ICSBE2016-18

A LIFE CYCLE PERSPECTIVE OF MUNICIPAL SOLID WASTE: HUMAN HEALTH RISK-ENERGY NEXUS

Hirushie Karunathilake, Kasun Hewage*, Rehan Sadiq

University of British Columbia, Canada
**E-Mail: kasun.hewage@ubc.ca, TP: +1 250.807.8176*

Abstract: With the rapid growth in urban population, sustainable waste management has become a major challenge. Despite being considered an economic, environmental and social burden on communities, waste can also be a resource. The potential of utilising MSW in energy generation has been widely investigated, as a dual solution to the issues of waste management and energy security. Different waste-to-energy conversion technologies have varying levels of impact on human health and environment. In assessing the viability of using MSW in renewable energy systems, it is necessary to understand associated risks. This study addresses the lack of information the link between MSW based-energy generation and human health risks. Mass incineration and refuse derived fuel (RDF) conversion technologies were assessed to evaluate the overall life cycle human health risks due to the processes. The life cycle emissions due to incineration and RDF were assessed using SimaPro software, for a case study on a region in British Columbia, Canada. The results indicate that RDF carries a lower health risk per GWh of energy generated per annum, when compared with incineration. The analysis was further extended to the Sri Lankan context, considering the local waste mix. This information will be useful for urban developers and decision makers in selecting the most suitable waste-to-energy conversion technologies, while mitigating the health risks to population.

Keywords: Municipal solid waste; waste-to-energy; human health risk; life cycle impacts.

1. Introduction

With rapid growth in global population, particularly in the urban areas, managing the generated waste has become a critical issue. If not properly managed, waste can lead to multiple problems such as contamination of air and water and serious human health impacts [1]. While conventional waste management practices focus on the disposal and hygiene aspects, interest has been growing with regards to the energy generation potential of waste [2]. Waste to Energy (WtE) technologies are employed in recovering energy from waste matter using different methods, usually in the form of electricity, heat or fuels [3]. WtE has the potential of turning waste into a valuable resource.

The origin of the waste may be due to residential, commercial, industrial, institutional, municipal or construction and demolition (C&D) activities [4]. Due to this, MSW may be composed of a multitude of material types, both organic and inorganic, and often toxic in nature. The complex composition of the waste mater makes waste disposal and treatment more challenging, requiring sophisticated collection and sorting mechanisms, and different treatment processes based on the type of waste [2][3].

1.1 Waste-to-energy technologies

With the increasing need for sustainable waste management, WtE technologies have been commonly used at a commercial level in many parts of the world. The most widely utilised energy recovery method is mass combustion of waste in incineration plants [3]. Another commonly used WtE technology is Refuse Derived Fuel (RDF) [5].

Thermochemical processes subject the waste matter to high temperatures, subsequently releasing energy as well as gaseous and solid by-products [3]. In incineration, waste matter is burned in excess of air to release energy. In mass burn incineration, the combustion process produces a flue gas, which can be used to run a Rankine cycle through heat exchange in a boiler for combined heat and power generation [3]. Refuse derived fuel (RDF) technology is used for producing alternative fuels with a high energy content [6]. Solid waste is sorted, shredded and dehydrated in the process of producing RDF, and the quality of the fuel depends on the MSW composition and the conversion process [7]. The high calorific value content in MSW such as paper, cardboard, wood, plastic and rubber are used in RDF production[6]. RDF is used as a main fuel or co-fuel for electricity generation and thermal applications, in various industries such as cement kilns [8]. The gaseous emissions resulting from these processes may contain greenhouse gases (GHG), as well as other toxic chemicals, heavy metals, and particulate matter [3][9]. Emissions control is an important factor in managing the environmental and health impacts of waste management technologies.

1.2 Human health impacts of WtE

Waste treatment and management is associated with environmental and human health risks, due to contaminants, toxins and other hazardous material present in the waste matter, and the emissions and other by-products arising from the treatment processes [1][10]. Waste management carries health risks for human populace, due to exposure to pollutants via inhalation, ingestion or other mans of contact [11]. Toxic substances such as heavy metals and dioxins are released to air, water and soil mediums in the course of WtE processing [12][8]. The release of such contaminants may occur during the processing, as air borne emissions, as well as due to the release of by-products. The key pathways of exposure for waste management related health impacts are inhalation, water consumption and food chain [1]. The discharges from a WtE facility can be gaseous emissions, liquid effluents, and solid residue such as fly ash and slag. Air, water, soil and plant matter can get polluted due to various contaminants such as greenhouse gases, furans, dioxins and polycyclic aromatic hydrocarbons (PAH), bacteria and viruses, heavy metals, Sulphur and Nitrogen Oxides, volatile organic compounds (VOC) and particulate matter (PM).

1.3 Human health risk assessment framework

US Environmental Protection Agency defines human health risk assessment (HHRA) as the process which evaluates the characteristics and probability of negative health impacts which may be caused by exposure to harmful contaminants [13]. Four key steps have been identified in risk assessment procedure [13][14].

