# 5

# COST OF GREENHOUSE GAS MITIGATION [21jun, 10jul 1pm]

Fix of Section 5 tables, but no change needed. EEH 955am 11nov00:

The cost of greenhouse gas mitigation using renewable energy technologies depends on both the difference between the generation costs of the renewable energy option (e.g. wind or biomass generation) and the low-cost alternative (e.g. coal or natural gas generation) and the carbon emissions that are displaced by the renewable energy generation. The mitigation costs are usually expressed in units of the cost per unit fossil carbon emissions that are avoided, offset, captured, sequestered, etc.

Section 4 presented the costs of renewable energy and derived the extra costs for renewables above fossil by taking diffferences: renewables less the fossil alternative. In this section, the extra costs of the renewable power generation technologies are converted into terms of cost per unit fossil carbon emission avoided.

It is known that several "greenhouse gases" contribute to humanity's effect on the radiation balance in the atmosphere and, hence, on potential global temperature and climate effects. They include carbon dioxide (CO2), methane (CH4), nitrous oxide (NO2), and certain chloro-fluorocarbons (CFCs). (The CFCs have become most widely known for their chemical effects in the stratosphere, reacting with and depleting the ozone layer. They also absorb infrared radiation and affect global heat balance. This occurs much lower than the stratosphere, down in the main mass of the atmosphere, i.e., the troposphere.) The relevant impacts of the greenhouse gases on the radiation balance vary between the greenhouse gases. Table 5-1 presents numbers that show this (Ref.9).

**Table 5-1**
**Greenhouse Warming Strengths of the Key Gases**

| Gas | Lifetime in the Atmosphere | Infrared absorbing strength relative to CO2 20-year | 100-year | 500-year |
|---|---|---|---|---|
| Carbon dioxide (CO2) | variable | 1 | 1 | 1 |
| Methane (CH4) | 12 years (+-3) | 56 | 21 | 7 |
| Nitrous oxide (N2O) | 120 years | 280 | 310 | 170 |
| Chlorofluorocarbons (CFC) | not given | 4900 | 3800 | not given |

Source: U.S. Dept. of Energy EIA, "Emissions of Greenhouse Gases in the US: 1996" Oct.1997.

In Table 5-1, different timeframes, as well as the four different gases, are shown because the non-CO2 gases gradually are converted into CO2 over the years and will eventually be at the same strength as CO2, but not until well beyond the timeframes of interest here. In order to assess emission controls applied to different gases on a common basis for global warming purposes, the emissions of the different greenhouse gases are normalized to a common basis by expressing them as equivalent $CO_2$ emissions. On a mass basis, and for a 100-year timeframe, methane ($CH_4$) absorbs 21 times as much of the earth's outgoing infrared radiation as carbon dioxide ($CO_2$). Therefore, we say that the mass of the equivalent CO2 emission is 21x the mass of the methane put into the landfill gas energy system. In this section of the report the costs of greenhouse gas reduction will be expressed and compared on the basis of dollars per metric ton (tonne) of elemental carbon ($/tonne C), based on the absorbing strength when that carbon atom is in a CO2 molecule--the "CO2 equivalent." When methane is the fuel, the carbon atom is in a CH4 molecule. Hence, the factor per unit of energy will be less than the 21x. Here we use a factor of only 7.64, which is 21 x (16/44). The 16/44 is because each molecule of methane has a mass of 16, molecular weight, and goes into one atom of carbon in a carbon dioxide molecule of weight 44.

In addition to depending on the type of gas whose emission is reduced or avoided, the analysis leading to cost per unit weight of fossil $CO_2$ emissions avoided must take into account the type of fuel, technology and emitted gas that would otherwise have been used to generate the electricity replaced low by the renewable technology. The amount of fossil carbon emission avoided by using a renewable resource instead of a fossil fuel power generation technology depends on the fossil fuel type that is "avoided" and on the conversion technology that would have been used to make the power from that fossil fuel. Table 5-2 shows the fuel effect, based on the carbon intensity of the various fuels, as measured in units of weight of carbon per unit of energy content of the fuel.

