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Country-Specific CO_2 and Non-CO_2 Emission Factor for Coal Electricity Generation in Malaysia

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Abstract

Malaysia's national greenhouse gas (GHG) emissions inventory for electricity generation utilises the default GHG emission factor values from the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines. Electricity generation is the key source of GHG emissions; hence, improvement in the emissions assessment through developing country-specific emission factors (EF) will increase the accuracy and further reduce the uncertainty of reported national GHG emissions. In 2019, the uncertainty of the total inventory without Land Use, Land-Use Change and Forestry (LULUCF) was ±15.12%, and the uncertainty in trend was ±12.70%, which is in the higher range. Thus, this study analysed 2017-2019, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emission factors from the stationary combustion of coal-fired power plants to develop the representative country-specific emission factor of the coal used in Malaysia using the fuel analysis and flue gas method. This study also supplements an assessment of relevant country-specific oxidation factors. The results indicate that the weighted average of each year for the CO_2 emission factor of Bituminous coal is lower than IPCC default values from 93,078 $kgCO_2/TJ$ to 93,224 $kgCO_2/TJ$, whilst Sub-Bituminous coal averages from 96,260 $kgCO_2/TJ$ to 96,714 $kgCO_2/TJ$ and Lignite coal higher than the IPCC values, from 101,720 $kgCO_2/TJ$ to 105,116 $kgCO_2/TJ$. In deriving the emission factor, the carbon content was lowest for Bituminous coal, followed by Sub-Bituminous coal, and significantly higher for Lignite coal. The CO_2 emission factors values analysed are 1% lower for bituminous coal and 1% to 4% higher for sub-bituminous coal and lignite compared with 2006 IPCC Guidelines default values. For Bituminous, the calculated emission factor of CH_4 is 0.1011 $kgCH_4/TJ$ and N_2O is 0.7047 kgN_2O/TJ. As for Sub-Bituminous, the calculated CH_4 emission factor is 0.0883 $kgCH_4/TJ$ whilst for N_2O is 0.9516 kgN_2O/TJ. The emission factor for Lignite's CH_4 is 0.0402 $kgCH_4/TJ$ and N_2O is 0.5563 kgN_2O/TJ respectively. The coal CH_4 and N_2O emission factors are lower than the Tier-1, fuel-based method suggested by the IPCC. The significant variations for coal depend on the differences between the producing regions and characteristics, chemical properties, and annual fluctuations in fuel quality. This study has shown that emission factors changed due to the variations of coal used by the power plant, either due to the carbon content or calorific value. This fact certainly will influence the decision-making process, affecting the choice of coal used in the power plants that will be included in future national energy systems.

1. Introduction

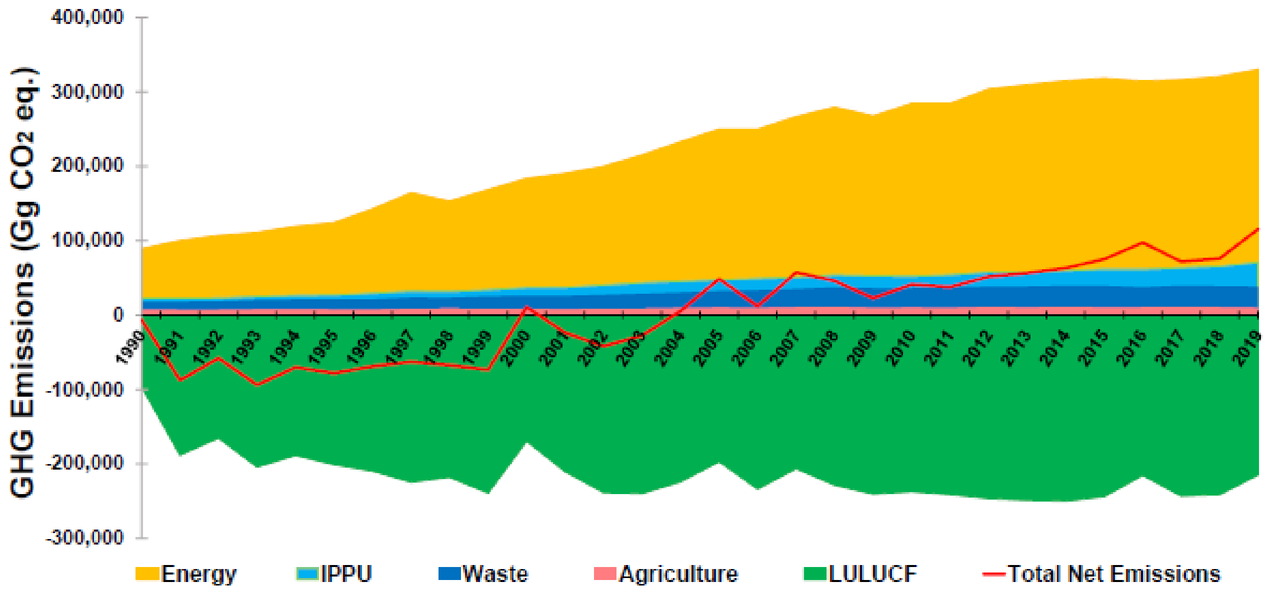
Climate change is evidence of increasing atmospheric GHG [1] through human-induced carbon dioxide emissions [2-4]. The primary sources are the combustion of fossil fuels from transport, buildings, and industrial and power plants. The main gases are CO_2, the most significant contributor to the greenhouse effect out of all the gases produced by human activities [5]. Besides CO_2, CH_4 and N_2O emissions are assumed to relate to combustion technology [1,6,7]. ICF report in 2017[8], stated that CH_4 is also present in the exhaust gas and is unburned gaseous, and the formation of N_2O level of N_2O emissions depends on the combustion temperature. Incomplete combustion is why most of the fuel carbon is not converted to CO_2.

The world electricity consumption is supplied from coal-fired power plants for about 40%-41% [9 -11] and they are forecasted to continue to provide a strategic share over the next three decades. The projections of coal in the foreseeable future will contribute to electricity generation by around 43% [10]. Due to growing concerns over the possible increases in CO_2 emissions, accurate estimates of CO_2 emissions are needed. The 2006 IPCC Guidelines propose the GHG emissions inventories calculation using IPCC emission factors; however, it recommends countries to develop emission factors through its calorific values, carbon content and oxidation factors that reflect their national features for calculating GHG emissions per country [12-13]. According to the U.S. Energy Information Administration (US EIA), their emission factors reflect the difference in the ratio of carbon to heat content by the rank of coal and State of origin, which improves the accuracy of estimates of carbon dioxide emissions, especially at State and regional levels [14]. Many countries, such as Korea, are actively establishing policies to reduce GHG emissions, which is vital in developing GHG emission factors [15-17]. India has also made limited efforts to measure plant-specific emissions of different gases and particulate matter to generate plant-specific emission factors [18]. IPCC default emission factor [12] and country-specific net calorific values (NCV) of Indian coal types were used [19]. Countries like Indonesia have a variation of coal rank and are concerned about the growth of CO_2 emissions caused by future coal-fired power plant development; thus, the characteristic of emission value becomes important [20].

Carbon dioxide (CO_2) emission varies systematically with the rank and type of coal combusted and also depends on the composition and characteristics. In developing country-specific emission factors, specific data such as the carbon content of the fuels used, carbon oxidation factors and fuel energy content are important. At higher tiers, the emission factors are determined by chemical analysis of carbon, and by measuring the net calorific value (lower heating value). By using carbon content and NCV, emission factor estimates can be expressed [19], [21-23], [24 - 27]. The fuel type will have the amount of carbon content translated into CO_2 emission factors. Indonesia's GHG emission factor, described by [20], has also been studied by referring to the IPCC Guidelines for the Energy sector. It highlights that higher carbon content results in a lower emission factor. This translated to higher heating values and carbon produced low emission factor.

The CO_2 emission factor for bituminous coal in Korea calculated by the fuel analysis method is 95,315 kg/TJ, which is 0.75% higher than the default value suggested by IPCC. Thailand's country-specific CO_2, NO_x, SO_2 and particulate matter emission factors were approximately 563.52, 1.26, 0.41 and 0.06 g/kWh respectively. Specifically for lignite, the CO_2 emission factor is 99.18 kg/GJ[28]. Indonesia's average CO_2 emission factor obtained in Indonesian coal is 99,718 kg CO_2/TJ with an average carbon content value of 27.2 kgC/GJ, and NCV equal to 19.8 TJ/Gg. Coal rank is categorized as lignite to sub-bituminous or bituminous [20].

