HYDROTHERMAL PROCESSING IN BIOREFINERIES – A CASE STUDY OF THE ENVIRONMENTAL PERFORMANCE

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ABSTRACT

Hydrothermal processes are possible attractive components for biorefineries, for converting different biomass streams into a range of products. This study investigates the environmental performance of a hydrothermal process plant in Carthage, Missouri under development by Changing World Technologies (CWT). The plant converts the refuse from Butterball Turkey production into diesel oil, fertilizer products and carbon. The CWT process is essentially a closed system with few emissions, avoiding odor problems from the handling and giving products free from pathogens. Life Cycle Assessment has been used to investigate the overall environmental performance of the process and the performance of this process is discussed in comparison to other process routes to give the same products.

KEY WORDS

biorefinery, hydrothermal processing, food industry, diesel oil, life cycle assessment.

INTRODUCTION

Since the early 1980s biorefineries have been discussed as means to displace fossil hydrocarbon feedstocks and utilize renewable sources for energy, materials and chemicals [Ng et al, 1983, Kamm and Kamm, 2004]. The concept was first discussed mainly in terms of biotransformation of material, but has now developed to consider the use of many sorts of chemical process solutions, including hydrothermal conversion, to reach the desired goals. A similar enlargement of scope can also be seen regarding raw materials, from focusing on specific biomass for the purpose of use in a biorefinery into a broad range of biomass and increased interest in biowaste. It should be remembered that chemical processes and products will not fit the criteria of sustainability solely because they are based on biomass, or even biowaste. All proposed processes should be evaluated from an environmental systems perspective to establish their environmental performance as well as identify possible improvements to the processes.

Hydrothermal processes are possible attractive components for biorefinery application as they could be used to convert a variety of wet biomass streams into a range of products. An example of a wet biomass feedstock is food industry waste. Large flows of material processed by the food industry are not converted into marketable food products. The hydrothermal conversion process studied in this paper has been designed to overcome some problems connected to this kind of material flow: odor, the risk of spreading of pathogens and contaminants (concerns over the possible propagation of Mad Cow disease have emphasized this problem) and low market value of recovered products (often the case with compost products).

This study investigates the environmental performance of a hydrothermal process plant in Carthage, Missouri under development by Changing World Technologies (CWT). The plant converts the refuse from Butterball turkey production into diesel oil, fertilizer products and carbon. It is possible to incinerate this kind of organic waste, thereby eliminating the risk of spreading pathogens, but water content makes it a troublesome fuel.

The technology has been developed by CWT and tested in a pilot plant in Pennsylvania [CWT, 2004]. A full scale commercial plant has now been constructed to handle the turkey offal from a ConAgra

Butterball turkey processing facility in Carthage, Missouri. The process is described by Roberts *et al* [2004] and Adams *et al* [2004]. This study gives a preliminary environmental system evaluation of the Carthage hydrothermal conversion process, based on this information. Processes to convert organic waste into liquid fuels have been studied earlier, see e.g. the review given by Zahang *et al* [1999], but have often been hampered by low grade of conversion into the desired product or low energy efficiency.

PROCESS OVERVIEW

The hydrothermal conversion process flow sheet is shown in Figure 1 (see Roberts *et al*, [2004] and Adams *et al* [2004] for further details). The process is divided into two main stages. In the first stage the feed is pulped into slurry, then pressurized to about 40 bar and heated to the reaction temperature (200-300°C). The solids are separated and the liquid is flashed to separate water. The non-aqueous phase is further processed by heat treatment in a second stage reactor (around 500°C). Recovered from the first stage are a solid phase (minerals) and liquid phase (containing nitrogen), both possible to use for fertilizing purposes. From the second stage fuel gas, carbon and diesel oil are recovered. The fuel gas is used for the internal heat needs. The minerals, the liquid containing nitrogen, the carbon and the diesel oil are all marketable products, but in this preliminary environmental evaluation only the oil has been considered. The oil is dominated by straight hydrocarbons with a chain length between 15 and 20, in the shorter range of conventional diesel oil [Roberts *et al*, 2004]

LIFE CYCLE MODEL OF THE CARTHAGE PLANT

Two benefits of using hydrothermal conversion of food industry waste can be identified immediately: fewer odors from open processing and transport of non-processed organic waste and sterilized process outputs minimizing risks for spreading of pathogens. Here, however, the focus is on the environmental systems performance in terms of impact on global warming, acidification and photo oxidant creation from the generation of synthetic diesel oil from a renewable feed stock.

