GHG Inventory for Opencast Coal Mining in India Based on Stoichiometric Combustion of Diesel and Simulation of Ethanol-Diesel Blend for Emission Reduction

Ambasht Kumar and Suresh Pandian Elumalai

***Abstract*—Use of HEMMs in mining is predominant key activity which results in increased CO_2 emission and thus contributing to the GHG due to diesel combustion in engine cylinder of HEMMs. This study involves the theoretical estimation of theoretical CO_2 emission based on the stoichiometric combustion of diesel consumed during the mining in India. Moreover, ethanol-diesel blending was simulated and reduction in theoretical CO_2 emission due to different blending fraction was estimated based on total fuel consumption by opencast coal mining industry in India. According to this study the increasing trend of diesel consumption and associated theoretical CO_2 emission was observed due to opencast mining as compared to present scenario in India. Average percentage reduction of theoretical CO_2 emission for simulated ethanol-diesel blending fraction E5, E10, E20, E25, E35 and E40 are 1.95, 3.95, 7.76, 9.79, 13.82 and 15.80 % respectively.**

***Index Terms*—HEMMs emission, GHG inventory, diesel combustion, ethanol blending.**

I. Introduction

Climate change is among more discussed issues now a days. Greenhouse gases (GHG) are considerably contributing to the climate change due to global warming effect. CO_2 is one of the important GHG which is mainly contributed to the atmosphere due to anthropogenic activities [1]. Combustion of fossil fuel like diesel and gasoline are the main anthropogenic activity contributing to the CO_2 emission to the atmosphere.

Vehicular emission are of utmost concern now a days due to gaseous and particulate emissions [2]. During the recent years vehicular contribution to the CO_2 emission was found to be increasing [3]. Mining activities also includes the use of different heavy mining machineries. Generally, use of high speed diesel and their combustion inside the engine cylinder of heavy earth moving machineries (HEMMs) is the major cause of CO_2 emission due to mining.

Environmental concern due to emissions from combustion engines motivated the researchers to think about the possible alternative nonpetroleum fuels. Ethanol being a green, renewable and biodegradable fuel is used as an alternative fuel in combustion engines [4]-[7]. Different researchers tested the diesel engine fueled with ethanol–diesel blends to know the exhaust emission characteristics [8], [9]. Ethanol is blended with gasoline or diesel to control the engine exhaust emissions [10], [11].

This study is focused on the theoretical estimation of CO_2 emission based on the stoichiometric combustion of diesel consumed by the mining and quarrying industries in India. Ethanol and diesel blending was simulated to obtain different blending fraction and theoretical CO_2 emission factor was developed based on the stoichiometric equation. Further average percentage reduction in theoretical CO_2 emission for different blending fraction of blended fuel (BF) was estimated based upon the forecasted diesel consumption data.

II. Methodology

IPCC has reported various guidelines to estimate the GHG inventory for various sectors which are internationally accepted [12]. In this study, those guidelines are considered as the baseline for the GHG emission (mainly CO2) estimation. Detailed methodology for CO2 emission estimation is shown in Fig. 1.

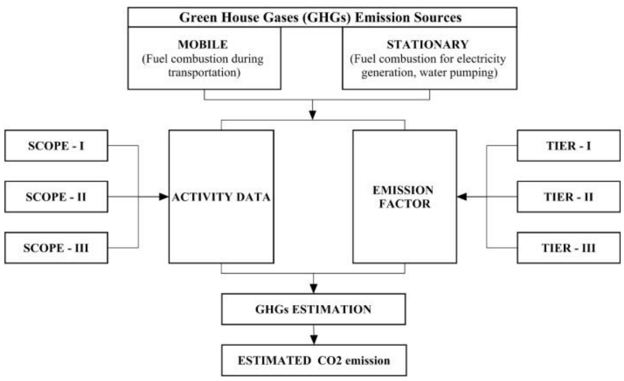

Fig. 1. Detailed methodology for CO_2 estimation based upon IPCC, 2006 guidelines.

Overall approach is divided in the different sections. First section deals with the collection of the activity data from various sources or activities. All these selections are based upon the different SCOPEs defined by the IPCC, 1996 guidelines [13] which are SCOPE- I, II & III. Another section deals with the consideration of the emission factor for different type of emissions based upon different category of activity. Emission factors are required to quantify the GHG emission by multiplying it with the corresponding activity data gathered from different category of sources. Selection of emission factor for specific activity of different categories is based upon the three approaches i.e. TIER-I, II & III, defined in the IPCC, 2006 guideline. Among all the approaches, activity data are directly multiplied with the activity data in

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A. Kumar and S. P. Elumalai are with the Department of Environmental Science and Engineering, Indian Institute of Technology Indian School of Mines, Dhanbad, Jharkhand, India (e-mail: ambashtict@gmail.com, espandian@iitism.ac.in).

