CEI Analysis Methodology

Gap Analysis vs World's Best CEI

2008 Worldwide Paraffinic Lube Refinery Performance Analysis

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Introduction

HSB Solomon Associates LLC's (Solomon's) Carbon Emissions Index (CEI™) measures a refinery's actual carbon dioxide–equivalent (CO_2e) emissions relative to a standard based on its process capacity, configuration, utilization, feedstock characteristics, and other relevant operating parameters—analogous to Solomon's Energy Intensity Index™ (EII®) methodology. In the *Worldwide Paraffinic Lube Refinery Performance Analysis (Lube Study)* for operating year 2008, 87–99% of CO_2e emissions originate from energy consumption, namely fuel, steam, and electricity. Other sources of CO_2e emissions include hydrogen production, flaring, fugitive methane emissions, nitrous oxide (N_2O) emissions from combustion equipment, and asphalt blowing. The sinks for CO_2e emissions considered in the CEI calculation include methanol synthesis and CO_2 sales.

In recent years, reducing greenhouse gas (GHG) emissions has become a priority for many companies in order to respond to emerging policies and comply with regulations. Some near-term solutions for reducing GHG emissions from operations include reducing flare loss and vents, improving energy efficiency, and producing electricity by cogeneration. Carbon capture and storage, gasification, and bio-fuels are potential long-term solutions.

One key consideration in assessing a refinery's CEI is the "boundary" defined for GHG emissions. In the past, Solomon's CEI methodology provided two different metrics—"direct-only" and "total" emissions. The former includes emissions occurring within the refinery fence line while excluding all indirect emissions associated with electricity, steam, and hydrogen purchases or transfers from affiliates, while the latter is an index of estimated total emissions including indirect emissions. In the 2008 *Lube Study*, the calculation of CEI adopts the same boundary condition for EII on a net energy consumption basis. This definition implies that all net energy consumed at a refinery (i.e., total energy produced, purchased, or transferred from affiliates subtracting the energy sold or transferred to affiliates), is attributable to carbon emissions.

This document describes the CEI Analysis Methodology (CEI Analysis) and outlines the CEI performance gap in various areas between an individual refinery and a "World's Best" CEI Peer Group. Both energy-related and non-energy-related GHG emissions are analyzed. For energy-related emissions, the gaps are further divided into two categories—one is energy consumption expressed in Solomon's proven EII and the other is energy mix (i.e., the respective carbon emission potential in terms of carbon emission factor (CEF))[1]. This approach allows *Lube Study* participants to prioritize and focus their efforts toward reducing carbon emissions.

In addition to the CEI Analysis, other analyses may be beneficial for refineries seeking an accurate benchmarking for GHG emissions, such as the selection for a custom peer group, evaluations based on alternative boundary scenarios, or an assessment of certain sources or sinks for CO_2e emissions in the calculation of CEI. Solomon is committed to supporting all study participants on a custom basis, and welcomes questions and comments regarding our CEI methodology.

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[1] CEFs are based on "The API Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Gas Industry" *(API Compendium)* with a simple factor of 0.90 for liquid fuels and 0.95 for gaseous fuels to convert from HHV to LHV. A factor of 3.66 (i.e., 44.01/12.01) has been used to convert the unit from metric ton (MT) carbon emissions (CE) to MT CO_2e emissions.

CEI Analysis Methodology

Solomon defines "World's Best" as the weighted average data of four individual lube refineries with excellent performance in CEI. This "World's Best" CEI Peer Group consists of two solvent plants and two hydroprocessing plants that meter and calculate unit energy consumption daily or calculate unit energy balances multiple times per year. Each refinery is evaluated based upon its selected base case, either including or excluding a vacuum distillation unit (VDU). For refineries including/excluding a VDU, the composite 2008 World's Best CEI is 82.8/87.0, with an EII of 76.6/78.5. The imputed ("actual") CO_2e emissions in the calculation of CEI are based on the validated input from each refinery participating in the 2008 *Lube Study*.

