ENVIRONMENTAL EVALUATION OF HOUSEHOLD WASTE MANAGEMENT SYSTEM IN SOUTHERN GERMANY

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SUMMARY: In order to quantify and compare the environmental impacts caused by several modern household waste management strategies in the federal state of Baden-Württemberg, Germany, the Life Cycle Assessment (LCA) cradle-to-grave analysis, which accounts for the material and energy flows during the life cycle of a product or service, has been applied. In the case of household wastes, the environmental impacts through out the waste management chain correspond to the sum of the impacts that arise during the end-of-life operations of each product that leaves households as waste. The LCA carried out included the evaluation of the direct impacts arising from household waste management strategies, as well as the benefits obtained through the substitution of raw material and primary energy sources. The operations evaluated include the collection and transportation of wastes, material and energetic recovery, anaerobic digestion, residual waste treatment and final disposal. For the treatment of residual waste, incineration, mechanical-biological treatment, and mechanical biological stabilization were modeled, since they represent the state of the art in the Federal Republic of Germany in terms of waste treatment technologies.

1. INTRODUCTION

As one of the cornerstones of sustainable materials management, integrated solid waste management strives towards the harmonization of economic, environmental and social benefits by appropriately steering post-consumer material flows. The adequate management of waste streams from society requires the integration of different technologies into a system, which minimizes the hazards on human health and the environment and maximizes the resource recovery, while being economically and socially sustainable.

Today, the complexity of the waste management sector requires a holistic approach, in which waste management systems as a whole are assessed. Based on the analysis of material, substance and energy flows, and the associated cost, the most sustainable waste management system can be identified. This integrated assessment has to be in accordance with the current trend of management of material flows as main task of the solid waste management sector. The concept of material flow management focuses on steering material, energy and substance flows,

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in such a way that resource efficiency is achieved, and cyclic flows of materials within society are attained. At the same time it strives for the reduction of environmental burdens, while increasing economic and social benefits. This can only be achieved if the technological and non-structural measures needed to appropriately handle each individual waste stream leaving society are customized taking into consideration the technological, economical, political and social boundary conditions. Additionally, synergetic effects, which lead to increased benefits, are achieved through the integration of the different management strategies for the materials streams.

In order to quantify and compare the environmental impacts caused by several modern household waste management strategies in the federal state of Baden-Württemberg, Germany, the Life Cycle Assessment (LCA), a cradle-to-grave analysis, which accounts for the material and energy flows during the life cycle of a product or service, has been applied. In the case of household wastes, the environmental impacts through out the waste management chain correspond to the sum of the impacts that arise during the end-of-life operations of each product that leaves households as waste.

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With the help of *Umberto*, an LCA software package developed by *IFU*[1] and *IFEU*[2], the necessary input and output material and energy flows of the waste management strategies were obtained by combining the results of external process models, literature values, and the program's module library. The present article focuses on the methodology applied, the results from the assessment of each of the individual waste fractions, as well as the difficulties encountered during the execution of the LCA.

2. LIFE CYCLE ASSESSMENT FOR WASTE MANAGEMENT SYSTEMS

The two main differences between LCAs for product systems and LCAs in waste management are the functional unit and the definition of the system boundaries. In the case of product systems, the functional unit is generally the output product (e.g. kg of product). In contrast, the functional unit of waste management systems is the input waste to be treated. The largest problem with this definition of functional unit is that it is a not a homogeneous material, like in the case of single products. Instead, it is a mixture of several kinds of products, thus having specific physico-chemical properties depending on its composition. In turn, the environmental burdens resulting from the management of this mixed material matrix are also dependent on the composition.

In a product LCA the system boundaries go from the extraction of raw materials, to the final disposal of the product after its use. Since the functional unit, the waste is a conglomerate of different products, the system boundaries of the waste management system must reflect the end-of-life phase of all of the products included in the waste material. The "cradle" of the waste management system corresponds to the point in time in which the product loses value for its

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[1] Institut für Umweltinformatik Hamburg GmbH

[2] Institut für Energie- und Umweltforschung Heidelberg GmbH

owner, and he or she wishes to dispose of it or required by law to do so. In the case of household waste, the cradle is represented by the waste bin or container, in which each residue is collected. The "grave" of the waste management system is much more complicated to define. In the case of materials with a commercial value, the system boundary goes up to the point in which the material recovers value, either as a secondary raw material, or an alternative energy source. In the case of waste, which is disposed of in landfills, there is no agreement about the time horizon in which the environmental impacts of waste buried in landfills take place. Common time frames include 100, 1000 and up to 65,000 years, which is the period of time estimated for the next glaciation to take place.