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order to estimate the GHG emission inventory.

A. Activity Data

Theoretical Estimation of CO_2 emission based on the general stoichiometry equation of combustion inside internal combustion engine (ICE) requires different activity data. Initial requirement is type of fuel being used, Carbon (C) present in the fuel composition are mainly responsible for total amount of CO_2 emission. For this study purpose, stoichiometric combustion of diesel fuel ($C_{12}H_{23}$) and ethanol (C_2H_5OH) are considered to estimate the theoretical CO_2 emission rate. Moreover other major responsible factors are amount of available Oxygen (O_2) in air supplied during combustion, air-fuel ratio (A/F) supplied during combustion and type of combustion. Various activity data required for calculation purpose are listed below (Table I).

TABLE I: DETAIL OF ACTIVITY DATA REQUIRED FOR THE ESTIMATION OF STOICHIOMETRIC EMISSION OF CO_2

Type of fuel	Unit	Details	Source
Chemical formula of Diesel	--	$C_{12}H_{23}$	[14], [15]
Density of Diesel	kg/m^3	835	National Market
Cost of Diesel	Rs/liter	67	National Market
Thermal Energy (Calorific Content) of Diesel	kWh /kg	12.9	[16]
Chemical formula of Ethanol		C_2H_5OH	
Density of Ethanol	kg/m^3	782	National Market
Cost of Ethanol	Rs/liter	41	National Market
Thermal Energy (Calorific Content) of Ethanol	kWh/kg	8.3	[16]
Combustion type		Complete combustion	
Volume of Oxygen in Air	%	21	
Volume of Nitrogen in Air	%	79	

In this study coal production and fuel consumption data for the opencast coal mines in India are considered as the major activity (Table II). Coal production data during last two decade were collected from a report by Directorate General of Mines Safety (DGMS) [17]. Diesel consumption data for the opencast mining activity was estimated by multiplying the coal production data by specific fuel consumption (SFC) by diesel equipments like HEMMs. SFC for the diesel equipments in some of the opencast mines was reported by [18]. Average value of SFC by the diesel equipments was 2.835 liter per tonne of coal produced, which was used for calculation purpose. Diesel consumption during the mining operations mainly depends upon the total operating hours of the HEMMs, road gradients etc. Moreover trip distance is also one of the major factor in deciding the diesel consumption in dumpers. SFC are considered without including the influence of all of these factors along with various other factors of the country.

All the calculation are based upon the assumption of complete combustion of considered fuel. One kg of fuel was considered for calculation purpose. Air composition considered to contain mainly Oxygen and Nitrogen with volume percentage of 21% and 79% respectively. General stoichiometric equation used for hydro fuel combustion is given as below [19].

TABLE II: COAL PRODUCTION AND ESTIMATED DIESEL CONSUMPTION DATA IN THE OPENCAST COAL MINING INDUSTRY IN INDIA

Year	Average coal production* (million tonnes)	Diesel consumed (000 tonnes)
1991	167	395
1992	179	423
1993	187	443
1994	197	466
1995	216	511
1996	234	554
1997	248	586
1998	251	595
1999	247	585
2000	268	635
2001	277	657
2002	298	705
2003	316	747
2004	347	822
2005	357	845
2006	369	874
2007	419	991
2008	440	1042
2009	492	1165
2010	532	1259
2011	538	1274
2012	554	1311
2013	525	1242
2014	586	1388

*Only coal production by opencast mines in India. (Source: Statistics of Mines in India, volume-1 (Coal), 2014).

$$C_aH_bO_cN_d + \left(a+\frac{b}{4}-\frac{c}{2}\right)\left(O_2+\frac{79}{21}N_2\right) \rightarrow a\,CO_2 + \frac{b}{2}H_2O + 3.76\left(a+\frac{b}{4}-\frac{c}{2}+\frac{d}{2}\right)N_2$$

Total amount of theoretical Oxygen and Air required per kg of fuel combusted was calculated. Based upon those values theoretical CO_2 emission per kg of fuel combusted under stoichiometric condition was estimated.

