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Kasbit Business Journal

8 February 2013

Online at <https://mpra.ub.uni-muenchen.de/53524/>

MPRA Paper No. 53524, posted 10 Feb 2014 00:20 UTC

## Greenhouse Gas Emissions from Small Industries and its Impact on Global Warming

Haradhan Kumar Mohajan

### ABSTRACT

This paper discusses mathematical calculations of the greenhouse gas emissions from small industries, which cause global warming in the atmosphere. Global warming is causing an increase in ocean levels, it is estimated that most of the coastal areas of the world will be submerged by 2050, resulting in extinction of some insects and animals. Simple calculations are presented to estimate three greenhouse gases, carbon dioxide, methane, and nitrous oxide emissions from small industry. The emissions from fossil fuels in a small mill are given with mathematical calculations. Emissions from combined heat and power plants are allocated in this paper by using 'The World Resources Institute and World Business Council for Sustainable Development Efficiency' method.

### JEL. Classification:

**Keywords:** Greenhouse gas emissions, Biomass, Fossil fuels, Kyoto Protocol 1997, Small industries

### 1. INTRODUCTION

The six gases; Carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), sulphurhexafluoride (SF<sub>6</sub>), hydrofluorocarbon (HFC) and perfluorocarbon (PFC), together constitutes six greenhouse gas (GHG) emissions. When an emission estimate is the sum of several GHGs expressed as the equivalent amount of CO<sub>2</sub>, the estimate is said to be in CO<sub>2</sub>-equivalents (CO<sub>2</sub>e). CO<sub>2</sub>e gases covered in the Kyoto Protocol 1997, which is an international agreement linked to the United Nations Framework Convention on Climate Change (UNFCCC). In environment science CO<sub>2</sub>e emissions are defined as the sum of the mass emissions of each individual GHG adjusted for its global warming potential (EPA 2011).

Greenhouse gases are often compared on the basis of their estimated potential to cause global warming. Factors called Global Warming Potentials (GWPs) have been developed, and can be used to convert a quantity of non-CO<sub>2</sub> greenhouse gas into an amount of CO<sub>2</sub> with an equivalent warming potential. Although the derivation of these factors involves a large number of assumptions, GWPs are almost universally used to compare one greenhouse gas to another.

In this paper we consider the emissions of three GHGs, CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O, and an emission estimate is the sum of these three GHGs expressed as in CO<sub>2</sub>-equivalents (CO<sub>2</sub>e). The International Council of Forest and Paper Associations (ICFPA), Climate Change Working Group retained the research institute, National Council for Air and Stream Improvement, Inc. (NCASI) to review existing GHG protocols and assist the industry in developing calculation tools for estimating GHG emissions. These industry specific tools should be used in conjunction with an accepted GHG accounting protocol such as the "Greenhouse Gas Protocol" issued by the World Resources Institute/World Business Council for Sustainable Development (WRI/WBCSD), the "Climate Leaders Greenhouse Gas Inventory Protocol Core Module Guidance" issued by the United States Environmental Protection Agency (USEPA), the "Challenge Registry Guide to Entity and Facility-Based Reporting" issued by the Voluntary Challenge and Registry (NCASI 2005).

Biofuels are combustible materials directly or indirectly derived from biomass, commonly produced from wood, agricultural crops and products, aquatic plants, forestry products, wastes and residues, and animal wastes (Mohajan 2012a). The forest products' industries contribute to reduce global GHG emissions. Forests also provide multiple environmental, societal, and economic benefits. It has been estimated that the amount of carbon stored in forest products is increasing by 139 million metric tons of carbon per year on a global basis which reduce GHG emissions (Winjum, Brown and Schlamadinger 1998). Most protocols for developing corporate GHG inventories, including the WRI/WBCSD GHG Protocol, can help to understand the variety of uses for GHG inventory results in industries (WRI and WBCSD, 2004a). Most of the industries rely on biomass fuels that displace fossil fuels, which are the primary contributor to rising atmospheric levels of carbon dioxide. In a number of countries of the world, more than half the industries' energy requirements are faced using biomass fuels (NCASI 2005).

