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A COMPARATIVE LIFE CYCLE ASSESSMENT APPROACH OF 5 ALTERNATIVE TECHNOLOGIES FOR CONVERTING MUNICIPAL SOLID WASTE (MSW) INTO CHEMICALS AND ELECTRICITY IN THE UK

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Abstract. This study develops a systematic life cycle assessment approach for 5 alternative technologies that can be used to convert municipal solid waste (MSW) into chemicals and electricity. Particular attention is given to the combustion and gasification as the main conversion processes and the UK's MSW is used here as the case study. The investigation focusses on 5 different scenarios: (1) combustion and electricity generation, (2) gasification and electricity generation, (3) methanol synthesis from syngas with electricity co-production (4), dimethyl ether (DME) synthesis from produced methanol by syngas (indirect synthesis) and power generation, and (5) DME synthesis from syngas (direct synthesis) and electricity co-production. The unreacted gas left from the methanol or DME synthesis process can also be employed as a fuel gas for the electricity generation. As the result, it is interesting to find out which method is the most appropriate and optimal to convert the UK's MSW. The environmental impacts are evaluated by IMPACT2002+ method using Ecoinvent 3 as a database. The results show that scenario 5 (direct DME synthesis with electricity co-production) causes the least climate change impact (532 kg CO_2 eq.) and resource impact (-5560 MJ primary), followed by scenario 4 (544 kg CO_2 eq. and -5250 MJ primary), scenario 3 (569 kg CO_2 eq. and -4820 MJ primary), scenario 1 (591 kg CO_2 eq. and -3880 MJ primary) and scenario 2 (881 kg CO_2 eq. and -3900 MJ primary) respectively. However, the study also demonstrates that the scenarios involving methanol and DME synthesis have more impacts on human health category due to the required metal oxide catalysts. The impact of a change in total yield of methanol and DME synthesis is also investigated and analysed along with the associated potential environmental benefits.

Key-words. MSW, Waste-to-Energy, Waste-to-Chemicals, LCA, Methanol production, DME production

1. Introduction

The total amount of municipal solid waste (MSW) generated in 27 EU countries exceeds 240 million tons each year. In the case of the UK, the amount of the waste generated by the households was 31.5 million tons in 2015, nearly 7 million tons were sent to landfill (1). Therefore, there is still a growing need to develop a decision-making framework to help select the most environmentally friendly options considering the wastes utilization or conversion to energy and/or chemical products. Life Cycle Assessment (LCA) represents a powerful tool to address some of these questions.

Currently, two techniques are mainly used to convert MSW to energy: thermochemical processes (combustion and gasification) and biochemical process (anaerobic digestion). Unsorted UK wastes, which contain an organic fraction less than 40%, are commonly treated by thermal processes (2). Combustion technologies are well established and generally recognized as the most widespread thermal process waste to energy (WTE) systems worldwide. The gasification, which offers tremendous advantages, received an increasing interest over the last decade. Gasification can process any variety of waste including bottom ashes from combustion processes (3). Over the last few years, different options of valorizing syngas obtained from gasification of coal or biomass, including wastes, received a growing interest in academia, industry along with the policy makers. The production of high value chemical is one the most attractive options, particularly high-value chemicals. Methanol, which represents an important chemical that can be used in various applications can be synthesized from syngas. Dimethyl ether (DME) represents a potential fuel that can substitute LPG and can be synthesized from methanol (indirect synthesis) or directly from syngas (direct synthesis) (4). Both chemicals are considered in the case studies with the objective to develop more viable and environmentally friendly technologies for MSW conversion. Different possible scenarios will be compared to the conventional combustion and gasification options.

The objective of this work is to develop a decision-making framework to help identify systematically the most suitable way to valorize the UK's wastes remaining after the recycling process, by considering 5 options: (1) power generation based on combustion, (2) power generation based on gasification, (3) methanol and electricity co-production (4) indirect DME synthesis and electricity co-production (5) direct DME synthesis and electricity co-production. These scenarios are compared in term of the environmental impacts using life cycle assessment (LCA). The life cycle inventory (LCI) data of the selected processes are analyzed by means of mass and energy balance based on the UK waste compositions available in the literature. The scenarios associated with the material recovery from the solid residue and their inherent treatment processes are also considered in the study.