TABLE III: SIMULATED ETHANOL BLENDING WITH DIESEL PER KG OF FUEL WITH VARYING PERCENTAGE

Ethanol Blending	Blending Percentage	Blending fraction (E - D)	
		Diesel	Ethanol
Notation	%	kg	kg
E0	0	1	0
E5	5	0.95	0.05
E10	10	0.9	0.1
E15	15	0.85	0.15
E20	20	0.8	0.2
E25	25	0.75	0.25
E30	30	0.7	0.3
E35	35	0.65	0.35
E40	40	0.6	0.4
E45	45	0.55	0.45
E50	50	0.5	0.5

A. Simulation for Diesel-Ethanol Blending

Blending of diesel with ethanol was simulated. Blending fraction during blending simulation was varied from 0 to 50 % mixing of ethanol with diesel. Mixing of ethanol with diesel was simulated at an interval of 5%. Thus the observed blending fraction of ethanol-diesel blending per kg of blended BF is tabulated below (Table III).

Blending of ethanol with diesel results in change in properties of the blended fuels with different BF. Some of the properties of the blended fuels with different BF are presented below (Table IV & V).

TABLE IV: CHANGE IN PROPERTIES OF BLENDED FUELS DUE TO BLENDING OF ETHANOL WITH DIESEL [20]

Blend fraction	Relative Density	Density	CV	Viscosity	Flash point	Pour point
		kg/m^3	MJ/kg	(mPa.S)	˚C	˚C
E0	0.8458	843.08	44.52	4.69	74	-36
E5	0.8365	833.81	43.63	4.49	24	-5
E10	0.834	831.32	43.19	4.25	25	-7
E15	0.8318	829.13	42.75	4.00	27	-10
E20	0.8314	828.73	41.87	3.87	25	-13
E25	0.8266	823.95	41.00	3.44	25	--
E30	0.8286	825.94	40.58	3.07	26	--

TABLE V: PHYSICAL AND CHEMICAL PROPERTIES OF BLENDED FUELS DUE TO BLENDING OF ETHANOL WITH DIESEL [21]

Fuel properties	Unit	Diesel	Blended fuel		
		E0	E5	E10	E15
Density at 15˚C	(kg/m^3)	837.3	834.3	831.7	829.4
Cloud point	(˚C)	-3	-3	19	21
Pour point	(˚C)	-9	-9	-12	-36
Flash point	(˚C)	66	25	25	25
CFPP	(˚C)	-8	-8	-7	-8
Lubricity WS 1.4	µm	448	399	406	395
Cetane index	--	51.8	--	--	--
FPT	--	1.02	1.01	1.01	1.01
Pressure/volume	(kPa/ml)	20/300	17/300	13/300	12/300
C content	(%w/w)	86.13	84.55	82.94	81.31
H content	(%w/w)	13.87	13.84	13.8	13.76
O content	(%w/w)	0	1.61	3.26	4.93
Kinematic viscosity at 40˚C	(mm^2/s)	2.78	2.53	2.31	2.19
Water content	mg/kg	50	100	130	140

These change in properties of the blended fuels also result in their combustion behavior and thus emissions after combustion. Various researchers reported about the effect on combustion, performance and exhaust emissions due to blending of ethanol with diesel fuel [22]-[24]. Blending fractions E5 to E20 of ethanol with diesel have acceptable properties for use as supplementary fuel to diesel engines [20]-[23].

B. Emission Factor

Theoretical CO_2 emission factor estimated using the stoichiometric equation during the complete combustion condition of hydrocarbon fuel is tabulated below (Table VI). Stoichiometric emission factor obtained for CO_2 emission was compared to the emission factor developed by different organisations like Intergovernmental Panel on Climate Change (IPCC) and Department for Environment, Food and Rural Affairs (DEFRA).

TABLE VI: THEORETICAL CO_2 EMISSION FACTOR ESTIMATED USING THE EQUATION FOR COMPLETE COMBUSTION OF DIESEL FUEL UNDER STOICHIOMETRIC CONDITION

Default Emission Factor	Stoichiometry	IPCC	DEFRA
kg of CO_2 per liter Fuel (Diesel)	2.640	2.550	2.717
kg of CO_2 per kg Fuel (Diesel)	3.162	3.054	3.254

C. Forecasting using ETS and HW Method

Forecasting for the total coal production and diesel consumption in opencast coal mining industry in India and associated theoretical CO_2 emission due to their stoichiometric combustion was performed using univariate ETS (Exponential Smoothing) and Holt-Winters (HW) forecast models through R [25]. These forecasting methods were performed for the available activity data to forecast the total coal production and diesel consumption in India due to opencast coal mining upto 2039.

