

Environmental and Climate Impacts Associated with Refuse Derived Fuel (RDF) Production: a Case Study in Thailand

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Abstract. Improper waste management poses considerable risks to both the environment and human health. Despite Refuse Derived Fuel (RDF) is one of promising alternative technologies of waste management, however, it is necessary to gain insight into all environmental impacts of RDF as alternative fuel. This study, therefore, aimed to investigate potential environmental footprints and climate change related impacts from a case study of RDF power plant in Thailand. By employing the life cycle assessment (LCA) concept, gate-to-gate approach was selected as a study boundary. Functional unit was defined as “1MWh of electricity generation”. IMPACT2002+, Greenhouse Gas Protocol and IPCC2013 methods were chosen to determine life cycle potential environmental impacts and carbon-based emission. The key findings revealed that resources impact showed the highest environmental footprint, followed by climate change, human health, and ecosystem quality categories, respectively. Electricity consumption was considered the most important environmental burden associated with the RDF production (1.66 mPt). By considering the climate change impacts, the results shown that electricity-consumed in the RDF generation emitted the largest share of greenhouse gas emissions (6.81 kgCO₂e), compared to diesel and natural gas utilizations. Overall, proper management efforts to minimize all negative environmental and climate impacts are necessary in the RDF electricity operation.

1 Introduction

Presently, poor waste disposal practice is considered one of the most critical challenges for environmental sustainability. A holistic approach for waste management should be urgently taken. In general, there are many factors that can affect the effectiveness of municipal solid waste management, such as waste generation rate, consumption level, and economic growth [1]. Herein, the key concept of sustainable development regarding waste management is to prevent waste generation by 7 Rs actions (e.g., Re-use, Re-cycle, Recovery, and ETC) [2]. Beside this, by the ambitions of global society that have moved forward to a reduction of

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greenhouse gas emissions by 2050 [3], waste to energy pathway is recognized as an important role-player in the transition towards circular economy (CE) to serve the sustainable waste management.

In the view of circular economy, promoting use of waste for energy production can positively deliver an energy sustainability, especially, in terms of Refuse-Derived-Fuel (RDF) [4]. The fuel obtained from dry residual and waste can be used as material for energy generation. Although RDF has been commonly used in energy plant, it is important to explore all potential environmental impacts accounting in the life cycle assessment (LCA) concept. The LCA has been highlighted as the most suitable technique to gain an integrated and systematic assessment of both positive and negative environmental effects of the processes within different environmental impact categories throughout the life cycle of the products (e.g., global warming, human toxicity, etc.) [2]. There are many researches on LCA of municipal waste management. For instance, a study of Laurent et al. [5] compared the environmental footprints between landfill treatment and alternative waste treatment technologies (e.g., RDF) and found that landfill treatment system delivered the worst environmental impacts compared to other waste management techniques. Further to this, Mendes et al. [6] applied the LCA concept to evaluate environmental burdens of landfilling, incineration, and combustion techniques. In this context, incineration showed a lower environmental impact than other treatment techniques. In terms of environmental impact analysis for RDF using LCA, Lima et al. [7] pointed out that replacement of RDF to the conventional fossil fuel (i.e., coal) can reduce energy demand, greenhouse gas emissions and other potential environmental impacts. Similarly, a study conducted by Reza et al. [8] reported that the RDF power generation consumed electricity less than the utilization of coal and fossil fuel, and contributed to the reduction of carbon emissions.

In Thailand, there has been few studies assessing environmental life cycle impact of waste treatment and disposal processes, including RDF technology [9]. Besides the significance of greenhouse gas emissions databases, there is a lack of research database on carbon footprint from waste to energy technologies. Therefore, this study purposed to investigate all potential environmental and climatic-related impacts from the production of RDF in a case study of Thailand (Power Plant A). The key results, in turn, could guide academics, policymakers, and related stakeholders in the waste sector with a deeper understanding of environmental impacts and sustainability of waste management.

2 Literature review

Alternating waste into energy is one of the most effective management systems for addressing the climate change. Due to avoiding the use of fossil fuels, methane emissions are retarded by the waste to energy process. Refuse Derived Fuel or RDF is produced from municipal solid waste (MSW) which comprises of biodegradable and plastic materials. Fuel, then, is generated from the combustion of materials. Thus, fuel is used as an alternative source of energy in power plant generation [10]. As mentioned by [11], energy obtained from the RDF production could minimize tons of greenhouse gas emissions (i.e., carbon dioxide and methane) compared with landfill site management. Hence, by converting waste from landfill into energy, the RDF technology can divert the effective waste approach and can mitigate carbon emissions to the environment.