In striving towards increased eco-efficiency in society, it is widely recognized that an activity must bear the burden not only of direct emissions from the activity but also from all directly and indirectly related activities brought on by its existence. This ‘life cycle thinking’ has stimulated the development of tools to study the total life cycle environmental impact of products or services. Life cycle assessment (LCA) is a structured way to calculate and evaluate, quantitatively, the environmental load caused by a product or a service during all phases of its life cycle; the environmental impact from “cradle to grave”. In an LCA, extraction and transports of raw materials, upgrading of raw materials, actual production and use of the product, necessary energy requirements and transformations, waste collection and treatment, etc., are studied in order to determine the total life cycle impact.

In this study, a life cycle approach has been used for a preliminary evaluation of the hydrothermal process in Carthage, Missouri as waste handling method for food industry organic wastes. An overview of the systems model is given in Figure 2. The activities are briefly described below.

The CWT TP Carthage box in Figure 2 describes the entire conversion plant and is modeled based on data from the process simulations use to design the plant, as given by Roberts *et al* [2004] and Adams *et al* [2004]. Feedstock inflows per day to the process are 191 metric tonnes of wet turkey offal, 3.0 tonnes of sulfuric acid and 91.2 MJ of grid electricity. Product outflows per day from the process are 2506 GJ diesel oil, 274 GJ fuel gas, 30.6 tonnes liquid nitrogen fertilizer, 7.5 tonnes mineral fertilizer, 6.1 tonnes carbon and 79.9 m^3 waste water. Of the outflows the use of the two fertilizer products and the carbon have not been followed downstream further than transport of the products from the plant.

Sulfuric acid is assumed to be produced from a mix of mined virgin sulfur (60%) and sulfur from desulphurization of oil at refineries (40%) [Greshick *et al*, 1998]. The latter form of sulfur has been considered a residual product, and no environmental impacts from the crude oil processing have been included. Sulfuric acid production is an exothermic process, creating surplus heat. No beneficial use of this heat has been included. The grid electricity from the local utility used by the Carthage plant are generated from coal and nuclear plants; around 96% from coal condensing power and around 4% from nuclear power [Adams, 2004]. The environmental impact has been described under the assumption of a 9% grid loss [Frees *et al*, 1998; Brännström-Norberg *et al*, 1996].

The fuel gas produced is a mixture of methane, carbon monoxide, carbon dioxide and low molecular-weight hydrocarbons. The fuel gas is used internally, covering the heat need of the hydrothermal process. The plant is predicted to generate a surplus of fuel gas, but here all gas is assumed to be used internally. Again this can be seen as a worst case scenario. The combustion of the fuel gas has been described by emission factors for combustion of LPG [Corinair, 1996], but the carbon dioxide produced is regarded as of biologic and not fossil origin.

In more conventional turkey processing waste treatment, the turkey offal is subjected to dehydration and fat removal to transform it into meat and bone meal, which is then used as animal feed. This process is known as rendering. Our study has been expanded to take into account this process that now is avoided by instead using CWT hydrothermal conversion. The model system is also expanded to include the animal feed production that is necessary to make up for the meat and bone meal that no longer is produced. The avoided rendering process is described according to UNEP [2000] and Nielsen [2003]. The animal feed that now is necessary to produce by other means is assumed to be based on soybeans, which gives a similar protein contents in the feed. The feed production process is described according to Hospido *et al* [2003] and Nielsen [2003b]. For the agricultural production of the necessary soybeans, average data for fertilizer and fuel use in seven states in the US have been used [Kim and Dale, 2004]. It could be argued that there should not be any system expansion for animal feed production, e.g. if meat food processing waste by reasons of food safety precautions should be phased out anyway, but in this study we have chosen to include these activities.

The outflows of fertilizers and carbon represent useful and marketable products. However, no system expansion has been made to take into account the benefits from these products. Transport of these products to use has been included as a 250 km transport with a light truck (tailpipe emissions [NTM, 1998] and environmental impacts from diesel oil production [Frischkknecht *et al,* 1994] have been included).

