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EXERGY ANALYSIS OF ALUMINUM RECOVERY FROM MUNICIPAL SOLID WASTE INCINERATION

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Abstract

Two main challenges, associated with the recovery of aluminum from state-of-the-art municipal solid waste (MSW) incineration plants, are yield as well as quality losses of metallic aluminum due to particle surface oxidation and presence of impurities. Yet, in the framework of life cycle assessment (LCA) a direct measure for expressing the quality of primary and secondary resources is missing. In view of a possible solution, exergy has been proposed as a concept to evaluate the quality of resources. In this paper, LCA and exergy analyses for two waste treatment approaches are conducted in parallel to each other, with a goal to evaluate the added value of exergy for LCA studies in the resource recovery context. The functional unit is the treatment of 1 ton MSW. Two alternative approaches for recovering aluminum from MSW directed to a waste-to-energy plant are considered. A) MSW is treated in a two-step system consisting of a waste-to-energy process and a consequent bottom ash treatment. B) An aluminum-pre-sorting step takes place prior to the thermal treatment. In case of B, an additional exergy is spent on pre-sorting, but, in return, a metal of higher quality is obtained. The discussion of exergy analysis in the LCA framework represents an important contribution to address resource quality in environmental assessment of thermal waste treatment.

Keywords: *Exergy Analysis; LCA; aluminum recovery; incineration*

1. Introduction

For treatment of residual waste in Denmark, incineration is a favored waste management option, in fact 24% of the total waste generated within the country was incinerated in the year 2009, resulting in about 726 kt of solid residues [1]. Several recent publications highlight economic and other benefits of Al recovery from incineration bottom ash (BA) (see e.g. [2, 3, 4, 5, 6]). Recovery of ferrous (Fe) metals and aluminum (Al) is an established practice in Denmark and the state-of-the-art Al recovery takes place from BA fraction >2mm.

Another option for Al recovery is its separation directly from municipal solid waste (MSW) prior to thermal treatment, as for example in material recovery facilities or mechanical-biological treatment plants. Because no waste incineration has taken place at this point, the Al scrap fraction recovered in a pre-sorting process is of higher quality than the partly oxidized scrap originating from the BA.

Life cycle assessment (LCA) is a well-established method to compare the environmental impacts and benefits of waste treatment scenarios. In LCA, the difference in qualities of the two Al scrap fractions can be taken into account by changing the aluminum yield at the recycling process, modifying the substitution ratio between secondary and primary aluminum, and by including additional burdens due to recycling of low-quality metal scrap. However, lack of data has been limiting the inclusion of the resource quality aspect. In order to address this issue, exergy has been proposed as a concept to evaluate the quality of resources (see e.g. [7]), but no comprehensive exergy analysis has been conducted for resource flows in waste management systems yet.

The goal of this paper is to provide a preliminary evaluation of combined exergy analysis and LCA in relation to resources in waste. A simple case-study model has been created for this purpose, focusing on Al scrap in waste. This work is a first case study within a larger research project that aims at assessing the applicability of exergy analysis to derive resource quality indicators for waste management systems.

2. Case study

First, two waste treatment scenarios (scenario A and B) have been defined, within which Al flows have been modeled. Second, an LCA was performed to compare the environmental performance of two scenarios. Third, exergy analysis was conducted for Al flows in both scenarios. Finally, the added value of performing exergy analysis on this system was discussed.

2.1. Description of the scenarios

In *scenario A*, 1 ton of MSW was an input to the incineration process without any pre-treatment. In *scenario B*, 1 ton of MSW was input to a material recovery facility for the recovery of Al-containing packaging, disregarding any recovery of other metals such as Fe or Cu. As it was assumed, only Al scrap is sorted out during the mechanical processing, and all the remaining waste is directed to incineration. Acknowledging that this is hypothetical (other outputs such as ferrous metal scrap fractions as well as high calorific waste fractions are typically produced in addition), the simplifications serve the purpose of focusing only on the Al flows and qualities in the scenarios. Therefore, the present analysis is not suitable to compare the scenarios on a more general basis, apart from Al. In both scenarios, BA produced at the incineration plant was treated and used as aggregate in road construction. The treatment of BA includes the ageing process and a material recovery facility for the recovery of ferrous and non-ferrous (NFe) metal scraps. The energy demand for Al recovery before incineration was assumed 23 kWh (or 82.8 MJ) per ton of waste input [8]. The energy demand of scrap recovery from bottom ash per ton of bottom ash is approximately 39 MJ and 38 MJ in scenarios A and B, respectively [9].