For evaluating environmental impacts, life cycle assessment (LCA) is a systematic environmental tool for estimating the potential environmental impacts associated with a product, service or activity by identifying and quantifying energy and materials used and wastes released to the environment. To estimate the impacts, the assessment covers the throughout life cycle of the product, comprising of five determined stages: extracting and processing materials, manufacturing, transportation and distribution, use, re-use,

maintenance, and recycling and final disposal [12]. Life cycle assessment can be employed based on the ISO 14040 principles and framework including ISO 14041: goal and scope definition and inventory analysis (LCI), ISO 14042: life cycle impact assessment (LCIA) and ISO 14043: life cycle interpretation [13]. The boundary of assessment is considered from the first stage of production as extraction and manufacture (cradle) through the use phase to the disposal phase (grave) which is known as a full life cycle assessment (cradle-to-grave). Moreover, cradle-to-gate is an assessment of a partial product life cycle starting from the extraction of raw material to the manufacture of product (cradle). The phase of product consumption and waste disposal are usually neglected. Meanwhile, the cradle-to-cradle is another specific aspect of cradle-to-grave assessment, thereby the end-of-life or disposal phase is a recycling process of product [14], see Fig.1.

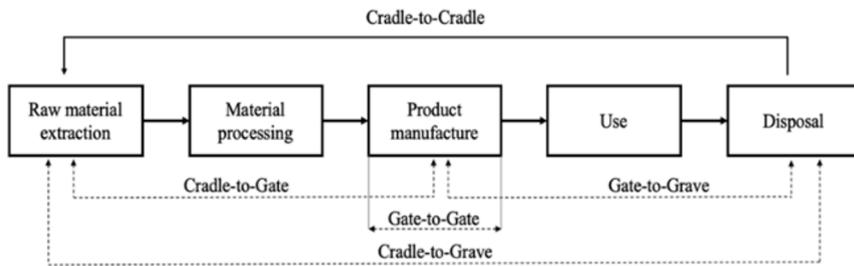


Fig.1. System boundary of the LCA

3 Materials and methods

1) Goal and scope

The goal of this study was to assess all related environmental impacts of “1 MWh electricity generation from the RDF power plant”. By scope, a gate-to-gate analysis was conducted to evaluate all associated environmental and greenhouse gas burdens of the RDF operation.

Table 1. Life cycle inventory data of 1 MWh electricity generation from RDF power plant

| Inventory data (Inputs) | Categories | Unit |
|----------------------------|------------|------|
| Electricity | 9.46 | KWh |
| Diesel | 1.06 | L |
| Natural gas | 0.16 | Kg |

2) Life cycle inventory

Table 1 depicts the data of life cycle inventory (inputs) of the RDF production from municipal solid waste project design document of Thailand Voluntary Emission Reduction Program (T-VER) [15]. A project installation (Power Plant A) was located upcountry region near Bangkok city, Thailand. The Power Plant A obtained municipal solid wastes from nearby communities through sorting and selecting processes which could provide heat energy; plastic waste carries a high caloric heat value (RDF-H) while organic substance offers a low caloric heat value (RDF-L). Hereby, one mega-watt-hour or one MWh was considered as a functional unit of LCA study. Furthermore, as depicted in Fig.2, the system boundary included inputs of RDF energy production. The life cycle inventory (LCI), afterwards, was aligned per functional unit.

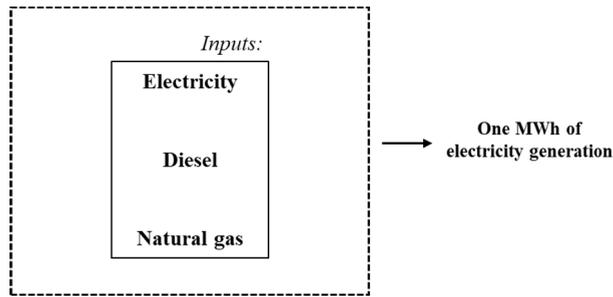


Fig.2. System boundary of the production RDF for 1 MWh of electricity.