The waste water is sent to a municipal waste water treatment plant. The environmental impacts from the waste water treatment have in this screening evaluation been described with an approximate electricity use for waste water treatment, based on Dennison *et al* [1998]. No other impacts from waste water treatment have been accounted for.

The thermal conversion diesel oil acts as a drop-in substitute for conventional diesel oil. In the model this flow is used to generate the avoided emissions from production of an equivalent amount of conventional diesel oil production based on energy content as well as the carbon dioxide emissions that are avoided when diesel derived from a renewable source is used compared to fossil diesel [Frischkknecht *et al,* 1994]. This serves to give an understanding of the magnitude of the environmental impacts caused by hydrothermal conversion of the turkey wastes. Furthermore, the diesel oil produced from the hydrothermal conversion process has a composition that might give a cleaner combustion compared to conventional diesel oil, since the slightly shorter chain length of the hydrocarbons can be assumed to give less particle formation, but no such beneficial effects have been included in the present study.

RESULTS AND DISCUSSION

The summarized emissions from the activities described in the environmental systems model have been characterized into global warming potential, acidification potential and photo oxidant creation potential [Hauschild and Wenzel, 1998].

In Figure 3 the modeled impact on global warming from processing of one wet tonne of turkey offal is given in kg of carbon dioxide equivalents. The production of the electricity used in the process is clearly of importance, and it would be beneficial to investigate if it is possible to further optimize the process to lower the electricity use. The second largest impact occurs from the agricultural production of soybeans as alternative to the animal feed no longer produced from the turkey offal. The global warming impact from the model of the agricultural production of soybeans originates to a large extent from the production and use of nitrogen fertilizer. In Figure 3 the impact from each activity is divided into the species of emissions generating the global warming potential. The main species contributing to global warming are carbon dioxide and, for the soybean production, nitrous oxide. The nitrous oxide is generated partly in the production of the nitrogen fertilizer and partly from soil microbial transformation of added fertilizer nitrogen (1.5% of added nitrogen is transformed into nitrous oxide [Kim and Dale, 2004]). The result indicates that if crops are grown specifically for use in biorefineries it will be important to optimize the environmental performance of the feed generation; it is not enough to rely on a renewable feedstock, renewable resources must also be managed in a sustainable manner.

Figure 4 gives the results for global warming impact when also taking into account the avoided conventional diesel production and the fossil carbon dioxide emissions which are avoided by displacing conventional diesel with non-fossil diesel. The avoided impacts from these processes are clearly dominating the picture.

In Figure 5 the acidification potential for the investigated system is shown, and the outcome is similar to that of the global warming characterization.

In Figure 6 the photo oxidant creation potential for the investigated system is shown. The outcome is totally dominated by the emissions of volatile organic compounds avoided from conventional diesel production (extraction and refining). The animal feed production gives an impact, mainly connected to diesel use in agricultural production of soybeans.

The outflows from the hydrothermal process are sterile. The process conditions are such that even relatively heat-stabile infectious materials like prions can be expected to be destroyed [Casolari, 1998]. This is a beneficial outcome that is not covered by characterizations into global warming, acidification and photo oxidant creation potentials. The production of other useful materials, fertilizers and carbon, can be compared in terms of global warming and acidification potentials but this part of the system has not yet been studied.

The environmental impacts from generating the turkey offal have not been included in the study, but allocated to the production of turkey food items. Thus, the results from this study does not implicate that increased poultry production is a good way to generate all diesel needed in society, but that hydrothermal conversion as a way to handle waste from food processing industry comes out positively in this screening life cycle assessment.

The environmental systems performance of hydrothermal conversion of organic waste should be studied further to describe the system in detail, to refine the description of animal feed production and to include the fertilizer and carbon by-products in the investigated system. In future work more environmental impact categories should be investigated to get a more detailed understanding of benefits and drawbacks of the process.