**Table 5-2**
**Fuel Effect on Fossil Carbon Intensity**

| Name | Heat Content - HHV | | Carbon Content | | Fossil Carbon Intensity | |
|---|---|---|---|---|---|---|
| of Fuel | (Btu/lb) | (MJ/kg) | (lb-C/lb) | (kg-C/kg) | (lb-C/MBtu) | (kg-C/MJ) |
| Coal | 13,700 | 31.798 | 0.78 | 0.78 | 56.9 | 24.5 |
| Oil | 18,000 | 41.778 | 0.85 | 0.85 | 47.2 | 20.3 |
| Natural gas | 23,800 | 55.240 | 0.76 | 0.76 | 31.9 | 13.8 |
| Wood (dry) | 8,000 | 18.568 | 0.45 | 0.45 | Zero* | Zero* |

*Note: "Fossil" carbon intensity is the measure relevant to greenhouse gas, and by this measure wood from renewable growth of trees is zero in carbon intensity. If the carbon in the fuel is put straight into the same formula used for the fossil fuels, then the carbon intensity for the wood is 54.2 lb-C/MBtu or 23.4 kg-C/MJ.

Next, Table 5-3 shows the effect of conversion technology, and, therefore, combines the effects of carbon intensity in the fuel with the efficiency of converting the fuel to electricity. Table 5-3 gives the emissions of carbon dioxide (or carbon) from present and future fossil fuel technologies, both coal-based and natural-gas-based. (Ref.9). Efficient pulverized coal units emit about 0.95 tons $CO_2$ per MWh of electricity generation, which is 0.26 tons C per MWh. Advanced IGCC technology will reduce these CO2 emissions factors by about 20%. Advanced natural gas-combined cycle plants with efficiencies as high as 54% will emit about 0.37 tons $CO_2$ (0.10 tons C) per MWh. Therefore, to convert the extra cost of the renewable electricity, given in $/MWh, into units of $/tonne-C for the greenhouse gas reduction achieved, the $/MWh is simply divided by the tonne-C/MWh of the fuel-technology combination that is considered to be the fossil technology replaced by the renewable one.

**Table 5-3**
**Technology Effect on Fossil Carbon Intensity**

| English units: | Carbon | Heat | Fossil Carbon Emission | |
|---|---|---|---|---|
| Fuel - Technology (HHV eff.) | Content (lb/MBtu) | Rate (Btu/kWh) | CO2 (ton/MWh) | C (ton/MWh) |
| Coal - | | | | |
| Typical existing (0.341) | 56.9 | 10,000 | 1.04 | 0.28 |
| Pulverized, 95% scrubbed (0.376) | 56.9 | 9,087 | 0.95 | 0.26 |
| Advanced, IGCC (0.467) | 56.9 | 7,308 | 0.76 | 0.21 |
| Natural gas - | | | | |
| Existing steam plant (0.331) | 31.9 | 10,300 | 0.60 | 0.16 |
| Advanced, CC (0.538) | 31.9 | 6,350 | 0.37 | 0.10 |
| Advanced, CT (0.427) | 31.9 | 8,000 | 0.47 | 0.13 |
| Advanced, fuel cell (0.637) | 31.9 | 5,361 | 0.31 | 0.09 |

| SI units: | Carbon (kg/GJ) | Heat Rate (kJ/kWh) | CO2 (tonne/MWh) | C (tonne/MWh) |
|---|---|---|---|---|
| Coal - | | | | |
| Typical existing (0.341) | 24.52 | 10,550 | 0.95 | 0.26 |
| Pulverized, 95% scrubbed (0.376) | 24.52 | 9,587 | 0.86 | 0.24 |
| Advanced, IGCC (0.467) | 24.52 | 7,710 | 0.69 | 0.19 |
| Natural gas - | | | | |
| Existing steam plant (0.331) | 13.74 | 10,867 | 0.55 | 0.15 |
| Advanced, CC (0.538) | 13.74 | 6,699 | 0.34 | 0.09 |
| Advanced, CT (0.427) | 13.74 | 8,440 | 0.43 | 0.12 |
| Advanced, fuel cell (0.637) | 13.74 | 5,656 | 0.29 | 0.08 |

Source: Ref.15 ("EIA Kyoto"), Tables 16, 17 (pages 73-75), U.S. DOE, October 1998.