The CH_4 and N_2O, carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs) are unburned gaseous combustibles that are emitted in small quantities due to incomplete combustion; more of these gases are released when combustion temperatures are relatively low. N_2O is emitted and produced directly from fuel combustion. The emission of N_2O is dependent on the temperature in the boilers. The highest N_2O emissions occur at a temperature of 1,000 degrees Kelvin. For combustion temperatures below 800 or above 1200 degrees Kelvin (980 to 1700 degrees Fahrenheit), the N_2O emissions are negligible [29]. However, non-CO_2, CH_4 and N_2O emissions vary with the type of fuel burned, the size and the vintage of the combustion technology [30-32] and also the maintenance and operation of combustion equipment and type of pollution control technology used. Figure 1 shows the trend of GHG emissions in Malaysia from 1990 until 2019, whereby the energy sector remained the largest contributor to emissions. It accounted for an average of 80.55% of the emissions from 2005 to 2019.



Source: Malaysia's Fourth Biennial Update Report, 2022

Fig. 1 *GHG emissions time series from 1990 to 2019*

Since the first Malaysia GHG emission inventory, the key source categories assessed that the energy industries are the most significant. The development of emission factors for this sector is highlighted as an important study to be conducted to reflect the actual GHG emissions. As also reiterated in the Malaysia Fourth Biennial Update Report, efforts are concentrated on improving the disaggregation and completeness of the activity data according to the 2006 IPCC Guidelines and developing country-specific emission factors for key categories. [33] In this regard, this study analysed the coal CO_2, CH_4 and N_2O emission factors as used in coal power plants in Malaysia, by performing the fuel and flue gas analysis. All coal power plants in Malaysia are assessed, and in addition, some of the plants in Malaysia used 2 types of coal, which shows that the correct estimation of GHGs is needed. Additionally, using default emission factor values as in Tier 1 becomes more questionable because some coal power plants in Malaysia operate by mixing coal from different origins and different types to meet the amount of energy needed to produce the required electricity. Primarily if countries use coal from various regions, CO_2 emission factors will vary with a larger range. The diversity of these fuel sources is the main reason for improving and adopting higher-tier methods in developing Malaysia's greenhouse gas emission inventory.

Table 1 *Coal fired power plants in Malaysia*

Coal	Combustion Technology	Installed Capacity (MW)
A	Sub Critical	2,070
B	Ultra SuperCritical	1,010
C	Ultra Supercritical	1,000
D	Sub Critical	1,486
E	Sub Critical	1,400
F	Sub Critical	2,100
G	Ultra Supercritical	1,000
H	Sub Critical	270
I	Sub Critical	210

2. Methodology

2.1 Site Selection

Nine coal power plants were examined to establish Malaysia's CO_2 and non-CO_2 emission factor as stated in Table 1. These coal plants which are baseload plants have different technology types either sub-critical boilers or ultra-super-critical boilers and are equipped with pulverized coal technology. Power plants in Malaysia use different qualities of coal, different combustion technologies and operating conditions whereby all coal is imported except for Coal H and I, where local coal is used. Classification of the Malaysia's coal type for this study refers to the coal rank and is further defined according to the definition of fuel types used in the 2006 IPCC Guidelines.

2.2 Methodology of Study

This study focused on 2 types of methodology, fuel and flue gas which referred to 2006 IPCC Guidelines in producing the country-specific emission factor. A total of 1,634 samples representing coal used in power plants, of which 534 coal Certificate of Analysis (COA) in 2017, 550 in 2018 and 559 in 2019 were analysed. Data for calculation and the identified sources and methodology associated with each analysis are divided into three categories: a) operational data, b) fuel data for CO_2, and c) flue data for non-CO_2.

2.3 Operational Data Method

For the operational category, data such as capacity, combustion technology, type of coal, consumption and generation is required, and the accessibility of data is provided by the power plant operator. The operational data and fuel data are needed to classify the coal type and emission factor, the weightage assignment of the emission factor.

2.4 Fuel Data Method

The CO_2 emission factor analysis is stated with the data from the Certificate of Analysis (COA) for coal supplied of each origin to power plants according to each shipment. It includes the ultimate analysis of coal that quantifies various elements present in the coal sample, including carbon, hydrogen, sulphur, oxygen, and nitrogen contents. The elemental content of the coal sample is usually presented in terms of the percentage of the mass fraction. The other important data is a proximate analysis of coal which involves the quantification of various elements present in the coal sample including moisture, ash, volatile matter, and fixed carbon contents. Other parameters that are also considered for the development of the GHG emission factor are the gross calorific values which then convert to net calorific values.

Coal condition requirements are important to analyse the conversion of coal composition to derive the emission factor. Appropriate methods published by a consensus-based standards organization, i.e. American Society for Testing and Materials (ASTM) D3180 are used. The determination of the first parameter which is the coal carbon content is based on the results of fuel sampling and analysis received from the fuel supplier, using the most appropriate method published by a consensus-based standards organization, i.e. ASTM D5373 & ISO 29541:2010. At higher tiers, the emission factors are determined by chemical analysis of carbon, and with fuels from measuring the net calorific value (lower heating value) where the As Received condition is used.

The second parameter which is the heating value can be either represented by Higher Heating Value (HHV) or Lower Heating Value (LHV). This study is converted from Gross Calorific Value (GCV) to NCV using known fuel characteristics (moisture, hydrogen, and oxygen contents). According to International Organization for Standardization (ISO) in As Received figures, it refers to the World Coal Institute where the Conversions of Gross/Net in MJ/kg: $NetCV = GrossCV - 0.212H - 0.0245M - 0.008Y$. M represents the percentage of Moisture, H represents the percentage of Hydrogen, and Y represents the percentage of Oxygen (from ultimate analysis, which determines the amount of carbon, hydrogen, oxygen, nitrogen and sulphur) (i.e. includes Total Moisture (TM)).

2.4.1 Coal CO_2 Emission Factor

In this study, emission factor equations are sourced from the Korean National GHG Emission and Absorption Factor Development and Verification 1st Plan Report (Aug. 2014), as stated in Equation 1. For different coal types, the CO_2 emission factor (EF) is generally defined as follows:

$$EF_{i,CO_2} = \frac{C_{ar,i}}{EC_i \times 3.664 \times 10^6} \tag{1}$$

In Equation 1, EF_{i,CO_2} is the CO_2 emission factor for fuel (i) in (kgCO_2/TJ-fuel), whereby 3.664 represent the Molecular weight of CO_2 (44.010) / Atomic weight of Carbon (12.011); $C_{ar,i}$ represents the Mass fraction of Carbon in fuel (i) (As received basis, between 0 and 1) and EC_i represents the Calorimetric number of fuel (i) (Net fuel calorific value, MJ/kg-fuel).

As parameters of $C_{AR,i}$ and EC_i are required to be in as received basis, these values would include the total moisture percentage and hydrogen content percentage in the emission factor. Both parameters are determined from laboratory analyses. In addition, the oxidation factor measures the percentage of carbon that is actually oxidized when combustion occurs. The oxidation factor is used to calculate the amount of fuel contributing to carbon dioxide emissions, which is also estimated in this study based on the most used coal in the country.

The oxidation factor calculation is based on Equations 2 and 3, sourced from Fott, 2006 [34]. The carbon content in ash C $A_{noncomb}$ (the so-called unburned carbon) must be reduced to the total weight of the raw fuel $Cr_{noncomb}$.

$$Cr_{noncomb} = A_r \left[\frac{C_{Anoncomb}}{(1 - C_{Anoncomb})}\right] \quad (2)$$

where A_r is the ash content in the raw fuel. As in the previous cases, the quality characteristics of the fuel are expressed in the equations by weight fractions. The oxidation factor is further calculated as the ratio of the weight fractions of the burned and total carbon contained in the raw fuel as in Equation 3.

$$fox = \left(\frac{C_{rcomb}}{C_r}\right) = 1 - \left(\frac{C_{rnoncomb}}{C_r}\right) \quad (3)$$

2.5 Flue Data Method

The non-CO_2 sample data were obtained using the direct measurement method which involved a stack sampling and actual measurement of the gas concentration as stated in Figure 2. The measurement was conducted at each of the power plant stacks. The gas concentration data were captured through a measurement taken every 3 minutes within 40 minutes with 3 complete cycles 12 times at each stack to represent the sampling of gases. The portable gas analyser produced the data during measurement and the parameters required for the calculation consist of a concentration of CH_4 and N_2O in [mg/Nm^3] with Lower Detection Limit (LDL) consideration and Volume of Oxygen (O_2) [%]. The measurement involved the identification of released greenhouse gas concentrations along with the heating value of the fuel at that time. The measurement activities were done using (Fourier Transform Infrared spectroscopy) FTIR technique. For all the samples chosen, every stack must be involved in the measurement and compliance with BS-EN 15259, EPA 320 and EPA 18 standards as mentioned. For every power plant involved, flue gas sampling must be done from all the chimneys in the plant. Based on the power plants involved in sampling, the minimum sampling frequency of flue gas from each plant is once every month. Hence, a total of 12 measurements were conducted over a 1-year duration.