The following elements illustrate the CEI gap between the World's Best CEI Peer Group and an individual refinery:

- Energy-Related GHG Emissions – Each of these gaps has been expressed in terms of EII and its respective CEF. The sum of all EII-related gaps demonstrates the portion of the CEI gap originating from EII differences.
  - Fuel Combustion
  - Steam Imports
  - Electricity Imports
- Non-Energy-Related GHG Emissions
  - Hydrogen Production
  - Flare Loss
  - All Other GHG Emissions

The calculations used in the CEI Analysis are based on Equation 1 and Equation 2:

$$CEI = \frac{CEI\ CO_2e\ \text{Actual}}{CEI\ CO_2e\ \text{Standard}} \times 100 = \frac{\sum_{\text{energy-related},i} AE_i \times CEF_i + \sum_{\substack{\text{non-energy}\\ \text{related}}} CO_2e\text{Actual}}{SE_{EII} \times CEF_{std}} \times 100$$

Equation 1

Where:

- CEI CO_2e Actual = Solomon's Estimate of Actual CO_2e Emissions, MT CO_2
- CEI CO_2e Standard = Solomon's CO_2e Emission Standard, MT CO_2
- AE_i = Actual Energy from Fuel Type *i* as reported in Input Table 16 (fungible fuels, natural gas, refinery fuel gas, low-Btu gas, net imported steam & electricity, etc.), MBtu/yr (GJ/yr)[2]
- CEF_i = Carbon Emission Factor from fuel type *i*, MT CO_2/MBtu (MT CO_2/GJ)
- SE_{EII} = Solomon's EII Standard Energy, MBtu/yr (GJ/yr)
- CEF_{std} = "*equivalent*" Standard Carbon Emission Factor, calculated by the CO_2e Emission Standard divided by the EII Standard Energy, MT CO_2/MBtu (MT CO_2/GJ)

[2] 1 MBtu = 1 million Btu = 1.055 gigajoule (GJ)

Thus, each energy-related CEI component from fuel type *i* is a product of its corresponding EII component and the CEF relative to a standard:

$$CEI_i = \frac{AE_i \times CEF_i}{SE_{EII} \times CEF_{std}} \times 100 = EII_i \times \frac{CEF_i}{CEF_{std}} \times 100$$

Equation 2

The description in this document is in sufficient detail to enable each 2008 *Lube Study* participant to self-calculate each of the main elements of the CEI gap by referring to the "CEI Analysis" tab in the attached *_CEIGap.xls* file[3].

Fuel Combustion

This element of the CEI Analysis addresses CO_2e emissions from the combustion of all fuel types including fungible fuels, natural gas, low-Btu gas, and refinery fuel gas for process heat requirements.

EII-Related

On average, 75% of CO_2e emissions at a refinery originate from fuel combustion (excluding steam and electricity imports). The energy-related component of the CEI gap from fuel combustion is based on the same fuel mix (i.e., that of the World's Best CEI Peer Group) between an individual refinery and World's Best CEI Peer Group, and may be determined by Equation 3:

$$\frac{L58}{L57} \times (L52\text{-}J52)$$

Equation 3

Where:

- L58[4] = Weighted-Average CEF for Fuel Combustion (fungible fuels, natural gas, refinery fuel gas, and low-Btu gas (World's Best Value)), MT CO_2/MBtu (MT CO_2/GJ)
- L57 = "*equivalent*" CEF_{std} (World's Best Value), MT CO_2/MBtu (MT CO_2/GJ)
- L52 = EII Component from Fuel Combustion (World's Best Value)
- J52 = EII Component from Fuel Combustion (Refinery Value)

[3] The *_CEIGap.xls* file is not attached for the internet copy of this white paper. However, an example waterfall diagram of CEI gaps is shown in Figure 1.

[4] These cell references correspond to the "CEI Analysis" tab in the *_CEIGap.xls* workbook.

CEF-Related

CEFs vary greatly depending on the fuel type. Given the same energy consumption from fuel combustion, one may generate up to 50% more GHG emissions due to a fuel mix rich in fuel types with a greater carbon emission potential, such as residual fuels. The CEI delta due to a difference in fuel mix (i.e., CEF) between an individual refinery and the World's Best CEI Peer Group is determined using Equation 4:

$$\left(\frac{L58}{L57}-\frac{J58}{J57}\right)\times J52$$

Equation 4

Where:

- J58 = Weighted-Average CEF for Fuel Combustion (fungible fuels, natural gas, refinery fuel gas, and low-Btu gas (Refinery Value)), MT CO_2/MBtu (MT CO_2/GJ)
- J57 = "*equivalent*" CEF_{std} (Refinery Value), MT CO_2/MBtu (MT CO_2/GJ)

Steam Imports

This element of the CEI Analysis addresses CO_2e emissions from the consumption of net imported steam, which was reported in Input Table 16 on a fuel-equivalent basis. Natural gas is used as a standard for assigning the CEF for all steam purchases and incoming transfers, with an equivalent CEF of 0.0590 MT CO_2/MBtu (0.0559 MT CO_2/GJ), since the data collected is not sufficient for determining the actual CEF of the source of imported steam.

