The application of Refuse Derived Fuel (FDR) from commercial solid wastes to reduce CO₂ emissions in the cement industry: a preliminary study

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Abstract. One of the issues faced by several cities in Indonesia is the management of their increasing generation of solid wastes. One of the largest waste generators include the commercial area, such as malls, restaurants, office buildings, motels, and others, which need to manage their wastes via more sustainable routes such as the application of these wastes as refuse derived fuel to mitigate the climate change causing by fossil fuel. This study aims to analyse the potential use of wastes generated from commercial areas such as refuse-derived fuel (RDF) in the cement industry for reducing CO₂ emissions. Five variants of RDFs were developed on the basis of commercial solid waste compositions. Results revealed that RDF variation 3 comprising 20% paper and 80% plastics exhibits the highest energy of 6272 kcal/kg. As preliminary study, cement industry Y is investigated as an example. During the simulation of the clinker production, RDF variation 3 is combined with petroleum coke, coal, fuel oil, or natural gas. Compared to other fuels, the combination of petroleum coke and RDF variation 3 exhibits the best CO₂ reduction of 2,155.3 10⁶ Kt CO₂/year, with the total annual clinker production of 12.64 million tons. These findings should aid policy and decision makers of waste management service provision and industry to design financially viable management systems based on resource recovery options.

1. Introduction
As one of the developing countries in the world, Indonesia is facing waste-related issues due to the significant annual increase of its population [1]. These waste-related issues are caused by the increased amount of generated wastes and the low level of social awareness, thereby leading to the implementation failure of national policy. Statistics have revealed that in 2015, 64 million tons of waste was generated annually. This value increased to 65 million tons of the annual waste generation in 2016 [2]. One of the largest sources of waste in Indonesia is the commercial sector such as malls, restaurants, office buildings, hotels, motels, traditional and modern markets, and others [3]. Mall X is one of the largest wholesaler malls in Jakarta, which accommodates 6000 kiosks on six floors and generates 27 tons of wastes daily. Some of the waste utilization methods performed by the Mall X management include the separation of plastic waste, which contain plastic bottles, plastic cups, and cardboards for sale to third parties and the utilization of organic waste as cattle feed.

To participate in tackling global issues, such as the steep plummet of fossil fuels, the greenhouse effect, and climate change, it is imperative to find a new method to utilize energy generated from unconventional materials using currently available natural or non-natural resources. Waste to Energy (WTE) is a technology application that encompasses waste treatment, generating energy in the form of electricity, heat, or fuel from waste [4]. One of the advantages associated with the application of WTE is
the generation of 600 kWh of electricity from the utilization of 1 ton of commercial wastes as fuel; furthermore, the said application can discourage the mining of a quarter ton of high-quality coals and the import of one barrel of fuel [5]. Moreover, the utilization of commercial wastes can reduce CO\textsubscript{2} gas emissions if used in power plants. The use of commercial waste as fuels leads to the generation of 379.66 kg/ MWh CO\textsubscript{2}, while coal generates 1020.13 kg/ MWh CO\textsubscript{2}; fossil fuel generates 758.41 kg/ MWh CO\textsubscript{2}; and natural gas generates 514.83 kg/ MWh CO\textsubscript{2} [6]. In this study, the preliminary objective was to investigate the application of Mall X wastes as an alternative fuel and their potential to reduce CO\textsubscript{2} emissions.