2.5.1 Coal Non-CO_2 Emission Factor

Additionally, there are several parameters required to perform the non-CO_2 emission factor such as Fuel Gross Calorific Value (GCV)/Fuel Net Calorific Value (NCV)/High and Low Heating Value (HHV and LHV) and Ratio of types of coal in energy [MJ/kg]. The non-CO_2 emission factor was derived as per Equations 4 and 5 based on direct measured emissions utilising the equations from the National Greenhouse Gas Inventory Report of Japan (Apr. 2015, in which $EF_{CH4/N2O}$ represents the CH_4/N_2O emission factor (kgCH_4 / TJ or kgN_2O / TJ). The emission factor from flue gas analysis is obtained by using the calculated volumetric flow rate value.

$$EF_{CH_4} = \frac{C_{CH_4} \times [G_0 + (m-1)A_0] mw_{CH_4}}{\frac{V_m}{NCV}} \quad (4)$$

$$EF_{N_2O} = \frac{C_{N_2O} \times [G_0 + (m-1)A_0] mw_{N_2O}}{\frac{V_m}{NCV}} \quad (5)$$

Where, m = 21 / (21 - CO_2). In Equation 4 and 5, the $EF_{CH4/N2O}$ is the emission factor for CH_4 or N_2O emission factor (kg/TJ), whereby, $C_{CH4/N2O}$ represent the CH_4 or N_2O concentration in exhaust gas (ppm), G_0 represent the theoretical exhaust gas volume for each fuel combustion (dry) (m^{3}N), A_0 represent the theoretical air volume for each fuel combustion (m^{3}N), m represent the air ratio (actual air volume divided by theoretical air volume), $mw_{CH4/N2O}$ represent the molecular weight of measured gas (constant at 16 g/mol for CH_4 or 44 g/mol for N_2O)

(g/mol), V_m represent one mole ideal gas volume in standardized condition (constant at 22.4 x 10^{-3} m^3/mol) (m^3/mol), NCV for each fuel combustion (MJ) and CO_2 represent the O_2 concentration in the exhaust gas (%).

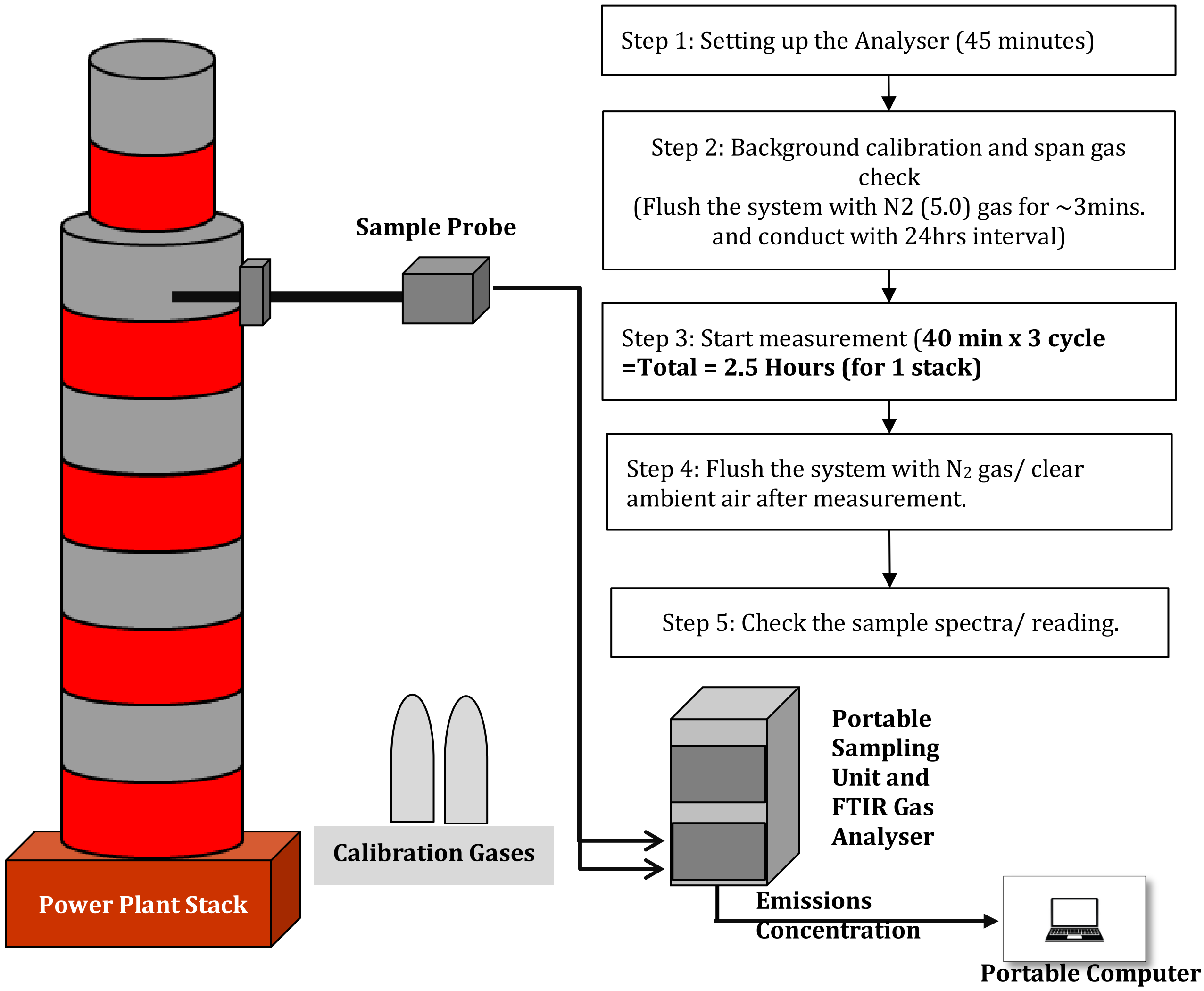


Fig. 2 *Schematic Diagram of Direct Measurement for Non-CO_2 emissions concentration*

2.6 Country Specific of CO_2, CH_4 and N_2O Emission Factor

As referred in the previous sections, from both methods, the uniform country-specific emission factor value is derived from the averaging of each data point produced by each power plant considered in the study. As such, different emission factors are produced for each type of emission gas from coal plants through both fuel analysis and flue gas measurement. A weighted average calculation method is utilized as in Equations 6 and 7:

$$\boldsymbol{Power\ Plant\ EF_{CO_2/CH_4/N_2O}} = \sum \frac{[(EF_{daily}) \times (weight_{daily})]}{(weight_{daily})} \quad (6)$$

$$\boldsymbol{Country\ Specific\ EF_{CO_2/CH_4/N_2O}} = \sum \frac{[(EF_{plant}) \times (weight_{plant})]}{(weight_{plant})} \quad (7)$$

Equation 6 describes the yearly average emission factor for one individual power plant based on the average of daily emission factors calculated from available data. On the other hand, Equation 7 summarizes the averaged emission factor for the country based on the yearly averages of power plants involved in the study. Calculation of the country-specific CO_2, CH_4 and N_2O emission factors is based on aggregated data from each power plant included in the study with weightage placed according to fuel consumption.

2.7 Quantifying Uncertainty

In terms of the emission factor, the standard deviation for the calculated factor averages can be determined using Equation 8:

$$Power\ Plant\ EF\ \sigma\ CO_2/\ CH_4/N_2O = \left[\sum \frac{[(EF\ i - EF\ ave,\ plant)2]}{(N-1)}\right]\frac{1}{2} \tag{8}$$

Symbols used in Equation 8 along with their definitions and units are listed as follows:
EF σ $CO_2/CH_4/N_2O$ - uncertainty of CO_2, CH_4, or N_2O emission factor for data obtained from power plant, [kg/TJ],
EFi - emission factor for the combustion fuel at data point i, calculated per shipment or daily or monthly, [kg/TJ],
EFave, plant - average emission factor of the power plant for the entire set of i data points, [kg/TJ]; and
N - total number of data points for the power plant

The difference between EFi and EFave is called variance and is calculated for every data point included in the emission data population. According to 2006 IPCC Guidelines, good practice requires the use of a 95 percent confidence interval for quantification of random errors. This may also be expressed as a percentage of the central estimate. Assuming a uniform probability density function, the confidence interval can be conveniently expressed as plus or minus half the confidence interval width divided by the estimated value of the variable (e.g., ± 10%). For normal distributions the 95 percent confidence interval would be plus or minus twice the estimated standard deviation of the population, as described in Equation 9:

$$Ui\ CO_2/CH_4/N_2O = 2\sigma CO_2/CH_4/N_2O \tag{9}$$

2.7.1 Methods to Combine Uncertainties

Combination of uncertainties is conducted when values that are contained in the uncertainties are used to calculate other values. For addition or summation operations involving values that have uncertainties attached, the uncertainties themselves can be resolved by Equation 10 and 11 which referred to the 2006 IPCC Guidelines.