3) Impact assessment methodology

By using SimaPro 9.0, IMPACT2022+, Greenhouse Gas Protocol and IPCC2013 methods were applied to investigate all potential environmental and climate change impacts of RDF electricity generation. The IMPACT2002+ was selected as the demonstration of midpoint and damage levels. All fourteen midpoint impact categories were considered as carcinogens (C), non-carcinogens (NC), respiratory inorganics (RI), ionizing radiation (IR), ozone layer depletion (OD), respiratory organics (RO), aquatic ecotoxicity (AE), terrestrial ecotoxicity (TE), terrestrial acid/nutria (TA), land occupation (LO), aquatic acidification (AA), aquatic eutrophication (AE), global warming (GW), non-renewable energy (NR) and mineral extraction (ME) and four endpoint impacts were classified as human health, ecosystem quality, climate change, and resources categories [16]. Secondly, the Greenhouse Gas Protocol method was further performed as the representative of midpoint-oriented damage in terms of fossil CO₂e, biogenic CO₂, CO₂e from land transformation and CO₂ uptake categories [17]. Moreover, climate change impact was also evaluated through greenhouse gas emissions (CO₂e) by the IPCC2013 method [3].

4 Result and discussion

1) Life cycle impact assessment for 1 MWh RDF electricity generation by IMPACT2002+ approach

All possible environmental impacts of 1 MWh RDF power generation were assessed using IMPACT2002+ methodology. At the midpoint impact level, the LCA results indicated aquatic toxicity, non-renewable energy, and terrestrial ecotoxicity categories contributed for about 395.39 kg TEG water, 147.39 MJprimary, and 61.59 kg TEG soil, respectively, (Table 2). Accordingly, both electricity and diesel consumption for the production of RDF were the dominant sources of environmental impacts, especially aquatic ecotoxicity impact (245.03 and 126.51 kg TEG water, respectively). Besides, the main impact of natural gas used in the process of RDF power generation was non-renewable energy (10.41 MJprimary). Similarly, the result of environmental footprint analysis by Silva et al. [18] found that electricity consumption in the RDF processes was the main cause of environmental impacts compared with other treatment techniques (i.e., Mechanical Biologic Treatment (MBT) and landfill site). Moreover, Anasstasia et al. [19] revealed that electricity usage in the RDF contributed the largest share of environmental impact compared to transfer station option and conventional incineration.

Table 2. Characterization of midpoint impacts associated with one MWh electricity generation.

| Impact categories | Unit | Total | Electricity | Diesel | Natural gas |
|---------------------------|-------------------------------------|---------|-------------|---------|-------------|
| Carcinogens | kg | 0.38427 | 0.34584 | 0.00626 | 0.0321702 |
| | C ₂ H ₃ Cl eq | 443 | 286 | 138 | |
| Non-carcinogens | kg | 0.07221 | 0.05874 | 0.00782 | 0.0056502 |
| | C ₂ H ₃ Cl eq | 875 | 24 | 615 | |
| Respiratory inorganics | kg | 0.00390 | 0.00315 | 0.00069 | 0.0000565 |
| | PM2.5 eq | 754 | 875 | 228 | |
| Respiratory inorganics | Bq C-14 eq | 25.6641 | 3.11194 | 22.3711 | 0.1810887 |
| | | 681 | 788 | 315 | 4 |
| Ozone layer depletion | kg | 0.00000 | 0.00000 | 0.00000 | 0.0000000 |
| | CFC-1 eq | 091 | 025 | 063 | 5 |
| Respiratory organics | kg | 0.00171 | 0.00097 | 0.00061 | 0.0001361 |
| | C ₂ H ₄ eq | 734 | 042 | 077 | 5 |
| Aquatic ecotoxicity | kg | 395.398 | 245.303 | 126.513 | 23.581572 |
| | TEG water | 877 | 498 | 807 | 7 |
| Terrestrial ecotoxicity | kg | 61.5904 | 32.2502 | 27.9126 | 1.4276194 |
| | TEG soil | 814 | 319 | 301 | 5 |
| Terrestrial acid/nutrient | kg SO ₂ eq | 0.07219 | 0.05875 | 0.01232 | 0.0011118 |
| | | 243 | 444 | 614 | 5 |
| Land occupation | m ² org. arable | 0.02271 | 0.01737 | 0.00515 | 0.0001799 |
| | | 782 | 996 | 788 | 8 |
| Aquatic acidification | kg SO ₂ eq | 0.02368 | 0.01860 | 0.00466 | 0.0004176 |
| | | 86 | 251 | 849 | |
| Aquatic eutrophication | kg PO ₄ P-lim | 0.00155 | 0.00129 | 0.00025 | 0.0000044 |
| | | 618 | 249 | 922 | 7 |
| Global warming | kg CO ₂ eq | 6.49901 | 5.98179 | 0.45580 | 0.0614120 |
| | | 217 | 875 | 138 | 4 |
| Non-renewable energy | MJprimary | 147.396 | 85.6070 | 51.3697 | 10.419370 |
| | | 17 | 438 | 561 | 4 |
| Mineral extraction | MJsurplus | 0.02217 | 0.01678 | 0.00472 | 0.0006671 |
| | | 557 | 558 | 285 | 3 |

