California Environmental Protection Agency
Air Resources Board

Detailed California-Modified GREET Pathway for California Average and Marginal Electricity

Stationary Source Division

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Version 2.1

The Staff of the Air Resources Board developed this preliminary draft version as part of the Low Carbon Fuel Standard Regulatory Process

The ARB acknowledges contributions from the California Energy Commission, TIAX, and Life Cycle Associates during the development of this document

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These comments will be compiled, reviewed, and posted to the LCFS website in a timely manner.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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SUMMARY

CA-GREET Model Pathways for California Electricity

A Well-To-Tank (WTT) Life Cycle Analysis of a fuel (or blending component of fuel) pathway includes all steps from feedstock production to final finished product. Tank-To-Wheel (TTW) analysis includes actual combustion of fuel (or use in a manner that generates power such as in electricity) for motive power. Together WTT and TTW analysis are combined together to provide a total Well-To-Wheel (WTW) analysis.

A Life Cycle Analysis Model called the **G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation (GREET)[1] developed by Argonne National Laboratory has been used to calculate the energy use and GHG emissions generated during the entire process required to produce electricity. The model however, was modified by TIAX under contract to the California Energy Commission during the AB 1007 process[2]. Changes were restricted mostly to input factors (emission factors, generation mix, transportation distances, etc.) with no changes in methodology inherent in the original GREET model. This California-modified GREET model formed the basis for many fuel pathways published by staff in mid-2008. Subsequent to this, the Argonne Model was updated in September 2008. To reflect the update and to incorporate other changes, staff contracted with Life Cycle Associates to update the CA-GREET model. This updated California modified GREET model (v1.8b)[3] (released February 2009) forms the basis of this document. It has been used to calculate the energy use and greenhouse gas (GHG) emissions associated with a WTW analysis for California Average and Marginal Electricity.

The California-modified GREET model, herein referred to as "CA-GREET", forms the basis of this document which details the energy use and GHG emissions for the generation and use of electricity as a transportation fuel. Figure 1 below shows the discrete components that form the electricity pathway. The original Argonne model uses a national average resource mix for electricity generation. The resource mix used here is however a California average electricity mix (resources are consistent with the mix of power consumed in California in 2005[4]). Figure 2 provides the 2005 resource mix for California average electricity used in this document. Also provided is a WTW analysis for California marginal mix which is assumed to be natural gas combusted in combined cycle turbines and renewables.

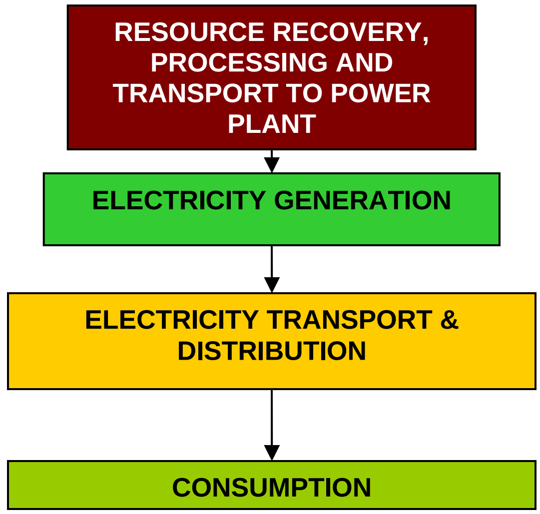
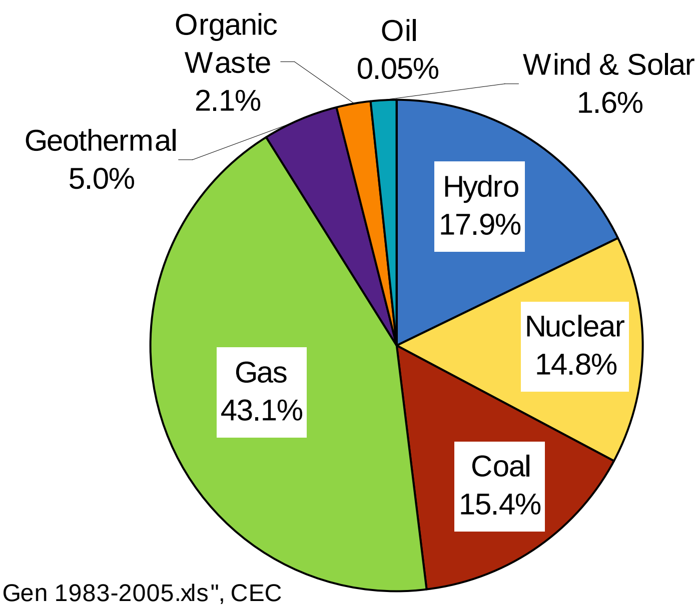


Figure 1. Discrete Components of the Electricity Pathway



"Electricity Gen 1983-2005.xls", CEC
Imports (22% of total) were asssigned according to "Proposed Methodology to Estimate the Generation Resource Mix of California Electricity imports", CEC 2006.

Figure 2. 2005 Resource Mix of Electricity Consumed in California

Several general descriptions and clarification of terminology used throughout this document are:

- CA-GREET employs a recursive methodology to calculate energy consumption and emissions. To calculate WTT energy and emissions, the values being calculated are often utilized in the calculation. For example, crude oil is used as a process fuel to recover crude oil. The total crude oil recovery energy consumption includes the direct crude oil consumption AND the energy associated with crude recovery (which is the value being calculated).

- Btu/mmBtu is the energy input necessary in Btu to produce or transport one million Btu of a finished (or intermediate) product. This description is used consistently in CA-GREET for all energy calculations. There are 1,055 MJ in one mmBtu of energy, so in order to convert one million Btu into MJ, divide the million Btu by 1055.

- gCO_2e/MJ provides the total greenhouse gas emissions on a CO_2 equivalent basis per unit of energy (MJ) for a given fuel. Methane (CH_4) and nitrous oxide (N_2O) are converted to a CO_2 equivalent basis using IPCC global warming potential values and included in the total.

- CA-GREET assumes that VOC and CO are converted to CO_2 in the atmosphere and includes these pollutants in the total CO_2 value using ratios of the appropriate molecular weights.

- Process Efficiency for any step in CA-GREET is defined as:

$$\text{Efficiency} = \text{energy output} / (\text{energy output} + \text{energy consumed})$$

Table A below provides a summary of the energy use and GHG emissions per MJ of electricity produced. Note that rounding of values has not been performed in several tables in this document. This is to allow stakeholders executing runs with the GREET model to compare actual output values from the CA-modified model with values in this document. Expanded details are provided in Appendix A. A list of input values is provided in Appendix B.

Table A. Total Energy Consumption and GHG Emissions for CA Average Electricity Pathway

	Energy Required (Btu/mmBtu)	**Share of Total Energy Required (%)**	**GHG Emissions (gCO_2e/MJ)**	**Share of Total GHG Emissions (%)**
Residual oil	1,847	0.1%	0.1	0.1%
NG	1,285,219	57%	76.2	61.5%
Coal	501,302	22%	47.1	38.0%
Biomass	38,509	2%	0.2	0.1%
Nuclear	168,513	7%	0.4	0.3%
Other	278,020	12%	0	0.0%
Energy Produced	-1,000,000			
Total Well to Tank	**1,273,410**	**100%**	**124.10**	**100.0%**
Carbon in Fuel	0	0.0%	0	0.0%
Vehicle CH_4 and N_2O	0	0.0%	0	0.0%
Total Tank to Wheel	**0**	**0.0%**	**0**	**0.0%**
Total Well to Wheel	**1,273,410**	**100%**	**124.10**	**100.0%**

Note: **For the marginal case**, the WTW emissions are **104.71 gCO_2e/MJ** and details are provided in Appendix A. Electricity generation in the future is likely to use higher renewables in the electricity mix (up to 33%) for marginal electricity and staff will address the use of higher renewables when updates are considered for this pathway.