$$U\ Total = [U12 + U22 + Ui2 + .. + Un2]\frac{1}{2} \tag{10}$$

Similarly, multiplication operations of uncertainties are calculated in Equation 11 with the use of multiplication factors:

$$U\ Total = \frac{[(U1 \times 1)2 + (U2 \times 2)2 + (Ui \times n)2]\frac{1}{2}}{|X1 + X2 + Xi + .. + Xn|} \tag{11}$$

Symbols used in Equation 10 and 11 along with their definitions and units are listed as follow:

- U total - percentage uncertainty in the sum or product of the quantities half the 95 percent confidence interval divided by the total and expressed as a percentage), [unit of the calculated quantity];
- U i, n - uncertain quantity being calculated, [unit of the calculated quantity]; and
- X i, n - percentage of uncertainties associated with the final quantity, [-]

As parameters of CAR,i and ECi are required to be in as received basis, these values would include the total moisture percentage and hydrogen content percentage in the emission factor. Considering xi as the weight values as in Equation 7, Equation 11 can be used to calculate the uncertainty for the country-specific greenhouse gas emission factor.

2.8 Verification

The verification process involved thorough checks on data health – pertaining consistency of data, existence of data, formula, and format. Verification is organized into two main groups as per below:

i. Certificate of Analysis / Certificate of Arrival – coal fuel data.
ii. Flue gas measurements (Gasmet® DX4000 flue gas analyser) – for non-CO_2 emissions for all plants.

The verification for coal samples from January to September 2019 consisted of analytical testing activities which involved sample preparation, calorific value determination, proximate analysis and ultimate analysis. TNBR Fuels and Combustion Unit carried these out according to various ASTM procedures. The verification for the non-CO_2 emissions (CH_4 and N_2O) and assessment process was structured by dividing the process into three sections, i.e., identification, screening, and eligibility. The identification process involved identifying the number of samplings, the source of samplings, assessing the accuracy of SI unit for each dataset and assessing the consistency of the equation utilised for the determination of emission factor. The screening process involved the assessment of any irregularities and missing metadata in both primary and secondary datasets. Meanwhile, the eligibility process evaluated the value of calculated emission factors by comparing the values with the range of default emission factors set by IPCC 2006 for the respective N_2O and CH_4 gases.

Benchmarking and expert review were then conducted after the data analysis had been implemented, comprising of the assessment of data, calculations and processes which were meant to determine that the greenhouse gas emissions developed were representative, accurate, complete, consistent, relevant, and transparent. The benchmarking is conducted against the other countries values, IPCC default factors and other published values. In the Expert review process, Experts from local and international universities who have a background in the GHG emission inventory process and have related work on IPCC GHG emission inventory will be conducting this process. The process involved the review of methodology and approach, data analysis and assessment the emission factors as well as comparing emission factor values to assure that there are no material discrepancies between what is claimed and what occurred.

3. Results and Discussion

The CO_2 emissions from fuel combustion depend on the amount of carbon in the fuel, specifically on the fuel type and grade. Assessment of the emissions are accurate estimates based on information on the amount of fuel combusted and fuel-specific emission factors as mostly all carbon in the fuel is typically oxidized in combustion. CO_2 emission factors vary considerably depending on the coal's composition of carbon, hydrogen, sulphur, ash, oxygen and nitrogen, and the weightage consumption. However, for the purpose of emission factor calculation, the carbon content and the lower heating value (net calorific value) and the percentage of carbon oxidised are important. The calculated oxidation factor is used and derived for the country-specific emission factor.

3.1 Coal Classification

All coal power plants in Malaysia except for 2 power plants as described in Section 2 used imported coal from countries such as Indonesia, Australia, and other coal-producing countries. This study includes a total of 5 origins, namely Indonesia, Australia, Russia, South Africa and from domestic. In total, 50 over brands were used in the power plants. Figure 3 & 4 shows the coal used from its origin and the coal properties from 2017-2019 for the nine power plants in this study. The most used coal every year originates from Indonesia at 59%-60%, Australia, at 21%-22, Russia, at 10%-11% and South Africa at a percentage less than 3%.

The classification of the different types of coal used in Malaysia was further defined as stated in Section 2 following the 2006 IPCC Guidelines. Table **2** shows the definition and reference of gross calorific value used for Malaysia coal classification. The low calorific value is dominated by low-rank coal from the class of lignite. The medium to very high calorific value is composed normally of sub-bituminous to bituminous coal.

Coal power plants in Malaysia generally use bituminous and sub-bituminous types of coal, with lignite making up a small percentage. From the assessment, specific profiles are derived for the different grades of coal produced in the origin countries. In each case, the assessment of the emission factor involves the carbon content figures and net calorific values which refer to the original substance. Figures 5 – 10 indicate the 2017-2019 carbon content and NCV for bituminous, sub-bituminous, and lignite coal for various coal origins.

In 2017, the bituminous coal average carbon content (25.66 -26.50 kg/GJ) and net calorific value (24.51-24.95 MJ/kg) observed from Australia, Russia and South Africa, sub-bituminous coal average carbon content (25.22 - 26.50 kg/GJ) and net calorific value (20.02-25.44 MJ/kg) from Indonesia and Australia and lignite average carbon content (29.15 - 30.77 kg/GJ) and net calorific value (15.25-15.59 MJ/kg) from Local_1 and Local_2. The maximum carbon content shows the highest range from lignite (Local_1 and Local_2) followed by bituminous (Australia, Russia, and South Africa) and sub-bituminous, Indonesia and Australia.

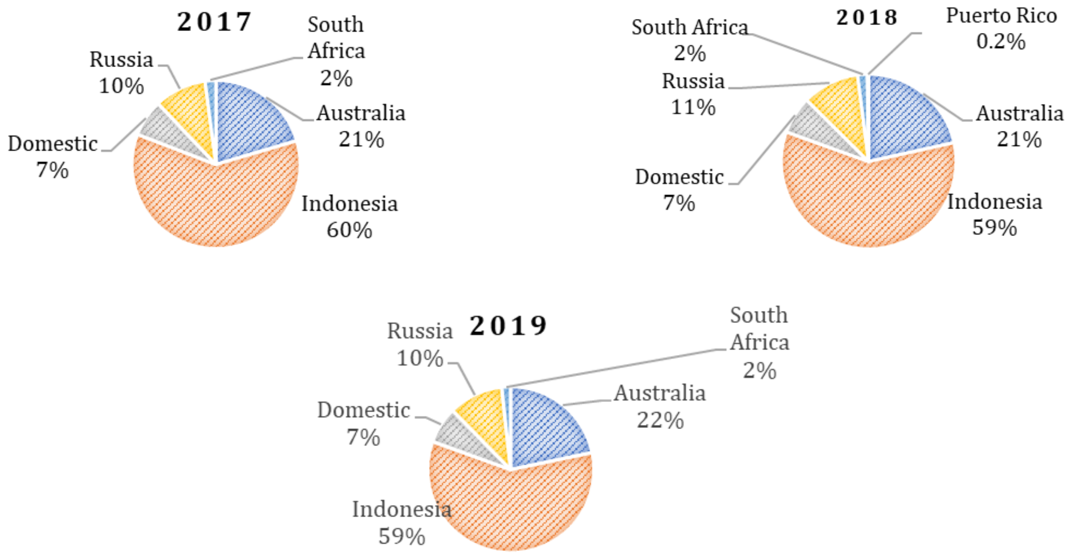


Fig. 3 *Coal consumption (%) based on coal origin from 2017-2019 for nine power plants*

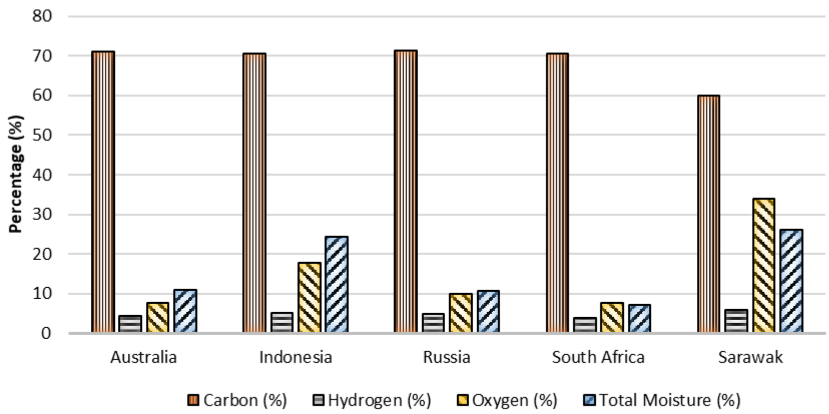


Fig. 4 *Coal properties (%) based on coal origin from 2017-2019 for nine power plants*

