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# Evaluation of the Life Cycle Greenhouse Gas Emissions from Different Biomass Feedstock Electricity Generation Systems

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**Abstract:** This paper evaluates life cycle greenhouse gas (GHG) emissions from the use of different biomass feedstock categories (agriculture residues, dedicated energy crops, forestry, industry, parks and gardens, wastes) independently on biomass-only (biomass as a standalone fuel) and cofiring (biomass used in combination with coal) electricity generation systems. The statistical evaluation of the life cycle GHG emissions (expressed in grams of carbon dioxide equivalent per kilowatt hour, $gCO_2e/kWh$) for biomass electricity generation systems was based on the review of 19 life cycle assessment studies (representing 66 biomass cases). The mean life cycle GHG emissions resulting from the use of agriculture residues ($N$ = 4), dedicated energy crops ($N$ = 19), forestry ($N$ = 6), industry ($N$ = 4), and wastes ($N$ = 2) in biomass-only electricity generation systems are 291.25 $gCO_2e/kWh$, 208.41 $gCO_2e/kWh$, 43 $gCO_2e/kWh$, 45.93 $gCO_2e/kWh$, and 1731.36 $gCO_2e/kWh$, respectively. The mean life cycle GHG emissions for cofiring electricity generation systems using agriculture residues ($N$ = 10), dedicated energy crops ($N$ = 9), forestry ($N$ = 9), industry ($N$ = 2), and parks and gardens ($N$ = 1) are 1039.92 $gCO_2e/kWh$, 1001.38 $gCO_2e/kWh$, 961.45 $gCO_2e/kWh$, 926.1 $gCO_2e/kWh$, and 1065.92 $gCO_2e/kWh$, respectively. Forestry and industry (avoiding the impacts of biomass production and emissions from waste management) contribute the least amount of GHGs, irrespective of the biomass electricity generation system.

**Keywords:** life cycle assessment; greenhouse gas emissions; biomass; biomass-only; cofiring; biomass feedstock; agriculture residue; dedicated energy crop; forestry; industry; parks and gardens; waste

## 1. Introduction

Biomass energy, also referred to as bioenergy, may be defined as the energy harnessed from plants and their derivatives (e.g., wood, food crops, residues from agriculture or forestry, oil-rich algae, and the organic component of municipal/industrial wastes). Biomass is a product of photosynthesis, in which the sun's energy converts water and carbon dioxide ($CO_2$) in plants into organic material [1]. The organic material stores sunlight in the form of chemical energy. The components of biomass include cellulose, hemicellulose, lignin, extractives, lipids, proteins, simple sugars, starches, water, hydrocarbons, ash, and other compounds. The composition of biomass varies among species. In general, lignin (~25%) and carbohydrates or sugars (~75%) are identified to be the dominant components [2–5]. The carbohydrate fraction contains many sugar molecules linked together in long chains or polymers. There are two distinguished categories of carbohydrates: cellulose and hemicellulose. The energy value of biomass is dependent on the moisture content. As the moisture content increases, the energy calorific values of biomass decreases. The decrease in energy calorific values is a result of the reduction in combustion temperatures [6]. Biomass with high moisture content may lead to incomplete combustion, thereby increasing the air emissions.

The total electricity generation in 2012 across the world was reported to be 21.53 trillion kilowatt hours (kWh) [7]. The projected world electricity generation for 2040 is 39 trillion kWh (an increase by 81% from 2012) [8]. The renewable energy sources have been projected to account for 9.6 trillion kWh (25%) of the world's total electricity generation in 2040. With the continuing depletion of traditional nonrenewable energy sources, the necessity for generating electricity through the use of renewable energy sources (hydro, wind, biomass, geothermal, solar) increased manifold. Biomass accounted for only 0.384 trillion kWh (2%) of the world's total electricity generated in 2012 despite its abundant availability across the world. Based on the 2012 statistics, biomass was identified to be the third largest renewable energy source for electricity generation after hydro (3.646 trillion kWh) and wind (0.52 trillion kWh) [7]. The majority of the global energy-use projection studies anticipate biomass to contribute about 10%–45% of the total primary energy demand in the coming decades [9].

One may adopt the use of the life cycle assessment (LCA) method to evaluate the net $CO_2$ equivalent ($CO_2$e) greenhouse gas (GHG) emissions from the use of biomass as a fuel. LCA is an analytical method that provides an assessment of the environmental impacts of the considered products and technologies from a "cradle to grave" systems perspective, utilizing the detailed input and output parameters that operate within the designated system boundaries. Depending on the net $CO_2$e GHGs emitted across the entire life cycle processes considered, the bioenergy resources may be considered to be carbon neutral (no net effect on GHGs), carbon negative (net reduction in GHGs), or carbon positive (net increase in GHGs) [10].

Electricity generation from biomass on a large scale is achieved through the use of (a) biomass-only fired power plants and (b) cofiring in existing coal power plants by replacing coal with biomass. Several studies have analyzed the LCA of biomass-only combustion [11–21] and biomass cofiring with coal [12,13,20,22–29]. The two distinct advantages of cofiring in existing coal power plants are the achievement of a higher net efficiency of biofuels conversion to electricity (the generally higher efficiency of very large-scale power plants offsets the lower efficiency of the coal boiler) and a significant reduction in the investment costs. However, the option of cofiring requires higher pretreatment consumption to achieve complete biofuel conversion in the coal utility boiler and longer transportation costs of the resources associated with the coal power plants not being placed in potentially important biomass production areas [20]. A more detailed description of the LCA boundary conditions, GHG emissions, and site-specific characteristics associated with each of the aforementioned biomass electricity generation system studies are provided in the sections titled "*Review of Biomass-Only LCA Studies*" and "*Review of Biomass Cofiring with Coal LCA Studies*".