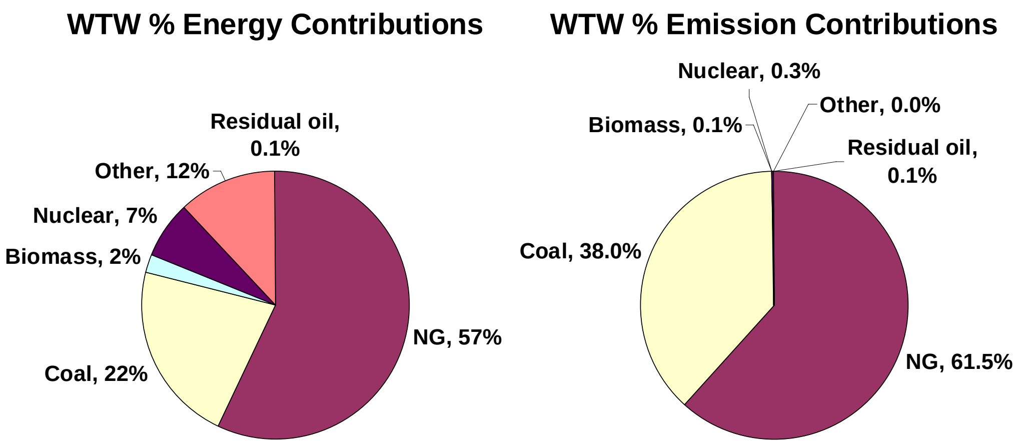


Figure 3. Percent Energy Contribution and Emissions Contribution from WTW for California Average Electricity

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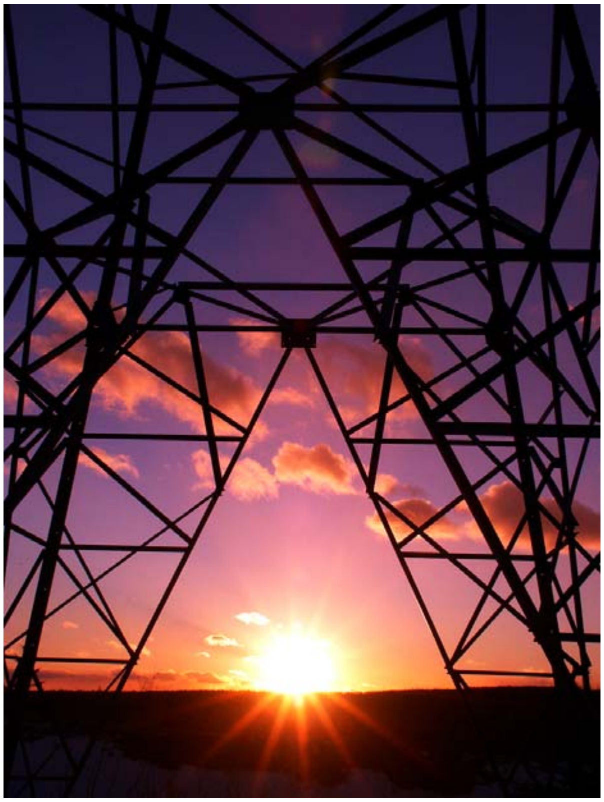
APPENDIX A

SECTION 1. DETAILS OF THE CALIFORNIA AVERAGE ELECTRICITY PATHWAY



1.1 Detailed Energy Consumption for the CA Average Electricity Pathway WTT

The first step in the electricity pathway is to determine direct fuel use at the electric power plants. Table 1.01 indicates how the different fuels are split by equipment type and the assumed unit efficiency (LHV basis) for each plant/fuel type combination. The weighted average efficiency for each fuel is shown in the last column. All power plant efficiencies shown are GREET defaults except slight adjustment to the natural gas combustion turbine efficiencies as follows:

- Simple Cycle Turbines: GREET default is 33.1% (LHV basis), the CA modified model uses 31.5%
- Combined Cycle Turbine: GREET default is 53% (LHV basis), the CA modified model uses 51.8%

Table 1.01 Power Plant Shares and Assumed Efficiencies for Each Power Plant Fuel Type

<table>
<tr><th>Process Fuel Type</th><th>Power Plant Type</th><th>Plant Type Shares</th><th>Plant Efficiency (LHV)</th><th>Average Efficiency for Fuel (LHV)</th></tr>
<tr><td>Residual Oil</td><td>Boiler</td><td>100%</td><td>34.8%</td><td>34.8%</td></tr>
<tr><td rowspan="3">Natural Gas</td><td>Boiler</td><td>20%</td><td>34.8%</td><td rowspan="3">39.0%</td></tr>
<tr><td>Simple Cycle Turbine</td><td>36%</td><td>31.5%</td></tr>
<tr><td>Combined Cycle Turbine</td><td>44%</td><td>51.8%</td></tr>
<tr><td>Coal</td><td>Boiler</td><td>100%</td><td>34.1%</td><td>34.1%</td></tr>
<tr><td>Biomass</td><td>Boiler</td><td>100%</td><td>32.1%</td><td>32.1%</td></tr>
<tr><td>Nuclear</td><td></td><td></td><td>100%</td><td>100%</td></tr>
<tr><td>Other</td><td></td><td></td><td>100%</td><td>100%</td></tr>
</table>

The intent of the California Average case is to reflect the resource mix of electricity consumed in California in 2005[4]. Table 1.02 illustrates how CA-GREET directly utilizes these splits (shown in Fig. 2), the average power plant efficiency, and the transmission and distribution loss factor to calculate direct power plant fuel consumption. Note that 1,000,000 Btu/mmBtu electricity of the fuel consumed becomes electricity, so this is subtracted from the total direct energy use to arrive at a net direct energy use.

Table 1.02 Calculation of Direct Energy Consumption (Btu/mmBtu) to Produce Electricity

Process Fuel Type	MWh Shares	Avg Eff. (LHV)	Calculation of Direct Energy Use per MJ Composite Electricity Produced	Direct Energy Use, Btu/mmBtu
Residual Oil	0.05%	34.8%	10^6 Btu/mmBtu/ (0.348) / (1-.081) * 0.0005	1,563
Natural Gas	43.1%	38.9%	10^6 Btu/mmBtu/ (0.39) / (1-.081) * 0.431	1,203,888
Coal	15.4%	34.1%	10^6 Btu/mmBtu/ (0.341) / (1-.081) * 0.154	491,418
Biomass	1.1%	32.1%	10^6 Btu/mmBtu/ (0.321) / (1-.081) * 0.011	37,288
Nuclear	14.8%	100%	10^6 Btu/mmBtu/ (1) / (1-.081) * 0.148	161,045
Other	25.5%	100%	10^6 Btu/mmBtu/ (1) / (1-.081) * 0.255	278,020
TOTAL DIRECT ENERGY USE				**2,173,222**
NET DIRECT ENERGY USE (less 1 mmBtu electricity produced)				**1,173,222**

Note: Other = hydro, wind, solar, geothermal and assumed Transmission Loss is 8.1%

The values provided in Table 1.02 are direct energy consumption per Btu of electricity produced. This is not the total energy required however, since CA-GREET also accounts for the "upstream" energy associated with each of the fuels utilized. For example, 1,563 Btu of residual oil are utilized to produce electricity. The total energy associated with the 1,563 Btu of residual oil includes the energy to recover the crude and refine it to residual oil. Table 1.03 demonstrates how the direct energy consumption values shown in Table 1.02 are utilized to calculate total energy required to produce electricity. Actual values used in the equations are shown in Table 1.04.

From Tables 1.02 and 1.03, the total energy to produce 1 mmBtu of electricity at the wall outlet is the sum of direct energy and upstream energy: **Total Energy = 1,173,222 Btu/mmBtu + 100,188 Btu/mmBtu = 1,273,410 Btu/mmBtu.** For each of the process fuel types, the total for each type is the sum of their respective contributions from Tables 1.02 and 1.03.

Table 1.03 Calculation of Upstream Energy Consumption from Direct Energy Consumption

Fuel Type	Formula	Btu/mmBtu
Residual Oil	A * (B*C + D)/ 10^6	284
Natural Gas	E * F / 10^6	81,331
Coal	G * H / 10^6	9,884
Biomass	I * (J) / K	1,220
Nuclear	L * M / N /1000/3412	7,469
Total		**100,188**

Note: There are 1,000 kWh/MWh and 3,412 Btu/kWh.

