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Recycling Flexible Polyurethane Foam via Chemical Recovery versus Incineration for Energy: A Comparison of Environmental and Economic Impacts

Thomas W McKay

A Thesis in the Field of Sustainability and Environmental Management in Partial Fulfillment of the Requirements for a Master of Liberal Arts (ALM) Degree in Extension Studies

Harvard University

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Abstract

Over five million metric tons (11 billion pounds) of flexible polyurethane foam were consumed in 2015 globally and continues to increase significantly year over year (Grand View Market Research, 2016). The primary modes of managing the polyurethane foam waste stream are down-cycling for use as carpet underlayment and fillers, as fuel for incineration, and landfilling. All of these methods devalue this material significantly and are not environmentally sustainable solutions.

Chemical recycling of polyurethane foams is an alternative not normally considered. Research on the economic and environmental impacts of glycolysis, a chemical recycling option, has not been done on. Chemical recycling approaches a closed loop supply scenario where some of the materials recovered from chemically decomposed foams are used to make foam again.

ISO 14044 Life Cycle Assessment Methodology was used to perform the comparative Life Cycle Assessment between glycolysis and incineration for energy of flexible polyurethane foam. GaBi modeling software was used as a source of Life Cycle Inventory data and to perform the Life Cycle Impact Assessment.

Model results show that in nearly every impact category, glycolysis when crude glycerol is used as a glycolysis agent resulted in lower environmental impacts when compared to incineration of the same foam at a Municipal Solid Waste to Energy facility. In the glycolysis process, two polyols were recovered that can be used to make additional foam. Electricity and steam were recovered in the incineration process. Multiple

scenarios were run for the glycolysis process which utilized different feedstock materials and multiple grades of recovered polyols because the burdens of these materials had the largest impacts on the LCA results by far.

The glycolysis process outperformed incineration economically as well. Glycolysis utilized relatively low-cost feed stocks like crude glycerol and the process recovered high value polyols which could be substituted for virgin polyols to manufacture foam again. Although incineration recovered energy in the form of electricity and steam, the value of these streams was relatively low, especially when compared to the operational cost of running an MSW incineration facility.

Acknowledgements

I'd like to thank Professors Gloria and Leighton whose guidance helped the development of an idea into something of value to me and hopefully others. My colleagues at BASF & thinkstep – Tom, Bruce, Irene and Manfred – who helped teach a novice the power of GaBi. To my parents, who are now gone, my thanks for giving me trust and freedom my entire life. And to my family – Bodie & Oshie (my faithful pups). My boys Patrick & Sean – everything I do, I do for you and I hope I lead by example. And finally, to my wife Laura who supported me without hesitation and had to endure a little whining and a lot of my time spent not only on this paper, but other educational endeavors. I'm done now!

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Chapter 1

Introduction

Plastic waste is recognized as a persistent and growing environmental issue. At the end of their life, nearly all plastics can be recycled or reprocessed in some way. However, one family of plastics, thermosets, are very difficult to recycle. Currently, the most common recycling option is mechanical down-cycling to create an inert filler or carpet underlayment foam. Other end of life options are incineration and landfilling. All of these methods devalue the material significantly and are not viewed as sustainable. Comprehensive evaluations of environmental impacts and economics have not been done on alternate methods for managing the end of life for these thermoset plastics.

Polyurethane foams (PUF) fall into this thermoset class of material. Although some of this material is down-cycled as fillers and carpet underlayment, much is incinerated or landfilled. However, landfills across the globe are starting to limit or refuse foam. California, Rhode Island and Connecticut have enacted laws requiring that mattresses be recycled (Mattress Recycling Council, 2107). Government regulations in Europe are being implemented which prohibit landfilling of PUF (Yang, et al, 2012). This research project compared the environmental and economic impacts of recycling flexible polyurethane foams (fPUF) via chemical recycling, a high value option, versus incineration to generate electricity and steam at a Municipal Solid Waste (MSW) "Waste to Energy" site.