All the prior biomass LCA studies focused on the determination of life cycle GHG emissions from the use of individual biomass feedstock for electricity generation. None of the earlier studies compared the life cycle GHG emissions for biomass electricity generation systems across the individual distinct feedstock categories. This study aims to fill this knowledge gap by following a two-step approach; the study included a review of the literature on biomass LCA studies followed by a statistical evaluation of the life cycle GHG emissions from feedstock-based biomass-only and cofiring electricity generation systems separately. A majority of the biomass LCA studies noted in the literature have not included specific details on the type of feedstock used for electricity generation. Resultantly, only the biomass LCA studies that clearly defined the biomass feedstock type utilized for electricity generation were considered for the review, classification, and statistical evaluation in this study. The performance of a comprehensive statistical evaluation of the life cycle GHG emissions will help understand the degree of confidence and variability in GHG emissions from different feedstock categories for the considered biomass electricity generation system. This study will assist energy policymakers and environmental professionals in identifying and encouraging the use of environmental-friendly biomass feedstock options to generate electricity with minimal GHG emissions.

## 2. Methodology

A review of the biomass literature showed that there are wide-ranging types of biomass that may be utilized in generating electricity. The numerous types of biomass may be classified into distinct categories depending on the type of feedstock. The Idaho National Laboratory Report [30] provided an extensive classification of feedstock-based biomass that included seven distinct categories as follows:

- Agriculture residues (AR): includes dry lignocellulosic agriculture residues (straw, sugar beet leaves) and livestock waste (solid manure, liquid manure)
- Dedicated energy crops (DEC): includes dry lignocellulosic wood energy crops (small round wood (SRW)—willow, short rotation coppice (SRC)—poplar, eucalyptus), dry lignocellulosic herbaceous energy crops (miscanthus, switchgrass, common reed, reed canary grass, giant reed, cynara cardu, Indian shrub), oil energy crops (sugar beet, cane beet, sweet sorghum, Jerusalem artichoke, sugar millet), starch energy crops (wheat, potatoes, maize, barley, triticae, corn, amaranth), and other energy crops (flax (*Linum*), hemp (*Cannabis*), tobacco stems, aquatic plants (lipids from algae), cotton stalks, kenaf)
- Forestry (F): includes forestry byproducts (bark, wood blocks, wood chips from tops and branches, wood chips from thinning, logs from thinning)
- Industry (I): includes wood industry residues (industrial waste wood from sawmills/timber mills (bark, sawdust, wood chips, slabs, off-cuts)), food industry residues (wet cellulosic material (beet root tails), fats (used cooking oils), tallow, yellow grease, proteins (slaughterhouse waste)), and industrial products (pellets from sawdust and shavings, briquettes from sawdust and shavings, bio-oil (pyrolysis oil), ethanol, biodiesel)
- Parks and gardens (P-G): includes herbaceous (grass) and woody (pruning)
- Wastes (W): includes contaminated wastes (demolition wood, biodegradable, municipal waste, sewage sludge, landfill gas, sewage gas)
- Others (O): includes roadside hay (grass/hay) and husks/shells (almond, olive, walnut, palm pit, cacao)

This study adopted the same classification (agriculture residues, dedicated energy crops, forestry, industry, parks and gardens, wastes, others) as proposed by the Idaho National Laboratory Report [30] to evaluate the life cycle GHG emissions of biomass-only and biomass cofiring with coal electricity generation systems utilizing different feedstock options. Each of the reviewed biomass-only and biomass cofiring LCA studies (with specific details on the biomass feedstock type) were first assigned a biomass category. Next, the feedstock-based GHG emissions from biomass-only and biomass cofiring electricity generation systems were evaluated using statistical metrics (sample size, mean, standard deviation, minimum, maximum, standard error of the mean, quartile 1, quartile 2 or median, quartile 3) and graphical representations (error bars representing the mean with 95% confidence intervals, box plots representing the quartiles with outliers). The sample size is a measure that indicates the total number of observations. The mean is a measure that represents the central tendency of the observed data. The standard deviation is a measure used to quantify the degree of variation within a set of observations from a single sample. The minimum and maximum measures define the lowest observation and the highest observation with a considered sample, respectively. The standard error of the mean is a measure that estimates the variability between sample means obtained by taking multiple samples from the same population. The standard error of the mean determines the precision between the mean of the sample estimates and the population mean. The quartile statistics are a set of three measures that divide a ranked set of observed data values into four equal groups, with each group comprising a quarter of the data. While the error bars demonstrate the degree of confidence in the mean GHG emissions, the box plots provide information on the degree of variation among the LCA studies characterized by different biomass feedstock categories.

## 3. Results and Discussion

### *3.1. Review of Biomass-Only LCA Studies*

Several studies [11–21] evaluated the life cycle environmental impacts of using biomass as a standalone fuel for electricity generation. When performing an LCA, one needs to define the system boundary conditions (which includes details on the activities or processes to be considered in the analysis) and a functional unit of measure (which enables quantification of the net environmental impacts from carrying out an activity or a process as defined within the LCA system boundary conditions).