1) ***Hazard identification:*** Potential causes of harm to humans and eco-system are identified.

2) ***Dose response (toxicity) assessment:*** The effects of exposure to the toxins are assessed. The numerical relationships between the level of exposure and negative consequences are explored.

3) ***Exposure assessment:*** The level of exposure (to which humans are subjected) is assessed. This may include information on frequency, timing, and level of contact. The pathways for toxins, their concentrations in particular mediums, and exposure routes are considered.

4) ***Risk characterisation:*** In the final stage, the impacts and risks of exposure to hazards are explained.

Risk characterisation is conducted for both carcinogenic and non-carcinogenic effects. Carcinogens are classified as non-threshold chemicals, and are assessed for the chronic daily intake (CDI) and the associated incremental lifetime cancer risk (ILCR) due to the presence of carcinogens [9].

While some studies have been carried out on quantifying the environmental impacts of WtE technologies, there is very limited information available on the human health impacts of the same. In order to manage and mitigate the human health risks associated with waste-to-energy transformation, it is necessary for first quantify and assess the risks. The aim of this study is to identify the human health risks of WtE conversion for selected technologies, with reference to by-products throughout the process life cycle from waste collection to residue disposal. The exposure pathways considered in the study are limited to inhalation.

2. Methodology

In the study, the human health risks associated with life cycle of energy generation through MSW was assessed for incineration and RDF production. A case study analysis was conducted based on the Regional District of Central Okanagan (RDCO), British Columbia (BC), Canada. A life cycle assessment (LCA) was conducted using SimaPro software tool for energy production using MSW as feedstock. The life cycle impact assessment (LCIA) data was used to derive information about contaminant production from WtE process, which was then used in the health risk assessment. This analysis was further extended to Sri Lankan context, to estimate and compare the health risks of energy recovery from waste.

2.1 Scenario development

RDCO consists of four municipalities, and has a total population of 189,289. The per capita MSW generation for the region for 2014 was 650 kg [15]. Waste generation in RDCO was considered for the MSW processing requirements. For MSW incineration, it is assumed that the generated MSW stock will be processed directly in a mass burn plant with not sorting at the source. In RDF production, MSW will be subjected to prior sorting to separate the waste components with high calorific value. Published literature was used in identifying the useful components of MSW for RDF recovery, as listed in Table 1 [6]. The waste characterisation applicable for the region was used in estimating the RDF recovery percentages by weight under different waste categories [16].

Table 1: RDF recovery fraction in MSW

Waste category	Percentage by weight
Wood	24.8%
Paper	14.7 %
Plastics	9.5%
Textiles`	4.8%
Rubber	0.5%
Total RDF fraction from MSW	**54.3%**

The life cycle impact assessment was conducted for one tonne of feedstock, based on Ecoinvent 3 database, and using ReCiPe Endpoint impact assessment method. The LCA scope definition was made to include the stages following waste collection, processing and treatment, to the eventual disposal of by-products as depicted in Figure 1. The functional unit used in analysis was 1 tonne of fuel used in WtE conversion (MSW or RDF).

The data derived on the outflows under the different impact categories were used to assess the health impacts. The total impacts of processing the net MSW generation of the region are calculated. An assessment is also done on the comparative impacts of generating 1 GWh of energy under each processing technology.

In the hazard identification phase, the most pertinent contaminants impacting human health under the given scenarios were identified as chemicals of concern based on literature for both cancer and non-cancer risks [6][17][18]. The potency of the contaminants in causing health impacts, as well as the dosage released was considered in doing this selection. The weight-of-evidence (WOE) values defined by

International Agency for Research on Cancer (IARC) and U.S. Environmental Protection Agency (U.S. EPA) were used in screening the contaminants for cancer risk [19]. The contaminants falling under highlighted categories in Table 2 were selected as the carcinogens of concern.

Figure 2 depicts the emission of contaminants from WtE processes, and the exposure pathways through which they reach the population at risk. In this study, exposure assessment is conducted for the inhalation route only, based on airborne contaminants identified through the LCA.

