/lcfs/030409lcfs_isor_vol1.pdf.
- S2. Parker, N.; Tittmann, P.; Hart, Q.; Lay, M.; Cunningham, J.; Jenkins, B. *Strategic Assessment of Bioenergy Development in the West: Spatial Analysis and Supply Curve Development*; 2008. Available from <http://www.westgov.org/wga/initiatives/transfuels/Task%203.pdf>.
- S3. Antares Group Inc. *Strategic Assessment of Bioenergy Development in the West: Bioenergy Conversion Technology Characteristics*; 2008. Available from <http://www.westgov.org/wga/initiatives/transfuels/Task%202.pdf>.
- S4. Nelson, R.; Skog, K.; Mallory, M. P.; Rummer, R.; Barbour, R. J. *Strategic Assessment of Bioenergy Development in the West: Biomass Resource Assessment and Supply Analysis for the WGA Region*; Kansas State University and the U.S. Forest Service 2008. Available from <http://www.westgov.org/wga/initiatives/transfuels/Task%201.pdf>.
- S5. U.S. DOE. *VISION*; Argonne National Laboratory, U.S. Department of Energy: 2008. Available from <http://www.transportation.anl.gov/software/VISION/index.html>.
- S6. Melaina, M. *VISION-CA model can be downloaded at* <http://www.lcfs.ucdavis.edu/vision.html>; 2008.
- S7. CARB. *Comparison of Greenhouse Gas Reductions for the United States and Canada Under U.S. CAFE Standards and California Air Resources Board Greenhouse Gas Regulations*; California Air Resources Board: Sacramento, CA, February, 2008.
- S8. CARB. *California Procedures for Evaluating Alternative Specifications for Phase 3 Reformulated Gasoline Using the California Predictive Model*; California Air Resources Board: Sacramento, CA, 2008.
- S9. General Motors Corporation. *General Motors Corporation 2009-2014 Restructuring Plan*. Presented to U.S. Department of the Treasury; February 17, 2009.
- S10. Chrysler. *Chrysler Restructuring Plan for Long-Term Viability*; February 17, 2009.
- S11. Ford Motor Company. *Ford Motor Company Business Plan*. Submitted to Senate Banking Committee; 2009.
- S12. EIA. *Annual Energy Outlook 2009*; Energy Information Administration: Washington, DC, 2009. Available from www.eia.doe.gov/oiaf/aeo/.
- S13. H. R. 6: Energy Independence and Security Act. In (*P.L. 110-140, H.R. 6*), 2007.