The majority of the aforementioned studies [13,17,18,21] that performed the LCA of biomass-only electricity generation systems defined the system boundary conditions to include activities such as biomass cultivation, harvesting, processing, transportation to warehouses and power plant, and combustion. Other studies [12,14,16] set up their LCA system boundary conditions by including the ash disposal activity in addition to the list of all activities associated with the majority of the studies. Sebastián et al. [20] considered the LCA system boundaries that included biomass cultivation, harvesting, processing, transportation to warehouses and power plant, construction and dismantling of power station, combustion, and ash disposal. One may note that all the above-mentioned activities are associated with the use of dedicated energy crops and agriculture residues as feedstock in biomass-only electricity generation systems.

The Environment Agency Report [14] defined the LCA system boundaries to include wood cutting, transportation, storage, and combustion for the case scenario of using forestry as feedstock for biomass-only electricity generation. The activity of ash disposal was additionally considered to be within the LCA system boundaries by another study [18] that examined the environmental life cycle impacts of using forestry as a feedstock for biomass-only electricity generation. Intini et al. [19] used industry residue as feedstock for biomass-only electricity generation, where the system boundaries included the activities of extracting virgin pomace from an olive oil mill, extracting dry pomace by drying virgin pomace, extracting deoiled pomace from pomace oil, combustion, and electricity transfer to the grid. The remaining studies [11,15] considered the LCA system boundaries to include collection, segregation and sorting, transportation, and incineration using waste as feedstock for biomass-only electricity generation.

The common functional unit of measure adopted by a majority of the biomass-only LCA studies is grams of $CO_2$e per kilowatt hour ($gCO_2e/kWh$) of electricity produced. Accordingly, this study also adopts the functional unit of measure for GHG emissions to be $gCO_2e/kWh$ of electricity produced.

Table 1 provides a summary of the biomass feedstock categorization (based on the type of biomass) and the corresponding GHG emissions (in $gCO_2e/kWh$) for each biomass-only electricity generation LCA study. Additional site-specific details on the power generation capacity (PGC, in MW), the power plant efficiency ($\eta$, in %), the power generation method (PGM—direct combustion (DC), pyrolysis combustion (PC)), and the geographical location (GL) for the biomass-only electricity generation system studies can also be obtained from Table 1. Based on the review of 11 biomass-only electricity generation LCA studies (refer to Table 1), one may note that dedicated energy crops ($N$ = 19) feedstock-based biomass-only electricity generation systems were more in number compared to forestry ($N$ = 6), agriculture residues ($N$ = 4), industry ($N$ = 4), and waste ($N$ = 2) feedstock-based biomass-only electricity generation systems. There were no studies on the use of parks and gardens and other feedstock-based biomass-only electricity generation applications.

In addition to computing the GHG emissions, one study [21] computed the acidification potential (expressed in grams of sulfur dioxide equivalent per kilowatt hour ($gSO_2e/kWh$)) and the eutrophication potential (expressed in grams of phosphates per kilowatt hour ($gPO_4e/kWh$)) for the AR (rice straw) biomass feedstock to be 6.78 $gSO_2e/kWh$ and 1.46 $gPO_4e/kWh$, respectively. Another study noted that the use of the DEC (switchgrass) having low sulfur content produced less $SO_2$ emissions when generating electricity through direct combustion [12].

**Table 1.** Greenhouse gas (GHG) emissions for biomass-only electricity generation systems.

| Source | Biomass Feedstock Category (Biomass Type) | GHG Emissions ($gCO_2e/kWh$) | Additional Features PGC (MW), η (%), PGM, GL |
|---|---|---|---|
| Intergovernmental Panel on Climate Change [11] | W (municipal solid waste incineration) | 922.22 | PGM = DC; GL = Germany (GHG emissions are computed using 415 $kgCO_2$ per ton of municipal solid waste and averaged electricity generation potential of 450 kWh per ton of municipal solid waste) |
| Qin et al. [12] | DEC (switchgrass) | 68.5 | η = 17–25; PGM = DC; GL = USA |
| Styles and Jones [13] | DEC (miscanthus) | 131 | PGC = 100–150 MW; PGM = DC; GL = Ireland |
| | DEC (willow) | 132 | PGC = 100–150 MW; PGM = DC; GL = Ireland |
| Environment Agency [14] | F (UK forest residues—chips) | 10 | PGM = DC; GL = UK |
| | F (Baltic forest residues—chips) | 22 | PGM = DC; GL = UK |
| | I (waste wood—chips) | 7 | PGM = DC; GL = UK |
| | DEC (SRC—chips) | 17 | PGM = DC; GL = UK |
| | DEC (miscanthus—chips) | 18 | PGM = DC; GL = UK |
| | F (UK forest residues—pellets) | 38 | PGM = DC; GL = UK |
| | F (Baltic forest residues—pellets) | 50 | PGM = DC; GL = UK |
| | I (waste wood—pellets) | 51 | PGM = DC; GL = UK |
| | I (Baltic waste wood—pellets) | 66 | PGM = DC; GL = UK |
| | DEC (SRC—pellets) | 100 | PGM = DC; GL = UK |
| | DEC (miscanthus—pellets) | 65 | PGM = DC; GL = UK |
| | AR (straw) | 73 | PGM = DC; GL = UK |
| Zaman [15] | W (municipal solid waste incineration) | 2540.5 | PGM = DC; GL = Sweden |
| Butnar et al. [16] | DEC (poplar) | 90 | PGC = 10 MW; η = 25; PGM = DC; GL = Spain |
| | | 95 | PGC = 25 MW; η = 28; PGM = DC; GL = Spain |
| | | 100 | PGC = 50 MW; η = 30; PGM = DC; GL = Spain |
| | DEC (Ethiopian mustard) | 250 | PGC = 10 MW; η = 25; PGM = DC; GL = Spain |
| | | 260 | PGC = 25 MW; η = 28; PGM = DC; GL = Spain |
| | | 260 | PGC = 50 MW; η = 30; PGM = DC; GL = Spain |
| Siemers [17] | AR (rice husk) | 67 | PGC = 190 MW; η = 20; PGM = DC; GL = Thailand |
| | AR (rice straw) | 180 | PGC = 1-60 MW; η = 18; PGM = DC; GL = Thailand |
| Fan et al. [18] | DEC (poplar) | 76 | PGC = 10 MW; η = 18; PGM = PC; GL = USA |
| | | 50 | PGC = 10 MW; η = 25; PGM = PC; GL = USA |
| | DEC (willow) | 50 | PGC = 10 MW; η = 18; PGM = PC; GL = USA |
| | | 35 | PGC = 10 MW; η = 25; PGM = PC; GL = USA |
| | F (logging residues) | 82 | PGC = 10 MW; η = 18; PGM = PC; GL = USA |
| | | 56 | PGC = 10 MW; η = 25; PGM = PC; GL = USA |
| Intini et al. [19] | I (deoiled olive oil pomace, waste wood) | 59.7 | PGC = 12 MW; PGM = DC; GL = Italy |
| Sebastián et al. [20] | DEC (wheat straw) | 1076.39 | PGC = 100 MW; η = 25.8; PGM = DC; GL = Spain |
| | DEC (*Brassica carinata*) | 1085.94 | PGC = 100 MW; η = 25.8; PGM = DC; GL = Spain |
| Shafie et al. [21] | AR (rice straw) | 845 | PGM = DC; GL = Malaysia |