## Results

The results of applying this procedure are shown in Table 5-4. Examples of how Table 5-4 was calculated for several cases follow, with special emphasis on two cases that are somewhat different from the rest: biomass cofiring, and landfill gas. In biomass cofiring the fossil alternative is not a new fossil power plant, but, instead, is simply the operation of the existing coal-fired plant on 100% coal, with no biomass displacing any of the coal. In landfill gas, which here refers to landfill gas power generation, the burning of the biomass-derived methane gas avoids the emission by the landfill of a greenhouse gas 21 times as powerful, per unit weight, as the carbon dioxide in infrared absorbing and warming strength. Taking this greenhouse strength into account makes the cost of avoiding the CO2 equivalent much lower, by the 7.64 factor derived above.

### Table 5-4
### Conversions of Power Costs into CO2 Reduction Costs

| | | Carbon Intensity Displaced | | Cost of CO2 Reduction | |
|---|---|---|---|---|---|
| Renewable Technology | Extra Cost ($/MWh) | Coal (tonne-C/MWh) | Natural Gas (tonne-C/MWh) | Coal ($/tonne-C) | Natural Gas ($/tonne-C) |
| Biomass cofiring (low cost end of range) | $ (5.00)* | 0.264 | not applicable | $ (18.97)* | not applicable |
| Biomass cofiring (high cost end of range) | $18.00 | 0.264 | not applicable | $68.28 | not applicable |
| Biomass gasification or other advanced biomass | $10.00 | 0.264 | 0.090 | $37.93 | $111.11 |
| Wind | $10.00 | 0.264 | 0.090 | $37.93 | $111.11 |
| Geothermal | $7.00 | 0.264 | 0.090 | $26.55 | $77.78 |
| Solar Thermal | $47.00 | 0.264 | 0.090 | $178.28 | $522.22 |
| Solar PV | $14.00 | 0.264 | 0.090 | $53.10 | $155.56 |
| Landfill gas*** | $5.00 | 2.013 | 0.687 | $2.48 | $7.28 |

***The landfill gas conversion factors are based on the 21x stronger greenhouse warming effect of CH4 vs. CO2, and also the factor of 16/44 to convert from a weight basis to a mole basis.

Fuel Effect on Fossil Carbon Intensity ← same as Table 5-2 above but "unformatted"

| Name | Heat Content - HHV | | Carbon Content | | | Fossil Carbon Intensity | |
|---|---|---|---|---|---|---|---|
| of Fuel | (Btu/lb) | (MJ/kg) | (lb-C/lb) | (kg-C/kg) | | (lb-C/MBtu) | (kg-C/MJ) |
| Coal | 13,700 | 31.798 | 0.78 | 0.78 | 56.9 | 24.5 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Oil | 18,000 | 41.778 | 0.85 | 0.85 | 47.2 | 20.3 | |
| Natural gas | | 23,800 | 55.240 | 0.76 | 0.76 | 31.9 | 13.8 |
| Wood (dry) | | 8,000 | 18.568 | 0.45 | 0.45 | Zero* | Zero* |

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*Note: "Fossil" carbon intensity is the measure relevant to greenhouse gas, and by this measure wood from renewable growth of trees is zero in carbon intensity. If the carbon in the fuel is put straight into the same formula used for the fossil fuels, then the carbon intensity for the wood is 54.2 lb-C/MBtu or 23.4 kg-C/MJ.

Calc of 17march02 for Steve Segrest email reply:

| | | | |
|---|---|---|---|
| Biomass lb-C/MMBtu | 54.2 | | |
| Heat rate in Btu/kWh | 11000 | | |
| Heat rate in MMBtu/MWh | 11 | | |
| Carbon emitted in lbs/MWh | 596.2 | C12 | Molecular wt. = 12 |
| CO2 emitted in lbs/MWh | 2186.067 | CO2 | Molecular wt. = 44 |
| CO2 emitted in tons/MWh | 1.09303 | | |
| CO2 emitted in tonne/MWh | | 0.99367 | |
| Carbon emitted in tonne/MWh | | 0.271 | Tonne = metric ton = 2200 lbs. |