## **2. GLOBAL GREENHOUSE GAS EMISSIONS ARE INCREASING**

Every nation in the world has realized that global warming is due to continuous GHG emissions. The people of the whole world are suffering from the effects of global warming and are projected to suffer much more acute effects as the climate change becomes more severe. Now we illustrate the inventories of three GHGs as follows (Mohajan 2011):

CO<sub>2</sub> is the most significant GHG for its natural high atmospheric concentration and heat-trapping abilities. CO<sub>2</sub> is accumulating in the atmosphere due to human activities. Pre-industrial revolution period CO<sub>2</sub> was at a level of 280 parts per million (ppm) and in 2005 it is increased 35% and is reached to a level of 379 ppm (IPCC 2007).

CH<sub>4</sub> is present in the atmosphere very low compared to CO<sub>2</sub> but it is 21 times more potent per unit as a greenhouse gas (EPA 2006). In the pre-industrial period CH<sub>4</sub> was 715 ppb (parts per billion) but in 2005 it increased 148% to reach 1,774 ppb (IPCC 2007). About half of this increase is due to decomposition of wastes in landfills, natural gas systems, and enteric fermentation (EPA 2006).

N<sub>2</sub>O is 310 times more potent than CO<sub>2</sub> as a heat trapping gas (EPA 2006). In pre-industrial period this gas was 270 ppb but in 2005 it increased by 18% to reach 319 ppb (IPCC 2007). This gas is mainly produced from agricultural soil management, mobile combustion, manure management, nitric acid production and human sewage.

Scientific research shows that ice losses from Antarctica and Greenland has accelerated over the last 20 years which will raise the sea level. From satellite data and climate models, scientists calculated that the two polar ice sheets are losing enough ice to raise sea levels by 1.3 mm each year and scientists observed that the sea levels are rising by about 3 mm per year. By 2006, the Greenland and Antarctic sheets were losing a combined mass of 475 Gt (gigatons) of ice per year. If these increases continue, water from the two polar ice sheets can rise by 15 cm from average global sea level by 2050. So that all the nations especially developed countries must take immediate steps to reduce GHGs to a substantial level. If GHG emissions can not be controlled then the people of most of the countries will suffer for drinking water, shortage of foods and various heat related diseases. Scientists declared that some plants and animals will extinct in the 21st century due to increased global warming (Mohajan 2011).

The National Academy of Sciences (NAS) has expressed its expert opinion that concentrations of CO<sub>2</sub> in the atmosphere have increased and continue to increase more rapidly due to human activities (NAS 2001; 2010). The NAS cites the burning of fossil fuels is the primary source of anthropogenic CO<sub>2</sub> emissions.

The GWP for CH<sub>4</sub> is 21 so, from the standpoint of potential global warming, every gram of CH<sub>4</sub> is equivalent to 21 grams of CO<sub>2</sub>. The following table-1 gives GWPs of six GHGs and atmospheric life in years (NCASI 2005; Sharma 2007; Mohajan 2011, 2012b).

**Table 1: The GWP of six GHGs, Source: IPCC, 2001.**

Gas	GWP	Atmospheric Life (years)
CO <sub>2</sub>	1	5 to 200
CH <sub>4</sub>	21	12
N <sub>2</sub> O	310	114
HFC	140 to 11,700	1.4 to 260
PFC	6,500 to 9,200	10,000 to 50,000+
SF <sub>6</sub>	23,900	3,200

The potency of the greenhouse effect is a radiative force which measures how much the gas affects the balance of heat coming in and going out of the atmosphere. Positive radiative force warms the surface of the earth while negative forcing cools it and which can be expressed in watts per square meter, Wm<sup>-2</sup> (IPCC 2007). The combined radiative forcing of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O is +2.30 Wm<sup>-2</sup> compared to the radiative forcing of solar irradiance of +0.12 Wm<sup>-2</sup>. Oceans have warmed from surface of the sea to up to a depth of at least 3 km. It is estimated that absorbed 80% of the additional heat is added to the climate. Warmer water is taking more spaces of the sea than the colder water, so that sea level is rising alarmingly (Sharma 2007; Mohajan 2011 2012b).