2. Methodology
The entire waste management system implemented by Mall X, including the handling, sorting, storage and processing, collection, and transfer of wastes to landfills, as well as the waste composition are analyzed according to the Indonesian Standard SNI 19-3694-1994 on commercial waste collection and measurement of wastes and composition. Chemical characteristics such as the water content and mass percentages of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) are analyzed according to ASTM D5373-14, “Standard Test Methods for Determination of Carbon, Hydrogen and Nitrogen in Analysis Samples of Coal and Carbon in Analysis Samples of Coal and Coke” and ASTM D3176-15, “Standard Practice for Ultimate Analysis of Coal and Coke.” In this study, the Dulong formula is used as follows:

\[
Q \text{ (MJ/Kg)} = 0.336 \text{ C} + 1.418 \text{ H} + 0.094 \text{ S} - 0.145 \text{ O} \tag{1}
\]

3. Results and discussion
3.1. Mall X Waste Management System
Based on the type of waste in the waste source area, waste separation is completed by Mall X, and the process is communally conducted on the 5th floor. Waste sorting is carried out by the separation of organic, paper, and plastic waste, which is later reused by mall management. With respect to the storage of wastes in Mall X, three containers are used: A 100-L stainless-steel container for indoor use, a 100-L metal barrel for parking area use, and a plastic container for the canteen and pedestrian area. Waste processing by sorting utilizes the Reduce, Reuse, and Recycle principle, which includes the Black Soldier Fly (BSF) method for the degradation of organic waste, composting, and incineration. Cardboard and plastic waste is sorted and sold later to third parties. Three tons of waste is sold daily to third parties. Waste processed using BSF include organic wastes generated from the mall food court. Food-court-generated organic waste processed by third parties is later used as cattle feed, reaching 0.5 ton daily. The composting of wastes generated by environmental maintenance is carried out using solid and liquid compost. Moreover, the compost is used to sow and fertilize plants within the Mall X area. The waste generated by environmental maintenance reaches 0.3–0.5 ton daily. In addition, incinerated waste residues reach 5 tons daily. A scrubber is applied as an air pollution control unit in this incinerator.

Waste collection in Mall X is carried out twice daily, in the afternoon and evening. Waste is directly collected from individual kiosks and that stored in the mall area using a wagon, and it is finally taken to the 5th floor for sorting. Next, the waste is transferred to the waste temporary collection station at Mall X and transported to the Bantar Gebang landfill. Mall X conducts a combination of manual and mechanical waste transfer. Manual transfer involves the staff filling a waste container, whereas mechanical transfer involves the loading of the waste container onto a truck using a load haul. In 2018, Mall X generated 27 tons of waste daily, as processing using 3R sorting generated 1 ton of wastes (3.7%), burning using the incinerator generated 5 tons of wastes daily (18.5%), composting generated 0.3 0.5 tons of wastes daily (1.4%), and processing using BSF generated 0.5 tons of waste daily (1.85%). The following figure shows the mass balance of the Mall X mall waste management.
3.2. Mall X waste composition

Table 1. Mall X waste composition

| Composition                        | Percentage (%) |
|-----------------------------------|----------------|
| Paper/Card                        | 36.32          |
| Plastic                           | 35.71          |
| Textile                           | 1.75           |
| Absorbent hygiene product         | 2.43           |
| Wood                              | 0.85           |
| Rubber                            | 1.24           |
| Styrofoam                         | 5.03           |
| Glass                             | 1.12           |
| Organic (leftovers and leaves)    | 14.54          |
| Metal                             | 0.328          |
| Electronic waste                  | 0.55           |
| Hazardous waste                   | 0.08           |

Table 1 shows the Mall X waste composition. It was found that the Mall X waste composition contains less organic than inorganic content. Paper waste dominates the composition by 36.2%, mostly comprising cardboards and duplex. Both paper wastes are usually utilized in the product packaging process. Also, plastic dominates the composition by 35%, which are predominantly comprising drink cups, mica plastics, and multilayered plastics that are utilized for food packaging.

3.3 Alternative Refuse-Derived Fuel (RDF) Composition Variations and Energy Potentials

Before using RDF as an alternative fuel, the composition of the waste obtained from mall X is varied to determine the most optimal composition for the purpose of obtaining the highest heating value from the waste. Tables 2 and 3 summarize the as-designed compositions of the five RDF variants and their ultimate analysis, respectively. Each of the variations is analyzed for the waste energy potential using the Dulong Formula [7] and shown in Table 4. As the preliminary study, the data shown in Tables 3 and 4 are obtained from the ultimate analysis reported in literature reviews on paper, plastics, and organics.