Table 1.04 Values used in Table 1.03 above

Factor	Value	Description	Source
A	1,563	Btu of direct residual oil used per mmBtu electricity produced.	CA-GREET calculation
B	105,647	Btu required to recover 1 mmBtu crude for US refineries.	CA-GREET calculation
C	1.0000	Loss factor for residual oil.	CA-GREET default
D	75,825	Btus are required to refine and transport 1 mmBtu residual oil.	CA-GREET calculation
E	1,203,888	Btu of direct NG used per mmBtu electricity produced.	CA-GREET calculation
F	67,557	The energy to recover, process and transport 1 mmBtu North American NG	CA-GREET calculation
G	491,418	Btu of direct coal use to produce 1 mmBtu electricity.	CA-GREET calculation
H	20,113	The energy to mine, clean and transport coal to the power plant	CA-GREET calculation
I	37,288	Btu of direct woody biomass use per mmBtu electricity produced.	CA-GREET calculation
J	550,200	Energy associated with tree farming, fertilizer application, pesticide application and tree transport in Btu/ton trees	CA-GREET default
K	16,811,000	LHV of trees is 16,811,000 Btu/ton trees.	CA-GREET default
L	161,045	Btu of nuclear energy used per mmBtu electricity produced.	CA-GREET calculation
M	1,095,963	To produce 1 g of U-235, this many Btu are required.	CA-GREET calculation
N	6.926	MWh of electricity produced per g U-235.	CA-GREET default

1.2 Detailed GHG Emissions for the CA Average Electricity Pathway WTT

The GHG emissions for this pathway consist of the emissions associated with generating electricity and the upstream emissions associated with producing and transporting each fuel to the power plant. The specific emission factors utilized here are presented in Table 1.05. All emission factors utilized are GREET defaults with the following exceptions which are from U.S. EPA Emissions Factors AP-42[5]:

- Coal fired Utility Boiler N_2O – default value is 1.06. Value utilized is 0.57
- Biomass Utility Boiler N_2O – default value is 11. Value utilized is 6.21
- Biomass Utility Boiler CH_4: Default value is 3.83. Value utilized is 10.03
- NG Utility Boiler N_2O: Default value is 1.10. Value utilized is 0.36
- CO_2 Emission factor for biomass fired boilers is set to zero[1].

Table 1.05 Emission Factors for Electricity Generation, g/MMBtu (LHV)

	Residual Oil	**Natural Gas**	**Natural Gas**	**Natural Gas**	**Coal**	**Biomass**
	Utility Boiler	Utility Boiler	Simple Cycle Turbine	Combined Cycle Turbine	Utility Boiler	Utility Boiler
VOC	2.023	1.557	1.000	3.429	1.140	5.341
CO	15.764	16.419	24.000	24.000	100.000	76.800
CH_4	0.910	1.100	4.260	4.260	1.200	10.030
N_2O	0.360	0.315	1.500	1.500	0.570	6.210
CO_2	85,048	58,198	58,179	58,171	96,299	0

These emission factors are subsequently converted to an output basis (g/kWh) as follows:

$$\text{Emission factor g/kWh} = \text{g/MMBtu} / \text{efficiency} / 10^6 \text{ Btu/MMBtu} * 3{,}412 \text{ Btu/kWh}$$

Table 1.06 provides the output based emission factors by fuel type; for natural gas, the weighted average emission factor for each of the combustion device types is shown.

[1] In the electric worksheet in GREET1.8b, the biomass direct CO2 emissions are not set to zero (in other sections of the worksheet, the biomass CO2 emissions are added and subtracted from the composite CO2 values).

Table 1.06 Emission Factors for Electricity Generation, Average for Fuel Type, g/kWh (LHV)

	Residual Oil	**Natural Gas**	**Coal**	**Biomass**
	Utility Boiler	Weighted Avg of Boiler, SCCT, CCCT	Utility Boiler	Utility Boiler
VOC	0.0198	0.0169	0.0114	0.057
CO	0.1546	0.1953	1.0006	0.816
CH_4	0.0089	0.0311	0.012	0.107
N_2O	0.0035	0.0108	0.006	0.066
CO_2	834	510	964	0

The last step is to multiply the output based emission factors by the specified fuel share and then divide by (100-8.1) to account for the 8.1% transmission loss (default). These values are subsequently multiplied by 1,000,000 and divided by 3,412 to convert back to g/MMBtu at the wall outlet. The final direct emissions are provided in Table 1.07. There are no direct emissions for nuclear power or the “other” non-combustible power categories.

Table 1.07 Direct Emissions for Electricity Production, g/mmBtu at Wall Outlet

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**GHG**	**GHG gCO_2e/MJ**
Residual Oil	0.0032	0.0246	0.0014	0.0006	133	133.217	0.127
Natural Gas	2.32	26.85	4.28	1.49	70,043	70,642	66.96
Coal	0.56	49.142	0.59	0.2801	47,323	47,500	45.024
Biomass	0.199	2.86	0.374	0.232	0	83.48	0.079
Total	**3.08**	**78.88**	**5.24**	**2.00**	**117,499**	**118,359**	**112**

The emissions associated with recovering, processing, and transporting the electricity generating fuels to the power plants are the “upstream” emissions. These are calculated from the direct energy consumption values shown in Table 1.02. Table 1.08 illustrates the upstream calculations for CO_2 with Table 1.09 providing the values for entries in Table 1.08. Table 1.10 provides the upstream emissions for each pollutant and fuel type.

Table 1.08 Calculation of Upstream CO_2 Emissions from Direct Energy Consumption

Fuel Type	**Formula**	**gCO_2/mmBtu**
Residual Oil	$A^* (B+ C)/ 10^6$	20
Natural gas	$D * E /10^6$	6,019
Coal	$F * G / 10^6$	736
Biomass	H * I / J	90
Nuclear	K * L / M / 1000 / 3412	425
Total		**7,289**

Table 1.09 Values used in Table 1.08

Factor	**Value**	**Description**	**Source**
A	1,563	Btu of direct residual oil used per mmBtu electricity produced	CA-GREET calculation
B	7,302	The crude recovery and transport CO_2 emissions in g/mmBtu	CA-GREET calculation
C	5,299	The CO_2 emissions from producing and transporting residual oil in g/mmBtu	CA-GREET calculation
D	1,203,888	Btu of direct NG fuel used per mmBtu electricity produced	CA-GREET calculation
E	4,999	Total CO_2 emissions to recover, process and transport NG is g/mmBtu	CA-GREET calculation
F	491,418	Btu of direct coal used per mmBtu electricity produced	CA-GREET calculation
G	1,499	Total CO_2 emissions to recover, clean and transport coal in g/mmBtu.	CA-GREET calculation
H	37,288	Btus of direct biomass use per mmBtu electricity produced.	CA-GREET calculation
I	40,383	Total CO_2 emissions associated with tree farming, fertilizer application, pesticide application and tree transport in /ton trees.	CA-GREET calculation
J	16,811,000	LHV of trees in Btu/ton trees	CA-GREET default
K	161,045	Btu of nuclear energy used per mmBtu electricity produced.	CA-GREET calculation
L	62,325	gCO_2 emitted per g U-235 produced	CA-GREET calculation
M	6.926	MWh of electricity produced per g U-235	CA-GREET default

Table 1.10 Upstream Emissions for Electricity Production, g/mmBtu at Wall Outlet (by fuel)

	VOC	CO	CH_4	N_2O	CO_2	GHG	GHG gCO_2e /MJ
Residual Oil	0.0147	0.045	0.167	0.0003	19.70	24.14	0.023
Natural Gas	7.42	13.52	145.44	0.0754	6018.80	9721.67	9.215
Coal	3.85	1.91	58.88	0.0161	736.49	2228.33	2.1122
Biomass	0.08	0.29	0.11	0.039	89.57	104.70	0.099
Nuclear	0.24	1.669	0.85	0.0073	424.73	451.7	0.4282
Total	**11.61**	**17.44**	**205.46**	**0.14**	**72,89.31**	**12530.56**	**11.87**

Finally, Table 1.11 combines the direct and upstream emissions, converts CO and VOC to CO_2, and calculates total GHG emissions for this pathway.

Table 1.11 Total GHG Emissions for Electricity Production, g/mmBtu at Wall Outlet (by fuel)

	VOC	CO	CH_4	N_2O	CO_2	GHG	GHG gCO_2e/MJ
Residual Oil	0.02	0.07	0.17	0.0008	152.66	157	0.15
Natural Gas	9.746	40.37	149.72	1.56	76,061.7	80,364	76.17
Coal	4.412	51.05	59.47	0.29	48,059	49,729	47.1
Biomass	0.28	3.15	0.4865	0.27	89.57	188	0.18
Nuclear	0.24	1.67	0.85	0.007	424.7	452	0.429
Total	**14.7**	**96.32**	**210.70**	**2.13**	**124,788.3**	**130,890**	**124.06**

1.3 TTW Portion from Vehicle

For electric vehicles, the tailpipe emissions are zero, so the entire fuel cycle emissions would be:

Total WTW = WTT + Vehicle = 124.1 + 0 = 124.1 gCO_2e/MJ

SECTION 2. DETAILS OF THE CALIFORNIA MARGINAL ELECTRICITY PATHWAY

2.1 Detailed Energy Consumption for the CA Marginal Electricity Pathway WTT

The first step in the electricity pathway is to determine direct fuel use at the electric power plants. Table 2.01 indicates how the different fuels are split by equipment type and the assumed unit efficiency (LHV basis) for each plant/fuel type combination. The weighted average efficiency for each fuel is shown in the last column. All power plant efficiencies shown are GREET defaults except slight adjustment to the natural gas combustion turbine efficiencies as follows:

- Simple Cycle Turbines: GREET default is 33.1% (LHV basis), the CA modified model uses 31.5%
- Combined Cycle Turbine: GREET default is 53% (LHV basis), the CA modified model uses 51.8%

Table 2.01 Power Plant Shares and Assumed Efficiencies for Each Fuel Type

Process Fuel Type	Power Plant Type	Plant Type Shares	Plant Efficiency (LHV)	Average Efficiency for Fuel (LHV)
Natural Gas	Boiler	20%	34.8%	39.0%
	Simple Cycle Turbine	36%	31.5%	
	Combined Cycle Turbine	44%	51.8%	

The intent of the California Marginal case is to reflect the marginal resource mix of electricity consumed in California. This is assumed to be natural gas combusted in combined cycle combustion turbines (CCCTs) and renewables. Table 2.02 illustrates how CA-GREET directly utilizes these splits (shown in Fig. 2), the average power plant efficiency, and the transmission & distribution loss factor to calculate direct power plant fuel consumption. Note that 1,000,000 Btu/mmBtu electricity of the fuel consumed becomes electricity, so this is subtracted from the total direct energy use to arrive at a net direct energy use.