### 3. GHG EMISSIONS FROM FOSSIL FUELS IN A SMALL INDUSTRY

#### 3.1 Heat Content of Fuels

Some countries of the world measure fuel according to its gross calorific value (GCV) or higher heating value (HHV), while other countries use net calorific value (NCV) or lower heating value (LHV). The distinction between GCV and NCV arises from the different physical states (liquid or gaseous) of water, which may be in following combustion. The GCV includes the latent energy of condensation of water following combustion. The NCV is computed for product water in the gaseous state. The latent energy of vaporization of water is deducted from the GCV. When a moist fuel is combusted, two sources of product water exist, the moisture present in the fuel and the water formed from the hydrogen in the fuel during the combustion. The NCV of a fuel at any moisture content can be determined as follows (Kitana and Hall 1989):

$$NCV = (1 - M_{wet}) (GCV_{solids} - \lambda (M_{dry} + 9H)), \tag{1}$$

where,  $NCV$  = net calorific value at any moisture content,  
 $GCV_{solids}$  = gross calorific value of dry fuel (zero moisture content),  
 $\lambda$  = latent heat of vaporization of water (2.31 MJ/kg at 25°C),

$M_{wet}$  = moisture content of fuel on a wet basis (expressed as a fraction),  
 $M_{dry}$  = moisture content of fuel on a dry basis (expressed as a fraction), and  
 $H$  = mass fraction of hydrogen in dry fuel (expressed as a fraction).

If the  $NCV$  be expressed in terms of dry fuel i.e., to the dry solids in the fuel, then it can be determined from the  $GCV$  of the dry fuel as follows:

$$(2) \quad NCV_{solids} = GCV_{solids} - 9\lambda H$$

where,  $NCV_{solids}$  = net calorific value of dry fuel (zero moisture content).

Equation (2) can be used to develop a relationship between  $NCV$  and  $GCV$  for biomass fuels on a dry basis. A hydrogen content value representative of many wood species is approximately 6% = 0.06 (Browning, 1975). A typical  $NCV_{solids}$  value for wood is 20 MJ/kg (IPCC, 1997). Hence (2) can be expressed as follows:

$$NCV_{solids} = 20\text{MJ/kg dry wood} = GCV_{solids} - 9 \times 2.31 \text{ MJ/kg water} \times 0.06,$$

$$(3) \quad GCV_{solids} = 21.25 \text{ MJ/kg dry wood.}$$

From (3) we an approximate relationship between  $NCV_{solids}$  and  $GCV_{solids}$  be as follows:

$$(4) \quad \frac{NCV_{solids}}{GCV_{solids}} = \frac{20}{21.25} \approx 0.95.$$

The relation (4) is only valid when the energy contents are expressed in terms of the dry fuel i.e., energy expressed in terms of biomass solids, such as 20 GJ NCV/ton dry wood.

### 3.2 GHG Emissions from Natural Gas Use at a Mill

Usually a mill uses natural gas in a small boiler and in several infrared dryers. Let the mill use 20 Mm<sup>3</sup> (million cubic meters) of natural gas. The mill decides to estimate the emissions from overall natural gas consumption instead of attempting to separate boiler emissions from the infrared dryer emissions. The mill does not know the carbon content of its gas supply, but the IPCC emission factor is 55.9 metric tons CO<sub>2</sub>/TJ (Tera joule). Let the mill use the CH<sub>4</sub> and N<sub>2</sub>O emission factors 5 kg CH<sub>4</sub>/TJ and 0.1 kg N<sub>2</sub>O/TJ and let it estimates the heating value of the natural gas to be 52TJ/kton and the density to be 0.673 kg/m<sup>3</sup>. The annual emissions being estimated as follows:

CO<sub>2</sub> emissions;

$$20 \times 10^6 \text{ m}^3 \text{ gas/y} \times 0.673 \text{ kg/m}^3 = 13.46 \text{ kton gas/y,}$$

$$13.46 \text{ kton gas/y} \times 52\text{TJ/kton} = 699.92 \text{ TJ/y, and}$$

$$699.92 \text{ TJ/y} \times 55.9 \text{ ton CO}_2/\text{TJ} = 39,125.53 \text{ ton CO}_2\text{e/y.}$$

CH<sub>4</sub> emissions;

699.92 TJ NCV/y × 5 kg CH<sub>4</sub>/TJ NCV = 3.4996 ton CH<sub>4</sub>/y.

Using the IPCC GWP of 21, this is equal to 73.491 ton CO<sub>2</sub>e/y.