2.2. Material flows and oxidation levels

Material flows for both scenarios were modeled in STAN software [10]. The software allows for structuring of the system according to key processes on several levels of processes and subordinate systems. *Scenario A* is composed of two processes, both of which are subsystems at the same time: *waste-to-energy (WtE)* and *bottom ash treatment (BAT),* while *scenario B* additionally contains a process *mechanical sorting* (Figure 1).

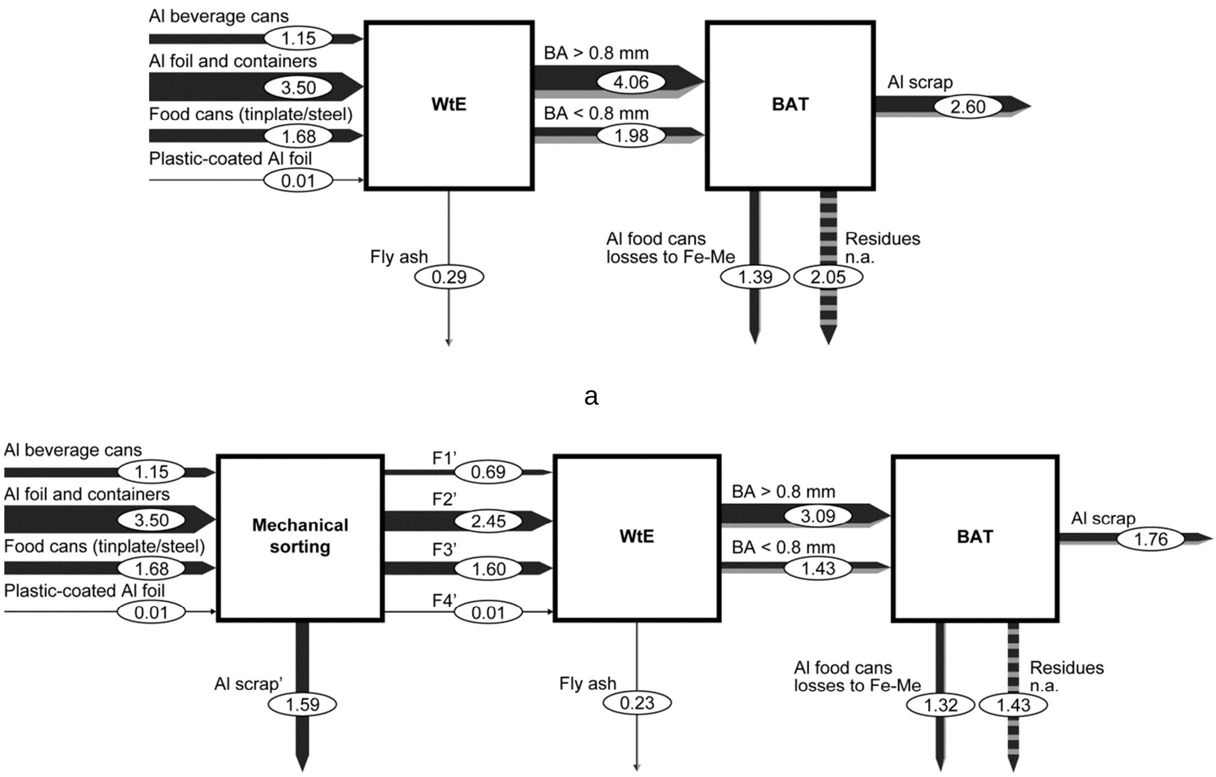


Fig.1: *(a) STAN model of Al flows in scenario A; (b) STAN model of Al flows in scenario B, in [kg]. This figures show the total flow of Al, considering the surface oxidation of Al and illustrating ratios of Al (black) and Al_2O_3 (grey) in flows after incineration.*

The total input of Al in each scenario was 6.33 kg per 1 ton of MSW, originating from four metal fractions: 1. Al beverage cans, 2. Al foils and containers, 3. Food cans (tinplate/steel), and 4. Plastic-coated Al-foil. The MSW composition data from EASETECH database were used. Al concentrations in non-metal products are negligible (see e.g. [11, 12]) and not relevant from the recovery perspective.