Table 2.02 Calculation of Direct Energy Consumption (Btu/mmBtu) to Produce Electricity

Process Fuel Type	MWh Shares	Avg Eff (LHV)	Calculation of Direct Energy Use per MJ Composite Electricity Produced	Direct Energy Use, Btu/mmBtu
Natural Gas	43.1%	38.9%	10^6 Btu/mmBtu/ (0.389) / (1-.081) * 0.431	1,653,215
Other				231,774
TOTAL DIRECT ENERGY USE				**1,884,989**
NET DIRECT ENERGY USE (less 1 mmBtu electricity produced)				**884,989**

Note: Other = hydro, wind, solar, geothermal and assumed Transmission Loss is 8.1%

The values provided in Table 2.02 are direct energy consumption per Btu of electricity produced. This is not the total energy required however, since CA-GREET also accounts for the "upstream" energy associated with each of the fuels utilized. Table 2.03 demonstrates how the direct energy consumption values shown in Table 2.02 are utilized to calculate total energy required to produce electricity. Actual values used in the formulae are shown in Table 2.04.

From Tables 2.02 and 2.03, the total energy to produce 1 mmBtu of electricity at the wall outlet is the sum of direct energy and upstream energy: **Total Energy = 884,989 Btu/mmBtu + 111,058 Btu/mmBtu = 996,047 Btu/mmBtu**.

Table 2.03 Calculation of Upstream Energy Consumption from Direct Energy Consumption

Fuel Type	Formula	Btu/mmBtu
Natural Gas	$E * F / 10^6$	111,058

Note: There are 1,000 kWh/MWh and 3,412 Btu/kWh.

Table 2.04 Values used in Table 1.03 above

Factor	Value	Description	Source
E	1,653,215	Btu of direct NG used per mmBtu electricity produced.	CA-GREET calculation
F	67,177	The energy to recover, process and transport 1 mmBtu North American NG	CA-GREET calculation

2.2 Detailed WTT GHG Emissions for the CA Marginal Electricity Pathway

The GHG emissions for this pathway consist of the emissions associated with generating electricity in NG CCCTs and the upstream emissions associated with producing and transporting natural gas to the power plant. The specific emission factors utilized here are presented in Table 2.05. All emission factors utilized are GREET defaults.

Table 2.05 Emission Factors for Electricity Generation, g/mmBtu (LHV)

	Natural Gas
	Combined Cycle Turbine
VOC	3.43
CO	24
CH_4	4.26
N_2O	1.50
CO_2	58,171

These emission factors are subsequently converted to an output basis (g/kWh) as follows:

Emission factor g/kWh = g/mmBtu / efficiency / 10^6 Btu/mmBtu * 3,412 Btu/kWh

Table 2.06 provides the output based emission factors by fuel type; for natural gas, the weighted average emission factor for each of the combustion device types is shown.

Table 2.06 Emission Factors for Electricity Generation, Average for Fuel Type, g/kWh (LHV)

	Natural Gas
	CCCT
VOC	0.0178
CO	0.1244
CH_4	0.0221
N_2O	0.0078
CO_2	302

The last step is to multiply the output based emission factors by the specified fuel share and then divide by (100-8.1) to account for the 8.1% transmission loss (default). These values are subsequently multiplied by 1,000,000 and divided by 3,412 to convert back to g/MMBtu at the wall outlet. The final direct emissions are provided in Table 1.07. There are no direct emissions for nuclear power or the "other" non-combustible power categories.

Table 2.07 Direct Emissions for Electricity Production, g/mmBtu at Wall Outlet

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**GHG**	**GHG gCO_2e/MJ**
Natural Gas	5.67	39.68	7.04	2.48	96,170	97,164	92.1

The emissions associated with recovering, processing, and transporting the electricity generating fuels to the power plants are the "upstream" emissions. These are calculated from the direct energy consumption values shown in Table 2.02. Table 2.08 illustrates the upstream calculations for CO_2 while Table 2.09 provides the values for entries in Table 2.08. Table 2.10 provides the upstream emissions for each pollutant and fuel type.

Table 2.08 Calculation of Upstream CO_2 Emissions from Direct Energy Consumption

Fuel Type	Formula	gCO_2/mmBtu
Natural gas	A * B /10^6	8,217

Table 2.09 Values used in Table 2.08

Factor	Value	Description	Source
A	1,653,219	Btu of direct NG fuel used per mmBtu electricity produced	CA-GREET calculation
B	4,970	Total CO_2 emissions to recover, process and transport NG is g/mmBtu	CA-GREET calculation

Table 2.10 Upstream Emissions for Electricity Production, g/mmBtu at Wall Outlet

	VOC	CO	CH_4	N_2O	CO_2	GHG	GHG gCO_2e /MJ
Natural Gas	10.19	18.478	199.72	0.10	8217.28	13302.36	12.61

Finally, Table 2.11 combines the direct and upstream emissions, converts CO and VOC to CO_2, and calculates total GHG emissions for this pathway.

Table 2.11 Total GHG Emissions for Electricity Production, g/mmBtu at Wall Outlet

	VOC	CO	CH_4	N_2O	CO_2	GHG	GHG gCO_2e/MJ
Natural Gas	15.86	58.15	206.76	2.58	104386.95	110,467	104.71

2.3 TTW Portion from Vehicle

For electric vehicles, the tailpipe emissions are zero, so the entire fuel cycle emissions would be:

Total WTW = 104.7 + Vehicle = 104.7 + 0 = 104.7 gCO_2e/MJ

SECTION 3. ENERGY USE AND GHG EMISSIONS FROM FEEDSTOCK RECOVERY, PROCESSING AND TRANSPORT FOR CALIFORNIA AVERAGE ELECTRICITY GENERATION PATHWAY

The California Electricity pathways utilize five feedstocks for electricity production: **residual oil, natural gas, coal, biomass and uranium**. The total upstream contribution to WTT energy and emissions is less than 10 percent. The majority of the upstream emissions are attributable to recovery, processing and transport of natural gas and coal to the power plants. Figure 4 indicates the relative contribution of each upstream component to total GHG emissions.

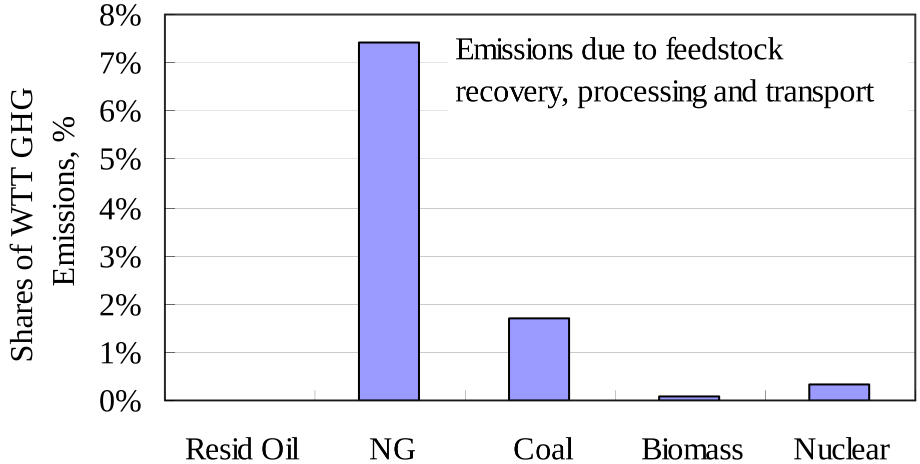


Figure 4. Contribution of Recovery, Processing and Transport of Electricity Feedstocks to the California Average Electricity Pathway Total GHGs

Table 3.01 provides a summary of the feedstock energy and GHG emissions values calculated by CA-GREET that are used to estimate upstream energy and emissions for the California Average electricity pathway.