Table 2 *Definition and reference of GCV for Malaysia's coal classification*

No.	GCV (kCal/kg) (Definition of Fuel Types Used in 2006 IPCC Guidelines)	Coal Type Define/Classified in this study	2017	2018	2019
1.	Bituminous - GCV is greater than 23 865 kJ/kg (5 700 kcal/kg) on an ash-free but moist basis.	Bituminous	6,158	6,194	6,205
2.	Sub- Bituminous - Gross calorific value between 17 435 kJ/kg (4 165 kcal/kg) and 23 865 kJ/kg (5 700 kcal/kg) containing more than 31 percent volatile matter on a dry mineral matter free basis.	Sub-Bituminous	5,141	5,171	5,272
3.	Lignite - Gross calorific value of less than 17 435 kJ/kg (4 165 kcal/kg), and greater than 31 percent volatile matter on a dry mineral matter free basis.	Lignite	4,060	3,947	4,251

Note: As received basis

Notes: 1. B- Bituminous, 2. SB-Sub-Bituminous, 3. L-Lignite, 4. CC-Carbon Content, 5. NCV- Net Calorific Value

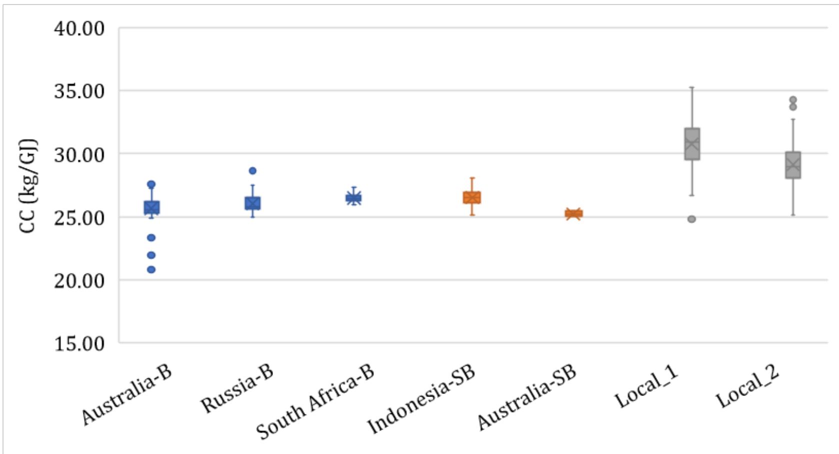


Fig. 5 *Coal carbon content in 2017 from various origin*

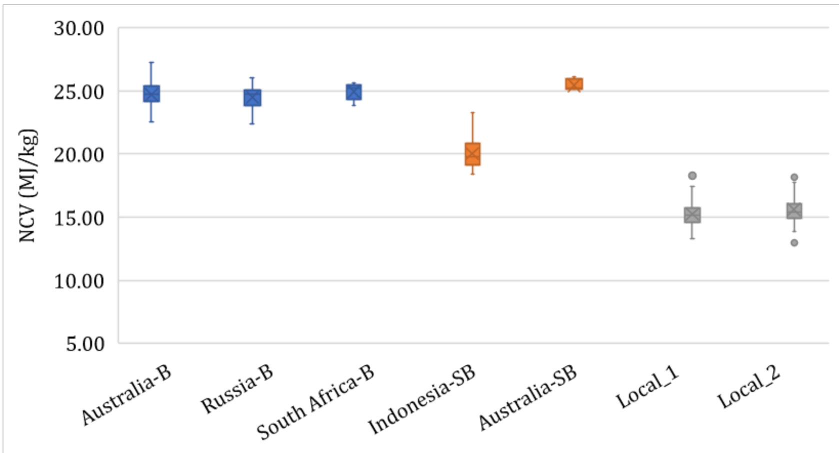


Fig. 6 *Net calorific value in 2017 from various origin*

The 2018 coal profile analysis of bituminous coal from Australia and Russia shows average carbon content of 25.49 to 25.63 kg/GJ, net calorific value of 23.85 -24.75 MJ/kg, sub-bituminous coal shows average carbon content of 25.45 – 26.49 kg/GJ, net calorific value from (20.20 -24.86 MJ/kg) from Indonesia and Australia, and lignite coal shows average carbon content of 29.84 -32.17 kg/GJ, net calorific value of 14.62 -15.23 MJ/kg from Local_1 and Local_2. The maximum carbon content shows the highest range from lignite (Local_1 and Local_2) followed by bituminous (Australia,) and sub-bituminous, Indonesia and Australia.

In 2019, the bituminous coal average carbon content (25.39 -25.72 kg/GJ) and net calorific value (23.40-24.93 MJ/kg) observed from Indonesia, Australia, Russia and South Africa, sub-bituminous coal average carbon content (25.37 -26.40 kg/GJ) and net calorific value (20.37-25.02 MJ/kg) from Indonesia, Russia and Australia and lignite average carbon content (29.71-29.74 kg/GJ) and net calorific value (15.54-15.86 MJ/kg) from Local_1 and Local_2. The maximum carbon content shows the highest range from lignite (Local_1 and Local_2) followed by sub-bituminous (Indonesia, Russia, Australia) and bituminous, Indonesia, Australia, Russia and South Africa.

The profile from each region or origin is combined based on each coal type which shows in Figure 11-13. It shows the cluster of carbon content and net calorific value from Indonesia, Australia, Russia, South Africa, Local_2 and Local_1, for bituminous, sub-bituminous and followed by lignite coal. The results show that the carbon and heating values of each coal type have different sets of values. This finding highlighted that the bituminous carbon content is in the range of 25.49 -25.54 kg/GJ and net calorific value is from the range of 24.8 - 24.95 MJ/kg for each year. The sub –bituminous carbon content is in the range of 26.34 -26.48 kg/GJ and net calorific value is from the range of 20.15 – 20.57 MJ/kg for each year, whilst the lignite is in the range of 28.25 - 29.18 kg/GJ and net calorific value is from the range of 15.09 – 15.39 MJ/kg for each year. This difference can be explained by the known rank of coals from the same mine or location.