EII-Related

Nearly 50% of refineries consume imported steam. On average, 12% of imputed CO_2e emissions at a refinery originate from steam imports. The energy-related component of this CEI gap is based on the same natural gas standard between an individual refinery and the World's Best CEI Peer Group, and may be determined by Equation 5:

$$\frac{L59}{L57}\times\left(L53\text{-}J53\right)$$

Equation 5

Where:

- L59 = CEF of Natural Gas (World's Best Value), 0.0590 MT CO_2/MBtu (0.0559 MT CO_2/GJ)
- L57 = "*equivalent*" CEF_{std} (World's Best Value), MT CO_2/MBtu (MT CO_2/GJ)
- L53 = EII Component from Steam Imports (World's Best Value)
- J53 = EII Component from Steam Imports (Refinery Value)

CEF-Related

The CEF-related gap for steam imports is based on the difference in the ratio of CEF of natural gas versus the *"equivalent"* CEF_{std} between an individual refinery and the World's Best CEI Peer Group, as determined by Equation 6:

$$\left(\frac{L59}{L57} - \frac{J59}{J57}\right) \times J53$$

Equation 6

Where:

- J59 = CEF of Natural Gas (Refinery Value), 0.0590 MT CO_2/MBtu (0.0559 MT CO_2/GJ)
- J57 = *"equivalent"* CEF_{std} (Refinery Value), MT CO_2/MBtu (MT CO_2/GJ)

Electricity Imports

90% of refineries consume imported electricity from either an adjacent facility or purchased from the electricity grid. On average, 9% of imputed CO_2e emissions at a refinery originate from electricity imports. This element of the CEI Analysis illustrates the impact of imported electricity on the calculated CEI of the refinery. An electricity emission factor (EEF)[5] is allocated to the imported electricity consumed by each refinery and can be considered as an equivalent CEF. EEF is defined as the national average of CO_2e emissions per unit of electricity supplied of the country in which the refinery is located and is beyond the direct control of the refinery. The national average EEF is based on the percentage of electric power generation data (from hydropower, coal, oil, gas, nuclear, etc. respectively) in *World Development Indicators 2006* published by the World Bank. If the refinery does not consume any imported electricity, a favorable gap will be shown in the "Electricity Imports EII-Related" category versus the World's Best CEI Peer Group. However, the lack of purchased electricity is usually compensated by increased fuel consumption.

[5] EEFs are based on the data published in the *API Compendium* and in *World Development Indicators 2006* by the World Bank.

EII-Related

The CEI gap due to a difference in imported electricity consumed between an individual refinery and the World's Best CEI Peer Group is determined by Equation 7:

$$\frac{L60}{L57} \times (L54\text{-}J54)$$

Equation 7

Where:

- L60 = EEF for Electricity Imports @ 9,090 Btu/kWh or 9.59 MJ/kWh (World's Best Value), MT CO_2/MBtu (MT CO_2/GJ)
- L57 = "*equivalent*" CEF_{std} (World's Best Value), MT CO_2/MBtu (MT CO_2/GJ)
- L54 = EII Component from Electricity Imports (World's Best Value)
- J54 = EII Component from Electricity Imports (Refinery Value)

"Equivalent" CEF (EEF)-Related

The EEFs of the imported electricity consumed in a refinery may vary greatly depending on the country location of the refinery. The CEI delta due to an EEF difference between an individual refinery and the World's Best CEI Peer Group is determined using Equation 8:

$$\left(\frac{L60}{L57} - \frac{J60}{J57}\right) \times J54$$

Equation 8

Where:

- J60 = EEF for Electricity Imports @ 9,090 Btu/kWh or 9.59 MJ/kWh (Refinery Value), MT CO_2/MBtu (MT CO_2/GJ)
- J57 = "*equivalent*" CEF_{std} (Refinery Value), MT CO_2/MBtu (MT CO_2/GJ)

Hydrogen Production

Hydrogen production via a reformer (steam naphtha reforming or steam methane reforming) or partial oxidation unit (POX) produces CO_2 in addition to H_2. In the CEI Analysis for hydrogen production, two elements are analyzed— one is percent of H_2 loss as reported in Input Table 2 and the other simply reflects the inherent ("standard") CO_2e emissions in the reformer or POX, depending on the utilized capacity and stoichiometric yield of CO_2 adjusted for a standard H_2 loss of 12.5% from pressure swing adsorption (PSA) and other process vents. Reducing H_2 loss in operations will reduce the CO_2e emissions from hydrogen production. However, its impact is usually relatively small compared to the inherent emissions associated with the H_2 production facilities.