### *3.2. Review of Biomass Cofiring with Coal LCA Studies*

There are numerous studies [12,13,20,22–29] that evaluated the life cycle environmental impacts of using biomass in combination with coal fuel for electricity generation.

The majority of the biomass cofiring studies [12,13,22,28,29] defined the LCA boundary conditions to include activities such as extraction of the raw materials (mining of coal, cultivation and harvesting of biomass), processing of fuel (coal and biomass torrefaction/pelletization), transport and distribution of coal and biomass, combustion in power plant, and final waste (ash) disposal. In addition to these activities, some studies [20,25] also included the construction and dismantling of a power station within their system boundaries. Other studies [23,24,26,27] did not consider ash disposal within their system boundaries.

Paengjuntuek et al. [29] evaluated the life cycle GHG emissions for cofiring utilizing an integrated biomass gasification fuel cell (BGFC) that combined the use of solid oxide fuel cell with the integrated gasification combined cycle (IGCC) technology to enhance the energy efficiency. The IGCC technology enables the conversion of coal and biomass fuel into a pressurized gas (referred to as synthesis gas (syngas)) using a high-pressure gasifier. The remaining 10 cofiring studies reviewed for this paper were performed though direct combustion in coal power plants.

Table 2 provides a summary of the biomass feedstock categorization (based on the type of biomass) and the corresponding GHG emissions (in $gCO_2e/kWh$) for each biomass cofiring electricity generation LCA study. Additional site-specific details on the PGC (in MW), η (in %), PGM (DC, PC, gasification (G)), GL, and the biomass contribution level in cofiring with coal (BCL) for the biomass cofiring electricity generation system studies can be obtained from Table 2. Based on the review of 11 biomass-cofiring electricity generation LCA studies (refer to Table 2), one may note that agriculture residue (*N* = 10) feedstock-based biomass-cofiring electricity generation systems were more in number compared to dedicated energy crops (*N* = 9), forestry (*N* = 9), industry (*N* = 2), and parks and gardens (*N* = 1) feedstock-based biomass cofiring electricity generation systems. There were no studies on the use of waste and other feedstock-based biomass-cofiring electricity generation applications.