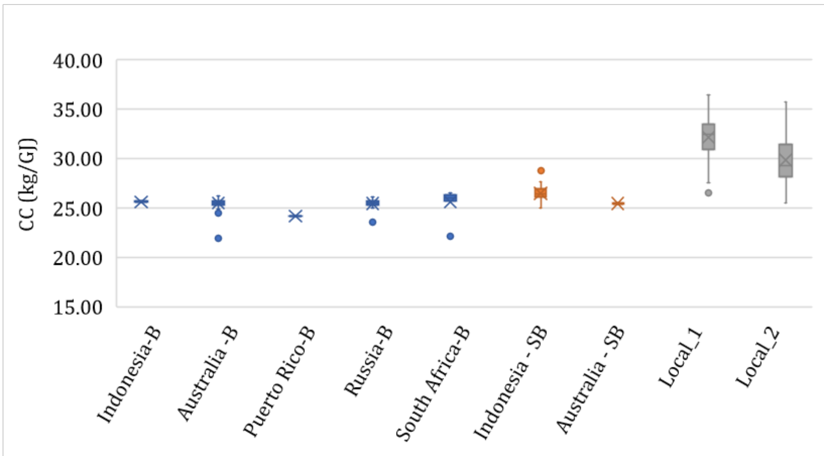


Fig. 7 *Coal carbon content in 2018 from various origin*

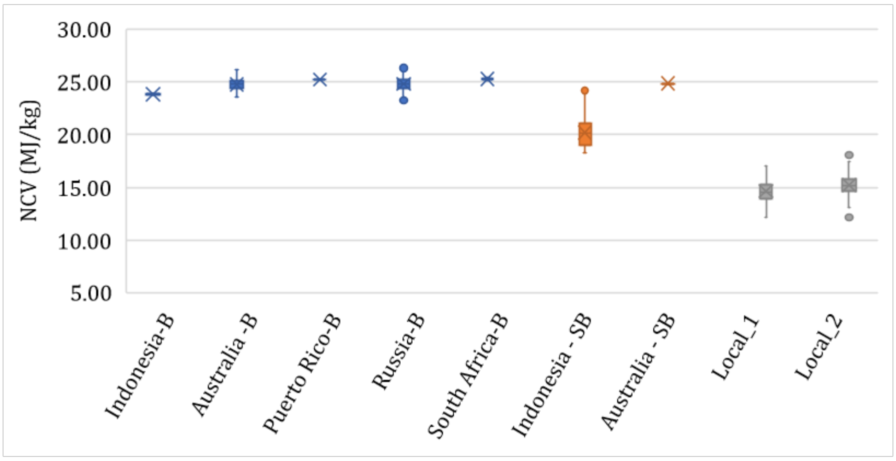


Fig. 8 *Net calorific value in 2018 from various origin*

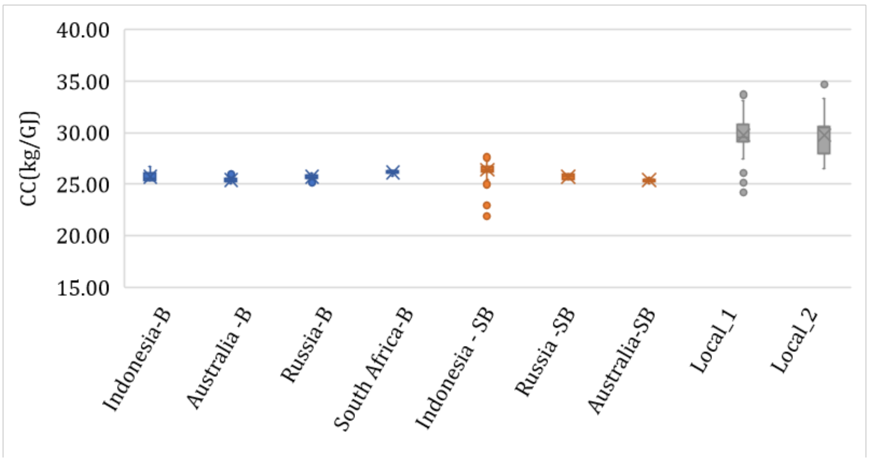


Fig. 9 *Coal carbon content in 2019 from various origin*

Table 3 provides the summary of coal carbon content, net calorific value and oxidation factor derived from 2017 to 2019. The bituminous carbon content is in the range of 25.49-25.54 kg/GJ and the net calorific value is in the range of 24.8-24.95 MJ/kg for each year. The sub-bituminous carbon content is in the range of 26.34-26.48 kg/GJ and the net calorific value is in the range of 20.15-20.57 MJ/kg for each year, whilst the lignite is in the range of 28.25-29.18 kg/GJ and net calorific value is from the range of 15.09-15.39 MJ/kg for each year. This difference is explained by the rank of coals from the same mine or location. In computing the oxidation factor, the analytical content of carbon in the initial fuel and in the ash, which is created after the fuel is burned in the given facility (ash, fly ash, clinker), was used. For coal, the unburned carbon in the fly ash was determined at each plant which represents the carbon that remained in the ash unburned. The weight fractions of carbon in the fuel were determined and then the oxidation factor was calculated. The oxidation factor values for solid fuels are slightly lower than the existing 2006 IPCC, which gives 1 for solid fuels as default values.

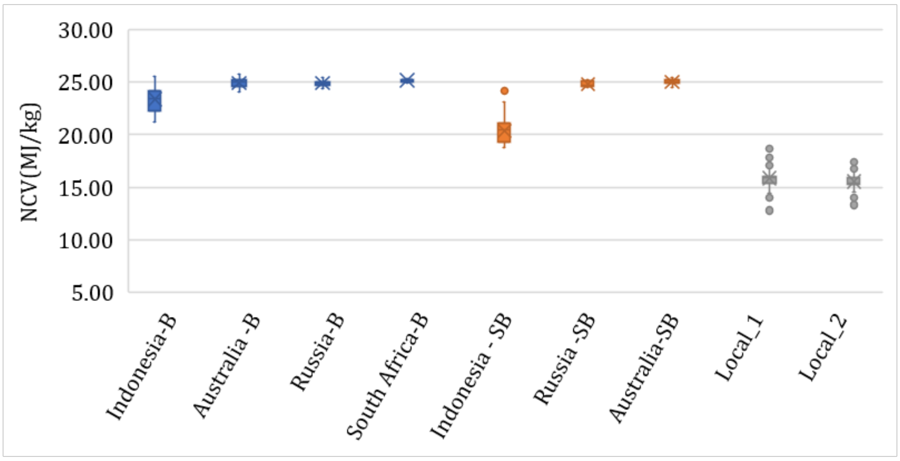


Fig. 10 *Net calorific value in 2019 from various origin*

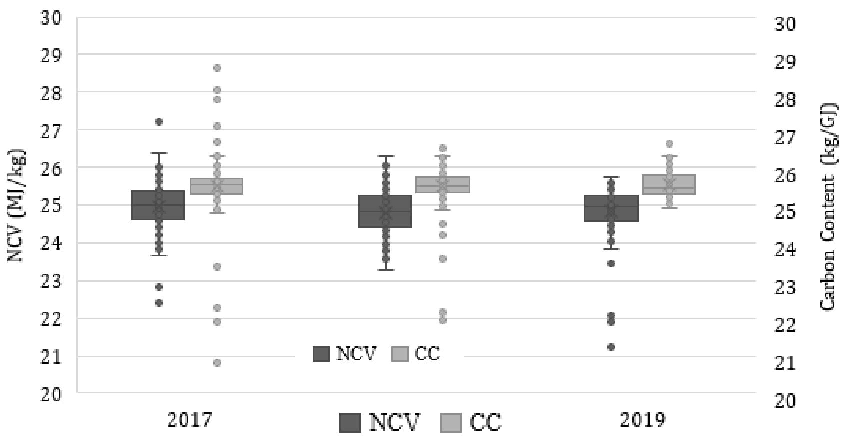


Fig. 11 *Bituminous coal relationship between NCV and carbon content from 2017-2019*

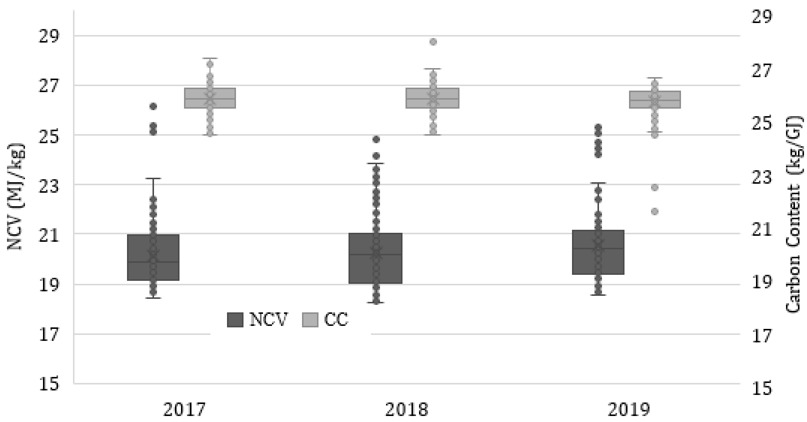


Fig. 12 *Sub-bituminous coal relationship between NCV and carbon content from 2017-2019*

3.2 Coal CO_2 Country-Specific Emission Factor

The carbon content is converted to CO_2 in perfect combustion conditions and expressed in terms of mass or volume. In assessing the CO_2 emission factor, each plant has its unique set of carbon content and net calorific values to assess as country specific. In Malaysia, the power plants either use only 1 type of coal or have 2 types of coal mixed for combustion. Most of the power plants use Sub-Bituminous coal as the main coal source. However, two (2) coal-fired power plants have a mix of 70:30 ratio of bituminous to sub-bituminous.

Results shown in Table 4, the yearly weighted average for each year for the CO_2 emission factor of Bituminous coal is lower than the IPCC whilst Sub-Bituminous and lignite coal are higher than the IPCC values. It was in the range of 93,078 $kgCO_2/TJ$ to 93,224 $kgCO_2/TJ$, for bituminous coal and 96,260 $kgCO_2/TJ$ to 96,714 $kgCO_2/TJ$, for sub-bituminous coal. The lignite coal shows a higher value than the IPCC default which is at a range of 101,720 $kgCO_2/TJ$ to 105,116 $kgCO_2/TJ$. The CO_2 emission factor for Bituminous coal is lower by about 1%-2% than the default value given by the 2006 IPCC Guidelines at 94,600 $kgCO_2/TJ$. The default value for the emission factor of sub-bituminous coal is 96,100 $kgCO_2/TJ$ and the value developed here is higher than the default value with around a 1% difference. For three consecutive years, lignite coal resulted in a higher value of emission factor than the default value (101,200 $kgCO_2/TJ$) of about 1%-4%. This emission factor value is not significantly different from the default value.

The country-specific carbon content derived for Bituminous and Sub-Bituminous was in the range of 25.48 kg/GJ – 25.51 kg/GJ and 26.10 kg/GJ – 26.47 kg/GJ for three years (3) which was lower than IPCC default value. However, Lignite coal's carbon content was higher than the IPCC default value. In comparison with IPCC, the three (3) years country specific net calorific value was in the range of 24.80 MJ/kg – 24.96 MJ/kg for Bituminous, 20.15 MJ/kg – 20.40 MJ/kg for Sub-Bituminous and 15.05 MJ/kg – 15.66 MJ/kg for Lignite coal. Bituminous NCV was slightly lower than IPCC compared to sub-bituminous and lignite. The Sub-Bituminous coal is 7%-8% whilst values for lignite coal are 26%-32% higher than the IPCC default value.