CONCLUSIONS

The importance of evaluating environmental performance for new and proposed processes from a systems perspective has been emphasized. This is particularly relevant to processes that have significant feedstock and energy requirements where large impacts may occur from processes outside the boundaries of the chemical process plant itself. The use of combinations of hydrothermal processes seems to have a role in future biorefineries. In this screening life cycle assessment study hydrothermal conversion of turkey offal into diesel oil comes out beneficial regarding global warming potential, acidification potential and photo oxidant creation potential. When considering biomass as a renewable feedstock for a more sustainable chemical industry it is important to also environmentally optimize biomass production and agricultural processes. For a total evaluation of the CWT hydrothermal system further refinements are needed to describe the utilization of all products.

ACKNOWLEDGEMENT

We would like to thank Terry Adams and Brian Appel of Changing World Technologies, Inc., for sharing information on the Carthage plant and for the many open discussions during the project. We also gratefully acknowledge economic support for this study from the Knut and Alice Wallenberg foundation, the Society for Energy and Environmental Research (SEER) and from the US Department of Energy (DOE) under the award DE-FG36-04GO14268. Economic support does not constitute an endorsement by the DOE or any of the other funding agencies of the views expressed in this research paper.

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FIGURES

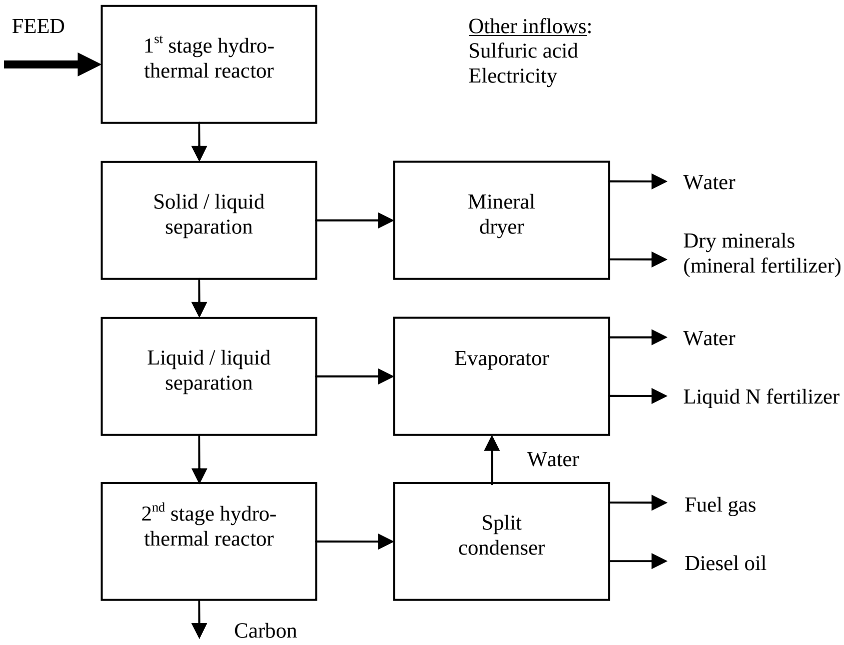

FIGURE 1 – OUTLINE OF THE HYDROTHERMAL CONVERSION PROCESSING OF TURKEY OFFAL INTO DIESEL OIL, ADAPTED FROM ROBERTS *ET AL* [2004].