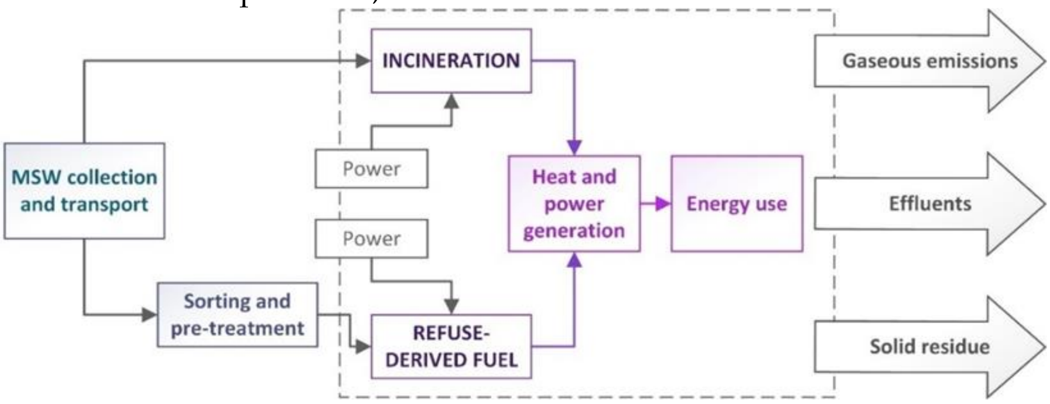

Fig 1: LCA system boundary

Table 2: Cancer risk categorisation for contaminants

IARC		U.S. EPA (1986 guidelines)		U.S. EPA (2005 guidelines)	
WOE	**Definition**	**WOE**	**Definition**	**WOE**	**Definition**
1	Carcinogenic	**A**	Human carcinogen	**CH**	Carcinogenic to humans
2A	Probably carcinogenic	**B1**	Probable carcinogen-limited human evidence	**LH**	Likely to be carcinogenic
2B	Possibly carcinogenic	**B2**	Probable carcinogen-sufficient animal evidence	**InI**	Inadequate information to assess
3	Not classifiable	**C**	Possible human carcinogen	**NH**	Not likely to be carcinogenic
4	Probably not carcinogenic	**D**	Not classifiable		
		E	Non-carcinogenic		

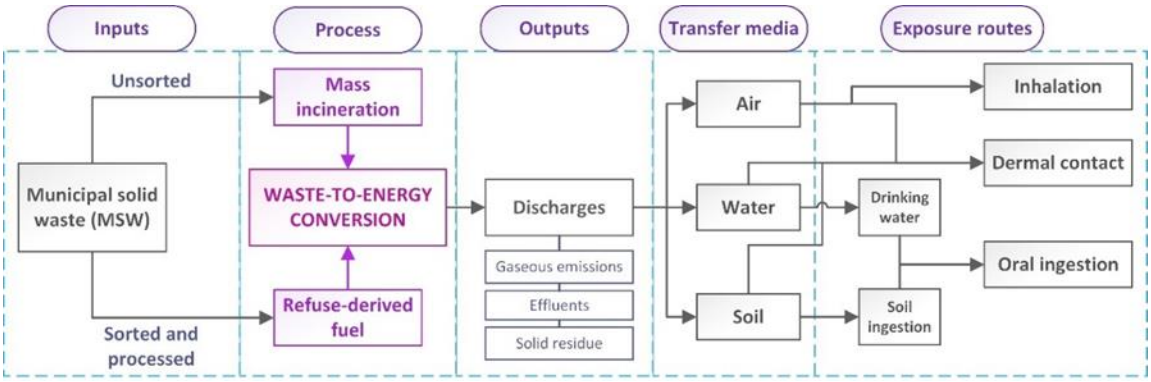

Fig 1: Contaminants and exposure pathways and routes

The potency factors and inhalation unit risks for the contaminants were identified through the Integrated Risk Information System (IRIS) database published by the U.S. EPA, and the toxicity data published by California Environmental Protection Agency (CalEPA) [20]. CalEPA data was used in assessment where U.S.EPA data was not available.

2.2 Exposure factors

The factors used in assessing the human exposure to the chemicals of concern are listed in Table 3. The values provided were identified based on literature, as applicable to the selected region. The assumptions used in the analysis are listed below.

a) In MSW mass incineration, it is assumed that the entire mass of MSW is subjected to thermal processing for energy generation. For RDF production, collected MSW is assumed to have been subjected to sorting, treatment and shredding prior to the WtE transformation.

b) The analysis is conducted under the assumption that the entire waste mass generated at a given location is subjected to one of the two treatment methods considered.

c) In health risk assessment, polycyclic aromatic hydrocarbons (PAH) are approximated by Benzene in calculations. Dioxins are represented by 2,3,7,8-Tetrachlorodibenzo-p-dioxin.

d) A steady-state fixed box model is taken for air dispersion analysis for the contaminants, under the assumption of a completely stirred tank reactor (CSTR) conditions for the volume considered [23]. The concentration of pollutants in air is assumed to be uniform and constant.

Table 2: Human health risk assessment parameters

Parameter	Unit	Value
Body weight (BW)	kg	70 [10]
Exposure duration (D)	years	30 [21]
Exposure frequency (F)	Days/year	350 [8]
Averaging time (AT)	years	75 (for carcinogens) [9] 30 (for non-carcinogens) [21]
Inhalation rate (IR_a)	m^3/day	20 [8]
Concentration in air (C_a)	mg/m^3	*Varies by chemical*
Slope factor (SF)	kg-day/mg	*Varies by chemical*
Inhalation unit risk (IUR_a)	µg/m^3	*Varies by chemical*
Reference daily dose (RfD)	mg/kg-day	*Varies by chemical*
Reference concentration (RfC)	mg/m^3	*Varies by chemical*
Average wind velocity (U)	m/s	**1.5 [22]**

e) The average human lifetime of 75 years is taken as the averaging time (AT) in assessing the chronic daily intake for carcinogens. (Averaging time is given in days, with 365 days in a year.) 24-hour exposure is assumed throughout the exposure duration.
f) Averaging time for non-carcinogens is taken as the exposure duration in days as per U.S. EPA guidelines.
g) The addition of contaminants to air through re-volatilisation from water or soil mediums is not considered in the study.
h) An additive model is used in assessing the aggregate risk due to all chemicals of concern, for both cancer and non-cancer risks [24].