**Table 2.** GHG emissions for biomass cofiring electricity generation systems.

| Source | Biomass Feedstock Category (Biomass Type) | GHG Emissions ($gCO_2e/kWh$) | Additional Features PGC (MW), η (%), PGM, GL, BCL |
|---|---|---|---|
| Qin et al. [12] | DEC (switchgrass) | 935.1 | PGC = 100 MW; η = 34.13; PGM = DC; GL = USA; BCL = 10% |
| | | 966 | PGC = 100 MW; η = 34.13; PGM = DC; GL = USA; BCL = 5% |
| | | 875.6 | PGC = 100 MW; η = 34.13; PGM = DC; GL = USA; BCL = 20% |
| Styles and Jones [13] | DEC (miscanthus) | 1150 | PGC = 100-150 MW; η = 38.4; PGM = DC; GL = Ireland; BCL = 30% |
| | DEC (willow) | 990 | PGC = 915 MW; η = 37.5; PGM = DC; GL = Ireland; BCL = 10% |
| Sebastián et al. [20] | DEC (wheat straw) | 1065.92 | PGC = 350 MW; η = 36.55; PGM = DC; GL = Spain; BCL = 10% |
| | DEC (*Brassica carinata*) | 1072.79 | PGC = 350 MW; η = 36.55; PGM = DC; GL = Spain; BCL = 10% |
| Mann and Spath [22] | I (wood residue: clean urban waste wood, mill residue, biomass generated during timber stand improvements, some construction and demolition residues, and industrial wood residues) | 849.3 | PGC = 350 MW; η = 31.1; PGM = DC; GL = USA; BCL = 15% |
| | | 1002.9 | PGC = 354 MW; η = 31.5; PGM = DC; GL = USA; BCL = 5% |
| Heller et al. [23] | DEC (willow) | 883 | PGC = 96 MW; η = 33.17; PGM = DC; GL = USA; BCL = 10% |
| Kabir and Kumar [24] | F (forest residue—torrefied pellets) | 957 | PGC = 450 MW; η = 34; PGM = DC; GL = Canada; BCL = 20.45% |
| | F (forest residue—pellets) | 1004 | PGC = 450 MW; η = 34; PGM = DC; GL = Canada; BCL = 17.04% |
| | F (forest residue—chips) | 1003 | PGC = 450 MW; η = 33; PGM = DC; GL = Canada; BCL = 16.54% |
| | F (whole tree—torrefied pellets) | 967 | PGC = 450 MW; η = 34; PGM = DC; GL = Canada; BCL = 20.45% |
| | F (whole tree—pellets) | 1014 | PGC = 450 MW; η = 34; PGM = DC; GL = Canada; BCL = 17.04% |
| | F (whole tree—chips) | 1013 | PGC = 450 MW; η = 33; PGM = DC; GL = Canada; BCL = 16.54% |
| | AR (straw—torrefied pellets) | 1065 | PGC = 450 MW; η = 34; PGM = DC; GL = Canada; BCL = 7.76% |
| | AR (straw—pellets) | 1082.8 | PGC = 450 MW; η = 34; PGM = DC; GL = Canada; BCL = 9.3% |
| | AR (straw—bale) | 1083.4 | PGC = 450 MW; η = 33; PGM = DC; GL = Canada; BCL = 7.53% |

**Table 2.** *Cont.*

| Source | Biomass Feedstock Category (Biomass Type) | GHG Emissions ($gCO_2e/kWh$) | Additional Features PGC (MW), η (%), PGM, GL, BCL |
|---|---|---|---|
| Royo et al. [25] | AR (wheat straw) | 1059.95 | PGC = 350 MW; η = 36.55; PGM = DC; GL = Spain; BCL = 10% |
| | P-G (fruit tree pruning) | 1065.92 | PGC = 350 MW; η = 36.55; PGM = DC; GL = Spain; BCL = 10% |
| | F (Spain forest) | 1066.03 | PGC = 350 MW; η = 36.55; PGM = DC; GL = Spain; BCL = 10% |
| | DEC (brassica carinata) | 1073.99 | PGC = 350 MW; η = 36.55; PGM = DC; GL = Spain; BCL = 10% |
| Huang et al. [26] | AR (rice straw torrefaction) | 1040 | PGM = DC; GL = Taiwan; BCL = 10% |
| | | 990 | PGM = DC; GL = Taiwan; BCL = 20% |
| Kaliyan et al. [27] | AR (corn stover) | 1181.7 | PGM = DC; GL = USA; BCL = 10% |
| | | 1071.2 | PGM = DC; GL = USA; BCL = 20% |
| | | 960.8 | PGM = DC; GL = USA; BCL = 30% |
| Tsalidis et al. [28] | F (Dutch forestry materials) | 811 | PGC = 500 MW; η = 40; PGM = DC; GL = The Netherlands |
| | F (Canadian forestry materials) | 818 | PGC = 500 MW; η = 40; PGM = DC; GL = The Netherlands |
| Paengjuntuek et al. [29] | AR (rice straw) | 864.3 | PGC = 0.65 MW; PGM = G; GL = Thailand |

Some of the LCA studies [24,26,28,29] summarized in Table 2 computed the acidification and the eutrophication potentials for the corresponding biomass feedstocks considered in their respective studies. One study [24] noted the acidification potentials for F (forest residue—torrefied pellets, 20.45% cofiring), F (forest residue—pellets, 17.04% cofiring), F (forest residue—chips, 16.54% cofiring), F (whole tree—torrefied pellets, 20.45% cofiring), F (whole tree—pellets, 17.04% cofiring), F (whole tree—chips, 16.54% cofiring), AR (rice straw, 7.76% cofiring), AR (rice straw, 9.3% cofiring), and AR (rice straw, 7.53% cofiring) biomass feedstocks to be 5.16 $gSO_2e/kWh$, 5.38 $gSO_2e/kWh$, 5.39 $gSO_2e/kWh$, 5.18 $gSO_2e/kWh$, 5.41 $gSO_2e/kWh$, 5.41 $gSO_2e/kWh$, 5.86 $gSO_2e/kWh$, 5.77 $gSO_2e/kWh$, and 5.93 $gSO_2e/kWh$, respectively. Another [26] noted the acidification potential for the AR (rice straw) biomass feedstock to be 21.07 $gSO_2e/kWh$ under 10% cofiring operating conditions and 22.04 $gSO_2e/kWh$ with 20% cofiring operating conditions, while that of the eutrophication potential was computed to be 0.02 $gPO_4e/kWh$ under 10% cofiring operating conditions and 0.06 $gPO_4e/kWh$ with 20% cofiring operating conditions. The acidification potentials for F (Dutch forestry materials with pelletization) and F (Canadian forestry materials with torrefied pellets) were determined to be 88.1 $gSO_2e/kWh$ and 105 $gSO_2e/kWh$, respectively [28]. The acidification and the eutrophication potentials for the AR (rice straw) biomass feedstock were noted to be 2.6 $gSO_2e/kWh$ and 0.15 $gPO_4e/kWh$, respectively [29]. The variations in the acidification and eutrophication potentials may be attributed to the variations in the life cycle process stages and the cofiring conditions.