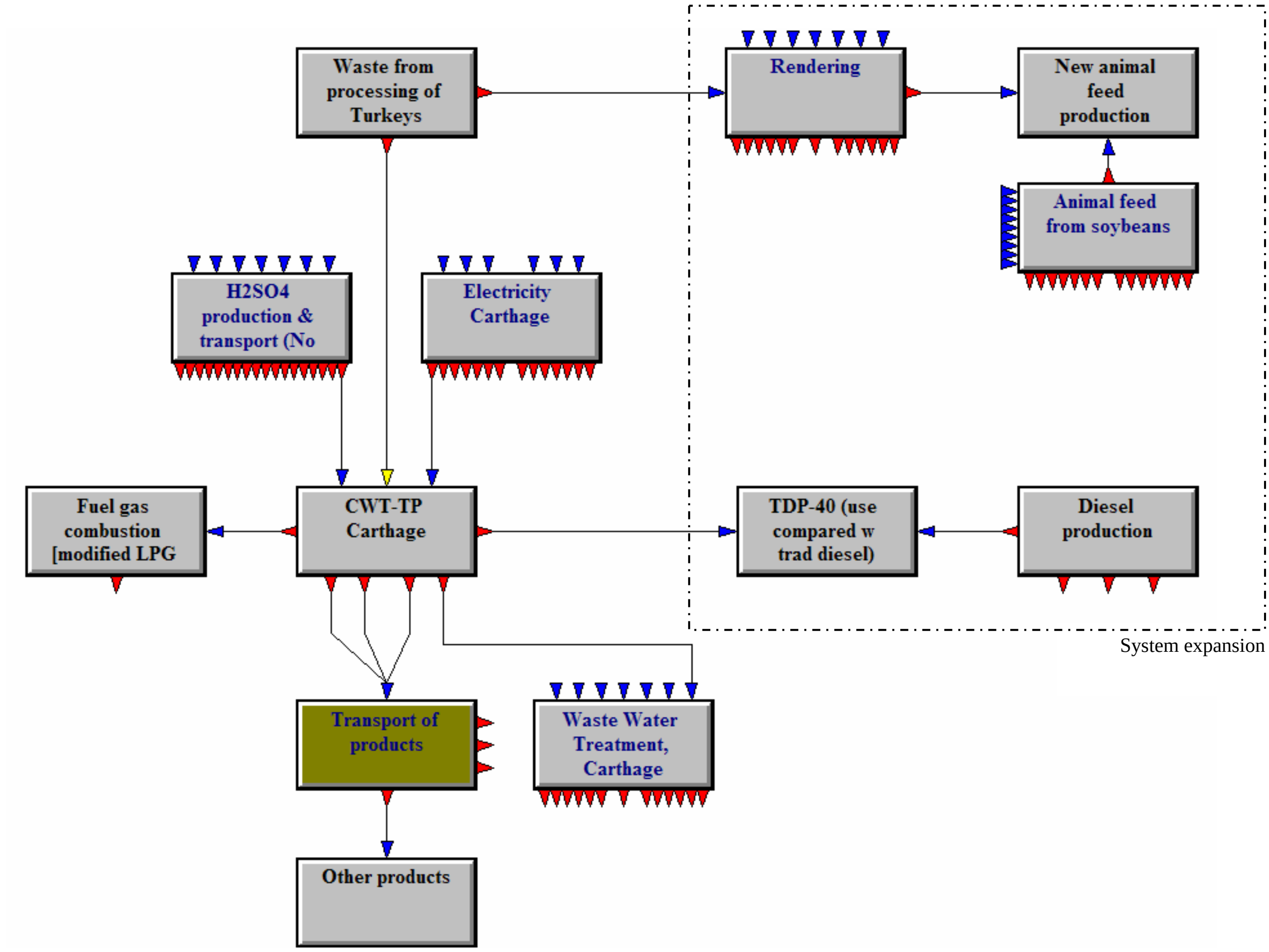

FIGURE 2 – ACTIVITIES IN THE ENVIRONMENTAL SYSTEMS STUDY OF THE HYDROTHERMAL PROCESSING OF TURKEY OFFAL INTO DIESEL OIL (SEE TEXT FOR DETAILS)