The equations used in the analysis to estimate the health risks are given below.

Incremental concentration of contaminants in air (C_a) due to WtE process

$$C_a = \frac{Q}{W \times H \times U} \qquad (1)$$

Where; W = Width of the area
H = Mixing height
Q = Mass flow rate of contaminants

The area of 50×50 km is used to present RDCO, where the total land area is approximately 2900 km². City of Kelowna (CK), which is the most highly populated municipality in the region (population - 123,500) was separately analysed for the risk, assuming that a WtE plant is located there. A 15×15 km grid was used to analyse CK. The model mixing height was set to 1.5 km based on previous studies.

Cancer risk

Chronic daily intake (CDI) through inhalation [25]

$$CDI_a = \frac{C_a \times IR_a \times D \times F}{BW \times AT} \qquad (2)$$

Chronic exposure concentration (EC) for inhalation [26]

$$EC = \frac{C_a \times D \times F}{AT} \qquad (3)$$

Incremental risk of cancer due to inhalation exposure (R_c)[26]

$$R_c = SF \times CDI_a \qquad (4)$$

$$R_c = IUR_a \times EC \qquad (5)$$

Non-cancer risk

Average daily dose during exposure period (ADD) [8]

$$ADD = \frac{C_a \times IR_a \times D \times F}{BW \times AT} \qquad (6)$$

Hazard quotient (HQ) [8]

$$HQ = \frac{ADD}{RfD} \qquad (7)$$

$$HQ = \frac{EC}{RfC} \qquad (8)$$

Risk assessment has been conducted based on the Inhalation Dosimetry Methodology recommended by U.S. EPA for toxicity studies on airborne chemicals. However, chronic daily intake method has been used in instances where unit risk data was unavailable, or accuracy of data could not be verified.

The mass flow rate of the contaminants was derived assuming a process capacity for the entire waste generation of the region, under continuous operation. The energy generation through WtE facilities were calculated based on the following information. MSW incineration plants have an average conversion factor of 0.6 MWh/tonne [27]. The conversion factor for RDF was estimated as 4.4 MWh/tonne based on previous studies [6]. Based on this data, health impacts per one GWh of annual energy generation was compared for incineration and RDF technologies, to identify the relationship between energy recovery and human health in waste management.

The local waste mix for Sri Lanka (SL) was considered in determining the emissions and their impacts. The composition of the local waste streams by weight in MSW in SL are as follows; plastics – 10.5%, Wood – 6.1%, paper – 3.7%, textiles – 1.2%, rubber – 0.5% [28][29]. The technology and conversion efficiencies were assumed to be similar to the state defined for BC, and the same exposure parameters were used in assessment. A 15×15 km grid was taken for the analysis, with a mixing height of 1.5 km, in order for the results to be comparable with those for BC case study.

3. Results

Based on the life cycle impact inventory for the WtE processes under consideration, the emissions data for chemicals of concern from the WtE processes are provided in Table 4. The emissions values provided are given for a tonne of MSW or RDF. From this emissions inventory, the airborne emissions were considered in the health risk assessment. In the analysis, toxic equivalency factors were used in deriving the potency factors for furans and dioxins [30]. For dioxins, a TEF of 1 is used with reference to 2,3,7,8-Tetrachlorodibenzodioxin, while a TEF of 0.1 is used for furans. Similarly, Polycyclic Aromatic Hydrocarbons (PAH) are assumed be equivalent to Benzo(a)pyrene in toxicity [31]. Table 5 and Table 6 detail the incremental cancer risk and non-cancer risk occurring due to the chemicals of concern emitted through the WtE processes, assuming that the entire waste mass generated in the locale is used in energy production

Table 3: Emissions inventory for WtE processes

Released substance	Unit	MSW			RDF		
		Air	Water	Soil	Air	Water	Soil
Arsenic	mg/T	1.27E+01	1.56E+03	9.98E-02	7.23E+00	8.85E+02	1.03E-01
Cadmium	mg/T	5.74E+00	7.38E+02	2.73E-02	2.28E+00	1.89E+02	1.55E-02
Chromium	mg/T	7.15E+01	1.54E+01	6.75E-01	4.59E+02	7.64E+01	5.16E-01
Nickel	mg/T	5.68E+01	5.22E+04	1.57E-01	2.05E+01	6.87E+03	7.23E-02
Dioxins	mg/T	9.88E-05	-	-	1.40E-03	-	-
Furans	mg/T	5.44E-01	-	-	5.03E-01	-	-
Benzo(a)pyrene	mg/T	1.87E+00	-	-	1.72E+00	-	-
PAH	mg/T	3.47E+00	1.13E+00	1.28E-02	3.26E+00	7.44E-01	4.30E-03
Mercury	mg/T	1.98E+01	4.98E+01	7.62E-04	7.88E+00	2.47E+01	1.25E-03
Lead	mg/T	5.91E+01	2.85E+05	6.97E-01	2.12E+01	1.69E+04	3.20E-01
NO_x	kg/T	6.22E+00	-	-	5.55E-01	-	-
SO_2	g/T	8.27E+01	-	-	9.83E+01	-	-
PM	g/T	4.00E+01	-	-	1.82E+01	-	-