Table 2. Five RDF composition

| RDF Variation | Composition                        |
|---------------|-----------------------------------|
| Variation 1   | Same as that generated by mall X waste |
| Variation 2   | 80% Paper, 20% Plasctics           |
| Variation 3   | 20% Paper, 80% Plastics            |
| Variation 4   | 20% Paper, 60% Plastics, 20% Organics |
| Variation 5   | 60% Paper, 20% Plastics, 20% Organics |

Once the chemical composition of waste for use as an alternative fuel source in the form of RDF is calculated, the chemical formula of the RDF is shown in Table 5 for each RDF variation. Furthermore, the theoretical stoichiometry for the combustion of 1 kg of RDF from Mall X waste is calculated.

For example, the combustion of 1 kg of RDF variation 1 generates 1.75 kg CO$_2$, 0.64 H$_2$O, 0.0184 NO$_2$, and 0.0041 SO$_2$. Table 5 shows the summary of the calculated stoichiometry for the combustion of RDF from Mall X:
Table 3. Ultimate analysis of RDF variations 1–5

| Element     | Unit | RDF Var 1 | RDF Var 2 | RDF Var 3 | RDF Var 4 | RDF Var 5 |
|-------------|------|-----------|-----------|-----------|-----------|-----------|
| Carbon      | %    | 47.81     | 38.49     | 54.7      | 49.3      | 36.87     |
| Hydrogen    | %    | 7.16      | 6.23      | 8.84      | 7.93      | 5.79      |
| Oxygen      | %    | 29.37     | 38.36     | 26.87     | 28.79     | 36.91     |
| Nitrogen    | %    | 0.56      | 0.49      | 0.37      | 0.4       | 0.67      |
| Sulphur     | %    | 0.214     | 0.163     | 0.127     | 0.121     | 0.165     |

Table 4. Calculated RDF calorific values by the dulong formula

| Type of RDF | Btu lb⁻¹ | kcal kg⁻¹ | MJ kg⁻¹ |
|-------------|----------|-----------|---------|
| Var 1       | 9074.748 | 5044.9    | 21.107  |
| Var 2       | 6467.82  | 3595.63   | 15.044  |
| Var 3       | 11283.84 | 6272.99   | 26.246  |
| Var 4       | 9799.403 | 5447.75   | 22.793  |
| Var 5       | 6076.963 | 3378.35   | 14.135  |

Table 5. The summary of the calculated stoichiometry for the combustion of RDF from Mall X

| Parameter                        | RDF Var 1 | RDF Var 2 | RDF Var 3 | RDF Var 4 | RDF Var 5 |
|----------------------------------|-----------|-----------|-----------|-----------|-----------|
| Chemical Formula                 | C_{39}H_{70}O_{18}N_{0.4}S_{0.07} | C_{32}H_{61}O_{24}N_{0.35}S_{0.05} | C_{45}H_{87}O_{17}N_{0.26}S_{0.04} | C_{41}H_{78}O_{18}N_{0.29}S_{0.04} | C_{31}H_{57}O_{23}N_{0.48}S_{0.05} |
| Calorific value (kcal/ kg)       | 5044.9    | 3595.63   | 6272.99   | 5447.75   | 3378.35   |
| Air requirements (kg O2/1 kg RDF)| 1.86      | 1.53      | 2.17      | 1.95      | 1.45      |
| Flue Gas Total (kg flue gas/ kg RDF) | 2.42     | 1.99      | 2.82      | 2.54      | 1.90      |
| Composition of gases produced    | CO₂ = 72.44% | CO₂ = 70.87% | CO₂ = 71.22% | CO₂ = 71.25% | CO₂ = 55.86% |
|                                  | H₂O = 26.62% | H₂O = 28.15% | H₂O = 28.25% | H₂O = 28.13% | H₂O = 26.16% |
|                                  | NO₂ = 0.7%  | NO₂ = 0.8%  | NO₂ = 0.47% | NO₂ = 0.51% | NO₂ = 1.15% |
|                                  | SO₂ = 0.17% | SO₂ = 0.15% | SO₂ = 0.129% | SO₂ = 0.123% | SO₂ = 0.16% |