In the subsystem *mechanical sorting*, we assume a simplified scenario, with only Al separation. While we recognize that this is not the case in existing facilities, as previously mentioned, it serves the purpose to show the difference in the resulting Al scrap qualities. Due to lack of information about transfer coefficients of Al in the mechanical separation step, we assume the following sorting efficiencies; 0.4 for beverage cans, 0.3 for Al foil and containers, 0.05 for food cans, and 0.1 for plastic-coated Al foil, resulting in an overall Al sorting efficiency of 25%.

In the subsystem *waste-to-energy*, the transfer coefficients to fly ash (FA), BA<0.8mm and BA>0.8mm have been defined for fractions Al beverage cans ("Cans" in [3]), Al foil and containers ("Trays"), and plastic-coated Al foil ("Foils"), as in [3]. This information is not available for food cans, therefore we assume the same partitioning as beverage cans. The losses to off-gas are negligible from the mass perspective (<0.1% of Al input) (see e.g. [13, 14]). The Al contained in FA is currently not relevant from a recovery perspective [3].

The subsystem *bottom ash treatment* is composed of 3 processes: *Sieve 2mm*, *Fe-metal recovery*, and *Al recovery*. The sieve separates the BA fraction relevant for state-of-the-art Danish Al recovery (BA >2mm). Next, part of Al leaves the system boundary during the Fe-metal recovery; these are mostly food cans consisting of tinplate/steel-Al alloys. We assumed efficiencies as reported in the literature (see e.g. [2, 5, 15, 16]), and corresponding to the Danish state-of-the-art: 83% for Fe metals and 58% for NFe metals.

The data on amount of Al_2O_3 present in different Al packaging after incineration are taken from [3] and from personal communications with stakeholders in the Al upgrading & recycling sector [9], and illustrated in Figure 1 in grey. It was assumed that food cans exhibit the same oxidized fractions as beverage cans in the process WtE.

3. LCA

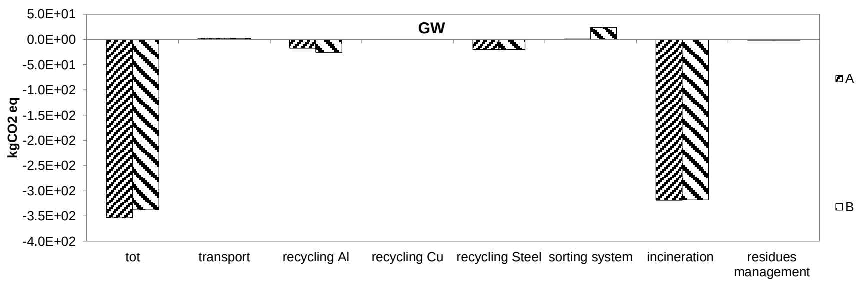
3.1. Method

The aim of the LCA was to identify the benefits and burdens that Al recovery before the incineration process can inflict to the environment. The functional unit was the treatment of 1 ton of MSW (wet weight) in Denmark, with a time horizon of 100 years. A consequential approach was used and coal was chosen as marginal technology for electricity production and district heating. A zero-burden assumption was applied to disregard all impacts related to waste provision. The newly developed LCA model EASETECH [17] was used for the purpose of this study, and input processes for energy provision and material recycling were obtained from the ECOINVENT database. Concerning Al recycling, the substitution rate between primary and secondary Al was set to 1. The effect of scrap quality was introduced by reducing the ratio between input scraps to the recycling process and the produced secondary Al. The ratio was adjusted by applying different oxidation levels to individual Al fractions.