Table 4: Incremental cancer risk for emitted chemicals of concern

Released substance	SF for carcinogens (kg-day/mg)	IUR for carcinogens ($m^3/\mu g$)	Incremental cancer risk (R_c)			
			RDCO		CK	
			INC	RDF	INC	RDF
Arsenic	1.20E+01	4.30E-03	7.25E-10	2.24E-10	1.58E-09	4.88E-10
Cadmium	1.50E+01	1.80E-03	1.37E-10	2.96E-11	2.99E-10	6.44E-11
Chromium	5.10E+02	1.20E-02	1.14E-08	3.98E-08	2.48E-08	8.65E-08
Nickel	9.10E-01	2.40E-04	1.81E-10	3.55E-11	3.94E-10	7.71E-11
Dioxins	1.30E+05	3.30E+01	4.33E-11	3.33E-10	9.43E-11	7.23E-10
Furans	1.30E+04	3.30E+00	2.39E-08	1.20E-08	5.19E-08	2.61E-08
Benzo(a)pyrene	3.90E+00	1.10E-03	2.74E-11	1.36E-11	5.95E-11	2.97E-11
PAH	3.90E+00	1.10E-03	5.08E-11	2.59E-11	1.10E-10	5.63E-11
Lead	4.20E-02	1.20E-05	9.44E-12	1.84E-12	2.05E-11	4.00E-12
Aggregated			3.65E-08	5.24E-08	7.93E-08	1.14E-07
Additional annual cancer cases			9.20E-05	1.32E-04	1.31E-04	1.88E-04

.

Table 5: Non-cancer risk for emitted chemicals of concern

Released substance	RfC: non-cancer (mg/m^3)	Hazard Quotient (HQ) RDCO INC	RDCO RDF	CK INC	CK RDF	Possible health issues [20][32]
Arsenic	1.50E-05	2.81E-05	8.70E-06	6.11E-05	1.89E-05	Cardiovascular, respiratory, neurological, dermal
Cadmium	1.00E-05	1.91E-05	4.11E-06	4.15E-05	8.94E-06	Kidney, respiratory
Chromium	1.00E-04	2.38E-05	8.28E-05	5.17E-05	1.80E-04	Respiratory
Nickel	9.00E-05	2.10E-05	4.10E-06	4.56E-05	8.92E-06	Respiratory and haematological
Dioxins	4.00E-08	8.21E-08	6.30E-07	1.79E-07	1.37E-06	Liver, reproductive, endocrinal, respiratory, haematological
Furans	4.00E-09	4.52E-03	2.27E-03	9.84E-03	4.93E-03	
Lead	1.50E-04	1.31E-05	2.55E-06	2.85E-05	5.55E-06	Neurological, haematological
Mercury	3.00E-02	2.20E-08	4.75E-09	4.78E-08	1.03E-08	Neurological, kidney
NOx*	4.00E-02	5.17E-03	2.51E-04	1.12E-02	5.45E-04	Respiratory
SO2*	2.00E-02	1.37E-04	8.88E-05	2.99E-04	1.93E-04	Immunological, respiratory
PM*	2.00E-02	6.65E-05	1.64E-05	1.45E-04	3.58E-05	Respiratory, cardiovascular [33]
Aggregated		**1.00E-02**	**2.73E-03**	**2.18E-02**	**5.93E-03**	

*The toxicity reference values (RfC) for NO_x, SO_2 and PM were obtained from health risk data published by Metro Vancouver [34].

The results in Table 6 indicate that aggregated non-cancer HQ value remains below 1 for both incineration and RDF under all scenarios.

A HQ<1 shows that the non-cancer health risks are not significant for the proposed plants.

The energy generation potential of the two WtE processes were compared with the associated health risk, for the City of Kelowna. The incremental cancer and non-cancer risks caused by supplying 1 GWh of the city's annual energy demand are given under Table 7.