III. RESULTS AND DISCUSSION

A. Forecasting of Coal Consumption

Forecasting trend of coal production by two different approaches is shown in Fig. 2. Mean of forecasted coal production through both the approach was used for predicting the diesel consumption by the opencast coal mining industry in India. Result reveals that coal production and thus associated diesel consumption in next two decades will be doubled as compared to the present scenario (Fig. 2).

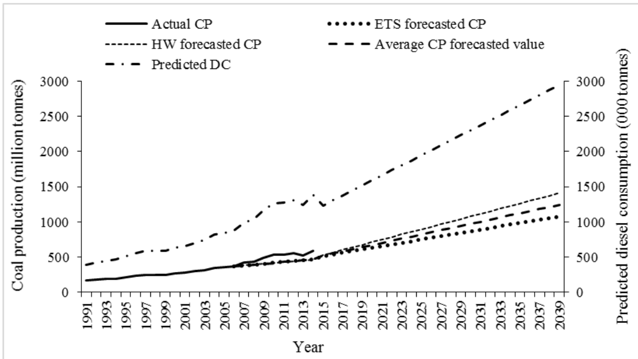

Fig. 2. Total coal production (CP) forecasts through ETS and HW forecast models for opencast coal mining and predicted diesel consumption (DC) in India upto 2039.

B. CO_2 Emission Prediction

Total amount of theoretical CO_2 emission due to opencast coal mining in India was estimated based upon the predicted total diesel consumption till 2039. Theoretical CO_2 emission for diesel consumption was estimated by multiplying the diesel consumption data of different years with the CO_2 emission factor due to complete combustion of diesel under stoichiometric condition. Further, CO_2 emission was estimated for the simulated fraction of ethanol and diesel blend. Comparison of predicted CO_2 emission till 2039 for diesel and blending fraction E5, E10, E20, E25, E35 & E40 are presented below (Fig. 3).

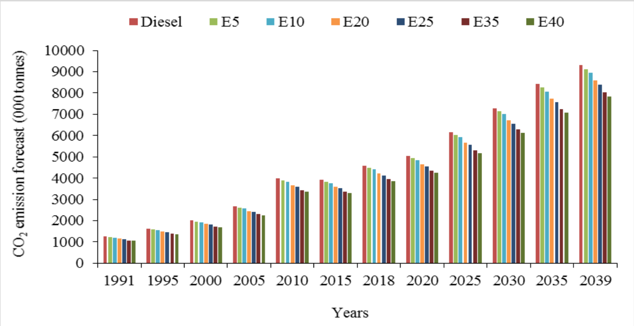

Fig. 3. Theoretical CO_2 emission prediction for the consumption of diesel and simulated ethanol-diesel blending fraction by opencast coal mining industry in India.

Theoretically interpreted result reveals that blending of ethanol to diesel in different fraction result in reduction in CO_2 emission. Average percentage reduction in CO_2 emission for different blending fraction (E5, E10, E20, E25, E35 and E40) as compared to diesel fuel is shown below (Fig. 4). Percentage reduction in CO_2 emission was more with increase of ethanol in blending fraction.

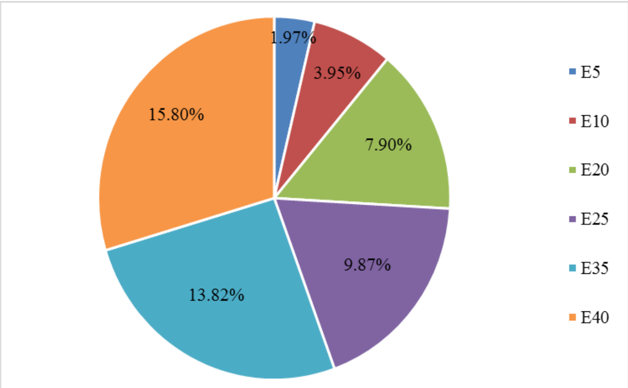

Fig. 4. Average percentage reduction in theoretical CO_2 emission based upon predicted diesel consumption and simulated ethanol-diesel blending fraction consumption for opencast coal mining in India.

C. Fuel Consumption and Cost Analysis per kWh Energy Produced

Theoretical reduction in CO_2 emission and increase in fuel consumption and cost for each blending fraction of ethanol – diesel BF per kWh of energy produced from blended fuel under stoichiometric condition is shown below (Fig. 5). Increase in BF consumption and cost per kWh of energy produced curves intercept at E40 which represents the optimum condition.