2. LCA methodology

2.1 Functional unit and system boundaries

The functional unit is based on 1000 kg of the waste received at the plant. The wastes are processed without any prior treatment to produce electricity exclusively (scenarios 1 and 2), methanol and electricity (scenario 3) and DME and electricity (scenarios 4 and 5). The material recovery from the bottom ashes and the residues from the air pollution control units (APC) are also considered as detailed in the overall mass balances shown in figure 1. The electricity generated in the different scenarios is assumed to be directly supplied to the UK grid. The chemical products and materials obtained from the recovery of the bottom ash, slag and residues were considered as by-products that can substitute similar products on the markets as described in the avoided burden method for the LCA model [5].

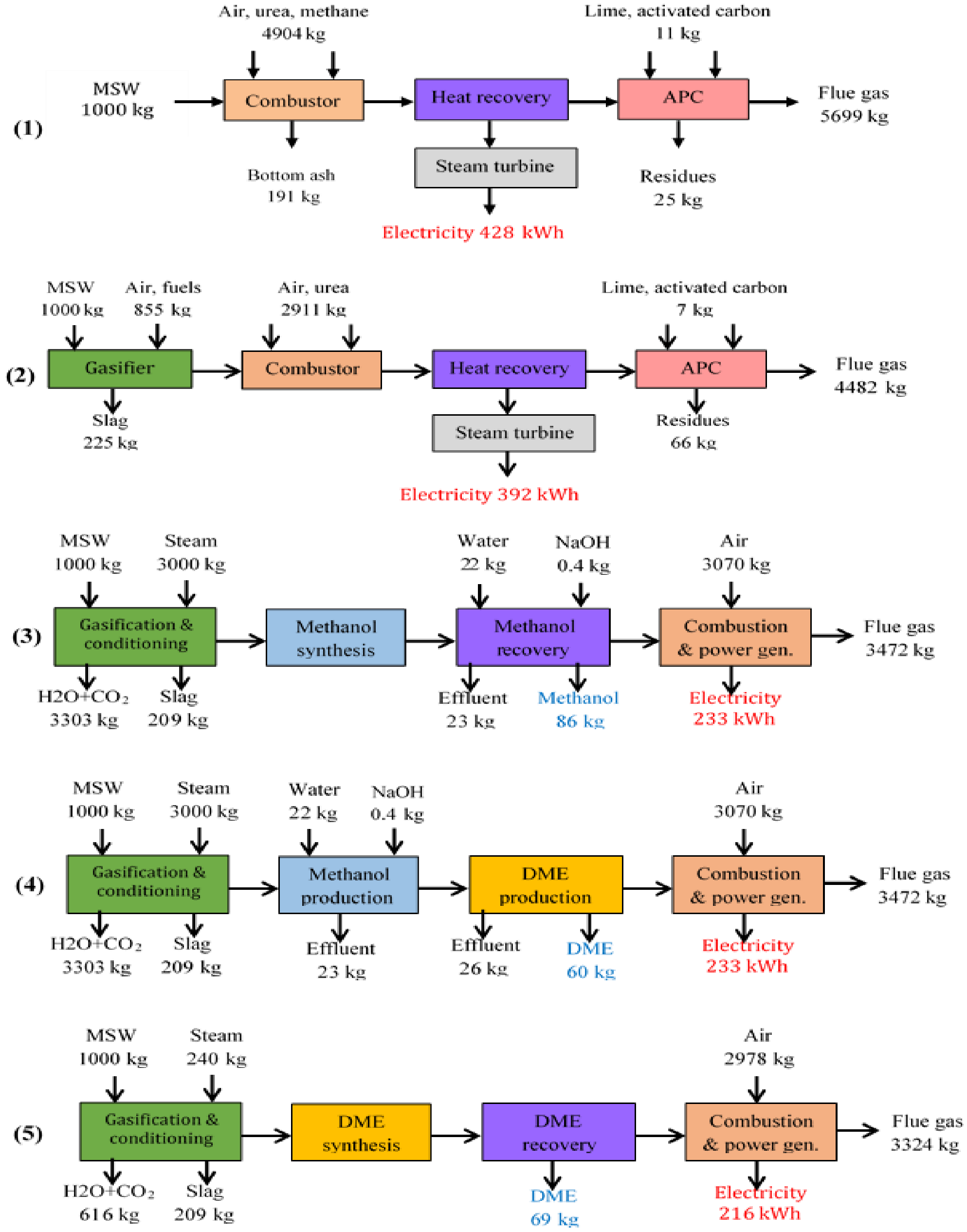

Figure 1. Flow diagrams of the waste-to-energy scenarios considered in this work with material balances.

Table 1. UK MSW average compositions [2].

Waste fractions (% as received)		Ultimate analysis (dry ash free basis)	
Paper	22.7	% C	49.7
Wood	3.7	% H	6.1
Textile	2.8	% O	42
Plastics	10	% N	1.2
Organic	35.3	% S	0.3
Metals	4.3	% Cl	0.7
Glass	6.6	% Ash	12.5
Electrical and electronic equipment (WEEE)	2.2	Lower heating value (LHV)	9 MJ/kg
Inert/aggregates	5.3		
Miscellaneous	7.1		

2.2 Characterization method