Table 6: Health risks associated with 1 GWh of annual energy supply

Released substance	City of Kelowna: Incremental cancer risk (R_c) INC	Incremental cancer risk (R_c) RDF	HQ for non-cancer risk INC	HQ for non-cancer risk RDF	Sri Lanka (RDF) R_c	Sri Lanka (RDF) HQ
Arsenic	3.27E-11	2.55E-12	1.27E-06	9.87E-08	2.68E-12	1.04E-07
Cadmium	6.21E-12	3.36E-13	8.62E-07	4.66E-08	5.98E-13	8.30E-08
Chromium	5.15E-10	4.51E-10	1.07E-06	9.39E-07	3.03E-10	6.32E-07
Nickel	8.18E-12	4.02E-13	9.47E-07	4.65E-08	5.70E-13	6.59E-08
Dioxins	1.96E-12	3.77E-12	3.71E-09	7.14E-09	9.88E-12	1.87E-08
Furans	1.08E-09	1.36E-10	2.04E-04	2.57E-05	2.25E-10	4.27E-05
Benzo(a)pyrene	1.24E-12	1.55E-13	-	-	1.71E-13	-
PAH	2.29E-12	2.94E-13	-	-	3.36E-13	-
Mercury	-	-	9.93E-10	5.38E-11	-	4.32E-11
Lead	4.26E-13	2.08E-14	5.92E-07	2.90E-08	3.13E-14	4.35E-08
NO_x	-	-	2.33E-04	2.84E-06	-	2.93E-06
SO_2	-	-	6.21E-06	1.01E-06	-	1.22E-06
PM	-	-	3.00E-06	1.86E-07	-	1.15E-07
Aggregate value	**1.65E-09**	**5.94E-10**	**4.52E-04**	**3.09E-05**	**5.43E-10**	**4.79E-05**

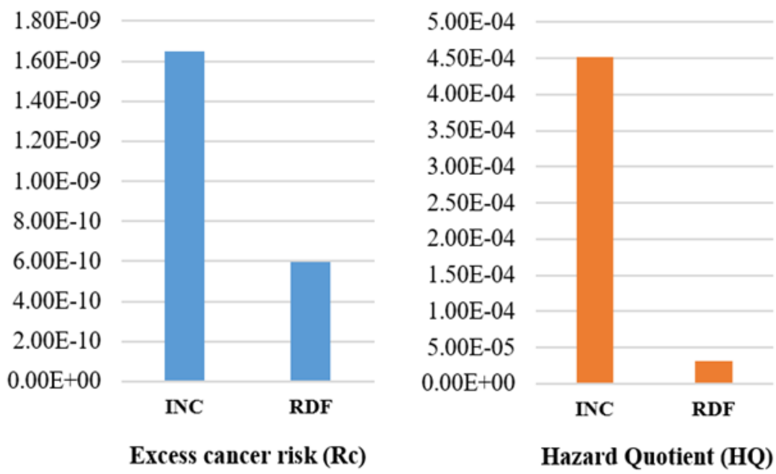

Fig 2: Comparison of health risks per GWh of annual energy supply for City of Kelowna

A graphical comparison of the additional cancer and non-cancer health risk posed by 1 GWh of WtE supply is depicted in Figure 3. The results in Figure 3 indicate that the health risks associated with producing a GWh of energy annually through RDF are significantly lower. Therefore, RDF can provide the same amount of energy for a community with a lower health risk compared to incineration. After identifying this, an analysis was carried out to estimate and compare the health effects of RDF for Sri Lanka, for a GWh of annual energy generation. For SL, the total RDF fraction recoverable from MSW is 22%. It can be seen that can the incremental risk indicators Rc and HQ remain in the same order for Sri Lanka in developing 1 GWh of annual energy through MSW, when the same waste quality is assumed. The cancer risks are slightly lower, while the non-cancer risks are slightly higher.

4. Discussion and conclusions

Energy and human health are key nodes in an interconnected nexus, which encompass many elements such as water, resources and carbon emissions. While WtE is commonly considered a renewable energy source [35], the GHG emissions and other discharges result in adverse environmental and human health impacts. In cancer risk assessment results presented in Table 5, RDF appears to carry a higher health risk on a per tonne basis, in comparison to incineration. This is partially due to the fact that RDF emits greater amounts of the contaminants such as dioxins and Chromium, which carry a higher carcinogenicity. In contrast, the HQs for non-cancer risk are lower in RDF. None of the HQs exceed 1, thereby indicating that introduction of the WtE plants by themselves does not lead to any significant non-cancer risks.

Since only 54.3% of the MSW stock goes towards RDF production, the actual contamination potential of RDF by itself for the selected region is lower than that of incineration. However, the remaining fraction of MSW which is not utilised in RDF production goes to other disposal avenues such as landfilling. Therefore, the overall impacts of this WtE path needs to be assessed with consideration to the disposal of the leftover waste mass. Moreover, use of WtE technologies can decrease the amount of waste sent to landfilling, which is associated with adverse impacts such as toxic airborne contaminants and leachate pollution [6]. These avoided impacts should also be considered in estimating the net ecological and human health related costs and benefits of WtE technologies.

RDF has a significant advantage over incineration when the health risks are compared on the basis of annual energy generation. For one GWh of energy per annum, a health risk reduction of approximately 64% can be gained through RDF. The higher calorific values in RDF feedstock and the higher process efficiency in contrast to conventional mass burn incineration of unsorted and unprocessed

MSW are the factors responsible for this trend [5]. When Sri Lankan waste generation case is studied and compared with the case study results, it can be seen that there are no significant differences in health risks related to the generation of 1 GWh annual energy through RDF (which was identified as the technology with lower health impacts). However, it should be noted that this analysis is done under the assumption that Sri Lankan waste content has the same quality as the MSW considered under the Canadian context. The airborne emissions from WtE processing changes not only with the waste mix, but also due to the differences in feedstock sources and their contamination levels. While the waste mix identified by previous studies was used to estimate the potential airborne chemicals in this study, the actual toxin content may be higher in Sri Lankan waste due to source contamination. To assess the exact impacts of applying the above WtE technologies in Sri Lanka, it is necessary to conduct a detailed study on the levels of hazardous contamination in Sri Lankan waste.