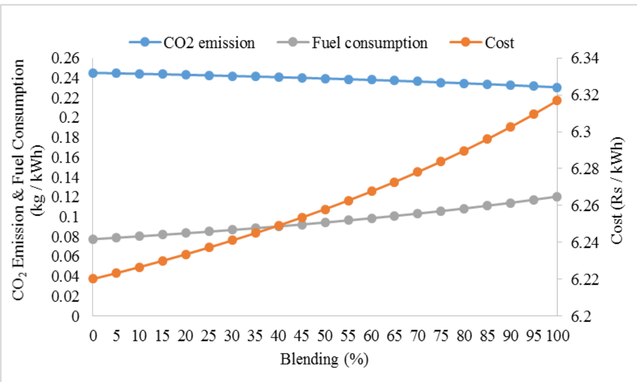

Fig. 5. Theoretical CO_2 emission, fuel consumption and fuel cost per kWh energy generation for the simulated ethanol-diesel blending fraction.

Simulated fraction of blending fuel shows that the percentage fuel consumption per kWh of energy produced under stoichiometric combustion increases with increasing fraction of blending fuel (Fig. 6).

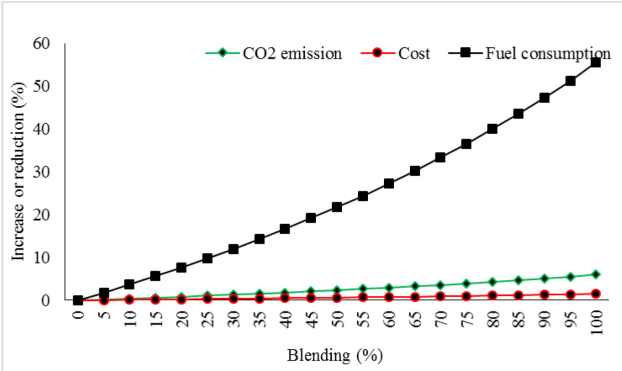

Fig. 6. Simulated impact (% increase or decrease per kWh) of ethanol and diesel blending on CO_2 emission (% decrease), fuel cost (% increase) and fuel consumption (% increase) per kWh.

IV. Conclusions

Forecast result shows the increasing trend of diesel consumption and associated CO_2 emission due to opencast coal mining as compared to present scenario in India. Average percentage reduction of theoretical CO_2 emission for simulated ethanol-diesel blending fraction E5, E10, E20, E25, E35 and E40 are 1.95, 3.95, 7.76, 9.79, 13.82 and 15.80 % respectively. Blending fuel fraction E40 found to be economical based on consumption and cost analysis per kWh of energy generation. According to this study use of blended fuel E40 will be more economical with 16 % (approx.) reduction in theoretical CO_2 emission. Whereas in practical E5 to E15 are the most suitable for the diesel engines based on the different literatures.

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Ambasht Kumar was born at Bokaro Steel City, Jharkhand, India on October 3rd, 1985. He completed his elementary education at Bokaro Steel City. He holds a B.E. degree in mechanical engineering from University of Rajasthan, Jaipur, Rajasthan, and a M.Tech. degree in environmental science and engineering from Department of Environmental Science and Engineering, Indian Institute of Technology (Indian School of Mines, Dhanbad, Jharkhand, India in 2016. At present he is pursuing Ph.D. in environmental science and engineering from Department of Environmental Science and Engineering, Indian Institute of Technology (Indian School of Mines, Dhanbad, Jharkhand, India. His field of study is development of emission inventory associated with mining activities, carbon foot printing and air pollution dispersion modeling. Mr. Kumar is an associate member of The Institution of Engineers (India).

Suresh Pandian Elumalai holds a B.Tech degree in chemical engineering from University of Madras, Chennai, Tamil Nadu in 2002, and a M. Tech. degree in environmental engineering from Pondicherry University, Puducherry, India in 2005 and Ph.D. from Indian Institute of Technology, Guwahati, India in 2011. Since then he is serving as an assistant professor in environmental science and engineering at the Department of Environmental Science and Engineering, Indian Institute of Technology, Indian School of Mines, Dhanbad, Jharkhand, India to till date. His major area of research are heterogeneous traffic emission and dispersion modeling, rain water analysis for air pollutants reaction, PM exposure dose, urban heat island effects and emission inventory.