N<sub>2</sub>O emissions;

699.92 TJ NCV/y × 0.1 kg N<sub>2</sub>O/TJ NCV = 0.069992 ton N<sub>2</sub>O/y,

Using the IPCC GWP of 310, this is equal to 21.7 ton CO<sub>2</sub>e/y,

Total GHG emissions = 39,125.53 + 73.491 + 21.7 = 39221 ton CO<sub>2</sub>e/y.

### 3.3 GHG Emissions from a Large Dry-bottom, Wall Fired Boiler Burning Pulverized Bituminous Coal Use at a Mill

Let the boiler produces 400,000 kg steam per hour. Over a year's time, the mills' records indicate that the boiler consumed 336,000 ton (370,000 short tons) of coal having a higher heating value (HHV), on average, of 13,000 Btu HHV/lb. The mill has information on the carbon content of the coal being burned in the boiler (80.1% carbon by weight). The mill decides that the default IPCC correction for unburned carbon in coal-fired boilers (2% unburned carbon) is appropriate. The IPCC Tier 2 emission factors for dry bottom, wall fired boilers burning pulverized bituminous coal are 0.7 kg CH<sub>4</sub>/TJ NCV and 1.6 kg N<sub>2</sub>O/TJ NCV. The mill applies the usual assumption that the NCV (or LHV) for coal is 5% lower than the GCV (or HHV).

CO<sub>2</sub> emissions:

336,000 Mg/y coal × 0.801 Mg carbon/Mg coal × 0.98 Mg carbon burned × 44Mg CO<sub>2</sub>/12 Mg carbon = 967 × 10<sup>3</sup> t CO<sub>2</sub>/y

CH<sub>4</sub> emissions:

370,000 short tons coal/y = 740 × 10<sup>6</sup> pounds/y,

740 × 10<sup>6</sup> pounds/y × 13,000 Btu HHV/pound = 9.62 × 10<sup>12</sup> Btu HHV/y for coal.

Given that LHV is 0.95 times HHV,

9.62 × 10<sup>12</sup> Btu HHV/y × 0.95 to correct to LHV = 9.14 × 10<sup>12</sup> Btu LHV/y,

9.14 × 10<sup>12</sup> Btu LHV/y × 1055 J/Btu = 9.64 × 10<sup>15</sup> J NCV/y = 9.64 × 10<sup>3</sup> TJ NCV/y.

CH<sub>4</sub> emissions = 9.64 × 10<sup>3</sup> TJ NCV/y × 0.7 kg CH<sub>4</sub>/TJ NCV = 6.75 × 10<sup>3</sup> kg CH<sub>4</sub>/y or 6.75 t CH<sub>4</sub>/y.

Using the IPCC GWP of 21 for CH<sub>4</sub>, this equals to 142t CO<sub>2</sub>e/y.

N<sub>2</sub>O emissions:

N<sub>2</sub>O emissions = 9.64 × 10<sup>3</sup> TJ NCV/y × 1.6 kg N<sub>2</sub>O/TJ NCV = 15.4t N<sub>2</sub>O/y.

Using the IPCC GWP of 310 for N<sub>2</sub>O, this equals to 4780t CO<sub>2</sub>e/y.

Total GHG emissions = 967,000 + 142 + 4,780 = 972,000t CO<sub>2</sub>e/y.

### 3.4 GHG Emissions from a Natural Gas-fired Lime Kiln

A 1,000 ton/day kraft mill has a single gas-fired lime kiln. The mills' records indicate that it used  $28.6 \times 10^6$  pounds of gas last year with a typical heat content of 21,000 Btu HHV/lb and a density of  $0.77 \text{ kg/m}^3$ . The IPCC  $\text{CO}_2$  emission factor for natural gas from boilers can be used for lime kilns since the  $\text{CO}_2$  emissions are a function only of gas composition. The IPCC  $\text{CO}_2$  emission factor for natural gas is  $55.9 \text{ tCO}_2/\text{TJ}$  (after correcting for 0.5% unoxidized carbon). For  $\text{CH}_4$ , the mill decides to use the only available emission factor for kraft mill lime kilns ( $2.7 \text{ kg CH}_4/\text{TJ}$ ) and assumes that  $\text{N}_2\text{O}$  emissions are negligible based on the IPCC discussion of temperatures needed to generate  $\text{N}_2\text{O}$ . The kiln's GHG emissions are estimated as follows (NCASI 2005):

$\text{CO}_2$  emissions:

$28.6 \times 10^6 \text{ pounds gas/y} \times 21,000 \text{ Btu HHV/lb} = 601 \times 10^9 \text{ Btu HHV/y}$ , for natural gas.