The impacts of the integrated waste management system can be seen as the aggregation of the impacts from the upstream processes for the supply of materials and energy consumption, the logistic operations, treatment and disposal processes, and recycling and energetic recovery processes. The contribution to reduction of environmental burdens through material and energetic recovery has to be deducted to the direct impacts caused by the management of waste.

Since the evaluation of impacts depending on changes in the waste composition is one of the goals to be achieved through a LCA for waste management systems, static IO tables are unsuitable, since they have no capacity of prediction. Generation of inventory data for the evaluation of waste management systems can be carried out through deterministic Life Cycle Modeling, either through black-box modeling, where the each input and the output substance streams are linked through a transfer coefficient, assuming a linear relationship, and there is no consideration for the actual processes that take place within the black box, or through process modeling of each of the elements, as well as sub-elements, within the waste management chain.

Although Life Cycle Assessment provides a broad evaluation regarding the environmental burdens caused by waste management systems, and allows comparison and trade-offs between different waste management strategies, its application is not without shortcomings. First of all, by focusing on a wide range of impact indicators, instead on few robust indicators, a larger degree of uncertainty is introduced. Additionally, by seeking a higher detail in the Life Cycle Inventory analysis phase, data quality is sacrificed, and in the case of material flows from waste treatment facilities, for which very little information is available, Life Cycle Modeling makes assumptions about the operation of these facilities, which may not represent the real conditions. Finally, a pure environmental evaluation does not acknowledge the relationship between the capital invested in the waste management system, and the benefits received. This makes the economic optimization of waste management systems with regard to environmental efficiency difficult to achieve.

The application of the LCA to the evaluation of waste management systems is advantageous in the sense that it promotes a comprehensive evaluation of the whole waste management chain under the consideration of several environmental issues. The difficulty of implementing LCA studies in the waste management field is associated mainly to the lack of information regarding inventory data for each component. Additionally, in waste management practice, decisions are most of the time made considering costs as the limiting resource. The relevance of environmental issues in comparison is relatively small. A solution to this issue would be to transfer the absolute impact indicators, into eco-efficiency indicators, in which a cost-benefit relationship, in this case environmental benefit seen as a reduction of environmental burden, is considered.

3. GOAL AND SCOPE DEFINITION

The methodology employed in this study follows the guidelines established by the ISO 14040 series, including the Goal and Scope Definition, the Life Cycle Inventory (LCI), the Life Cycle

Impact Assessment (LCIA), as well as the interpretation of results. Household waste was not evaluated as a single material; instead, the individual waste fractions that make up household waste, recyclables and residual waste, were defined, and each of them as individually assessed. The valuable materials considered are:

- Biowaste
- Paper
- Glass
- Plastics
- Composite Packaging
- Ferrous Metals
- Non-Ferrous Metals

Additionally, residual waste was modeled as a conglomerate of several waste fractions, such as minerals, wood, textiles, sanitary products, a < 10 mm fraction, and a 10 – 40 mm fraction. For each assessment, a functional unit of 1 Mg of recyclables and residual waste was chosen.

Waste management strategies involve a combination of different waste management operations for each of the material streams. The operations considered for the management of household waste are:

a. Final Disposal:

- Landfill

b. Waste Treatment:

- Waste Incineration (WIP)
- Universidad de los Andes, Mechanical Biological Stabilization and Cement Kiln (MBS+CK)

c. Energetic Recovery:

- Mechanical Sorting and Cement Kiln (MRF+CK)

d. Material Recovery:

e. Biological Treatment:

- Anaerobic Digestion (AD):