### *3.3. Statistical Evaluation of Biomass-Only LCA Studies*

Figure 1 provides a graphical presentation of the (a) error bars (mean ± 95% confidence interval (CI) statistics) and (b) box plots (quartiles + outlier statistics) for GHG emissions from the different feedstock-based biomass-only electricity generation systems reviewed in this study. Table 3 provides a statistical summary of the life cycle GHG emissions that provides details on the sample size (N), mean (X) ± standard deviation (SD), minimum (Min.), maximum (Max.), standard error of the mean (SE), quartile 1 (Q1), quartile 2 or median (Q2), and quartile 3 (Q3) for the different feedstock-based biomass-only electricity generation systems reviewed in this study.

From Figure 1a and Table 3, one may note the mean life cycle GHG emissions obtained from the use of agriculture residues, dedicated energy crops, forestry, industry, and wastes in biomass-only electricity generation systems are 291.25 $gCO_2e/kWh$, 208.41 $gCO_2e/kWh$, 43 $gCO_2e/kWh$, 45.92 $gCO_2e/kWh$, and 1731.36 $gCO_2e/kWh$, respectively. The forestry and industry feedstock-based biomass produced considerably lower GHG emissions than the remaining three biomass feedstock categories. The lower GHG emissions resulting from the use of forestry and industry feedstock-based biomass may be attributed to the fact that bioenergy chains having resources/residues as raw materials avoid the high impacts of dedicated energy crop production and emissions from waste management [19,31,32].

Of the remaining three biomass feedstock categories, dedicated energy crops produced lower mean life cycle GHG emissions, followed by agriculture residues, and wastes. The use of dedicated energy crops in existing power stations has significant potential to reduce GHG emissions [13]. Mineral fertilizers accounted for the majority (62%–82%) of the GHG emissions resulting from cultivation of dedicated energy crops [16]. One needs to adopt the use of natural fertilizers to further reduce the GHGs emitted from the use of dedicated energy crops. Appropriate mitigating strategies, such as best farming practices to maximize the yield, are essential to control the GHG emissions resulting from an increased land footprint for natural fertilizers. Transportation accounted for the majority of the GHG emissions from rice straw preparation under the category of agriculture residues [21]. The composition and segregation of waste were identified to be the critical factors influencing life cycle GHG emissions from the waste feedstock-based biomass-only electricity generation systems [33].

From Figure 1b, one may note the degree of variation in GHG emissions was less between LCA studies based on forestry, followed by industry, dedicated energy crops, agriculture residues, and wastes. The median quartile statistic (Q2) showed a consistent pattern to that observed in the mean life cycle GHG emissions pattern, with forestry being the minimum, followed by industry, dedicated energy crops, agriculture residues, and wastes (refer to the box plots from Figure 1b and Table 3).

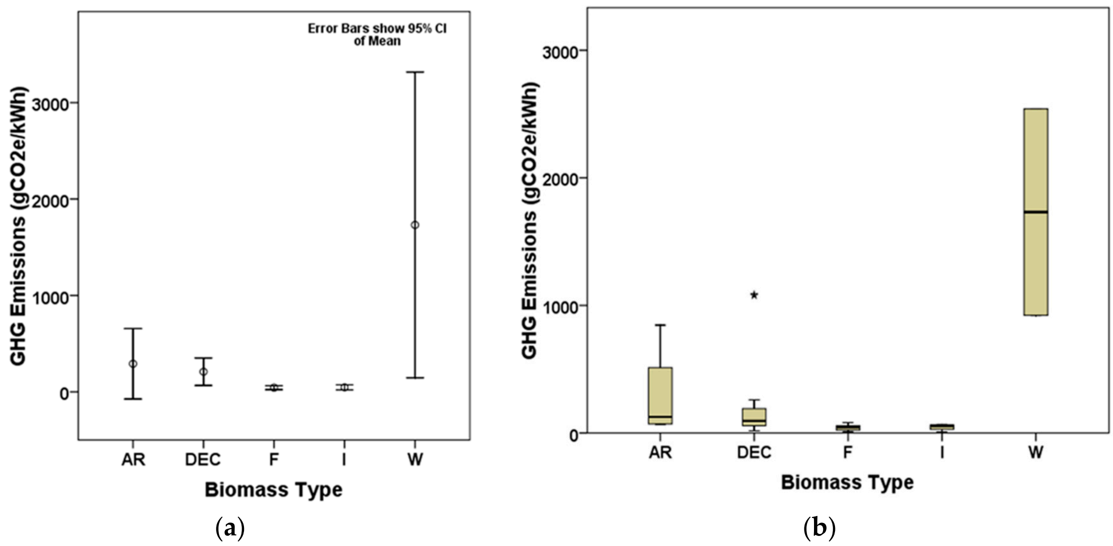


**Figure 1.** GHG emissions from biomass-only electricity generation systems: (**a**) mean ± 95% confidence interval (CI) error bars and (**b**) quartile box plots.