Table 3.01 Upstream Energy and CO_2 Emissions for California Average Electricity

	Upstream Energy Btu/mmBtu		Upstream gCO_2/mmBtu	
Residual Oil: Crude Recovery and Transport	105,647	"B" in Tables 1.03 and 1.04	7,302	"B" in Tables 1.08 and 1.09
Residual Oil: Refining and Transport	75,825	"D" in Tables 1.03 and 1.04	5,299	"C" in Tables 1.08 and 1.09
Natural Gas	67,557	"F" in Tables 1.03 and 1.04	4,999	"E" in Tables 1.08 and 1.09
Coal	20,113	"H" in Tables 1.03 and 1.04	1,499	"G" in Tables 1.08 and 1.09
Biomass	550,200 Btu/ton	"J" in Tables 1.03 and 1.04	40,383 g/ton	"I" in Tables 1.08 and 1.09
Nuclear	1,095,963	"M" in Tables 1.03 and 1.04	62,325 g/g U-235	"L" in Tables 1.08 and 1.09

The detailed derivation of the values for each feedstock in Table 3.01 is lengthy. In this document, we provide a derivation of the coal and nuclear feedstock values only. We refer the reader to companion documents for the remaining feedstocks (residual oil, biomass and natural gas) with the following comments:

Residual Oil

The GHG emissions attributed to crude recovery, transport and refining to residual oil for use as an electricity feedstock account for 0.02% of total WTT GHG emissions for the CA Average Electricity Pathway. The CARBOB Pathway document describes the calculation methodology and resulting values for residual oil. The values shown in the CARBOB document will be slightly different however since the underlying assumption here is US average crude oil while the CARBOB analysis assumes crude utilized in California.

Natural Gas

The GHG emissions attributed to natural gas recovery, processing and transport for use as an electricity feedstock account for 7.4% of total WTT GHG emissions for the CA Average Electricity Pathway. The CNG Pathway document describes the calculation methodology and resulting values for natural gas. The values shown in the CNG document are slightly different than in this document because pipeline transport distance assumptions are slightly different and the electricity generation mix for the CNG pathway is CA Marginal rather than CA Average.

Biomass
The GHG emissions attributed to natural gas recovery, processing and transport for use as an electricity feedstock account for less than 0.1% of total WTT GHG emissions for the CA Average Electricity Pathway. The biomass fuel assumed here for electricity production is Farmed Trees. Staff has published a document for cellulosic ethanol from Farmed Trees which has details of Farmed Trees cultivation. It should also be mentioned that in California, farmed trees are not utilized for biomass electricity production. The biomass utilized in California for electricity production is generally waste biomass such as agricultural waste, forest residue and sawdust. As a result, the energy and emissions associated with biomass feedstock preparation are overstated here – the energy and emissions associated with farm chemical use (fertilizers, pesticides and herbicides) should be removed. While farm chemical use only contributes a small fraction to total energy, about 20% of the GHG emissions are N_2O assumed emitted subsequent to nitrogen fertilizer application.

The following sections provide detailed descriptions of the calculations to estimate energy and emissions associated with recovery, processing and delivery of the two remaining electricity feedstocks not documented elsewhere: coal and uranium.

3.1 Coal

The energy and emissions associated with coal may be divided into two main activities: coal mining and coal transport. Table 3.02 provides a summary of the energy and emissions for supplying coal as a feedstock to electric power plants. Note that the values for total energy and total CO_2 emissions shown in Table 3.02 are the same as those indicated in Table 3.01.

Table 3.02 Summary of the Coal Feedstock for Electricity Production Pathway

	Energy Use Btu/mmBtu	**CO_2* Emissions gCO_2/mmBtu**	**GHG Emissions gCO_2e/MJ**
Mining	4,120	273	3.06
Transport	15,993	1225	1.21
Pathway Total	**20,113**	**1,499**	**4.27**

* Includes CO_2 equivalent VOC and CO emissions

3.1.1 Coal Mining Energy

As per standard CA-GREET methodology, the energy consumed in coal mining is set by specifying process efficiency and fuel shares. The process efficiency assumed in the AB1007 analysis is 99.78%, higher than the GREET default value of 99.3%. The AB1007 fuel shares are also significantly different; the GREET Default values had much higher diesel and much lower electric shares than those utilized for AB1007. The AB1007 data is based on more recent information from EIA and the U.S. Census Bureau. Please refer to Section 3 of the AB1007 WTT report for details.

Table 3.03 Calculating Direct Energy Consumption for Coal Mining Operations

Fuel Type	Fuel Shares	Calculating Direct Fuel Consumption from Efficiency (0.9978) and Fuel Shares	Direct Fuel Consumption Btu/mmBtu Residual Oil
Residual Oil	14%	(1,000,000)(1/0.9978 – 1)(0.14)	309
Diesel	9%	(1,000,000)(1/0.9978 – 1) (0.09)	198
Gasoline	2%	(1,000,000)(1/0.9978 – 1) (0.02)	44
Natural Gas	2%	(1,000,000)(1/0.9978 – 1) (0.02)	44
Coal	9%	(1,000,000)(1/0.9978 – 1) (0.09)	198
Electricity	64%	(1,000,000)(1/0.9978 – 1)(0.64)	1,411
Total Direct Energy Consumption for Coal Mining			**2,205**

The values in Table 3.03 only represent the direct fuel consumption. We need to account for the energy consumed to recovery and produce these process fuels, the upstream energy. Table 3.04 illustrates the equations used to determine total fuel consumption for crude refining to residual oil. Table 3.05 details the values and descriptions for the formulas presented in Table 3.04.

Table 3.04 Calculation of Total Fuel Consumption from Direct Fuel Consumption

Fuel Type	Formula	Btu/mmBtu
Residual Oil	$309*(1 + (A*B+C)/10^6)$	365
Diesel	$198*(1 + (A*D+E)/10^6)$	244
Gasoline	$44*(1 + (A*F+G)/10^6)$	56
Natural Gas	$44*(1 + H/ 10^6)$	47
Coal	$198*(1+I/ 10^6)$	199
Electricity	$2205*(J + K)/ 10^6)$	3,208
Total (direct + upstream) energy for coal mining		**4,120**

Table 3.05 Details for Entries in Table 2.30

Quantity	Description
A = 105,647	Energy required to produce and transport crude as feedstock for use in US refineries, a CA-GREET calculated value.
B = 1.000	Residual Oil Loss factor, a CA-GREET default.
C = 75,825	Energy (Btu/mmBtu of residual oil) to refine and transport residual oil, a CA-GREET calculated value.
D = 1.000	Diesel Loss Factor, a CA-GREET default.
E = 126,258	Energy (Btu/mmBtu of diesel) to refine and transport diesel, a CA-GREET calculated value.
F = 1.001	Conventional gasoline loss factor, a CA-GREET default
G = 166,069	Energy (Btu/mmBtu of gasoline) to refine and transport gasoline, a CA-GREET calculated value.
H = 69,323	Energy (Btu/mmBtu of natural gas) required to recover, process and transport natural gas as a stationary fuel, a CA-GREET calculated value.
I = 4,120	Energy (Btu/mmBtu of coal) required to recover, process and transport coal as a stationary fuel, a CA-GREET calculated value. This is an example of a CA-GREET iterative calculation.
J = 100,188	Total energy (Btu/mmBtu of electricity) required to recover, process and transport all feedstocks used to generation electricity, a CA-GREET calculated value.
K = 2,173,222	Energy required in Btu to produce one million Btu of electricity, a CA-GREET calculated value.

3.1.2 Coal Mining Emissions

The coal mining emissions are calculated from direct fuel use. The fuel is assumed split among different combustion devices as shown in Table 3.06. Table 3.07 provides direct emissions (direct fuel splits multiplied by CA-GREET default emission factors). Table 3.08 provides the upstream emissions associated with recovery, processing and transport of the direct fuel consumed. Finally, Table 3.09 summarizes total emissions associated with coal mining.