H_2 Loss

The CEI gap due to fraction of H_2 loss in H_2 production, between an individual refinery and the World's Best CEI Peer Group, may be determined by Equation 9:

$$\left[\frac{87.5}{100\text{-}L62}-\frac{87.5}{100\text{-}J62}\right]\times J63$$

Equation 9

Where:

- 87.5 = % of the basis adjusted for a standard H_2 loss of 12.5%
- L62 = Fraction of H_2 Loss in H_2 Production (World's Best Value), %
- J62 = Fraction of H_2 Loss in H_2 Production (Refinery Value), %
- J63 = Standard CO_2e Emissions from H_2 Production (Refinery Value), % of Total Standard CO_2e Emissions

Standard CO_2e Emissions from H_2 Production (Adjusted for Standard H_2 Losses)

This element of the CEI Analysis illustrates the impact of standard CO_2e emissions from H_2 production, which is adjusted for standard H_2 losses of 12.5%. Reducing H_2 loss will not affect this CEI gap, since it is inherent to the process. If the refinery has no hydrogen generation facilities, a favorable gap will be shown in this category versus the World's Best CEI Peer Group. The CEI delta for the inherent CO_2e emissions from H_2 production between an individual refinery and the World's Best CEI Peer Group can be calculated by Equation 10:

$$\frac{87.5}{100\text{-}L62}\times(L63\text{-}J63)$$

Equation 10

Where:

- L63 = Standard CO_2e Emissions from H_2 Production (World's Best Value), % of Total Standard CO_2e Emissions

Flare Loss

The imputed CO_2e emission is directly proportional to weight fraction of flare loss as reported in Input Table 15. Reducing flaring and venting is one of the most actionable improvements for reducing GHG emissions from operations. The CEI delta for flare loss between an individual refinery and the World's Best CEI Peer Group may be determined by Equation 11:

$$(L64\text{-}J64)\div 0.06\times J65$$

Equation 11

Where:

- 0.06 = % of Long-Term Historical Average of Flare Loss from Solomon's Lube Database
- L64 = Flare Loss (World's Best Value), wt % Feed
- J64 = Flare Loss (Refinery Value), wt % Feed
- J65 = Standard CO_2e Emissions from Flaring (Refinery Value), % of Total Standard CO_2e Emissions

All Other GHG Emissions

The remaining GHG emissions at a refinery include fugitive methane (CH_4) emissions (such as from storage tanks and wastewater treatment), N_2O emissions from combustion equipment[6], and process vents from asphalt blowing, etc. In addition, for refineries with a methanol plant (for methanol synthesis) or CO_2 sales, a "credit" was applied equally to both actual and standard CO_2e emissions. These emissions typically represent less than 1% of total CO_2e emissions.

This element of the CEI Analysis completes the CEI waterfall diagram, as shown in Figure 1 (example), by closing the remaining gap:

$$L24\text{-}L11\text{-}\sum(L13{:}L15, L19{:}L21)$$

Equation 12

Where:

- L24 = World's Best CEI
- L11 = Refinery CEI
- L13:L15 and L19:L21 = Sum of CEI-Deltas Calculated using Equations 1–11