The impact assessment was based on the recommended list of impact methods at a midpoint, as reported in [18]. Only non-toxic categories were included in this study. The impact categories considered were global warming (GW) [IPCC 2007], stratospheric ozone depletion (OD) [EDIP97], photochemical oxidant formation (POF) and terrestrial acidification (TA) [ReCiPe], eutrophication (EP) [CML2001], freshwater eutrophication (EF) [ReCiPe], and resource depletion abiotic (AD) [CML2001] Normalization was performed using the recommended normalization factors, and the normalized results were expressed as Person Equivalent (PE).

3.2. Results

On the basis of this LCA study, *scenario A* presented better environmental performance than *scenario B* with respect to all non-toxic impact categories. Particularly, GW potential resulted in -350 kgCO_2-eq in scenario A and -340 kgCO_2-eq in scenario B, and AD resulted in -0.47 kg antimony-eq and -0.31 kg antimony-eq, respectively in scenario A and B. The reason was the increased demand of energy for metal recovery in the mechanical sorting prior to the incineration process. In fact, even though the final amount of Al scraps collected for recycling was higher in *scenario B*, the benefits due to the increased metal recovery were outbalanced by the additional burdens for recovering metals from a larger and less concentrate stream (MSW). In *scenario A*, the Al present in the Al packaging represented approximately 0.6% of the initial MSW, while in the BA the Al scraps represented approximately 1.5%. All non-toxic impact categories resulted in net savings with the exception of EP. The impact on this category was 0.057 and 0.069 kgNOx-eq for scenario A and B respectively, and the major contribution came from the incineration process. Some of these results are shown in Figure 2.



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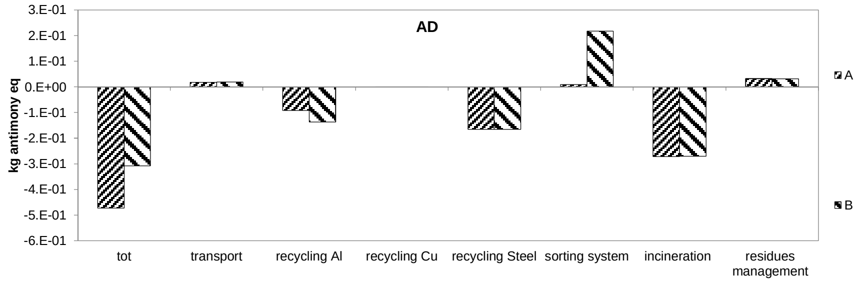

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Fig. 2: *(a) LCA results for GW; (b) LCA results for AD. The results are reported in function of the contribution of the main activities included within the system boundaries.*

Analyzing the input data to the LCA, the total amount of Al scraps recovered and sent to recycling in *scenario B* is 29% higher than in *scenario A*, but the amount of primary Al actually substituted is up to 244% more than in *scenario A*. This great difference in the amount of primary Al actually saved is related to the oxidation level of the Al scraps. The scraps recovered before incineration (representing approximately 47% of the total aluminum scraps recovered in *scenario B*) present low oxidation and contamination levels, achieving higher value of recycling ratio (approximately 0.79) than the scraps sorted from BA. Thus a minor increase in the metal recovery before incineration could lead to a significant increase in the amount of primary Al actually saved. Nevertheless, this aspect is not observable in the LCA results due to the importance of impacts related to other aspects such as energy consumption.

Figure 3 reports the normalized results. The impact categories mainly affected by the system were the depletion of abiotic resources (A:-0.50 PE; B:-0.32 PE) and global warming (A: -0.046 PE; B: -0.044 PE). Thus, the investigated scenarios had the greatest impact in terms of resource depletion with impacts after normalization corresponding to approximately 30% and 25% of the impact of an average person.