Table 3.06 Coal Mining Direct Fuel Consumption Splits

	Industrial Boiler	Commercial Boiler	Engine	Turbine
Residual Oil		100%		
Diesel		33%	33%	34%
Gasoline			100%	
Natural Gas		50%	50%	
Coal	100%			

Table 3.07 Direct Emissions for Coal Mining, g/mmBtu

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**
Residual Oil	0.0003	0.0049	0.0005	0.0001	26.2530
Diesel	0.0056	0.0254	0.0006	0.0003	15.4585
Gasoline	0.0783	0.5768	0.0043	0.0001	2.2260
Natural Gas	0.0010	0.0082	0.0082	0.0000	2.5295
Coal	0.0004	0.0151	0.0008	0.0001	19.1146
Electricity	0.0000	0.0000	0.0000	0.0000	0.0000
Non-combustion	6.9017		117.9286		
Total	**6.98**	**0.63**	**117.94**	**0.0007**	**65.58**

Table 3.08 Upstream Emissions for Coal Mining, g/mmBtu

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**
Residual Oil	0.0029	0.0099	0.0334	0.0001	3.8896
Diesel	0.0021	0.0066	0.0221	0.0000	3.1990
Gasoline	0.0013	0.0015	0.0050	0.0000	0.8240
Natural Gas	0.0003	0.0005	0.0057	0.0000	0.2241
Coal	0.0014	0.0002	0.0235	0.0000	0.0001
Electricity	0.0207	0.1359	0.2973	0.0030	176.3676
Non-combustion					
Total	**0.03**	**0.15**	**0.38**	**0.0031**	**184.50**

Table 3.09 Total GHG Emissions for Coal Mining, g/mmBtu

	VOC	CO	CH_4	N_2O	CO_2	GHG	GHG, g/MJf
Residual Oil	0.0032	0.0147	0.0339	0.0002	30.1426	31.0732	0.0295
Diesel	0.0077	0.0320	0.0227	0.0003	18.6574	19.3977	0.0184
Gasoline	0.0796	0.5783	0.0093	0.0001	3.0500	4.4752	0.0042
Natural Gas	0.0012	0.0087	0.0138	0.0000	2.7537	3.1299	0.0030
Coal	0.0018	0.0153	0.0243	0.0001	19.1148	19.7852	0.0188
Electricity	0.0207	0.1359	0.2973	0.0030	176.3676	184.9774	0.1753
Non-combustion	6.9017	0.0000	117.9286	0.0000	0.0000	2969.7261	2.8149
Total	**7.01**	**0.79**	**118.33**	**0.0038**	**250.09**	**3,232.56**	**3.06**

The energy and emissions associated with coal transport are based on assumptions of mode share and miles. Table 3.10 provides the default CA-GREET mode shares and miles for coal transport to power plants.

Table 3.10 Coal Transport Modes, Miles and Fuels

	Mode Share	Miles	Actual Miles	Fuel
Truck	100%	50	50	Diesel
Rail	100%	440	440	Diesel

3.1.3 Coal Transport Energy

Table 3.11 illustrates the energy calculations and Table 3.12 provides the values for the equations in Table 3.11.

Table 3.11 Details of Energy Consumed for Coal Transport

	Detailed Calculations	Btu/mmBtu
Truck	(Energy Intensity)*(miles)*(1+WTT of diesel)/(LHV of coal)*10^6	3,837
Rail	(Energy Intensity)*(miles)*(1+WTT of diesel)/(LHV of coal)*10^6	12,157
Total		**15,993**

Table 3.12 Values for Formulas in Table 3.11

Description	Value	Source
Truck miles	50	CA-GREET default
Rail transport miles	440	CA-GREET default
Lower heating value (LHV) of coal (Btu/ton)	16,497,700	CA-GREET default
Truck energy intensity (Btu/ton-mile)	1,028	CA-GREET calculation
Rail energy intensity (Btu/ton-mile)	370	CA-GREET calculation
WTT Energy Factor for Diesel, Btu/Btu	0.177	CA-GREET calculation

Note that the total coal energy (mining plus transport) is 20,113 Btu/mmBtu. This is the value used in Table 1.04 to calculate the upstream energy associated with coal use for electricity production.

3.14 Coal Transport GHG Emissions

Table 3.13 provides the emissions associated with transporting coal by rail and barge to the power plants.

Table 3.13 Coal Transport Emissions, g/mmBtu

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**GHG**	**GHG gCO_2e/MJ**
Truck, g/mmBtu	0.1379	0.6598	0.3511	0.0072	292.5332	304.9246	0.2890
Rail, g/mmBtu	0.6937	2.4487	1.1362	0.0218	925.4767	966.3906	0.9160
Total, g/mmBtu	**0.83**	**3.10**	**1.48**	**0.029**	**1218**	**1271.31**	**1.21**

3.2 Nuclear

The nuclear power plant feedstock is uranium. CA-GREET default values were exclusively utilized throughout. It is assumed that only light water reactors (LWR) are utilized. The pathway may be broken down into five steps:

- Uranium Mining
- Uranium Ore Transport
- Uranium Enrichment
- Uranium Conversion, Fabrication and Waste Storage
- Uranium Fuel Transport

Table 3.14 provides a summary of the energy consumption and emissions of the nuclear pathway.

Table 3.14 Summary of the Nuclear Feedstock for Electricity Production Pathway

	Energy		CO_2* Emissions	GHG Emissions	
	Btu/g U-235	Btu/mmBtu	g/g U-235	gCO_2e/g U235	gCO_2e/mm Btu
Mining	239,913	0.010	15,011	16,037	0.001
Ore Transport	658	0.000	50	52	0.000
Enrichment	764,926	0.032	42,120	44,106	0.002
Enriched Uranium Transport	108	0.000	8	9	0.000
Uranium Conversion	90,274	0.004	5,129	5,576	0.000
Uranium Transport	84	0.000	6	7	0.000
Pathway Total	1,095,963	0.046	62,325	65,788	**0.003**

* Includes CO_2 equivalent VOC and CO emissions

Note that all uranium values are calculated per gram of U-235 produced. To convert to a per mmBtu basis, we divide by 6.926 MWh per gram of U-235. This is converted to mmBtu by multiplying by 3.412 and 10^6:

g/mmBtu = (g/g U-235) / (6.926 MWh/g U-235) / 3412 Btu/kWh / 1000 kWh/MWh

Note that the Uranium Pathway total energy (1,095,281 Btu/g U-235) and total CO_2 emission values (70,340) are the same as the values shown in Tale 2.01.

3.2.1 Uranium Mining Energy Use

The uranium mining energy consumption is set by an assumed energy intensity of 167,452 Btu/g U-235 recovered. The process fuel shares and direct energy consumption are provided in Table 3.15.

Table 3.15 Direct Energy Use in Uranium Mining

Fuel Type	Fuel Shares	Calculating Direct Fuel Consumption	Direct Fuel Consumption Btu/g U-235
Diesel	26.8%	(167,452) * (0.268)	44,877
Gasoline	8.1%	(167,452) * (0.081)	13,564
Natural Gas	39.9%	(167,452) * (0.399)	66,813
Electricity	25.2%	(167,452) * (0.252)	42,198
Total Direct Energy Consumption for Uranium Mining			**167,452**

The values in Table 3.15 only represent the direct fuel consumption. We need to account for the energy consumed to recovery and produce these process fuels, the upstream energy. Table 3.16 illustrates the equations used to determine total fuel consumption for uranium mining. Table 3.17 details the values and descriptions for the equations presented in Table 3.16.

Table 3.16 Calculation of Total Fuel Consumption from Direct Fuel Consumption

Fuel Type	Formula	Btu/g U-235	Btu/mm Btu
Diesel	$44{,}877*(1 + (A*B+C)/10^6)$	55,285	0.002
Gasoline	$13{,}564*(1 + (A*D+E)/10^6)$	17,250	0.001
Natural Gas	$66{,}813*(1 + F/10^6)$	71,445	0.003
Electricity	$42{,}197*(G + H)/10^6)$	95,933	0.004
Total (direct + upstream) energy for uranium mining		**259,913**	**0.010**

Table 3.17 Details for Formulas in Table 3.16

Quantity	Description
A = 105,647	Energy required to produce and transport crude as feedstock for use in US refineries, a CA-GREET calculated value.
B = 1.000	Diesel Loss factor, a CA-GREET default.
C = 126,258	Energy (Btu/mmBtu of diesel) to refine and transport diesel, a CA-GREET calculated value.
D = 1.000	Gasoline Loss Factor, a CA-GREET default.
E = 166,069	Energy (Btu/mmBtu of gasoline) to refine and transport gasoline, a CA-GREET calculated value.
F = 69,323	Energy (Btu/mmBtu of natural gas) required to recover, process and transport natural gas as a stationary fuel, a CA-GREET calculated value.
G = 100,188	Total energy (Btu/mmBtu of electricity) required to recover, process and transport all feedstocks used to generation eletctricity, a CA-GREET calculated value.
H = 2,173,222	Energy required in Btu to produce one million Btu of electricity, a CA-GREET calculated value.

3.2.2 Uranium Mining GHG Emissions

The emissions associated with mining operations are split into direct emissions from direct fuel combustion and upstream emissions associated with recovery and processing of the process fuels. The direct, upstream and total emissions are provided in Tables 3.18 to 3.20.