Life cycle impact assessment is performed by the method IMPACT 2002+ (2.12) available in SimaPro 8.2 software using Ecoinvent 3 as a database. This method has four damage endpoint categories (human heath, ecosystem quality, climate change and resources depletion) and 15 impacts midpoint categories. The normalized impact factors can be obtained by dividing the impact per unit of emission by the total impact of all substances of the specific category for which the characterization factors exist, per person per year in Europe [6].

2.3 LCI data

The data representing the average waste compositions in the UK summarized in table 1 were obtained from literature [2]. The inventory data required for simulating the LCA models in this work are based on the work of Arena et.al. [7] for scenarios 1 and 2, while Larson and Tingjin [4] data were used for scenarios 3, 4 and 5. All the details of the process simulations are summarized in figure 1.

3. Results and discussion

The LCA results are summarized in Figures 2 and 3. The power generation based on combustion (scenario 1) and gasification process (scenario 2) have less human health impact than the methanol and electricity co-production (scenario 3), the indirect DME synthesis and power generation (scenario 4) and the direct DME synthesis and electricity co-production (scenario 5) as shown in figure 2. This is because an exclusive power generation without any chemical synthesis process requires no additional metal catalysts ($CuO/ZnO/Al_2O_3$) and as such it does not increase the burden in term of respiratory inorganics impact.

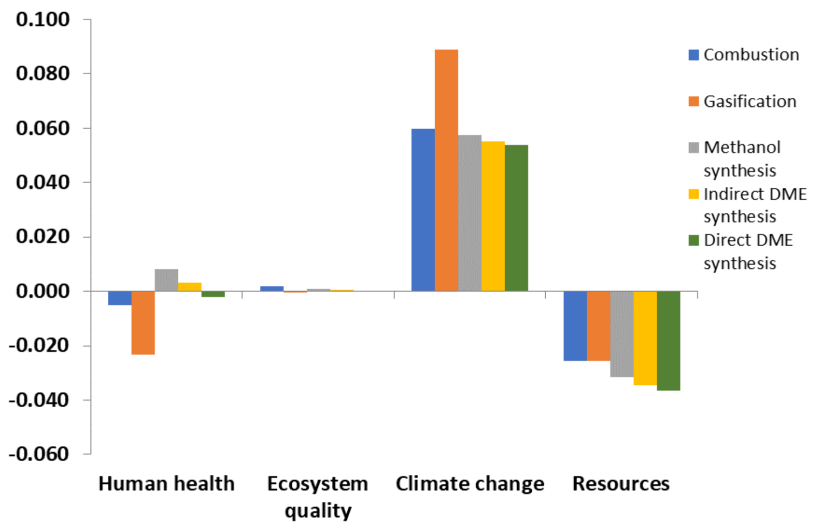

Figure 2. The normalized damage endpoint categories for all 5 scenarios.