As previously mentioned, in decision making for energy system planning, this information also needs to be supplemented with the avoided impacts, and the additional burden of disposing leftover waste from RDF sorting. Another factor to consider is the reduction in use of conventional energy sources such as coal and natural gas, and the decrease in life cycle health impacts due to this. The challenge present in utilising RDF technology instead of mass burn incineration is the additional cost and effort involved in sorting and pre-processing of waste to produce fuel. This aspect will have to be addressed through a detailed cost-benefit analysis in planning the deployment of WtE.

In assessing the health impacts of the contaminants emitted due to the installation of WtE plants, it is also important to consider the background concentrations of the said contaminants [34]. An area with an existing high concentrations of these chemicals may well pass over the maximum allowable levels of contamination with the addition of WtE technologies. Additionally, only the inhalation route is considered for HHRA in this analysis. In order to identify the complete impacts of utilising WtE technologies in a selected community, risks pertaining to oral ingestion and dermal contact routes should also be quantified and aggregated with inhalation risk.

While the integration of RE sources in energy systems is critical in achieving energy sustainability and energy security, the energy-human health nexus has to be effectively managed during planning and decision making for minimal adverse impacts due to energy use. A reverse assessment based on the maximum allowable limits of contamination for the region is necessary in integrating WtE technologies in urban energy system planning. By calculating the maximum mass of waste which can be processed annually without exceeding the contaminant emission limits, it is possible to size and determine to maximum allowable capacity for WtE plants in the district energy plan. The same approach could be used for risk assessment in the Sri Lankan context, and thereby to plan WtE policies through a risk-based model.

Data uncertainty is a main factor affecting the validity of HHRA. The toxicological information, and the impact inventory are derived based on a number of assumptions. These issues impact the accuracy of the ultimate assessment. A fuzzy logic-based decision making approach can be used to mitigate the issues resulting from data uncertainty. The results also depend on the scenarios developed in the HHRA. In the present study, the impacts of feedstock collection and transport were not considered. Further work needs to be conducted in extending the results of the study to an energy system scenario where all processes from supply to disposal are considered in the LCA, together with the avoided impacts of fuel substitution landfilling.

References

[1] L. Giusti, "A review of waste management practices and their impact on human health," *Waste Manag.*, vol. 29, no. 8, pp. 2227–2239, 2009.

[2] P. H. Brunner and H. Rechberger, "Waste to energy - key element for sustainable waste management," *Waste Manag.*, vol. 37, pp. 3–12, 2015.

[3] World Energy Council, "World Energy Resources: 2013 Survey," London, 2013.

[4] The World Bank, "What a Waste: A Global Review of Solid Waste Management," Washington, D.C., Oct. 2012.

[5] H. Friege and A. Fendel, "Competition of different methods for recovering energy from waste," *Waste Manag. Res.*, vol. 29, no. 10 Suppl, pp. S30–S38, Oct. 2011.

[6] B. Reza, A. Soltani, R. Ruparathna, R. Sadiq, and K. Hewage, "Environmental and economic aspects of production and utilization of RDF as alternative fuel in cement plants: A case study of Metro Vancouver Waste Management," *Resour. Conserv. Recycl.*, vol. 81, pp. 105–114, 2013.

[7] R. Sarc and K. E. Lorber, "Production, quality and quality assurance of Refuse Derived Fuels (RDFs)," *Waste Manag.*, vol. 33, no. 9, pp. 1825–1834, 2013.

[8] J. Rovira, M. Mari, M. Nadal, M. Schuhmacher, and J. L. Domingo, "Partial replacement of fossil fuel in a cement plant: Risk assessment for the population living in the neighborhood," *Sci. Total Environ.*, vol. 408, no. 22, pp. 5372–5380, Oct. 2010.

[9] C. A. Ollson, L. D. Knopper, M. L. Whitfield Aslund, and R. Jayasinghe, "Site specific risk assessment of an energy-from-waste thermal treatment facility in Durham Region, Ontario, Canada. Part A: Human health risk assessment," *Sci. Total Environ.*, vol. 466–467, pp. 345–356, 2014.

[10] R. J. Roberts and M. Chen, "Waste incineration - How big is the health risk? A quantitative method to allow comparison with other health risks," *J. Public Health (Bangkok).*, vol. 28, no. 3, pp. 261–266, 2006.

[11] J. Rovira, M. Mari, M. Nadal, M. Schuhmacher, and J. L. Domingo, "Use of sewage sludge as secondary fuel in a cement plant: Human health risks," *Environ. Int.*, vol. 37, no. 1, pp. 105–111, 2011.