Research Significance and Goals

End of life options for fPUF are limited due to the nature of their chemistry and the default position in industry to incinerate or landfill. The European Isocyanate Producers Association (ISOPA), in a summary paper outlining the handling of automotive fPUF waste, explicitly states the best option is via incineration (ISOPA, n.d.). The basis of these decisions is typically perceived cost and environmental impacts coupled with what is easiest to manage in the supply chain. No analysis has been done to quantify and compare the environmental impacts for all options of managing this waste material. Similarly, the economics of incinerating high value fPUF for energy versus recovering higher value chemical components have not been studied. MSW incineration in the United States has stagnated in recent years because of the cost associated with building facilities (Michaels, T., Shiang, I., 2016).

As a result, those managing end of life dispositions for this material don't have the information they need to make decisions which have the lowest environmental impact and/or the highest economic value. Given the enormous quantities of fPUF foam used globally, there is a huge opportunity to reduce our impacts to the environment, maximize the value of what is today considered a waste stream and support the concept of a circular economy.

The objectives of this research are to:

- Gain a better understanding of the environmental impacts for glycolysis and incineration for energy recovery of fPUF
- Provide information which will guide companies and the market on which end of life options for fPUF offer the lowest environmental impact in categories defined by TRACI 2.1

- Define what role chemical recycling of a waste product like fPUF has in supporting the concept of a circular economy
- Gain an understanding of the costs and recovered value for glycolysis and incineration for energy of PUF to aid in investment evaluations and the magnitude of incentives, if needed, that can be used to promote high value, low impact recycling of PUF

Background

Polyurethanes (PU) have existed since the 1940's and have evolved into one of the most important family of chemicals and plastics used in modern society. Their range of application is unmatched as they are used to make products such as bowling balls, high efficiency foam insulation, dash boards for automobiles and mattresses. The estimated global annual production of all polyurethane chemicals in 2005 was approximately 8.8 metric tons (19 billion pounds) (Zevenhoven, 2004). In a more recent study focusing on foams, Grand View Research (2016) estimated 9.5 million metric tons (20.9 billion pounds) of polyurethane foams were produced in 2015 and is expected to grow to 12.75 million metric tons (28.1 billion pounds) in 2024. They estimated that fPUF accounted for approximately 55% of this total (5.2 million metric tons).

PUF can be classified into two categories: flexible and rigid. Rigid foams (rPUF) are mainly used in insulating applications such a HVAC, refrigeration (commercial and residential) and buildings. Flexible foams are used in applications such as automotive seating and interior components, furniture, bedding (mattresses) and packaging (American Chemistry Council, 2017). Flexible foam was chosen as a focus for this

research versus rigid foams and other polyurethane types (elastomers, thermoplastic PU, coatings) because they are the best candidate for chemical recycling and the impacts are large due to the quantity of this type of foam produced every year. Another critical factor in choosing fPUF is that there is a large source of clean, valuable, post-industrial fPUF accessible. Approximately 20% of fPUF slab stock used in the furniture and bedding industry is wasted during the trimming process at the factory (Polyurethane Foam Association, 2003). As with any recycling process, the cleanliness and purity of feedstocks is critical to the recovery of high value materials. Recovering fPUF is also relatively easy to do versus rPUF. Removing rPUF from insulating panels used in buildings and in refrigeration units is a considerable hurdle to the financial viability of this option. Recovering fPUF from automobile seats, furniture and bedding, although not always easy, should have a lower cost.

Finally, there are market drivers in some regions which make flexible foam recovery critical. In Europe, there are laws for End of Life Vehicle (ELV) disposition. China, Korea, Japan and even Russia have laws mandating that certain components, or percentages of total vehicle weight, be recycled (Sakai, et al., 2014).

Thus, there is enough fPUF volume to create scale for recycling or material recovery - a requirement for economic success. There is legislation and consumer desire to recycle these materials. What is lacking is an understanding of environmental impacts and economics.

What is Flexible Polyurethane Foam?