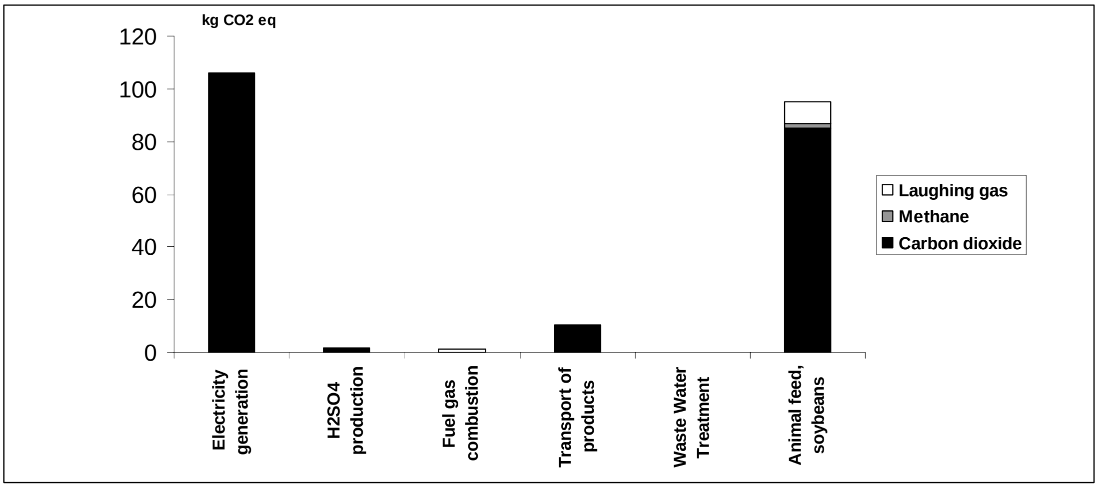

FIGURE 3 – GLOBAL WARMING POTENTIAL FOR ACTIVITIES CAUSED BY THE TURKEY WASTE PROCESSING. THE INDIRECTLY CAUSED AGRICULTURAL PRODUCTION OF SOYBEAN ANIMAL FEED HAS A LARGE IMPACT, MAINLY CONNECTED TO THE PRODUCTION AND USE OF NITROGEN ARTIFICIAL FERTILIZER. [KG CARBON DIOXIDE EQUIVALENTS PER WET OF TURKEY WASTE]

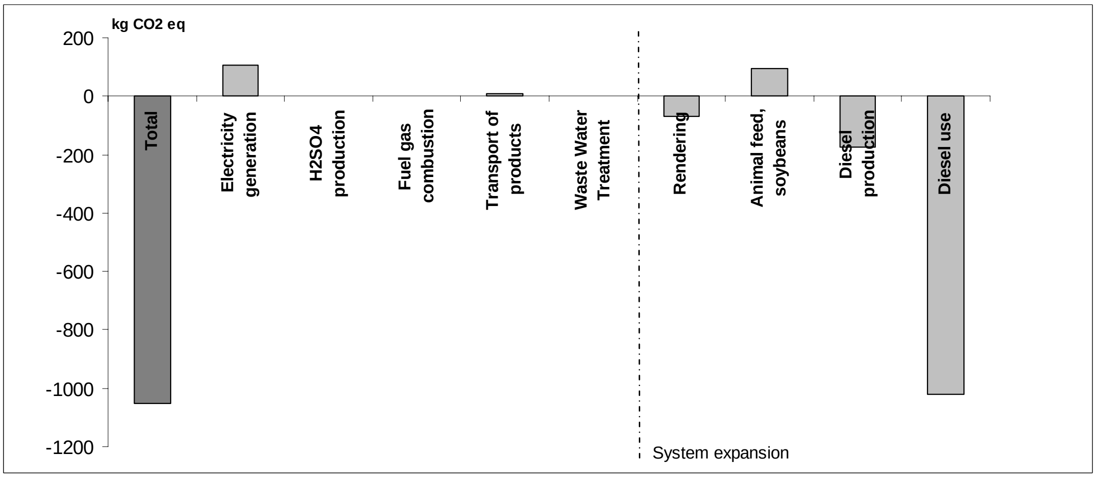

FIGURE 4 – GLOBAL WARMING POTENTIAL FOR ACTIVITIES IN THE SYSTEM INCLUDING AVOIDED RENDERING AND AVOIDED PRODUCTION AND USE OF CONVENTIONAL DIESEL TO AN EQVIVALENT AMOUNT. PROCESSES THAT ARE AVOIDED GENERATE NEGATIVE BARS. [KG CARBON DIOXIDE EQUIVALENTS PER WET OF TURKEY WASTE].