In terms of climate change and resource impacts, the direct DME synthesis (scenario 5) has the least total burdens in the both categories, followed by the indirect DME synthesis (scenario 4), methanol synthesis (scenario 3), power generation based on combustion (scenario 1) and gasification (scenario 2) as shown in figure 2. For climate change impact, all the processes involving chemical synthesis have less GWP than the others because some of C atoms in the syngas are converted to chemical products, so there is less amount of C released to the environment in form of CO_2 gas. The produced DME or methanol are also counted as the avoided burden in the LCA model, so it can help reduce the amount of primary energy extracted from non-renewable resource need for the process.

By considering the total burdens in terms of global warming potential (GWP), it was found that if the total yield of methanol and DME production increases from originally 0.4 to be 0.6, the total burdens associated with scenarios 3, 4 and 5 will significantly decrease from 568.68, 544.18 and 532.46 kg CO_2 eq. to 524.64, 468.88 and 462.32 kg CO_2 eq. respectively, as shown in figure 3. This is due to the decease of CO_2 emissions in the flue gas after the power generation step and consequently the gain in production.

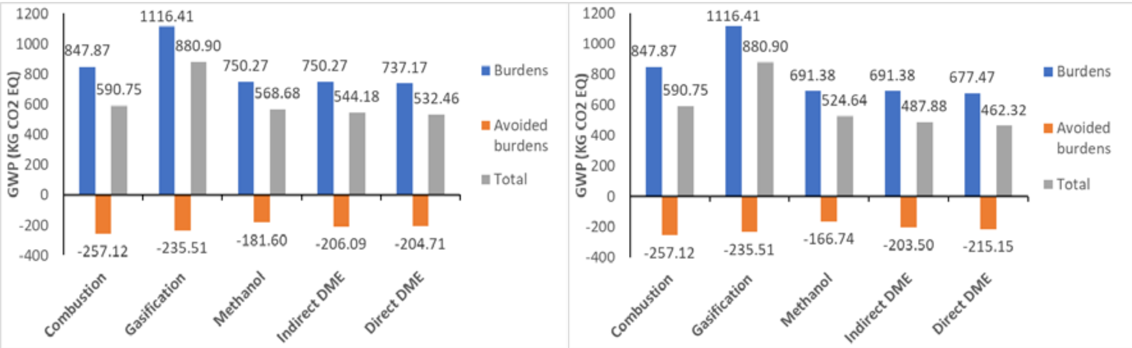

Figure 3. The total burdens of all 5 processes according to the impact category ‘‘Global warming potential’’ (a) Total yield of methanol and DME = 0.4 (b) Total yield of methanol and DME = 0.6.

4. Conclusions

A systematic comparative study for 5 waste-to-energy and chemicals scenarios was achieved using a rigorous LCA approach. The models were simulated based on 1 ton of the UK's municipal solid wastes. The electricity generated from the processes is directly supplied to the UK grid. Four impact endpoint categories were analyzed according to the method of IMPACT 2002+. Based on the LCA, scenario 5 which consists in direct DME synthesis showed the lowest burdens in terms of GWP and resources impacts, whereas the power generation from the gasification process (scenario 2) has the least impact on human health. The total burden expressed in GWP decreases for scenarios 3, 4 and 5 with the increase in methanol and DME production. The methodology shows the benefits of converting syngas into chemicals which may help develop more environmentally friendly processes to convert MSW under possible regulatory and economic constraints which are increasingly introduced in many countries. One possible improvement of the current approach would be to consider cost analysis which will be the scope of future investigations.

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