Given that LHV is 0.9 times HHV,

$601 \times 10^9 \text{ Btu HHV/y} \times 0.9$  (to convert to LHV) =  $541 \times 10^9 \text{ Btu LHV/y}$ ,

$541 \times 10^9 \text{ Btu/y} \times 1.055 \times 10^{-6} \text{ GJ/Btu} = 570,000 \text{ GJ/y} = 570 \text{ TJ/y}$ ,

$570 \text{ TJ/y} \times 55.9 \text{ t CO}_2/\text{TJ} = 31,900 \text{ t CO}_2/\text{y}$ .

$\text{CH}_4$  emissions:

$570 \text{ TJ/y} \times 2.7 \text{ kg CH}_4/\text{TJ} = 1540 \text{ kg CH}_4/\text{y}$ .

Using the IPCC  $\text{CO}_2$  equivalency factor of 21, this equals  $32 \text{ t CO}_2\text{e}$ .

$\text{N}_2\text{O}$  emissions:

IPCC's analysis of the temperatures needed to form  $\text{N}_2\text{O}$  in combustion processes suggests that it is unlikely that significant amounts of  $\text{N}_2\text{O}$  would be formed in lime kilns.

Total GHG emissions =  $31,900 + 32 + 0 = 31,900 \text{ tCO}_2\text{e/y}$ .

### 3.5 GHG Emissions when a Mill Operates with a Bark Boiler

A mill has a 250,000 kg steam/hour (550,000 pound/h) circulating fluidized bed (CFB) bark boiler. In a year, the boiler burns approximately  $6.9 \times 10^6 \text{ GJ}$  of bark and  $0.8 \times 10^6 \text{ GJ}$  of residual fuel oil. Because the boiler receives supplemental fossil fuel, it is necessary to estimate the  $\text{CO}_2$  from the fossil fuel use and the  $\text{CH}_4$  and  $\text{N}_2\text{O}$  emissions based on the total firing rate. The mill decides to use the IPCC emission factor for residual oil ( $76.6 \text{ tCO}_2/\text{TJ}$ , after correcting for 1% unoxidized carbon) and to estimate  $\text{CH}_4$  and  $\text{N}_2\text{O}$  emissions based on the total firing rate and the emission factors developed by Fortum on CFB boilers. The average emission factors found by Fortum are  $1 \text{ kg CH}_4/\text{TJ}$  and  $8.8 \text{ kg N}_2\text{O}/\text{TJ}$ .

$\text{CO}_2$  emissions from fossil fuel:

$0.8 \times 10^6 \text{ GJ/y} = 0.8 \times 10^3 \text{ TJ/y}$ ,

$0.8 \times 10^3 \text{ TJ/y} \times 76.6 \text{ t CO}_2/\text{TJ} = 61,300 \text{ t CO}_2/\text{y}$ .

$\text{CH}_4$  emissions:

Total heat input =  $6.9 \times 10^6 \text{ GJ/y} + 0.8 \times 10^6 \text{ GJ/y} = 7.7 \times 10^6 \text{ GJ/y} = 7.7 \times 10^3 \text{ TJ/y}$ ,

$7.7 \times 10^3 \text{ TJ/y} \times 1 \text{ kg CH}_4/\text{TJ} = 7,700 \text{ kg CH}_4/\text{y} = 7.7 \text{ t CH}_4/\text{y}$ .

Using the IPCC warming potential of 21, this equates to  $162 \text{ t CO}_2\text{e/y}$ .

$\text{N}_2\text{O}$  emissions:

Total heat input =  $7.7 \times 10^3$  TJ/y,

$7.7 \times 10^3$  TJ/y  $\times 8.8$  kg N<sub>2</sub>O/TJ = 67,800 kg N<sub>2</sub>O/y = 67.8 t N<sub>2</sub>O/y.

Using the IPCC warming potential of 310, this equates to 21,000 t CO<sub>2</sub>e/y.

Total CO<sub>2</sub> equivalents emitted = 61,300 + 162 + 21,000 = 82,500 t CO<sub>2</sub>e/y.