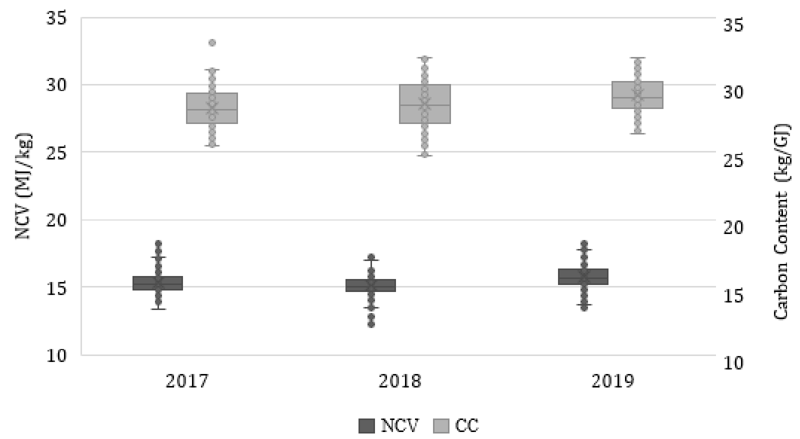


Fig. 13 *Lignite coal relationship between NCV and carbon content from 2017-2019*

Table 3 *Coal carbon content and net calorific value based on coal type from 2017-2019*

Year	2017	2018	2019
Annual average carbon content			
• Bituminous	25.66 -26.50 kg/GJ	25.49 - 25.63 kg/GJ	25.39 -25.72 kg/GJ
• Sub-bituminous	25.22 -26.50 kg/GJ	25.45 – 26.49 kg/GJ	25.37 -26.40 kg/GJ
• Lignite	29.15 - 30.77 kg/GJ	29.84 -32.17 kg/GJ	29.71-29.74 kg/GJ
Annual average net calorific value			
• Bituminous	24.51-24.95 MJ/kg	23.85 -24.75 MJ/kg	23.40-24.93 MJ/kg
• Sub-bituminous	20.02-25.44 MJ/kg	20.20 -24.86 MJ/kg	20.37-25.02 MJ/kg
• Lignite	15.25-15.59 MJ/kg	14.62 -15.23 MJ/kg	15.54-15.86 MJ/kg
Average annual carbon oxidation rate of coal combustion (%)	99.68	99.61	99.51

The study has assessed uncertainties of the best-rated emission factors for the CO_2 emission factor. The project used the methodology suggested in the 2006 IPCC Guidelines. According to IPCC, uncertainties in CO_2 emission factors from fossil fuel combustion are relatively low. These emission factors are determined by the carbon content of the fuel and thus there are physical constraints on the magnitude of their uncertainty. Equation 3.1 from IPCC 2006 Vol. 1 Ch. 3 was used to estimate the uncertainty for the result of emission factors calculation. The uncertainty reported was lower in which country-specific emission factors were used and in a range of the uncertainty suggested by IPCC.

Assessment of three (3) years of data shows that coal quality parameters for a particular coal type show significant change over the period as per Figure 14 and 15. Specifically for Malaysia, this shows Bituminous coal is better quality than Sub-Bituminous and Lignite. Bituminous coal from imported countries shows lower CO_2 emission factor with lower carbon content and higher NCV followed by Sub-Bituminous and Lignite, which originated locally. This has shown that the country-specific carbon content and heating value for coal are reflecting sensitively to changes in the power plants' supply pattern. Both factors may act together to bring out significant changes in CO_2 emission factors with respect to prevailing country-specific values.

Table 4 *Country specific CO2 emission factor, CC and NCV based on different coal types for Malaysia from 2017-2019*

Coal Type	Country Specific	2017	2018	2019	IPCC Default and Comparison %
Bituminous	Emission factor ($kgCO_2/TJ$)	93,224	93,078	93,089	94,600 (1%)
	Carbon content per unit calorific value of coal (kg/GJ)	25.51	25.48	25.51	25.8 (1-2%)
	Net calorific value (TJ/Gg)	24.96	24.80	24.88	25.8 (2%)
	Uncertainty	1.88%	1.33%	0.77%	7%
Sub-Bituminous	Emission factor ($kgCO_2/TJ$)	96,714	96,679	96,260	96,100 (1%)
	Carbon content per unit calorific value of coal (kg/GJ)	26.46	26.47	26.10	26.2 (1%)
	Net calorific value (TJ/Gg)	20.15	20.27	20.40	18.9 (1%)
	Uncertainty	0.84%	0.92%	1.21%	7%
Lignite	Emission factor ($kgCO_2/TJ$)	103,692	101,720	105,116	101,000 (1-4%)
	Carbon content per unit calorific value of coal (TJ/Gg)	28.37	27.85	28.81	27.6 (1-4%)
	Net calorific value (TJ/Gg)	15.05	15.07	15.66	11.9 (1-4%)
	Uncertainty	4.28%	3.96%	3.77%	7%

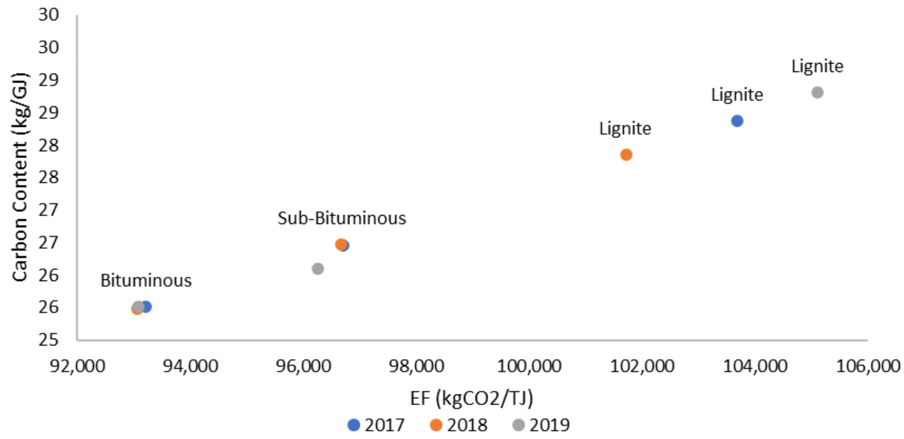


Fig. 14 *The relationship between carbon content and coal emission factor for Malaysia from 2017 to 2019*

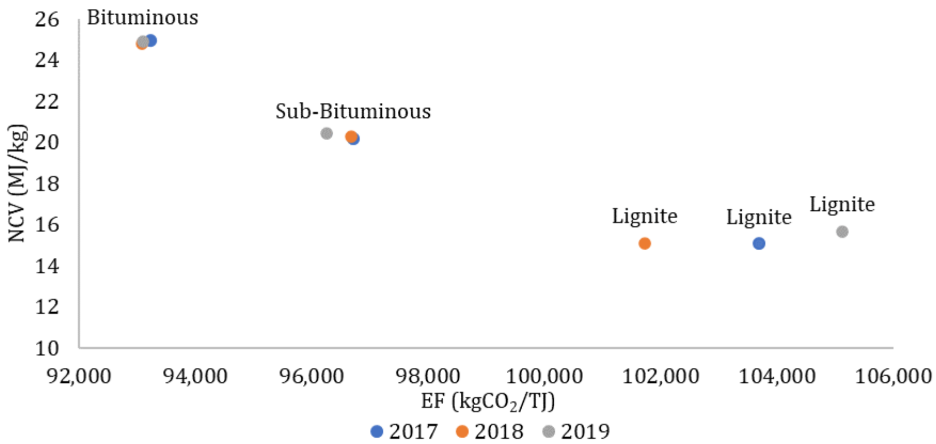


Fig. 15 *The relationship between Net Calorific Value (NCV) and coal emission factor for Malaysia from 2017 to 2019*

3.3 Coal Non-CO_2 Country-Specific Emission Factor

The non-CO_2 emission factor based on fuel type is also one of the outcomes of this study, the results of which are shown in Table 5. The national factor is calculated by weighted averaging of the emission factors with the fuel consumption for each of the power plants respectively for the year 2019. For Bituminous, the calculated emission factor of CH_4 is 0.1011 $kgCH_4/TJ$ and N_2O is 0.7047 kgN_2O/TJ. As for Sub-Bituminous, the calculated CH_4 emission factor is 0.0883 $kgCH_4/TJ$ whilst for N_2O is 0.9516 kgN_2O/TJ. The emission factor for Lignite's CH_4 is 0.0402 $kgCH_4/TJ$ and N_2O is 0.5563 kgN_2O/TJ respectively.