Upstream processes, which include the production of electricity, the extraction and refinement of fossil fuels, the extraction of raw materials, and the treatment of water for industrial use, are also taken into consideration in the LCA of household waste. As explained previously, the reduction of environmental stresses by the substitution of primary energy and raw material sources through material and energetic recovery have to be credited to the system; in other words, they are accounted as negative environmental burdens. The amount of electricity generated in waste incineration plants through waste combustion, as well as in combined heat and power units (CHPs) from biogas and landfill gas, substitutes the consumption of electricity from the power grid. In the same fashion, heat produced at WIPs is fed into the district-heating network, and replaces the production of steam from fossil fuels, while in cement kilns RDF is used to a certain extent instead of hard coal. In the case of material substitution, compost produced at anaerobic digestion plants serves as a surrogate for mineral fertilizers when applied to crop fields. In the same manner, the recovery and direct reuse, or use as secondary raw material of paper, glass, plastics and metals, reduces the need of extraction and processing of raw materials to produce new products. In the case of plastics, only substitution effects of polymers for which a market is available, e.g. polyethylene, are considered. In the case of plastics with no commercial value, recycling is not credited, since the production of materials from these materials result only in environmental burdens, and no substitution of primary sources is achieved.

The Life Cycle Impact Assessment considered the following impact categories used for the evaluation of the waste management strategies:

- Resource Consumption
- Global Warming
- Photooxidant Formation
- Terrestrial and Acquatic Eutrophicatioon
- Health Impact
- Ecotoxicological Impact
- Space Use

The valuation procedure in *Umberto* includes a **Normalization** step that leads to a one-point indicator in terms of *Normalized Person Equivalents* (*NPE*). This indicator reflects the relative contribution of environmental burdens by the system studied, in comparison to the total environmental burden covered by the impact categories for the Federal Republic of Germany. The new index is obtained by dividing the value of each environmental indicator by a reference value. This reference value reflects, in terms of each category, the impact the German economy on the environment. This is followed by the multiplication of this quotient by the total German population for a given year. As a result, an index is obtained in terms of number of person that causes the equivalent environmental burden. The *Normalized Person Equivalent* indicators from each category can be assigned a weighing factor, depending on the value judgment of the performer, and then added, resulting in a measure of the environmental performance of the system being evaluated. For sake of objectivity, the current study attributed the same importance to each impact category, so no weighing factors were assigned.

4. RESULTS

As an example, Figure 1[1] illustrates that for most categories the treatment of residual waste through incineration (**WIP**) is the option with the best environmental performance, mainly because points are credited due to the good performance of the system itself, as well as the substitution of energy and materials.. On the other hand, landfilling of residual waste presents the least environmentally friendly option for all of the impact categories, with the exclusion of health impact. Finally, although in comparison to **WIP** the substitution of energy and raw materials is higher for the systems **MBT+CK+Landfill** and **MBS+CK**, where energy is recovered in the cement production process, the direct impacts are also higher, leading to an overall less favorable environmental profile.

In contrast to the LCIA results from residual waste treatment, where waste incineration provided the best environmentally sound disposal, all technologies for the treatment of biowaste, except **Landfill**, present to some extent environmental benefits. A look at the net evaluation of Biowaste, presented in Figure 2, interestingly shows that **Anaerobic Digestion** and **WIP** present almost no difference in their absolute environmental profile. Therefore, the decision of which of the two systems to choose depends on the feasibility of the separate collection of biowaste. In urban areas, where separate biowaste collection is not widespread, the joint collection with residual waste, and its posterior treatment in an incineration furnace, is equally beneficial, from an environmental standpoint, as its anaerobic digestion.

[1] Positive NPE values, i.e. values at the right hand side of the y-axis, represent an additional environmental burden caused by a waste disposal technology, while negative values, i.e. values at the left of the y-axis, represent a reduction of the environmental damage thanks to recycling or to energy recovery.