#### 4. GHG EMISSIONS FROM COMBINED HEAT AND POWER SYSTEMS

Where electricity is produced by combined heat and power (CHP) systems, it may be necessary to allocate the emissions from the CHP system to the various output energy streams. The efficiency method is one of three methods recommended by World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) (WRI and WBCSD 2004 a; b). Of the two methods the simplified efficiency method is less complex but involves several assumptions about equipment efficiencies. It is expected that the simplified method will be adequate for many mills. The detailed efficiency method is more complicated but can use site-specific design and operating data that companies sometimes have for CHP systems. We will discuss both methods in some details as follows:

##### 4.1 Simplified Efficiency Method

This efficiency method requires use of assumed efficiency factors for the production of power and steam, or actual efficiency factors for each steam or power generation device based on detailed process design and operating information. It is assumed that the efficiency of producing hot water is the same as the efficiency of producing steam. The simplest approach to applying the efficiency method is to assign a single efficiency factor to all power output and a single efficiency factor to all heat output. This information is used to compute an efficiency ratio equal to the heat production efficiency divided by the power production efficiency. For example, if the CHP system produces steam at 90% efficiency and power at 45% efficiency, then the ratio is 2. Emissions from the CHP system are allocated between the heat and power outputs, based on this ratio of efficiencies being as follows:

$$E_H = \frac{H}{H + P \times R_{eff}} \times E_T, \quad (5)$$

$$\text{where } R_{eff} = \frac{e_H}{e_P}.$$

Here,  $E_H$  = emissions share attributable to heat production, t GHG/y,

$E_T$  = total emissions from the CHP plant, t GHG/y,

$H$  = heat output, GJ/y,

$P$  = power output, GJ/y,

$R_{eff}$  = ratio of heat production efficiency to power production efficiency,

$e_H$  = assumed efficiency of typical heat production (default = 0.8), and

$e_P$  = assumed efficiency of typical electric power production (default = 0.35).

The emission share trait to electric power production is assigned from the following relation;

$$E_p = E_T - E_H, \quad (6)$$

where,  $E_p$  = emissions share attributable to electric power production.

#### 4.1a Total System Emissions with WRI/WBCSD Recommended Default Efficiency Factors for the USA (for simplified efficiency method)

Fuel-1:

Natural gas used in Fuel-1 section = 1538 m<sup>3</sup>/h.

CO<sub>2</sub> = 1538 m<sup>3</sup>/h × 0.039 GJ/m<sup>3</sup> × 55.9 kg CO<sub>2</sub>/GJ = 3353 kg CO<sub>2</sub>/h,

CH<sub>4</sub> = 1538 m<sup>3</sup>/h × 0.039 GJ/m<sup>3</sup> × 0.0006 kg CH<sub>4</sub>/GJ × 21 CO<sub>2</sub>e/CH<sub>4</sub> = 0.76 kg CO<sub>2</sub>e/h,

N<sub>2</sub>O = 1538 m<sup>3</sup>/h × 0.039 GJ/m<sup>3</sup> × 0.0001 kg N<sub>2</sub>O/GJ × 310 CO<sub>2</sub>e/N<sub>2</sub>O = 1.86 kg CO<sub>2</sub>e/h.

Total Fuel-1 emissions = 3356 kg CO<sub>2</sub>e/h.

Fuel-2:

Natural gas used in Fuel-2 section = 974 m<sup>3</sup>/h.

CO<sub>2</sub> = 974 m<sup>3</sup>/h × 0.039 GJ/m<sup>3</sup> × 55.9 kg CO<sub>2</sub>/GJ = 2123 kg CO<sub>2</sub>/h.

CH<sub>4</sub> = 974 m<sup>3</sup>/h × 0.039 GJ/m<sup>3</sup> × 0.0014 kg CH<sub>4</sub>/GJ × 21 CO<sub>2</sub>e/CH<sub>4</sub> = 1.12 kg CO<sub>2</sub>e/h.

N<sub>2</sub>O = 974 m<sup>3</sup>/h × 0.039 GJ/m<sup>3</sup> × 0.0001 kg N<sub>2</sub>O/GJ × 310 CO<sub>2</sub>e/N<sub>2</sub>O = 1.18 kg CO<sub>2</sub>e/h.

Total Fuel-2 emissions = 2123 + 1.12 + 1.18 = 2126 kg CO<sub>2</sub>e/h.

Total CHP system emissions  $E_T$  = 3356 + 2126 = 5482 kg CO<sub>2</sub>e/h.