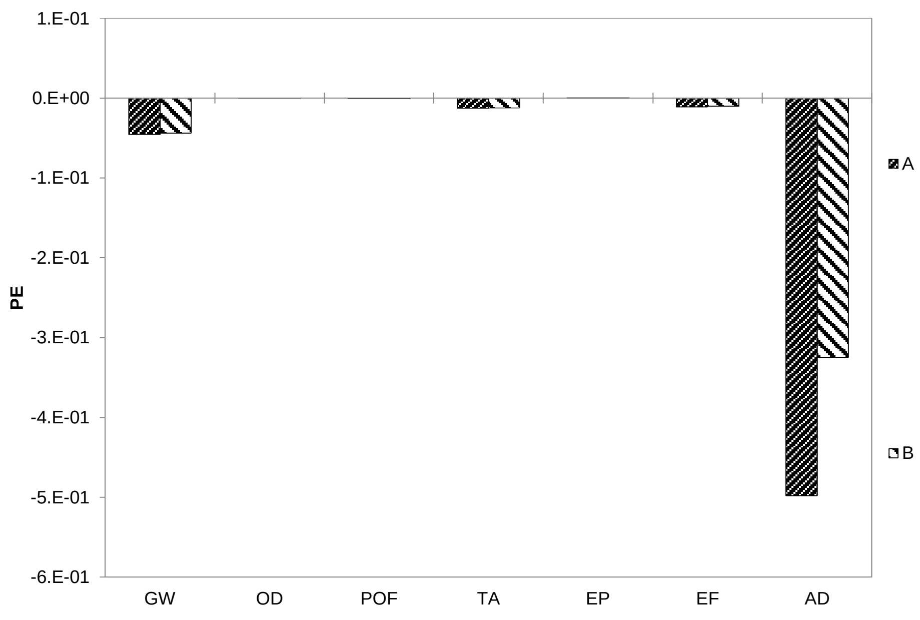


Fig. 3*: LCA normalized results [PE: person equivalent]*

4. Exergy analysis

4.1. Method

By means of exergy analysis, chemical exergies contained in all flows were quantified in scenarios A and B, for the model as described in the section 2 of this paper. The objective was to express the difference in qualities of Al scarps recovered prior to and after the incineration process, and to compare scenarios A and B, in addition to the comparison already conducted by the means of LCA. The scope of the exergy analysis was to exclusively investigate metallic Al in the waste input and how it is affected, quantity- and quality-wise, by the waste treatment scenarios.

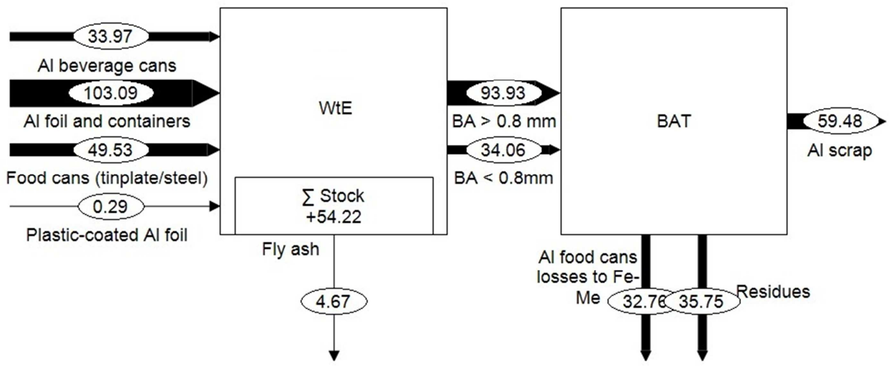
Hence for the purpose of this analysis, all flows were assumed to be composed of only metallic Al and Al_2O_3 (all flows prior to incineration were considered to be metallic Al only). Assuming an ideal mixture at standard temperature and pressure, the exergy of the flows was determined by Eq. 1 [19],

$$e_{ch;flow} = \sum_{i}^{n} x_i e_{ch;i}^{0} + RT_0 \sum_{i}^{n} x_i ln x_i \qquad (1)$$

where x_i is the molar ratio of substance i (here Al and Al_2O_3), $e_{ch;i}^{0}$ is the standard chemical exergy of a substance i based on reference values by [19], R is the gas constant, and T_0 is the temperature at standard conditions. The first term in the equation expresses chemical exergies of each constituent i of the mixture, while the second term gives the exergy of mixing of Al with Al_2O_3. Future work will extend this simplified system to consider more different Al species in the various waste streams and investigate the consequences of the more detailed waste characterization on the exergy results.