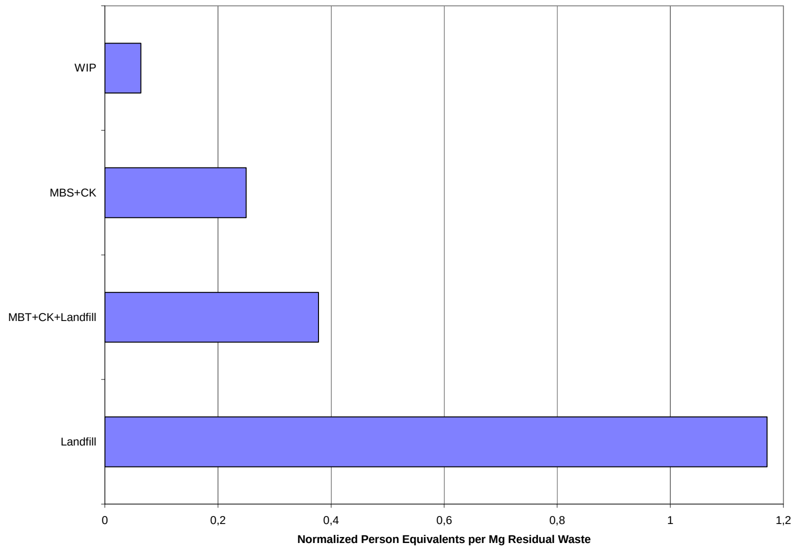

Figure 1. Net LCIA Results of Residual Waste Management Operations

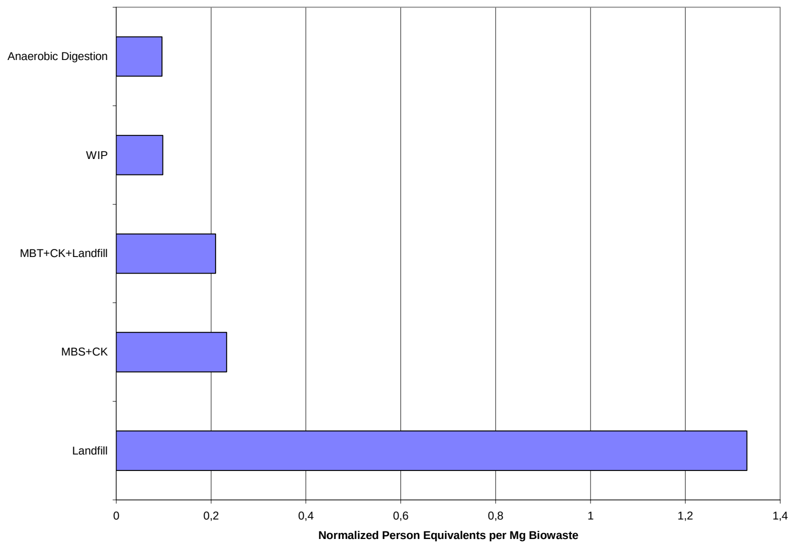

Figure 2. Net LCIA Results of Biowaste Management Operations

In a similar fashion, **MBT+CK+Landfill** and **MBS+CK** present only a slight difference in their net LCIA results. Since the results from the Life Cycle Assessment have only an orienting function, these small differences are not large enough to be conclusive regarding the environmental benefit of one option over the other.

From the LCIA results of the waste paper fraction it can be concluded that the most environmentally sound waste paper management option is clearly recycling. A detailed inspection shows that the environmental benefits of waste paper recycling overweight the direct impacts, making this the most suitable waste management operation for the material. Figure 3 illustrates that **Recycling** remains the best option for managing the waste paper stream from households, while **Landfill** is the least favorable one. Depending on the paper market situation, the production of RDF from paper could be a good alternative, if the demand post-consumer paper fibers is not high, as in the case of low quality paper, since the system **MBS+CK** also