Among the five variations, RDF variation 3 exhibits the highest calorific value of 6272 kcal/ kg, which is related to its highest H content of 8.84%, while RDF variation 5 exhibits the lowest calorific value of 3378.35 kcal/ kg, which is related to the H content of 5.79%. In terms of the total flue gas generated from the RDF, RDF variation 3 exhibits the highest amount (2.82 kg flue gas/ kg) of RDF burned, and CO₂ emissions generated from the combustion of 1 kg of RDF variation 3 reaches 2.01 kg. Compared to the others, RDF variation 5 exhibits 1.35 kg of CO₂ emissions from combustion, which is related to its lower C content (36.87%) than those of the other RDF variations. Hence, RDF variation 3 is selected because of its highest calorific value. Table 6 summarizes the comparison of the ultimate analysis of various fuels used in the cement industry [8]:

Table 6. Comparison of RDF variation 3 with other fuels

| Fuel type          | Carbon (C) | Hydrogen (H) | Oxygen (O) | Nitrogen (N) | Sulphur (S) |
|--------------------|------------|--------------|------------|--------------|-------------|
| RDF variation 3    | 54.7       | 8.84         | 26.87      | 0.37         | 0.127       |
| Bituminous coal    | 70.6       | 4.3          | 11.8       | 1.2          | 1.3         |
| Petroleum coke     | 89.5       | 3.08         | 1.11       | 1.71         | 4           |
| MBM (Meat bone meal) | 42.1     | 5.83         | 15.3       | 7.52         | 0.38        |
| Sewage Sludge      | 40.5       | 7            | 25.2       | 0.84         | 0.12        |
3.4. Emission reduction by the use of RDF in the cement industry

In this study, RDF variation 3 produced from Mall X waste is utilized as an alternative fuel for the cement industry, which previously used fossil fuels. In 2010, the cement industry contributed to 2,823 million metric tons of CO₂ emissions, which is equivalent to 9% of the global CO₂ emissions from the combustion of fossil fuels in 2010 [9]. On the other hand, cement production exhibited a global increase to 73%, which is equivalent to 2,310 metric tons of cement in 2005 and 4,000 metric tons of cement in 2013; hence, it is imperative to reduce the CO₂ emissions generated from the cement industry [10]. One of the several efforts toward the reduction of CO₂ emissions generated from the cement industry is the replacement of fossil fuels with alternative fuels. Table 7 summarizes the CO₂ emissions from fossil fuels [11]:

| Fuel             | Kt CO₂ GJ⁻¹ |
|------------------|-------------|
| Petroleum Coke   | 97.5        |
| Coal             | 94.6        |
| Fuel Oil         | 77.4        |
| Natural Gas      | 56.1        |

The use of fossil fuels as the main fuel affects CO₂ emissions due to their different compositions. For example, petroleum coke generates the highest CO₂ emissions of 98 Kt CO₂ per GJ due to its high C content of 89.5% (Table 5). Although natural gas generates the lowest CO₂ emissions of 56.1 Kt CO₂ per GJ, it is rarely used in the cement industry. The energy consumption for the clinker production differs on the basis of its production equipment. As a case study, cement industry Y is taken as an example, where 1,750 MJ of energy is required to produce 1 ton of clinker [10,12]. Table 8 summarizes the detailed calculation of RDF required to meet the annual cement production:

For the annual production of 12.64 million tons of clinker, 1,421.31 10³ tons of RDF is required to satisfy the total energy requirements. On the other hand, Mall X only generates 20 tons of wastes daily or 7,300 tons annually; therefore, RDF variation 3 only meets 0.51% of the total energy required daily for the cement industry. The total energy for the RDF variation 3 is 26.2 GJ/ton, with CO₂ emissions of 1.75 kg CO₂/ kg by RDF. Hence, the CO₂ emission ratio generated from RDF variation 3 reaches 0.062 tons of CO₂/ GJ, which is equivalent to 6.2 10⁻⁵ Kt of CO₂/ GJ. Table 9 summarizes the comparison of the total CO₂ emissions generated annually using different fuel sources if 12.64 million tons of clinker cement is produced annually:
Table 9. Total CO$_2$ emissions generated annually from various fuels for the production of 12.64 million tons of clinker cement by the application of RDF variation 3

| Fuel          | Emission Ratio (Kt CO$_2$/ GJ) | Total Energy Requirements(GJ/Year) | Total Emissions Generated Annually(Kt CO$_2$/year) | Total CO$_2$ Emission Annually from Combining RDF variation 3 and other fuel (Kt CO$_2$/year) |
|---------------|-------------------------------|------------------------------------|---------------------------------------------------|--------------------------------------------------------------------------------------|
| RDF variation 3 | 6.2 $10^5$                   | 1,371.44 $10^3$                   | -                                                 |                                                                                  |
| Petroleum coke | 97.5                          | 2,156.7 $10^6$                    | 2,155.3 $10^6$                                    |                                                                                  |
| Coal          | 94.6                          | 2.212 $10^7$                      | 2,092.5 $10^6$                                    | 2,091.1 $10^6$                                                                    |
| Fuel Oil      | 77.4                          | 1,712 $10^6$                      | 1,710.6 $10^6$                                    |                                                                                  |
| Natural Gas   | 56.1                          | 1,240.9 $10^6$                    | 1,239.5 $10^6$                                    |                                                                                  |

It is found that annually, RDF variation 3 generates 1,371.44 $10^3$ CO$_2$ emissions; hence when this RDF variation 3 combines with other fuel, the CO$_2$ emission can be reduced. When RDF variation 3 combines with petroleum coke, the CO$_2$ emissions are 2,155.3 $10^6$, coal 2091.1 $10^6$, fuel oil 1,710.6 $10^6$, and natural gas 1,239.5 $10^6$ respectively. In total, to produce 12.64 million tons of clinker cement, as wastes generated from Mall X only supplies 0.51% of the total energy, other wastes supplied from other malls are required to meet the annual energy requirements for the cement production.

4. Conclusion

As one of the largest sources of waste in Indonesia, the commercial sector such as malls, restaurants, office buildings, hotels, motels, traditional and modern markets, and others generate a huge amount of wastes. This study aims to analyse the potential use of wastes generated from commercial areas such as refuse-derived fuel (RDF) in the cement industry for reducing CO$_2$ emissions. As a case study, Mall X waste contains 36.2% paper, which are predominantly comprising cardboard and duplex, followed by 35% of plastic wastes, which are predominantly drink cups, mica plastics, and multilayered plastics for wrapping. Other waste includes hazardous waste, hygiene products, and organics.

Five variations of RDFs from the wastes from Mall X were developed. It was concluded that for the annual production of 12.64 million tons of clinker, 1,421.31 thousand tons of RDF which consist of 20% papers and 80% plastics are needed. However, since Mall X only generates 20 tons of wastes daily or 7,300 tons of wastes annually; therefore, waste supply from other sources is required as source of alternative energy sources. Compared to coal, fuel oil, and natural gas, the combination of petroleum coke and this RDF exhibits the best CO$_2$ reduction of 2,155.3 $10^6$ Kt CO$_2$/ year. By the application of these RDFs, impact the climate change can be reduced. Further research on the actual waste compositions is desired.

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