The basic formulation of all polyurethane foams consists of four main components:

- Polyol/diol: major component consisting of minimally two reactive hydroxyl (OH) groups. This material has the highest value in the system and is the main material recovered during glycolysis. There are many types of polyols, each giving different properties in a polyurethane system, including determining whether the system will be a flexible or rigid foam.
- Isocyanate: major component, typically methylene diphenyl diisocyanate (MDI) or toluene diisocyanate (TDI), containing N=C=O reactive groups. These materials, before reacting with polyols, are considered hazardous and are under scrutiny by the US EPA and EU REACH. This material is not recoverable during glycolysis.
- Blowing Agent: a material that creates the cellular structure of a foam. Early versions were CFC's which had very high global warming potential (GWP) and Ozone Depletion Potential (ODP). Today, materials such as HFO's (hydrofluoro olefins), water and cyclopentane are used, all having a GWP of near 0.
- Additives: small quantities used to affect the processing of the foam and its final properties, such as flame retardants.

The basic reaction of all isocyanates is shown in Figure 1 (Wang, 2006). For foams, a blowing agent is used to create the cells and expand the foam.

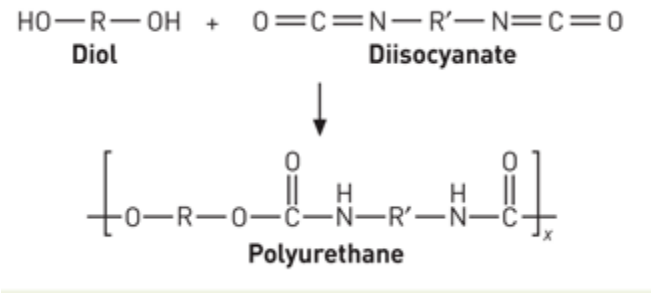

Figure 1. Basic reaction of a polyurethane.

Options for Managing Waste

Besides landfilling, there are three main pathways to manage PUF at the end of its useful life: (1) mechanical recycling, (2) chemical recycling and (3) incineration. Within each pathway, there are many options.

The American Chemistry Council (ACC) identifies four methods of mechanical recycling and four methods of chemical recycling (Table 1), while mentioning the possibility of incinerating PUF for energy, known as Waste to Energy (WtE) (ACC, 2017b).

Table 1. ACC list of mechanical and chemical recycling options.

Mechanical Recycling	**Chemical Recycling**
Rebonded Flexible Foam	Glycolysis
Regrind or Powdering	Hydrolysis
Adhesive Pressing/Particle Bonding	Pyrolysis
Compression Molding	Hydrogenation

Behrendt and Naber (2009) have compiled an overview of chemical recycling pathways that is more extensive than the ACC's. The identified pathways are (1) thermal decomposition (2) hydrolysis (3) alcoholysis (4) glycolysis (5) acidolysis (6) alkaline cleavage and (7) aminolysis.

Mechanical recycling typically requires the PUF to be cleaned, dried and ultimately pulverized or granulized into small particles for use as a filler in another product. Approximately 95% of carpet underlayment foam is made from recycled fPUF (ACC, 2017b).

Chemical recycling involves the breakdown of the PUF waste in a chemical process, using heat and/or other chemicals (usually a glycol). Typically, the majority of the material recovered is a polyol, or mixture of polyols, that can then be used to make another PUF. The type and quality of the recovered polyol will determine for which type of foam, rigid or flexible, it can be used. The closer the recovered polyol resembles a virgin polyol, the higher the value it will have after recovery.

The WtE process involves incinerating the PUF, typically in a Municipal Solid Waste stream, to create electricity and/or steam for local heating. This process displaces the use of typical fuels and processes for generating electricity and steam. PUF has a heat content of 25 Megajoules/kg, almost as much as coal at 29 Megajoules/Kg (ISOPA, 2001). This makes it an attractive material for incineration.

Mechanical recycling is not considered a viable end of life option because this method only delays the inevitability that the foam will end up in a landfill or will be incinerated.

In order to limit the scope of this analysis, the glycolysis method of chemical recycling and incineration for the purpose of generating electricity and steam were chosen for this study. Table 2 qualitatively outlines the performance of each recycling option relative to several key factors. Chemical recycling rates the highest in three of the five categories. It is rated lowest in the "Technology Status" category mainly because this process isn't used extensively in the market today. The technology to decompose fPUF via glycolysis has many different pathways, each giving varied results and recovered material properties. There are only two known companies performing glycolysis on a very limited scale in the world: Infichem Polymers, LLC and Getzner Mutter & Cie.

Table 2. Comparison of options for waste PUF.