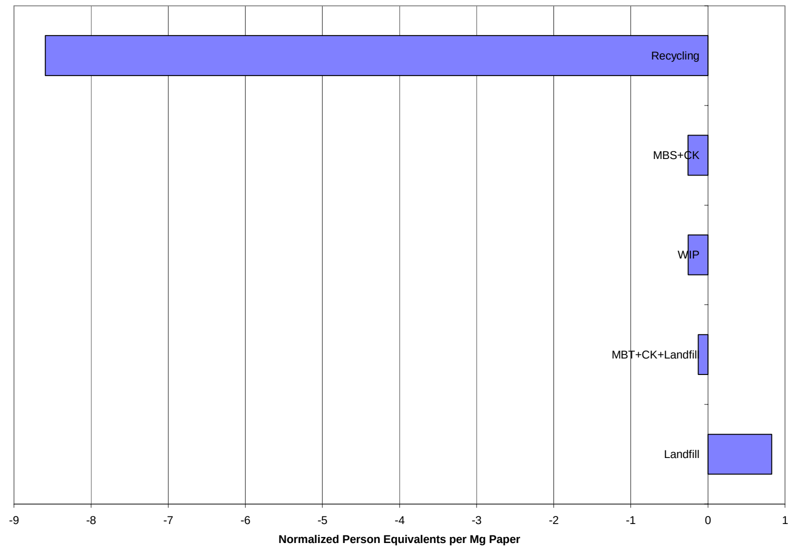

Figure 3. Net LCIA Results of Paper Management Operations

provides a certain reduction of environmental impacts.

The Life Cycle Impact Assessment for the waste glass management operations indicates that systems that recover glass for their use as feedstock materials should be preferred, since they reduce the environmental burden in comparison to production of glass from raw materials. Figure 4 confirms unambiguously that the current scheme of separate waste glass collection should be maintained, since in terms of environmental protection is the most beneficial option. Although the recovery of glass fraction in residual waste through in a mechanical-stabilization plant has only a slighter lower environmental benefit than separate collection and recycling, the environmental assessment does not consider the issues regarding the quality of the recovered material. The mechanically separated stream is a mix of different colors, which in practice does not make **MBS+CK** a viable technical solution for the recovery of the bulk of the glass from households.

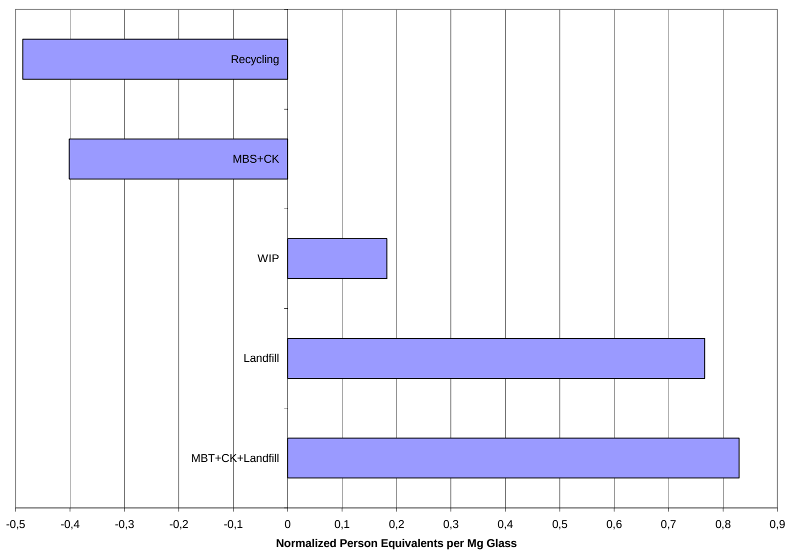

Figure 4. Net LCIA Results of Glass Management Operations

Management of the packaging waste from households has become a controversial issues in the waste management landscape, mainly because of the complexity of the system established and its high operational costs. Additionally, the lack of marketability for some of the sub-fractions recovered has also made decision makers and the general public question the system. Apart from the conventional system of separate collection and recycling, the LCA has considered the impacts of the operations treating plastics jointly with residual waste, as well as the use of plastics as an energy source in cement kilns after its separation from the waste packaging stream in a material recovery facility.

The net LCIA evaluation in Figure 5 illustrates that there are not very large differences between the environmental performance of material and energetic recovery from waste plastics. Depending on the situation of plastic and cement markets, and on the collection and treatment costs, any of the three best scoring variants, or a combination of them, can be chosen. If there is need for feedstock material in the plastics market, recycling of plastics, either separately collected or recovered through mechanical sorting, would be the best suiting operation. On the other hand, for plastic fractions with low commercial value in the secondary raw material market an appropriate solution would be the separation of these fractions in a material recovery facility, and its employment in cement production. Finally, if the joint collection with residual waste is economically advantageous, the production of RDF in a mechanical-biological stabilization plant, and its posterior use in a cement kiln, would be then beneficial. Though not as environmentally efficient as Recycling, MBS+CK and MRF+CK, grate incineration also reduces the environmental burdens, as well as the MBT+CK+Landfill system.