Table 3.18 Direct Emissions from Uranium Mining, g/g U-235

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**CO_2***	**GHG**
Diesel	1.2729	5.7426	0.1356	0.0659	3495.984	3508.975	3532.007
Gasoline	24.0913	177.4061	1.3314	0.0326	684.6894	1038.554	1081.54
Natural Gas	1.4544	12.4028	12.3618	0.0606	3832.615	3856.638	4183.752
Electricity	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**26.82**	**195.55**	**13.82**	**0.16**	**8013.28**	**8404.16**	**8797.29**

* Includes CO_2 equivalent VOC and CO emissions

Table 3.19 Upstream Emissions from Uranium Mining, g/g U-235

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG
Diesel	0.4756	1.4876	4.9905	0.0094	723.4614	727.2813	854.8474
Gasoline	0.4017	0.4713	1.5431	0.0032	253.4509	255.4434	294.9720
Natural Gas	0.4196	0.7680	8.6058	0.0044	339.5905	342.1050	558.5490
Electricity	0.6203	4.0646	8.8911	0.0902	5274.1246	5282.4451	5531.5938
Total	**1.91**	**6.79**	**24.03**	**0.10**	**6590.62**	**6607.27**	**7239.96**

* Includes CO_2 equivalent VOC and CO emissions

Table 3.20 Total Emissions from Uranium Mining, g/g U-235

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG
Diesel	1.7485	7.2302	5.1260	0.0753	4219.4459	4236.2572	4386.8544
Gasoline	24.4930	177.8773	2.8745	0.0357	938.1402	1293.9981	1376.5120
Natural Gas	1.8740	13.1708	20.9676	0.0650	4172.2063	4198.7439	4742.3016
Electricity	0.6203	4.0646	8.8911	0.0902	5274.1246	5282.4451	5531.5938
Total	**28.73**	**202.34**	**37.85**	**0.26**	**14603.91**	**15011.44**	**16037.26**

* CO_2 includes VOC and CO

3.2.3 Uranium Ore Transport Energy

The uranium ore is transported from the mine to the enrichment facility by truck. The default distance is 1,360 miles. The total energy to transport the ore is calculated with the following formula:

Transport Energy Btu/ton ore = Miles * Energy Intensity (Btu/ton-mile) * (1 + WTT of diesel)

The values for this equation are presented in Table 3.21

Table 3.21 Uranium Ore Transport Energy

Parameter	Value	Reference
Truck miles	1,360	CA-GREET Default
Truck Energy Intensity, Btu/ton-mile	1,028	CA-GREET calculated value
WTT energy of diesel fuel, Btu/Btu	0.232	CA-GREET calculated value
Transport Energy, Btu/ton ore	1,721,638	CA-GREET calculated value
Uranium Yellow Cake to U-235 Conversion Factor	0.29%	CA-GREET Default
Transport Energy, Btu/g U-235	658	CA-GREET calculated value

3.2.4 Uranium Ore Transport GHG Emissions

The emissions associated with truck transport of uranium ore to the enrichment facility are determined as follows:

$$\text{Emissions g/ton ore} = (A + B) * C * D / 10^6$$

where the parameters are described in Table 3.22. Resulting emissions in g/ton ore are converted utilizing the conversion factor indicated in Table 3.23. Table 3.23 provides ore transport emissions on a per g U-235 basis.

Table 3.22 Values of Properties Used to Calculate Ore Transport Emissions

Parameter	Source
A = diesel truck emission factor, g/mmBtu	AB1007 value
B = WTT diesel emissions g/mmBtu	CA-GREET calculation
C = truck transport energy intensity, Btu/ton-mile	CA-GREET calculation
D = transport miles	CA-GREET default

Table 3.23 Total GHG Emissions Uranium Ore Transport to Enrichment Facility, g/g U-235

GHG	(g/g U-235)	Formula to convert to CO_2e	gCO_2e/g U-235
CO_2	50.20	50.20*1	50.20
CH_4	0.06	0.06*25	1.51
N_2O	0.001	0.001*298	0.37
CO	0.113	0.095*0.43*(44/12)	0.18
VOC	0.024	0.028*0.85*(44/12)	0.07
CO_2*	**50.45**		
Total GHG emissions			**52.33**

* Includes CO_2 equivalent VOC and CO emissions

3.2.5 Uranium Enrichment Energy Use

The uranium enrichment energy consumption is set by an assumed (GREET default) energy intensity of 336,466 Btu/g U-235 recovered. It is further assumed that only electricity is used in the enrichment process. This is only the direct fuel consumption. We need to account for the energy consumed to recovery and produce the feedstocks to generate this electricity. The total energy consumption is calculated as follows:

$$\text{Total Energy, Btu/g U-235} = A * (B+C)/10^6$$

The total energy for uranium enrichment is 764,926 Btu/g U-235. Table 3-24 provides the values and descriptions of the parameters in the above formula.

Table 3.24 Details for Total Uranium Enrichment Energy Consumption

Quantity	Description
A = 336,466	Energy (100% electricity) required to enrich uranium, Btu/g U-235
B = 100,188	Total energy (Btu/mmBtu of electricity) required to recover, process and transport all feedstocks used to generation electricity, a CA-GREET calculated value.
C = 2,173,222	Energy required in Btu to produce one million Btu of electricity, a CA-GREET calculated value.

3.2.6 Uranium Enrichment GHG Emissions

Because electricity consumption does not result in any direct emissions, the only emissions associated with enrichment are upstream emissions from production and delivery of electricity feedstocks. Table 3.25 provides the total emissions associated with uranium enrichment.

Table 3.25 Total Emissions from Uranium Enrichment, g/g U-235

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG
Electricity	4.94	32.41	70.89	0.712	42053.42	42119.76	44106.36

* Includes CO_2 equivalent VOC and CO emissions

3.2.7 Energy Use for Uranium Conversion, Fabrication and Waste Storage

The energy and emissions associated with uranium conversion, fabrication and storage of waste are dictated by an assumed process energy intensity and fuel split. The process energy intensity is assumed to be 60,801 Btu/g U-235. Table 3.26 illustrates how the direct energy is split.

Table 3.26 Direct Energy Use in Uranium Conversion Fabrication & Waste Storage

Fuel Type	Fuel Shares	Calculating Direct Fuel Consumption	Direct Fuel Consumption Btu/g U-235
Natural Gas	65.5%	(60,801) * (0.399)	39,825
Electricity	34.5%	(60,801) * (0.252)	20,977
Total Direct Energy Consumption for Uranium Conversion			**60,801**

The values in Table 3.26 only represent the direct fuel consumption. We need to account for the energy consumed to recovery and produce these process fuels, the upstream energy. Table 3.27 illustrates the equations used to determine total fuel consumption for uranium mining. Table 3.28 details the values and descriptions for the parameters presented in Table 3.27.

Table 3.27 Calculation of Total Fuel Consumption from Direct Fuel Consumption

Fuel Type	Formula	Btu/g U-235
Natural Gas	$39{,}825*(1 + A/ 10^6)$	42,586
Electricity	$20{,}977*(B + C)/ 10^6)$	47,688
Total (direct + upstream) energy		**90,274**

Table 3.28 Details for Formulas in Table 2.61

Quantity	Description
A = 69,323	Energy (Btu/mmBtu of natural gas) required to recover, process and transport natural gas as a stationary fuel, a CA-GREET calculated value.
B = 100,188	Total energy (Btu/mmBtu of electricity) required to recover, process and transport all feedstocks used to generation electricity, a CA-GREET calculated value.
C = 2,173,222	Energy required in Btu to produce one million Btu of electricity, a CA-GREET calculated value.

3.2.8 GHG Emissions for Uranium Conversion, Fabrication and Waste Storage

The emissions associated with uranium conversion operations are split into direct emissions from direct fuel combustion and upstream emissions associated with recovery and processing of the process fuels. The direct, upstream and total emissions are provided in Tables 3.29 to 3.31.