Total system power output,  $P = P_1 + P_2 = 5 + 3 = 8$  MW.

Output heat,  $H = 15$  MW.

The efficiencies for power generation and for steam generation are used in the USA

respectively 0.35 and 0.8, then the ratio of efficiencies be,  $R_{eff} = \frac{0.8}{0.35} = 2.3$ .

$$E_H = \frac{15}{15 + 8 \times 2.3} \times 5482 = 2462 \text{ kg CO}_2\text{e/h}$$

= 20,681 tCO<sub>2</sub>e/y at 350 working days/year operation.

$$E_p = 5482 \text{ kg CO}_2\text{e/h} - 2462 \text{ kg CO}_2\text{e/h} = 3020 \text{ kg CO}_2\text{e/h}$$

= 25,368 tCO<sub>2</sub>e/y at 350 working days/year operation.

$$\text{Percentage of CHP emissions to heat output} = \frac{2462}{5482} \times 100 = 44.9\%.$$

$$\text{Percentage of CHP emissions to power output} = \frac{3020}{5482} \times 100 = 55.1\%.$$

These percentages can be used to allocate all GHG emissions from the CHP system. Emission factors can be developed for the energy outputs as follows:

Emission factor for CHP heat output = 2462 kg CO<sub>2</sub>e/h/15MW = 164.1 kg CO<sub>2</sub>e/MWh.

Emission factor for CHP power output = 3020 kg CO<sub>2</sub>e/h/8MW= 377.5 kg CO<sub>2</sub>e/MWh.

#### 4.2 Detailed Efficiency Method

Application of the relations in (5) and (6) to allocate GHG emissions among the energy outputs of a simple CHP system which includes only a single heat stream and a single electric power stream may be fairly straightforward. But many industrial CHP systems include multiple heat output streams and incorporate electric power production from multiple generators driven by different motive forces. To use the efficiency method to allocate GHG emissions among the multiple energy outputs of more complex CHP systems (5) and (6) can be modified to more general forms as follows:

$$E_{H_1} = \frac{\frac{H_1}{e_{H_1}}}{\frac{H_1}{e_{H_1}} + \frac{H_2}{e_{H_2}} + \dots + \frac{P_1}{e_{P_1}} + \frac{P_2}{e_{P_2}} + \dots} \times E_T, \quad (7)$$

$$E_{P_1} = \frac{\frac{P_1}{e_{P_1}}}{\frac{H_1}{e_{H_1}} + \frac{H_2}{e_{H_2}} + \dots + \frac{P_1}{e_{P_1}} + \frac{P_2}{e_{P_2}} + \dots} \times E_T \quad (8)$$

where,  $E_{H_1}$  = emissions share attributable to heat production as contained in steam stream-1,

$E_{P_1}$  = emissions share attributable to electric power production via generator-1,

$E_T$  = total emissions from the CHP plant,

$H_1$  = heat output contained in steam stream-1,

$H_2$  = heat output contained in steam stream-2,

$P_1$  = power output from generator-1,

$P_2$  = power output from generator-2,

$e_{H_1}$  = overall efficiency of producing heat contained in steam stream-1,

$e_{H_2}$  = overall efficiency of producing heat contained in steam stream-2,

$e_{P_1}$  = overall efficiency of producing electric power via generator-1, and

$e_{P_2}$  = overall efficiency of producing electric power via generator-2.

#### 4.2a Total System Emissions with WRI/WBCSD Recommended Default Efficiency Factors for the USA (for complex efficiency method)

We have obtained in the simple efficiency method;

Total Fuel-1 emissions,  $E_{F_1} = 3,356$  kg CO<sub>2</sub>e/h.

Total Fuel-2 emissions,  $E_{F_2} = 2,126$  kg CO<sub>2</sub>e/h.