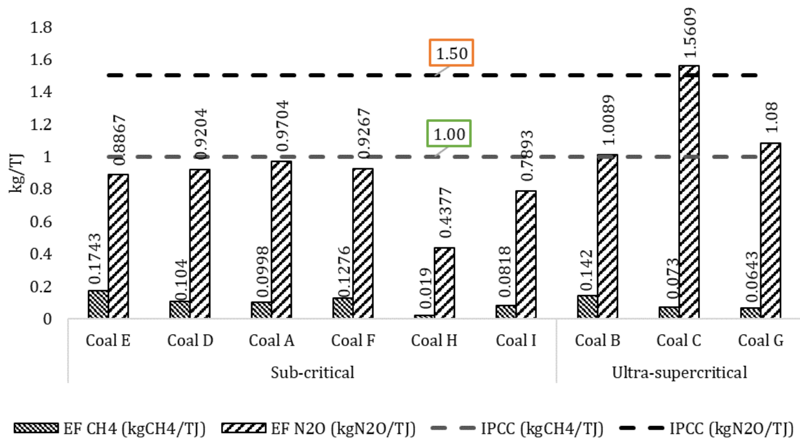
Table 5 *Country specific non-CO2 emission factor compared to IPCC value*

Coal Type	Country Specific Emission Factor		IPCC Default and Comparison %
Bituminous	CH_4 Emission factor ($kgCH_4/TJ$)	0.1011	1 (90%)
	N_2O Emission factor (kgN_2O/TJ)	0.7047	1.5 (53%)
	Uncertainty (CH_4)	22.29	50-150%
	Uncertainty (N_2O)	60.13	*Order of magnitude
Sub-Bituminous	CH_4 Emission factor ($kgCH_4/TJ$)	0.0883	1 (91%)
	N_2O Emission factor (kgN_2O/TJ)	0.9516	1.5 (37%)
	Uncertainty (CH_4)	16.42	50-150%
	Uncertainty (N_2O)	76.33	*Order of magnitude
Lignite	CH_4 Emission factor ($kgCH_4/TJ$)	0.0402	1 (96%)

N_2O Emission factor(kgN_2O/TJ)	0.5563	1.5 (63%)
Uncertainty (CH_4)	11.23	50-150%
Uncertainty (N_2O)	22.30	*Order of magnitude

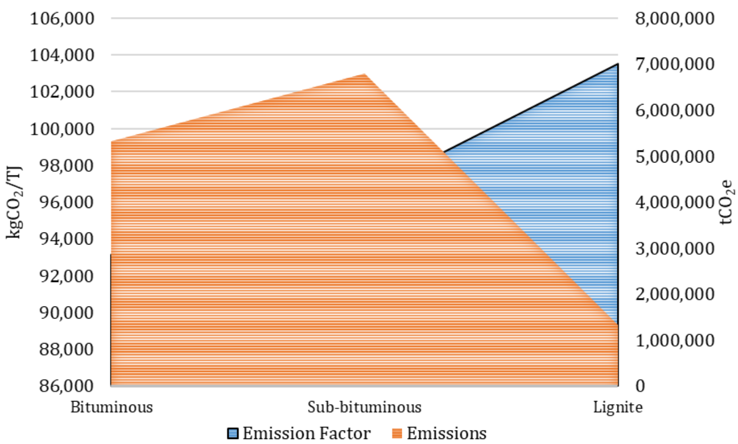
*i.e.: having an uncertainty range from one-tenth of the mean value to ten times the mean value.

Figure 16 shows the emission factors calculated in this project based on each power plant. The emission factor for CH_4 was in a range of 0.0190 – 0.2790 kgCH_4/TJ, whereas the emission factor for N_2O was in a range of 0.2684 – 1.5609 kgN_2O/TJ. The value of the calculated emission factors for CH_4 is around 72% to 98% lower than the default value suggested by the IPCC based on the emission factor of Tier 1. Meanwhile, the calculated value of emission factors for N_2O is around 82% lower to 4% higher than the value suggested by the IPCC. The study reveals that subcritical plants recorded a higher emission factor than ultra-supercritical plants. This is because each power plant has different operating conditions; the fuel consumed per the amount of electricity generated and the emission flue of exhaust gas. Overall, in relation to the GHG emissions derived from fuel consumption, the trend shows that Malaysia's lignite coal contributed to low emissions compared to bituminous and sub-bituminous coal, as stated in Figure 17. This is because only 2 plants, which are about 22% used the local coal in a small capacity.



Note: Coal A, D, E, F, H and I – Subcritical/Thermal coal plants and Coal B, C and G – Ultra Super Critical plant

Fig. 16 *CH_4 and N_2O emission factor by power plant in Malaysia*



Note: Graph shows CO_2 emission factor

Fig. 17 *Trend of GHG emissions in Malaysia*

The coal samples were verified to check the acceptable limit of each coal type. They were tested at the laboratory, and samples were analysed for calorific value and the breakdown of compositions via proximate analysis and ultimate analysis in the respective test equipment. The reference standards used were ASTM Volume 05.05 Gaseous Fuels: Coal and Coke.

Overall, all the coal samples met the acceptance limit for volatile matter content, hydrogen content and nitrogen content. All the analysed coal samples complied with the acceptance limit of volatile matter content, hydrogen content and nitrogen content. The fixed carbon contents for domestic coals showed lower fixed carbon than the accepted range. Furthermore, carbon contents for Local_2 and Local_1 coal are lower than the acceptance limit. Stack gas measurement verification is a crucial aspect of maintaining environmental compliance and ensuring that power plants adhere to established standards such as the United States Environment Protection Agency (USEPA) 320 and Continuous Emission Monitoring System (CEMS) DOE Guidelines. In the study, we found that these standards were successfully met. The verification exercise focused on ensuring that the dataset is complete without material misstatements and accurate, thereby demonstrating a level of assurance or confidence in the findings.

4. Conclusion

In understanding the electricity generation GHG emissions, the GHG emission factor was studied and constructed, through the fuel and flue gas data analysis. The study shows the yearly weighted average for each year for Malaysia's CO_2 emission factor of Bituminous coal is lower than the IPCC, whilst Sub-Bituminous and lignite coal are higher than the IPCC values. It was in the range of 93,078 kgCO_2/TJ to 93,224 kgCO_2/TJ, for bituminous coal and 96,260 kgCO_2/TJ to 96,714 kgCO_2/TJ, for sub-bituminous coal. The lignite coal shows a higher value than the IPCC default, which ranges from 101,720 kgCO_2/TJ to 105,116 kgCO_2/TJ. The coal CH_4 and N_2O emission factors are lower than the Tier-1 fuel-based method suggested by the IPCC. The CH_4 emission factor is 0.1011 kgCH_4/TJ for Bituminous, 0.0883 kgCH_4/TJ for Sub-Bituminous, and 0.0402 kgCH_4/TJ for lignite. Whereas the N_2O emission factor for bituminous was 0.7047 kgN_2O/TJ, sub-bituminous was 0.9516 kgN_2O/TJ, and lignite coal was 0.5563 kgN_2O/TJ, respectively. Furthermore, the carbon content which affects the CO_2 emissions is lower for bituminous followed by sub-bituminous and much higher for lignite coal. At the same time, lower carbon content and higher net calorific values can reduce fuel consumption and achieve CO_2 emission reduction. As for the non-CO_2 emissions, it shows much lower values, however, it depends on the technology.

This study has shown that emission factor and emission amount changed due to an annually changing coal composition i.e. carbon content and calorific value. The uncertainties also reported lower percentage for the country specific emission factor using the combined approach. Comparison to IPCC 2006 default values shows that data presented are reliable and valid within the acceptable level of confidence. Based on the data and information collected and the processes and analysis conducted, the assurance are within the materiality threshold of 5% for aggregate errors.

Coal by contrast, may be sourced from mines producing coals with a very wide range of carbon contents and calorific values and is mostly supplied under contract to users who adapt their equipment to match the characteristics of the coal. Hence, at the country-specific level, the single energy commodity of coal can have a range of CO_2 and non-CO_2 emission factors.

The study developed the country-specific emission factor that alleviates inventories to higher tiers through the analyses indicated in the methodology and approach. Improving estimates of emissions from the electricity sector - which is the primary source of national greenhouse gas - is challenging but in its due process, it has developed technical capacity for research and guided methodologies. In addition, the level of uncertainties in current emissions estimates for greenhouse gases from major sources could be lowered using the most accurate approach. Representative emission data is important for a country to set an effective GHG monitoring programme.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors are responsible for the study conception, research design, data collection, data analysis, result interpretation and manuscript drafting.

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