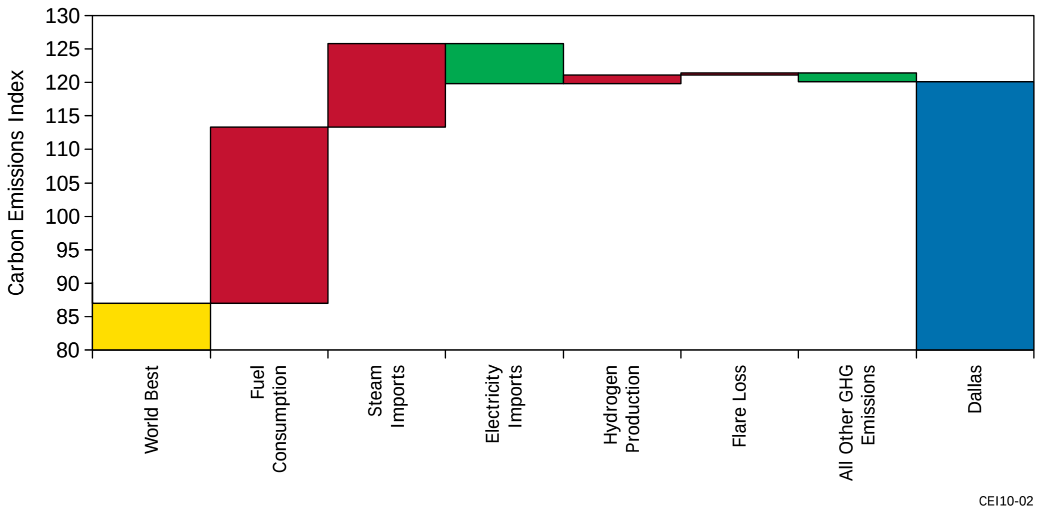

Figure 1. Waterfall Diagram of CEI Gaps (Example)

[6] The estimated N_2O emissions from combustion equipment are proportional to the actual energy of fuel combustion: natural gas, refinery fuel gas, low-Btu gas, and fungible fuels. Depending on the fuel mix, the estimated N_2O emissions account for an additional 0.6–1.1% of CO_2e emissions from fuel combustion.

CEI and EII Gap Analysis

Improving energy efficiency is critical for reducing GHG emissions. For lube refineries worldwide, 87–99% of CO_2e emissions originate from energy consumption (i.e., fuel, steam, and electricity). In this analysis, each of these energy-related elements in the CEI gap has been expressed in terms of EII and its respective CEF. Thus, it allows *Lube Study* participants to estimate the impact on CEI through improved energy efficiency.

In the final presentation for 2008 *Lube Study*, an *EII Gap Analysis* provides insight into a refinery's EII performance versus EII leaders from its respective technology group, solvent or hydroprocessing. The following elements of EII gaps are shown in a waterfall diagram:

- Power Generation
- Electricity Consumed
- Heater, Boiler, Cogen, and Purchased Steam
- Steam System Pressure
- Unexplained

This analysis highlights opportunities for *Lube Study* participants to reduce energy consumption, which will in turn improve the CEI performance. At times, a poor energy balance may lead to a substantial unexplained gap in the *EII Gap Analysis*, and a resolution is necessary in order to maximize the energy and GHG emissions improvement.

The other significant factor for GHG emissions is the carbon emission potential of energy (fuel) mix. In Appendix A, Table 1 and Table 2 list the CEFs for each source of fungible fuels and fuel gas components. Table 3 summarizes the national average EEFs, regarded as "equivalent" CEFs @ 9,090 Btu/kWh (9.59 MJ/kWh). The CEF information yields the basis for estimating the effect of energy (fuel) mix on CEI performance.

Introduced in 2003, Solomon's CEI is an accurate and reliable benchmarking metric for GHG emissions. The metric is gaining recognition and endorsement by the industry, and gradually achieving the same level of confidence and credibility that exists for EII. Solomon will continue to improve the CEI Analysis in upcoming studies, and will support all *Lube Study* participants on a custom basis upon emerging policies and various boundary scenarios considered by regulators and industry groups around the world. All questions or comments should be directed to:

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Appendix A Carbon Emission Factors

Table 1. Carbon Emission Factors for Fungible Fuels

Fungible Fuel	**CEF, MT CO_2/MBtu**	**CEF, MT CO_2/GJ**
Ethane	0.0627	0.0594
Propane	0.0664	0.0629
Butane	0.0685	0.0649
Naphtha/Gasoline	0.0700	0.0663
Distillate Fuels	0.0770	0.0730
Residual Fuels		
<0.3 wt % Sulfur	0.0856	0.0811
0.31–1.0 wt % Sulfur	0.0855	0.0810
1.01–2.0 wt % Sulfur	0.0854	0.0809
2.01–3.0 wt % Sulfur	0.0851	0.0807
> 3.0 wt % Sulfur	0.0849	0.0805
Extremely Viscous	0.0852	0.0808
Coal or Coke	0.1075	0.1019

Source: "The API Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Gas Industry" (API Compendium)