The net LCIA results (Figure 6) confirm that the most appropriate operation for the management of composite packaging is material recovery, since this is the option whose benefits overweight to largest extent the direct impacts from the system. As in the case of plastics, energetic recovery systems MRF+CK and MBS+CK have similar environmental profiles. Thus, the decision of which system to choose is independent of their environmental performance, and is determined by the cost and implementation ease of each waste management system.

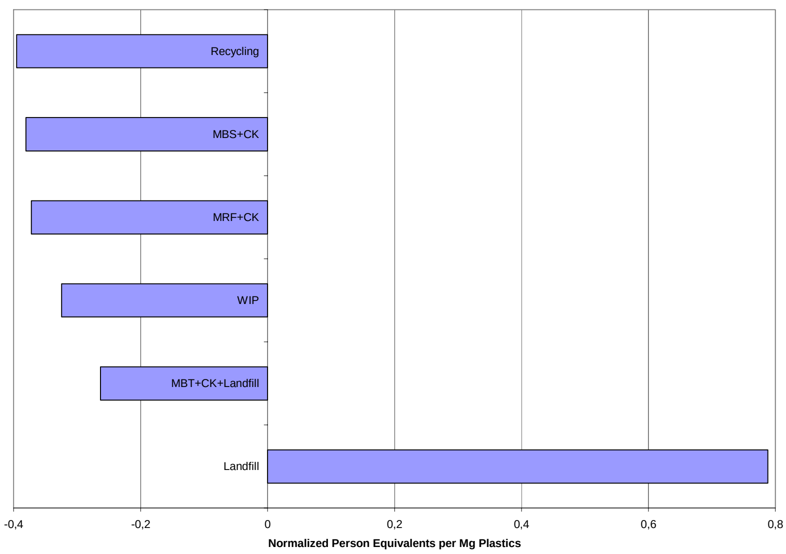

Figure 5. Net LCIA Results of Plastics Management Operations

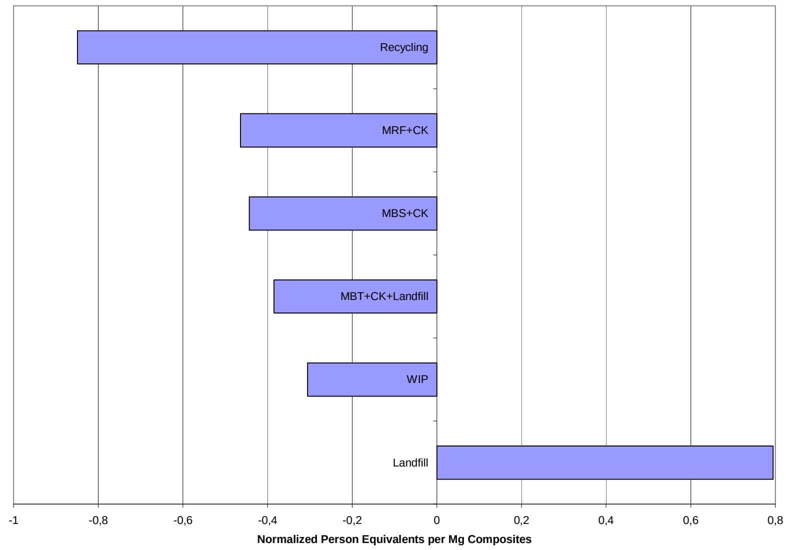

Figure 6. Net LCIA Results of Composite Packaging Management Operations

The results of the Life Cycle Impact Assessment of the ferrous metal fraction from household wastes point out that recycling this material group is the most favorable option, from an environmental point of view. The recovery of steel through waste management operations like **WIP**, **MBT+CK+LANDFILL** and **MBS+CK** proves to have also beneficial impact on the environment, in comparison to the production of steel from raw materials. Since higher recovery rates are attained through separate collection, and the credits assigned depend on the recovery rated, **Recycling** receives more points in comparison to the waste treatment operations where mechanical recovery takes place. Figure 7 illustrates the aggregated and net LCIA results for each individual waste management operations, which reflect the fact that the higher the recycling rate, the better the environmental performance of the strategy. While **WIP**, **MBT+CK+LANDFILL** and **MBS+CK** present recovery rates of 95%, **Recycling** achieves a theoretical 100% recovery of the material. The operations **MRF+CK** and **Landfilling** are in comparison are unfavorable, since no material is recovered.