The efficiency for  $P_1$ , the power output from the gas-fired turbine, has been estimated at 30% = 0.3 based on information from the manufacturer. Mechanical losses in the gas turbine are approximately 5% = 0.05, so the efficiency of producing the (waste) heat in the turbine exhaust,  $e_H = 1 - 0.05 - 0.3 = 0.65$ , or 65% and required heat,  $H = 10.83$  MW. The emissions from

combustion of fuel in the gas-fired turbine can now be allocated between  $P_1$  and the waste heat using (7) and (8), with one hour of operation as the basis for the calculations as follows:

$$E_H = \frac{\frac{H}{e_H}}{\frac{P_1}{e_{P_1}} + \frac{H}{e_H}} \times E_{F_1} = \frac{\frac{10.83}{0.65}}{\frac{5}{0.3} + \frac{10.83}{0.65}} \times 3356 = 1,678 \text{ kg CO}_2\text{e},$$

$$E_{P_1} = \frac{\frac{P_1}{e_{P_1}}}{\frac{P_1}{e_{P_1}} + \frac{H}{e_H}} \times E_{F_1} = \frac{\frac{5}{0.3}}{\frac{5}{0.3} + \frac{10.83}{0.65}} \times 3356 = 1,678 \text{ kg CO}_2\text{e}.$$

Development of efficiency factors for  $H_1$  and  $P_2$  are complicated by the fact that the CHP system incorporates two fuel inputs ( $F_1$  and  $F_2$ ). Steam energy produced in the heat recovery steam generator (HRSG) is derived from a combination of waste heat from the gas-fired turbine (heat that originated from part of the energy in fuel stream  $F_1$ ) and supplemental firing of natural gas. In allocating emissions associated with operating the HRSG, the exhaust from the gas turbine is treated as a fuel and the emissions allocated to this stream ( $E_{Heat}$ ) are added to the emissions associated with  $E_{F_2}$ , and these total emissions  $E_{F_2'}$  are allocated between  $H_1$  and  $P_2$ . The mill has information that indicates that the efficiency of the HRSG in converting the heat in the turbine exhaust gas into steam energy is 80%. The efficiency associated with combustion of the auxiliary fuel in the duct burner is 100%. This information can be used to develop an overall efficiency of the HRSG as follows:

$$eff_B = \frac{10.55}{10.55 + 10.83} \times 100\% + \frac{10.55}{10.55 + 10.83} \times 80\% = 90\%.$$

In the USA, the efficiency associated with  $H_1$  is equivalent to that of producing steam in the HRSG ( $H_s$ ), 90%. The mill has information indicating that the efficiency of the back pressure steam turbine in converting expansion into mechanical work (isotropic expansion efficiency) is 75%, and the generator which converts the mechanical work into electrical power is 95% efficient. Therefore, the efficiency of producing electrical power output  $P_2$  is given by:

$$eff_B \times eff_{Turbine} \times eff_{Generator} = 0.9 \times 0.75 \times 0.95 = 64\%.$$

$$E_{F_2'} = E_{F_2} + E_{Heat} = 2,126 + 1,678 = 3,804 \text{ kg CO}_2\text{e}.$$

$$E_{P_2} = \frac{\frac{3}{0.64}}{\frac{3}{0.64} + \frac{15}{0.9}} \times 3804 = 835 \text{ kg CO}_2\text{e},$$

$$E_{H_1} = \frac{\frac{15}{0.64} + \frac{0.9}{0.9}}{3} \times 3804 = 2,969 \text{ kg CO}_2\text{e.}$$

## 5. CONCLUDING REMARKS

In this paper we have shown the GHG emissions of mills with mathematical calculations in those use biomass and fossil fuels to run the mills. We have followed the techniques of the efficiency methods of World Resources Institute, World Business Council for Sustainable Development, National Council for Air and Stream Improvement, Inc. and Intergovernmental Panel on Climate Change. All the portions of the paper are given with detail and mathematical calculations. The readers can find a concept of total GHG emissions from a small mill. Calculations of GHG emissions from mills are given in various methods. We have used both SI and FPS units to calculate the GHG emissions. Factors called Global Warming Potentials have been developed, and used to convert a quantity of non-CO<sub>2</sub> greenhouse gas into an amount of CO<sub>2</sub> with an equivalent warming potential.

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## ACKNOWLEDGEMENT

Paper was presented in “1st International Conference on Global Sustainable development (1st ICGSD-2013), held on 27-28, February, 2013”.

Author(s) would like to thank the editors and anonymous referees for their comments and insight in improving the draft copy of this article. Author(s) further would like to declare that this manuscript is original and has not previously been published, and that it is not currently on offer to another publisher; and also transfer copyrights to the publisher of this journal.

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Received: 08-02-2013; Revised: 23-02-2013; Accepted: 30-12-2013; Published: 31-12-2013