Table 2. Carbon Emission Factors for Fuel Gas Components

Fuel Gas Components	**CEF, MT CO_2/MBtu**	**CEF, MT CO_2/GJ**
Carbon Monoxide	0.1645	0.1559
Methane	0.0579	0.0549
Ethane	0.0649	0.0615
Ethylene	0.0700	0.0663
Propane	0.0682	0.0646
Propylene	0.0722	0.0684
Butane	0.0700	0.0663
Isobutane	0.0700	0.0663
C_5+	0.0711	0.0674

Source: Based on the physical data of fuel gas components and the API Compendium

Table 3. Electricity Emission Factors

Country	CEF Applied, MT CO_2/MWh	Country	CEF Applied, MT CO_2/MWh	Country	CEF Applied, MT CO_2/MWh
Abu Dhabi	0.4577	Greece	0.7618	Paraguay	0.0000
Albania	0.0169	Guatemala	0.3653	Peru	0.1022
Algeria	0.5416	Haiti	0.3170	Philippines	0.5306
Angola	0.2430	Honduras	0.2525	Poland	0.8967
Argentina	0.2550	Hong Kong	0.7450	Portugal	0.5196
Armenia	0.2059	Hungary	0.4148	Qatar	0.4577
Aruba	0.6585	India	0.7571	Romania	0.4709
Australia	0.7908	Indonesia	0.5856	Russia	0.3954
Austria	0.2015	Iran	0.4701	Saudi Arabia	0.5786
Azerbaijan	0.5174	Iraq	0.6468	Senegal	0.6585
Bangladesh	0.4320	Ireland	0.7021	Serbia/Montenegro	0.6783
Belarus	0.4548	Israel	0.8608	Singapore	0.5772
Belgium	0.2514	Italy	0.4679	Slovakia	0.2199
Benin	0.6585	Ivory Coast	0.2910	Slovenia	0.3371
Bolivia	0.2261	Jamaica	0.6376	South Africa	0.8692
Bosnia/Herzegovina	0.4789	Japan	0.3932	Spain	0.4276
Brazil	0.0674	Jordan	0.6325	Sri Lanka	0.3500
Bulgaria	0.4350	Kazakhstan	0.7358	Sudan	0.3408
Cameroon	0.0099	Kenya	0.3067	Sweden	0.0330
Canada	0.2232	Korea	0.4614	Switzerland	0.0088
Chile	0.3324	Kuwait	0.6057	Syria	0.3100
China	0.7472	Kyrgyzstan	0.0605	Taiwan	0.6171
Colombia	0.1477	Latvia	0.1693	Tajikistan	0.0103
Congo, Dem. Rep.	0.0022	Lebanon	0.6255	Tanzania	0.0429
Congo, Rep.	0.0018	Libya	0.6585	Thailand	0.5152
Costa Rica	0.0253	Lithuania	0.0960	Togo	0.6585
Croatia	0.3067	Malaysia	0.4298	Trinidad	0.4386
Cuba	0.6226	Mexico	0.4980	Tunisia	0.4603
Czech Rep.	0.6794	Moldova	0.4548	Turkey	0.4962
Denmark	0.6237	Morocco	0.8014	Turkmenistan	0.4405
Dominican Rep.	0.6230	Mozambique	0.0029	UAE	0.4577
Ecuador	0.2118	Myanmar	0.3067	UK	0.4493
Egypt	0.3947	Namibia	0.0235	Ukraine	0.3576
El Salvador	0.3353	Nepal	0.0099	Uruguay	0.0231
Estonia	0.8919	Netherlands	0.5387	US	0.6083

Table 3. Electricity Emission Factors

Country	CEF Applied, MT CO_2/MWh	Country	CEF Applied, MT CO_2/MWh	Country	CEF Applied, MT CO_2/MWh
Ethiopia	0.0092	New Zealand	0.1598	US Virgin Islands	0.6585
Finland	0.3628	Nicaragua	0.5486	Uzbekistan	0.4298
France	0.0638	Nigeria	0.2906	Venezuela	0.1524
Gabon	0.1862	Norway	0.0022	Vietnam	0.2803
Georgia	0.0956	Oman	0.4808	Yemen	0.6585
Germany	0.5464	Pakistan	0.3980	Zambia	0.0051
Ghana	0.0799	Panama	0.2715	Zimbabwe	0.5409

Source: Based on the data published in the API Compendium and in World Development Indicators 2006 by the World Bank