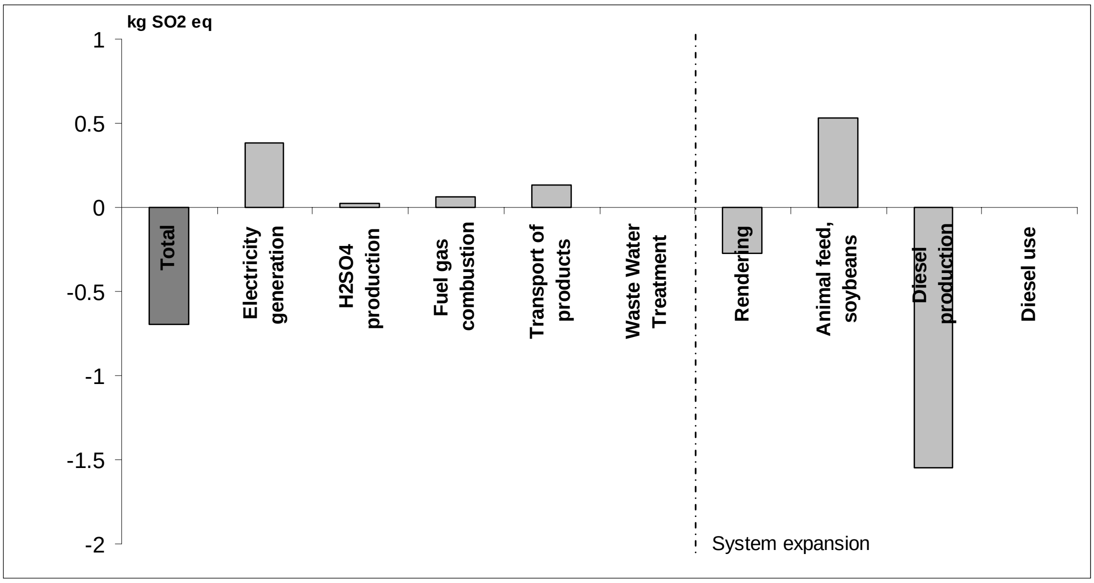

FIGURE 5 – ACIDIFICATION POTENTIAL FOR ACTIVITIES IN THE SYSTEM INCLUDING AVOIDED PRODUCTION OF CONVENTIONAL DIESEL TO AN EQVIVALENT AMOUNT (NEGATIVE BAR). THERE IS NO PREDICTED CHANGE IN ACIDIFYING EMISSIONS FROM USE OF THE DIESEL, AND THUS NO BAR SHOWS. [KG SULFUR DIOXIDE EQUIVALENTS PER WET TON OF TURKEY WASTE]

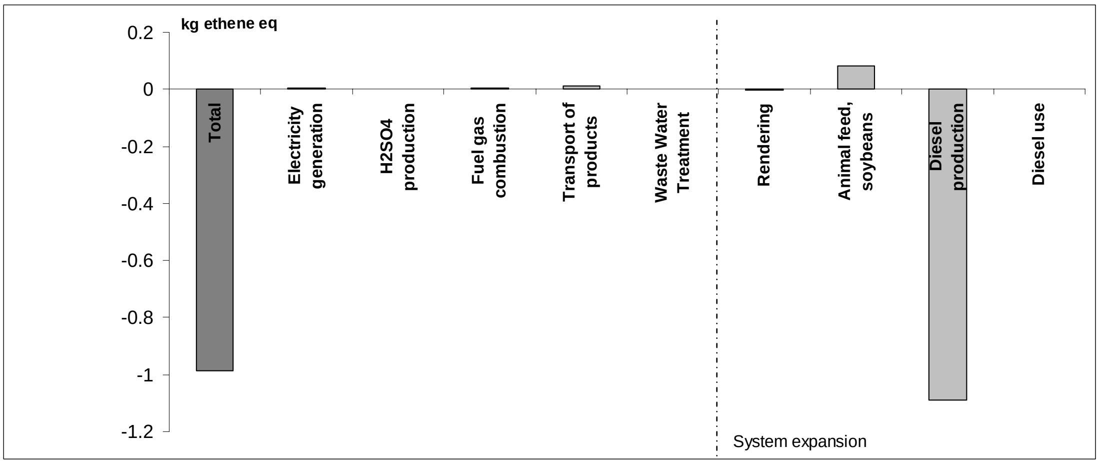

FIGURE 6 – PHOTOOXIDANT CREATION POTENTIAL FOR ACTIVITIES IN THE SYSTEM INCLUDING AVOIDED PRODUCTION OF CONVENTIONAL DIESEL TO AN EQVIVALENT AMOUNT (NEGATIVE BAR). THERE IS NO PREDICTED CHANGE IN EMISSIONS CONTRIBUTING TO PHOTOOXIDANT CREATION POTENTIAL FROM USE OF THE DIESEL, AND THUS NO BAR SHOWS. [KG ETHENE EQUIVALENTS PER WET TON OF TURKEY WASTE]