Fig. 2. demonstrates input-related data that were classified into four endpoint impacts on human health, ecosystems quality, climate change, and resources categories (see Fig. 3). The results of environmental impact analysis shown that “resources category” contributed the largest environmental burden from the RDF production of 1 MWh of electricity. Overall, electricity consumption in the RDF plant operation was the largest contributor to all environmental footprint profiles (i.e., human health, ecosystem quality, climate change, and

resources aspects). Diesel consumption making up larger share of environmental impacts than natural gas usage in generation processes.

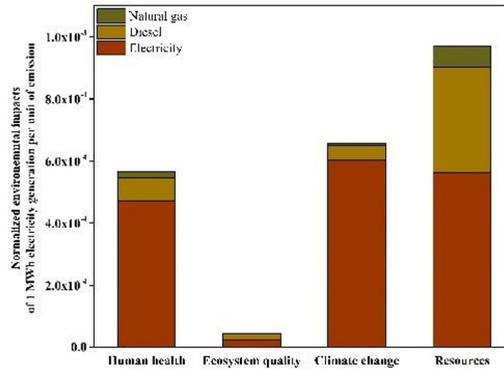


Fig. 3. The IMPACT2022+ normalized endpoint impacts of one MWh electricity generation.

Through the IMPACT 2002+ analysis, as shown in Fig.4, the single scores of potential environmental damages (i.e., human health, ecosystem quality, climate change, and resources) were 0.56, 0.04, 0.65 and 0.97 mPt, respectively. Obviously, electricity consumption showed the highest environmental contribution in all damage categories, including human health, ecosystem quality, climate change and resources (83%, 57%, 92% and 58%, respectively). Similar to the studies of [18] and [19], the findings indicated the importance of electricity consumption as the key-player of environmental emissions.

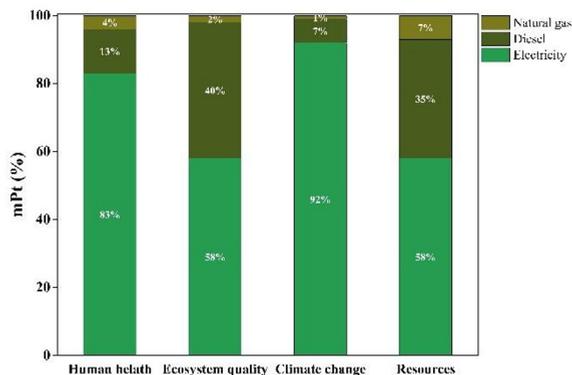


Fig.4. The IMPACT2022+ single score endpoint assessment of 1 MWh electricity generation by RDF power plant.

2) Life cycle impact assessment for one MWh RDF electricity generation by Greenhouse Gas Protocol approach

As illustrated in Fig. 5, electrical energy-consumed in the RDF production processes was the most significant greenhouse gas contributor for all impact categories, including fossil CO₂e, biogenic CO₂e, CO₂ from land transformation, and CO₂ uptake activities, which accounted

for approximately 80 to 98%. Consumption of electricity, obviously, dominated the carbon footprints ranged from 0.01 to 6.21 kgCO₂e, followed by diesel and natural gas consumption (< 0.001 to 0.4 tCO₂e and 0.00001 to 0.09 kgCO₂e, respectively). In contrast, a study of Kovacs et al. [20] indicated that electricity usage was more eco-friendly, in terms of climate change effect, than fuel energy consumption (e.g., natural gas). Furthermore, the above study pointed out that the RDF process had a higher contribution of carbon emissions than pyrolysis and internal combustion procedures.