4.2. Results

There is a notable difference in the exergy contained in the recovered Al between the two scenarios, as shown in Figure 4. In *scenario A*, the exergy of recovered Al scrap (2.60 kg) from incineration BA is 59.48 MJ (22.88 MJ/kg). In *scenario B*, the exergy content of Al scrap (1.76 kg) from incineration BA is 40.26 MJ, and of Al scrap from pre-sorting (1.59 kg) is 47.15 MJ. The total yield per 1 ton of MSW in *scenario B* is thus 3.35 kg Al, with total exergy content 87.41 MJ (26.09 MJ/kg). When comparing the two scenarios, we can express a ‘gain-factor’ for *scenario B* with respect to quality as 1.14.



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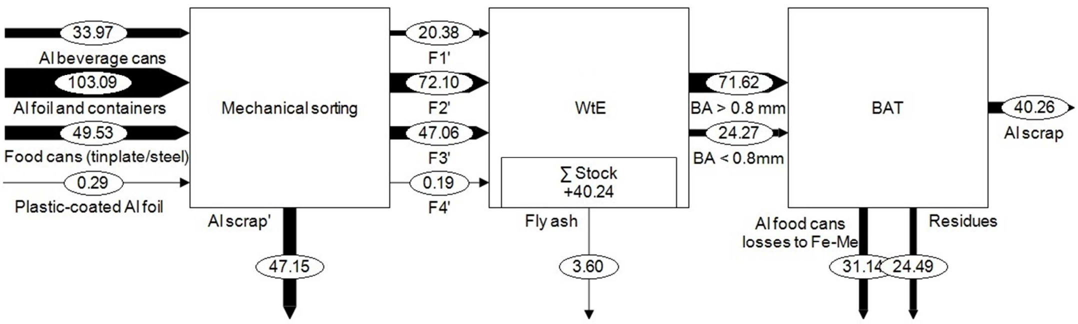

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Fig. 4: *(a) Exergy contents related to Al for scenario A; (b) Exergy contents related to Al for scenario B, in [MJ].*

5. Discussion and conclusion

In the LCA, scenario A presented a better environmental performance in category abiotic resource depletion, due to a relatively high energy demand of the waste pre-sorting step. This impact category was the most significant in the system, as can be observed from the normalized results in Figure 3. As all the energy demand of the sorting is allocated to the Al scrap in the present system, it must be noted that the results would look differently if other output fractions were accounted for as well.

In the exergy analysis, scenario B proved to be more effective, when looking at both weight gain (+0.75 kg Al/ 1t MSW) and exergy content (+27.93 MJ) of recovered Al. What may seem at first in contrast with the LCA results, it is less so when taking into account the -82.8 MJ exergy spent – directly comparable with the +27.93 MJ gain – in the mechanical pre-sorting step. Hence, the gain in chemical exergy due to the higher amount of recovered Al and the lower oxidized fraction in scenario B appears very small for the whole system. However, we would like to refrain from directly comparing exergy flows in energetic resources (i.e. destructive use) and material resources (i.e. non-destructive use), as the energetic resources (high chemical exergies) will dominate such analyses. Rather, we regard the exergy analysis of Al in the two scenarios as an add-on to the LCA expressing different material qualities in waste flows (due to dilution, contamination and transformation) in exergetic terms.

From the LCA results, the impact of the different quality of the recovered scraps is not noticeable, even if an improvement of both quality and quantity of Al scraps sent to recycling is achieved. In the LCA, the different scrap qualities of scenario A and B were essentially considered by choosing different substitution rates for the actual scrap entering secondary production. While this procedure is rather arbitrary and based on expert estimates (as detailed process data is not available), a distinct indicator, such as exergy, focusing only on the quality of the recovered resource from the waste stream adds rigor to the evaluation of mineral resource recovery in the LCA. Hence, exergy analysis of mineral resource flows in waste management systems may provide a basis for a more rigorous and transparent assessment of the quality of recyclables and the consequent effects on the recycling processes in LCA. As a part of such an endeavor, the utility of exergy as an indicator for expressing resource quality needs further testing in view of different materials and in comparison to real data of recycling processes confronted with different input qualities.

This case study will be extended in future works, where several issues need to be addressed. The two most important to consider, apart from the extension of the work mentioned above, are (1) uncertainties related to material flows, energy demand, partitioning, oxidation levels, and sorting efficiencies, and (2; in exergy analysis) presence of Al in other chemical species than Al and Al_2O_3, such as $Al(OH)_3$.

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