**Table 3.** GHG emission ($gCO_2e/kWh$) statistics from biomass-only electricity generation systems.

| Biomass Type | *N* | X ± SD | Min. | Max. | SE | Q1 | Q2 | Q3 |
|---|---|---|---|---|---|---|---|---|
| agriculture residue | 4 | 291.25 ± 372.8 | 67 | 845 | 186.4 | 67 | 126.5 | 180 |
| dedicated energy crops | 19 | 208.41 ± 316.54 | 17 | 1085.94 | 72.62 | 50 | 95 | 250 |
| forestry | 6 | 43 ± 25.67 | 10 | 82 | 10.48 | 22 | 44 | 56 |
| industry | 4 | 45.92 ± 26.67 | 7 | 66 | 13.33 | 7 | 55.35 | 59.7 |
| waste | 2 | 1731.36 ± 1144.3 | 922.22 | 2540.5 | 809.14 | 922.22 | 1731.36 | 922.22 |

The use of biomass has a potential to reduce the life cycle GHG emissions by 77%–99% in comparison to fossil fuel combustion, depending on the feedstock category and combustion technology used [18]. The biomass-only electricity generation system net electric efficiency was identified to be the most important factor that influences the final GHG emission savings [20]. The mode of transportation and distance would largely influence the GHG emissions from biomass electricity generation systems [14].

### *3.4. Statistical Evaluation of Biomass Cofiring with Coal LCA Studies*

Figure 2 provides a graphical presentation of the (a) error bars (mean ± 95% CI statistics) and (b) box plots (quartiles + outlier statistics) for GHG emissions from the different feedstock-based biomass cofiring electricity generation systems reviewed in this study. Table 4 provides a statistical summary of the life cycle GHG emissions for the different feedstock-based biomass cofiring electricity generation systems reviewed in this study.

From Figure 2a and Table 4, the mean life cycle GHG emissions from the use of agriculture residues ($N$ = 10), dedicated energy crops ($N$ = 9), forestry ($N$ = 9), industry ($N$ = 2), and parks and gardens ($N$ = 1) in biomass cofiring electricity generation systems are 1039.92 $gCO_2e/kWh$, 1001.38 $gCO_2e/kWh$, 961.45 $gCO_2e/kWh$, 926.1 $gCO_2e/kWh$, and 1065.92 $gCO_2e/kWh$, respectively. These results indicate that there is not much difference in the mean life cycle GHG emissions from cofiring electricity generation systems utilizing different biomass feedstock categories. This may be attributed to the fact that considerably higher GHGs are emitted from the combustion of coal than the combustion of biomass. More LCA studies utilizing parks and gardens feedstock-based biomass for biomass cofiring electricity generation systems are to be considered before one generalizes the influence of parks and gardens feedstock on life cycle GHG emissions (considering the need to have a minimum sample size of two to determine the degree of confidence in the mean life cycle GHG emission statistic of parks and gardens feedstock-based biomass). Amongst the different feedstock categories considered for biomass cofiring electricity generation systems, the mean life cycle GHG emissions were noted to be the minimum for industry, followed by forestry, dedicated energy crops, agriculture residues, and parks and gardens. One may note that the industry and the forestry feedstock-based biomass cofiring electricity generation systems produced the lowest GHG emissions (as also noted in the case for biomass-only electricity generation systems) owing to the elimination of GHG emissions resulting from biomass production and waste management during the implementation of bioenergy projects. The GHG mitigation per ton of dedicated energy crop during cofiring was noted to be better than that for dedicated energy crop biomass-only combustion [12]. The observations of life cycle GHG emissions being similar between dedicated energy crops and forestry in the cofiring process were also noted in another study [23]. The use of chemicals and fertilizers was identified to be the major contributor to life cycle GHG emissions with reference to biomass production [34].

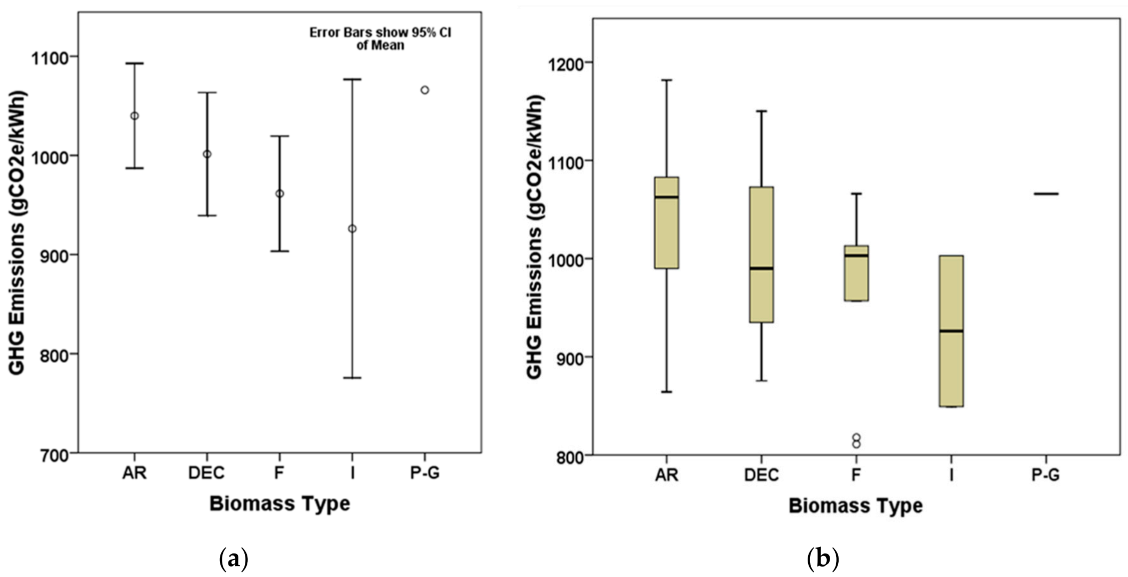


**Figure 2.** GHG emissions from biomass cofiring electricity generation systems: (**a**) mean ± 95% CI error bars and (**b**) quartile box plots.