Table 3.29 Direct Emissions from Uranium Conversion, Fabrication and Waste Storage, g/g U-235

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG
Natural Gas	0.8669	7.3928	7.3684	0.0361	2284.4806	2298.7998	2493.7802
Electricity	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**0.87**	**7.39**	**7.36**	**0.036**	**2284.48**	**2298.8**	**2493.78**

* Includes CO_2 equivalent VOC and CO emissions

Table 3.30 Upstream Emissions from Uranium Conversion, Fabrication and Waste Storage, g/g U-235

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG
Natural Gas	0.2501	0.4578	5.1296	0.0026	202.4173	203.9162	332.9304
Electricity	0.3084	2.0205	4.4198	0.0448	2621.7587	2625.8949	2749.7463
Total	**0.55**	**2.47**	**9.54**	**0.04**	**2824.17**	**2829.81**	**3082.67**

* Includes CO_2 equivalent VOC and CO emissions

*Table 3.31 Total Emissions from Uranium Conversion, Fabrication and Waste Storage, g/g U-*35

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG
Natural Gas	1.1170	7.8506	12.4980	0.0387	2486.8979	2502.7160	2826.7107
Electricity	0.3084	2.0205	4.4198	0.0448	2621.7587	2625.8949	2749.7463
Total	**1.42**	**9.87**	**16.91**	**0.08**	**5108.65**	**5128.61**	**5576.45**

* Includes CO_2 equivalent VOC and CO emissions

3.2.9 Energy Use for Enriched Uranium and Uranium Fuel Transport

This portion of the pathway calculates transport of enriched uranium to fabrication and uranium fuel to the reactor. Both assume 100% truck transport.

Transport Energy Btu/ton = Miles * Energy Intensity (Btu/ton-mile) * (1 + WTT of diesel)

The values for this equation are presented in Table 3.32.

Table 3.32 Enriched Uranium and Uranium Fuel Transport Energy

Parameter	Value	Reference
Enriched Ore Transport		
Truck miles	920	CA-GREET Default
Truck Energy Intensity, Btu/ton-mile	1,028	CA-GREET calculated value
WTT energy of diesel fuel, Btu/Btu	0.232	CA-GREET calculated value
Transport Energy, Btu/ton	1,164,637	CA-GREET calculated value
Weight conversion factor	1.18%	CA-GREET Default
Transport Energy, Btu/g U-235	108	CA-GREET calculated value
Uranium Fuel Transport		
Truck miles	500	CA-GREET Default
Truck Energy Intensity, Btu/ton-mile	1,028	CA-GREET calculated value
WTT energy of diesel fuel, Btu/Btu	0.232	CA-GREET calculated value
Transport Energy, Btu/ton	632,955	CA-GREET calculated value
Weight conversion to U-235	0.83%	CA-GREET Default
Transport Energy, Btu/g U-235	84	CA-GREET calculated value
Total Fuel Transport, Btu/g U-235	**192**	CA-GREET calculated value

3.3.0 GHG Emissions for Enriched Uranium and Uranium Fuel Transport

The emissions associated with truck transport of enriched ore and fuel are calculated as follows:

$$\text{Emissions g/ton} = (A + B) * C * D / 10^6$$

where the parameters are described in Table 3.33. Resulting emissions in g/ton ore are converted utilizing the conversion factor indicated in Table 3.32. Table 3.34 provides enriched uranium and uranium fuel transport emissions on a per g U-235 basis.

Table 3.33 Values of Properties Used to Calculate Ore Transport Emissions

Parameter	Source
A = diesel truck emission factor, g/mmBtu	AB1007 value
B = WTT diesel emissions g/mmBtu	CA-GREET calculation
C = truck transport energy intensity, Btu/ton-mile	CA-GREET calculation
D = transport miles	CA-GREET default

Table 3.34 Total GHG Enriched Ore and Fuel Transport Emissions , g/g U-235

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG
Ore Transport	0.0039	0.0186	0.0099	0.0002	8.2653	8.3067	8.61
Fuel Transport	0.0030	0.0144	0.0077	0.0002	6.3807	6.4127	6.65
Total	**0.0069**	**0.0330**	**0.0176**	**0.0004**	**14.65**	**14.72**	**15.27**

* Includes CO_2 equivalent VOC and CO emissions

APPENDIX B

INPUT VALUES FOR ELECTRICITY PATHWAY

California Average Electricity Mix

Parameters	**Units**	**Values**	**Note**
GHG Equivalent			
CO_2		1	
CH_4		25	
N_2O		298	
VOC		3.1	
CO		1.6	
Power Plants			
Equipment Shares, Emission Factors, and Efficiency			
Residual Oil fired Power Plant - Boiler		100%	Efficiency 34.8%
CO_2 Emission Factor	gCO_2/mmBtu	85,048	
Natural Gas fired Power Plant			Ave Efficiency of Natural Gas Plant 38.9%
Boiler		20%	Efficiency 34.8%
CO_2 Emission Factor	gCO_2/mmBtu	58,198	
Simple Cycle Turbine		36%	Efficiency 31.8%
CO_2 Emission Factor	gCO_2/mmBtu	58,179	
Combined Cycle Turbine		44%	Efficiency 51.8%
CO_2 Emission Factor	gCO_2/mmBtu	58,171	
Coal fired Power Plant - Boiler		100%	Efficiency 34.1%
CO_2 Emission Factor	gCO_2/mmBtu	96,299	
Biomass fired Power Plant - Boiler		100%	Efficiency 32.1%
CO_2 Emission Factor	gCO_2/mmBtu	102,224	
Nuclear			Efficiency 100%
Other (Hydro, Wind)			Efficiency 100%
Fuel Shares			
Residual Oil		0.05%	
Natural Gas		43.1%	
Coal		15.4%	
Biomass		1.1%	
Nuclear		14.8%	
Other (Hydro, Wind)		25.5%	
Upstream Fuel Process			
Residual Oil			
Residual Oil Refining			
Residual Oil Transport			
ocean tanker		24%	720 mi, 72 Btu/mile-ton

Parameters	Units	Values	Note
barge		40%	136 mi, 710 Btu/mile-ton
pipeline		60%	240 mi, 253 Btu/mile-ton
rail		5%	40 mi, 513 Btu/mi-ton
Coal			
Coal Mining			
Coal Transport			
barge		10%	33 mi, 403 Btu/mile-ton
rail		90%	396 mi, 370 Btu/mile-ton
Biomass			
Trees Farming			
Farm Chemicals			N_2, P_2O_5, K_2O, Herbicide, Pesticide
Biomass Transport			40 mi, 17 tons load, 25,690 Btu/mi by HDD truck
Nuclear			
Uranium Mining			
Uranium Ore Transport			1,360 mi, 1,028 Btu/mi-ton, 1,645,067 Btu/ton ore
Uranium Enrichment			
Uranium Conversion, Fabrication, Waste Storage			
Enriched Uranium Ore transport			920 mi, 1028 Btu/mi-ton, HHD truck
Uranium Fuel Transport			500 mi, 1028 Btu/mi-ton, HDD truck
Equipment Shares			
Commercial Boiler - Diesel		25%	
CO_2 Emission Factor	gCO_2/mmBtu	78,167	
Stationary Reciprocating Eng. - Diesel		50%	
CO_2 Emission Factor	gCO_2/mmBtu	77,349	
Turbine - Diesel		25%	
CO_2 Emission Factor	gCO_2/mmBtu	78,179	
Stationary Reciprocating Eng. - NG		50%	
CO_2 Emission Factor	gCO_2/mmBtu	56,551	
Small Industrial Boiler - NG		50%	
CO_2 Emission Factor	gCO_2/mmBtu	58,176	
Industrial Boiler - Coal		100%	
CO_2 Emission Factor	gCO_2/mmBtu	137,383	
Small Industrial Boiler - Biomass			
CO_2 Emission Factor	gCO_2/mmBtu	102,224	
Transmission and Distribution Loss			
Feed Loss in Transmission		8.10%	

Fuels Properties			
Fuels Specifications	LHV (Btu/gal)	Density (g/gal)	
Crude	129,670	3,205	
Residual Oil	140,353	3,752	
Conventional Diesel	128,450	3,167	
Conventional Gasoline	116,090	2,819	
CaRFG	111,289	2,828	
CARBOB	113,300	2,767	
Natural Gas	83,868	2,651	As Liquid
Ethanol	76,330	2,988	
Still Gas	128,590		
Conversion Factors			
For nuclear power plants	MWh/g of U-235	6.926	Light Water Reactor (LWR) Power Plant
	MWh/g of U-235	8.704	High-Temperature, Gas-Cooled Reactor (HTGR) Power Plant
Energy Btu to Kilowatt hour	Btu/K Wh	3,412	
Uranium Yellow Cake to U-235		0.29%	

[1] GREET Model: Argonne National Laboratory: http://www.transportation.anl.gov/modeling_simulation/GREET/index.html

[2] California Assembly Bill AB 1007 Study: http://www.energy.ca.gov/ab1007

[3] CA_GREET Model (modified by Lifecycle Associates) released February 2009 (http://www.arb.ca.gov/fuels/lcfs/lcfs.htm)

[4] Electricity Generation by Resource Type (1983-2006) http://energyalmanac.ca.gov/electricity/ELECTRICITY_GEN_1983-2006.XLS

[5] IPCC Vol 3, Table 1-15. - Climate Action Registry