[12] A. Porteous, "Energy from waste incineration - A state of the art emissions review with an emphasis on public acceptability," *Appl. Energy*, vol. 70, no. 2, pp. 157–167, 2001.

[13] U.S. Environmental Protection Agency, "Human Health Risk Assessment," 2015. [Online]. Available: https://www.epa.gov/risk/human-health-risk-assessment. [Accessed: 13-Sep-2016].

[14] K. P. Kumar, S. P. Kumar, and G. A. Nair, "Risk assessment of the amnesic shellfish poison, domoic acid, on animals and humans.," *J. Environ. Biol.*, vol. 30, no. 3, pp. 319–25, May 2009.

[15] Government of British Columbia - Canada, "Municipal Solid Waste Disposal in B.C. (1990-2014)," *Environmental Reporting BC*, 2016. [Online]. Available: http://www.env.gov.bc.ca/soe/indicators/sustainability/municipal-solid-waste.html. [Accessed: 29-Sep-2016].

[16] City of Kamloops, "Demolition , Land Clearing , and Construction (DLC) Waste Management Handbook," Kamloops, 2011.

[17] A. U. Zaman, "Comparative study of municipal solid waste treatment technologies using life cycle assessment method," *Int. J. Environ.*

Sci. Technol., vol. 7, no. 2, pp. 225–234, Mar. 2010.

[18] R. J. Roberts and M. Chen, "Waste incineration--how big is the health risk? A quantitative method to allow comparison with other health risks," *J. Public Health (Bangkok).*, vol. 28, no. 3, pp. 261–266, Sep. 2006.

[19] U.S. Environmental Protection Agency, "Dose-Response Assessment for Assessing Health Risks Associated With Exposure to Hazardous Air Pollutants," 2016. [Online]. Available: https://www.epa.gov/fera/dose-response-assessment-assessing-health-risks-associated-exposure-hazardous-air-pollutants. [Accessed: 07-Oct-2016].

[20] California Environmental Protection Agency - Office of Environmental Health Hazard Assessment, "Chemicals," 2016. [Online]. Available: http://oehha.ca.gov/chemicals. [Accessed: 08-Oct-2016].

[21] U.S. Environmental Protection Agency, "Risk Assessment Guidance for Superfund. Volume I Human Health Evaluation Manual (Part A)," Washington, D.C., 1989.

[22] Government of Canada, "1981-2010 Climate Normals & Averages," *Canadian Climate Normals*, 2016. [Online]. Available: http://climate.weather.gc.ca/climate_normals/index_e.html. [Accessed: 05-Oct-2016].

[23] B. Sportisse, "Box models versus Eulerian models in air pollution modeling," *Atmos. Environ.*, vol. 35, no. 1, pp. 173–178, Jan. 2001.

[24] K. Asante-Duah, *Public Health Risk Assessment*, vol. 6. Dordrecht: Springer Netherlands, 2002.

[25] U.S. Environmental Protection Agency, "Risk Assessment Guidance for Superfund. Volume I Human Health Evaluation Manual (Part A)," Washington, D.C., 1989.

[26] U.S. Environmental Protection Agency, "Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment)," Washington, D.C., 2009.

[27] BC Hydro, "2013 Resource Options Report Update," 2013.

[28] H. N. Hikkaduwa, K. W. Gunawardana, R. U. Halwatura, and H. H. Youn, "Sustainable Approaches to the Municipal Solid Waste Management in Sri Lanka," in *6th International Conference on Structural Engineering and Construction Management 2015*, 2015, no. December.

[29] S. N. M. Menikpura, S. H. Gheewala, and S. Bonnet, "Sustainability assessment of municipal solid waste management in Sri Lanka: problems and prospects," *J. Mater. Cycles Waste Manag.*, vol. 14, no. 3, pp. 181–192, Sep. 2012.

[30] U.S. Department of Energy, "Toxicity Values," *The Risk Assessment Information System*, 2016. [Online]. Available: https://rais.ornl.gov/tutorials/toxvals.html#Toxicity Equivalency Factors for Chlorinated Furans. [Accessed: 07-Oct-2016].

[31] C. L. Lemieux, A. S. Long, I. B. Lambert, S. Lundstedt, M. Tysklind, and P. A. White, "Cancer risk assessment of polycyclic aromatic hydrocarbon contaminated soils determined using bioassay-derived levels of benzo[a]pyrene equivalents," *Environ. Sci. Technol.*, vol. 49, no. 3, pp. 1797–1805, 2015.

[32] Agency for Toxic Substances and Disease Registry, "ATSDR Toxic Substances Portal," 2016. [Online]. Available: https://www.atsdr.cdc.gov/substances/index.asp. [Accessed: 08-Jul-2016].

[33] World Health Organization, "Health Effects of Particulate Matter: Policy implications for countries in eastern Europe, Caucasus and central Asia," Copenhagen, 2013.

[34] Metro Vancouver, "Literature Review of Potential Health Risk Issues Associated With New Waste-To-Energy Facilities," Burnaby, 2014.

[35] Natural Resources Canada, "Energy Fact Book 2015–2016," 2015.