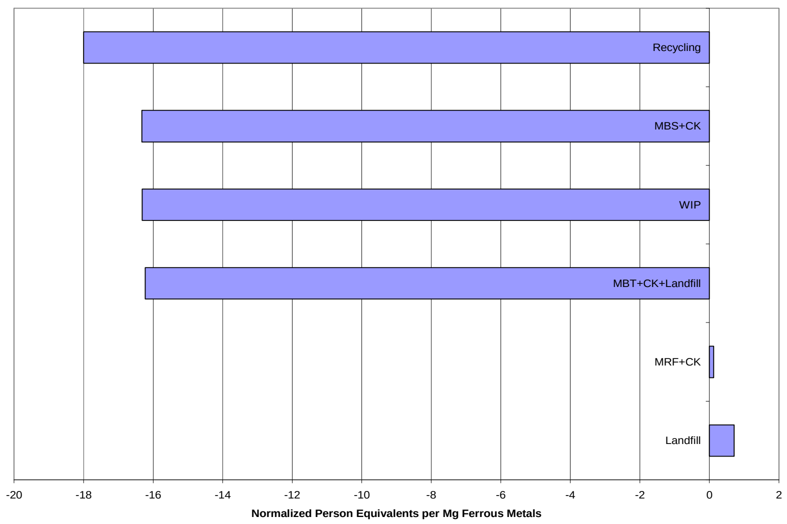

Figure 7 - Net LCIA Results of Ferrous Metals Management Operations

6. CONCLUSIONS

The LCA described out within the scope of this article had the objective of evaluating the environmental performance of several waste management strategies of household waste. The strategies involved recycling of valuable materials, energetic recover of plastic and composite packaging in cement kilns, anaerobic digestion of biowaste, and treatment and disposal of residual waste. Treatment operations of residual waste included waste incineration, mechanical-biological treatment, mechanical-biological stabilization, while disposal only considered landfilling.

In order to obtain the Life Cycle Inventories for the waste management strategies, a combination of process models for waste treatment, disposal and energetic recovery operations, and literature values for recycling operations, was carried out. Process models were calibrated for residual waste, and then the individual inventories were produced for each material subgroup of household wastes. Since environmental benefits are obtained through material and energetic recovery, heat and electricity production, and reduction of raw material consumption, substitution effects of the waste management operations were evaluated as well.

As observed in the environmental assessment, there is more than one household waste management strategy, and correspondingly waste treatment operation, that display equal environmental benefits. As seen in the analysis of each individual impact category, depending on the relevance given to each environmental issue, different strategies could achieve a maximal reduction of the impact of the household waste management. If all environmental issues are considered equally significant, then strategies that maximize recycling, or that achieve a combination of recycling and energetic recovery, are the most beneficial. The current management of household waste scores quite well, while those strategies that forego recycling are the least favorable.

In general terms, recycling of glass, paper, ferrous and non-ferrous metals, either through separate collection or mechanical sorting, should be maximized in order to receive maximum environmental benefits. Plastic and composite packaging can be either recycled, or used as secondary fuel in the production, reducing the environmental burden to a similar extent. Biogas recovery and compost production from the anaerobic digestion of biowaste is appropriate where separate collection is feasible, while joint collection and treatment with residual waste is beneficial where no separate collection is practicable.

The selection of the most appropriate household waste management strategy depends not only on its environmental performance. Economics of the waste management system, citizen acceptability, reduction of effort in households, marketing potential of the recovered materials, and quality of the substitutive fuels play a significant role. In the end, the results of the Life Cycle Assessment should only be given a guiding function, and should not be taken as absolutes regarding the environmental performance of the waste management systems.

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