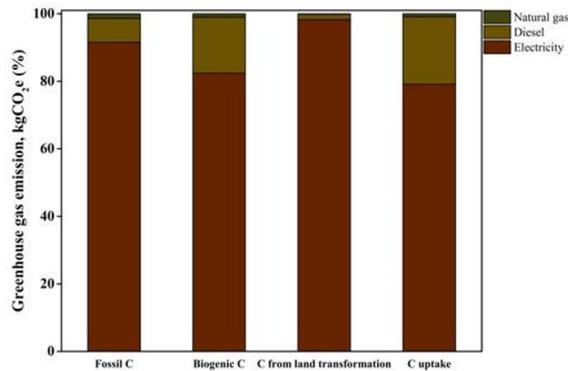


Fig.5. Characterization and weighting environmental impacts of one KWh electricity generation from RDF power plant.

3) Life cycle impact assessment for one MWh RDF electricity generation by IPCC2013 approach.

Regarding to IPCC2013 method, total greenhouse gas emissions of 6.80 kgCO₂e were emitted from the production of 1 MWh RDF electricity generation. The results shown that electricity utilization emitted the highest greenhouse gas compared to the consumption of diesel and natural gas. Carbon emission from electricity usage accounted for approximately 6.23 kgCO₂e (92% of total emissions). Comparatively, diesel and natural gas consumptions emitted greenhouse gas by 0.48 kgCO₂e and 0.09 kgCO₂e (7% and 1%, respectively) (Fig.6). As clearly revealed by [20], electricity consumption in the RDF energy production contributed the greatest amount of carbon emissions.

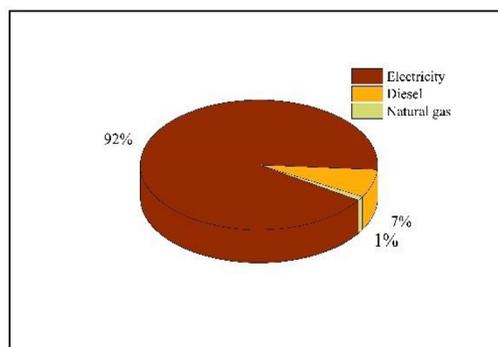


Fig. 6. The IPCC2013 approach characterized carbon emissions of RDF generation for 1 MWh electricity.

4) Discussion

The result of life cycle assessment identified the hotspot of environmental and climate change impacts associated with the energy production from the RDF technology. Electrical energy-consumed in the production processes showed a significant environmental impact in many ways, especially on resource, human health, climate change, and carbon footprints. Due to its high demand of energy, the majority of processes of the RDF mostly require electricity for the production system. Therefore, electricity consumption generated a higher risk to environmental footprints associated with the RDF power generation (e.g. greenhouse gas emission, human health, etc.) compared to usages of diesel and natural gas. However, it should be noted that the system boundary of this study focused on processes achieving the RDF products, excluding mechanical biological treatment (MBT) activity which has been reported the most significant environmental impact contributor [21, 22]. Therefore, the contribution assessment can serve as an energy indicator for improvement of the processes of RDF conversion. Also, it could provide recommendations and guide the appropriate procedures to operators, researchers, policymakers, and related stakeholders.

5 Conclusion

Life cycle assessment of RDF process production was employed by three life cycle impact approaches. The IMPACT2002+ method indicated electricity-consuming activity contributed the highest characterized environmental emissions compared to the usage of diesel and natural gas. Certainly, the normalized endpoint impacts analysis revealed the greatest contribution of endpoint damages including human health, ecosystem quality, climate change, and resources derived from the consumption of electricity in the RDF process. Further to this, all potential environmental impacts of RDF power generation for one KWh electricity were weighted into single scores, which demonstrated the dominant damage contributor of electricity usage. By using Greenhouse Gas Protocol approach, similarly, the results of characterization and weighting analysis illustrated that used electricity in the RDF production maximized the greenhouse gas emissions compared to other fuels. The IPCC2013 method also revealed the same trends of significant greenhouse gas emissions. Energy-consumed electricity had the largest share of carbon footprint, followed by diesel and natural gas, respectively. Ultimately, studies on entire life cycle environmental assessment of RDF production (i.e., complete RDF combustion and MBT technique) should be further considered and more focused.

6 Conflict of interest

The authors declare no conflict of interest.

7 Author contributions

AD and SK writing original draft, conceptualization, conducted research, analyzed data. AD and SK writing methodology and investigation. WN, TS and SS writing- review & editing and validation. All authors had approved the final version.

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