**Table 4.** GHG emission ($gCO_2e/kWh$) statistics from biomass cofiring electricity generation systems.

| Biomass Type | N | Mean ± SD | Min. | Max. | SE | Q1 | Q2 | Q3 |
|---|---|---|---|---|---|---|---|---|
| agriculture residue | 10 | 1039.92 ± 85.27 | 864.3 | 1181.7 | 26.96 | 990 | 1062.48 | 1082.8 |
| dedicated energy crops | 9 | 1001.38 ± 95.02 | 875.6 | 1150 | 31.67 | 935.1 | 990 | 1072.79 |
| forestry | 9 | 961.45 ± 88.85 | 811 | 1066.03 | 29.62 | 957 | 1003 | 1013 |
| industry | 2 | 926.1 ± 108.61 | 849.3 | 1002.9 | 76.8 | 849.3 | 926.1 | 1002.9 |
| parks and gardens | 1 | 1065.92 ± 0 | 1065.92 | 1065.92 | 0 | 1065.92 | 1065.92 | 1065.92 |

From Figure 2b, one may note the degree of variation in GHG emissions between LCA studies for forestry was minimal, followed by agriculture residues, dedicated energy crops, and industry. The median quartile statistic (Q2) showed a different pattern to that observed in the mean GHG emission pattern, with industry being the minimum, followed by dedicated energy crops, forestry, and agriculture residues (refer to the box plots from Figure 2b and Table 4).

All the reviewed studies on cofiring noted considerable reductions in GHG emissions when compared with fossil fuel combustion. It may be noted from the review of select studies [12,22,26,27] that as the percentage of biomass in cofiring increased, the life cycle GHG emissions decreased. Combustion and transportation were identified to be the major contributors to life cycle GHG emissions in cofiring [28]. Some studies [24,26] noted an increase in the energy density and cofiring efficiency will help reduce the life cycle GHG emissions.

## 4. Conclusions

This paper evaluated the life cycle GHG emissions from different feedstock category-based biomass-only and cofiring electricity generation systems using a two-step approach. The first step involved a comprehensive search for biomass-only and cofiring LCA studies, followed by a comprehensive review that included categorization of each of the identified biomass-only and cofiring LCA based on the type of feedstock. The second step involved the computation of statistical parameters that enables quantification of the life cycle GHG emissions with a degree of confidence and examination of the variability in life cycle GHG emissions.

A total of 11 biomass-only and 11 cofiring electricity generation LCA case studies were identified from the literature. The identified biomass-only and cofiring electricity generation LCA studies were categorized on the basis of the type of feedstock (agriculture residues, dedicated energy crops, forestry, industry, parks and gardens, wastes). While the use of mineral fertilizers was identified to be the major contributor to GHG emissions from dedicated energy crop production, transportation was identified to be the major contributor to GHG emissions from agriculture residue preparation. The use of forestry and industry feedstock categories avoided the higher emissions that would have been associated with the crop production and the waste management activities. For the biomass feedstock category of wastes, the composition and segregation of waste were identified to be the primary factors affecting life cycle GHG emissions. As the percentage of biomass increased in cofiring, the GHG emissions reduced.

Based on the statistical evaluation of the biomass-only LCA studies, the mean life cycle GHG emissions for agriculture residues ($N = 4$), dedicated energy crops ($N = 19$), forestry ($N = 6$), industry ($N = 4$), and wastes ($N = 2$) were computed to be 291.25 $gCO_2e/kWh$, 208.41 $gCO_2e/kWh$, 43 $gCO_2e/kWh$, 45.93 $gCO_2e/kWh$, and 1731.36 $gCO_2e/kWh$, respectively. In the case of cofiring, the mean life cycle GHG emissions for agriculture residues ($N = 10$), dedicated energy crops ($N = 9$), forestry ($N = 9$), industry ($N = 2$), and parks and gardens ($N = 1$) were computed to be 1039.92 $gCO_2e/kWh$, 1001.38 $gCO_2e/kWh$, 961.45 $gCO_2e/kWh$, 926.1 $gCO_2e/kWh$, and 1065.92 $gCO_2e/kWh$, respectively. The use of forestry and industry feedstock categories is recommended for extensive use in both biomass-only and cofiring electricity generation systems (considering that the mean life cycle GHG emissions were the lowest and there was not much difference). The variation in mean life cycle GHG emissions in cofiring electricity generation systems with respect to biomass feedstock categories was minimal (a consequence of considerably higher

GHGs being emitted from the combustion of coal in comparison with the combustion of biomass). Future feedstock-based biomass LCA studies need to focus on filling the knowledge gaps associated with the use of the parks and gardens feedstock-based biomass-only and waste cofiring electricity generation systems for which there were no references, which may provide valuable information on their applicability in producing electricity within a region. Future research efforts can also be aimed at increasing the number of real-world biomass LCA case studies, which can lead to further consolidation of the GHG emissions resulting from different biomass feedstock electricity generation systems.

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