Process	Value of recycled product	Support of Circular Economy	End of Life Supply Chain Status	Technology Status	Perceived Environmental Benefit
Mechanical Recycling	Low	Low	Exists	Developed	Low
Chemical Recycling	High	High	None	Less developed	High
Waste to Energy	Medium	Low	Exists	Developed	Medium

Previous LCAs on Polyurethane Foam

There are many cradle to grave LCAs that have been completed on PUF, mainly for rPUF in refrigeration, housing and building applications, where the PUF serves as an insulation material. Yang, et al. (2012) have looked at methods of recycling PUF, but

there was no analysis on the environmental impacts such as GHG, energy use or other traditional impact categories used in LCAs.

BASF Corporation's LCA (BASF, 2010) comparing multiple residential insulation methods showed that rPUF had 11% higher insulating properties than cellulose insulation and 21% more than fiberglass insulation relative to heating and cooling energy usage. In this study, the "use" phase of the insulation had the largest impact by far. The study assumed the end of life for the PUF was landfilling. Generally, this is the conclusion of most of these types of LCAs: the end of life impacts are small relative to the use phase of PUF. As a result, little work has been done to investigate alternative methods for managing this material at the end of its useful life.

Another Ecoefficiency Analysis (EEA) by BASF looked at the end of life of automotive fPUF seat cushions. Chemical recycling was not a consideration (Jenseit, Stahl, Wollny, & Wittlinger, 2003). In this analysis, mechanical recycling was the least favorable method while various recycling options, which include incineration, were viewed as the best.

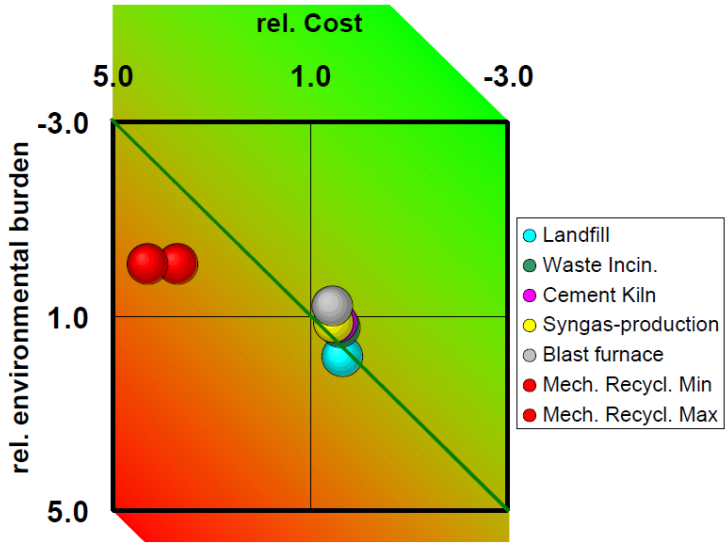

Figure 7.4 Eco-efficiency portfolio of seat cushions (polyurethane).

Figure 2. Eco-efficiency portfolio of seat cushions (polyurethane).

Figure 2 graphically shows the position of all options that were analyzed. The method closest to the upper right part in the figure has lowest relative environmental impact and lowest relative cost – the optimum solution. Mechanical recycling didn't perform well in cost and only slightly better than other methods in environmental impact. All the other methods performed similarly. Syngas production most closely resembles chemical recycling except that it is partially used for fuel and potentially the production of methanol. This method does not support closed loop re-processing.

Unlike glycolysis, the incineration of plastics, including polyurethane, is common. Industry tends to favor incineration while sustainability and environmental activists prefer other means of dealing with this waste.

Opponents to incineration most often argue that incineration removes the incentive and motivation for consumers to recycle, ultimately increasing the relative environmental burden. Incineration also has a much higher cost and relative

environmental impact per kWh generated compared to conventional electricity generation.

The capital costs to build an MSW facility with WtE capabilities varies widely in literature. A guide published by "GIZ" indicates that for European companies, the capital cost would be approximately $460,000 per ton processed per day (Deutsche Gesellschaft fur Internationale Zusammenarbeit GmbH ("GIZ"), 2017) while a publication by Ecocycle shows the cost to be $560,000 per ton processed per day (Ecocycle, 2011). The incineration of MSW, including any plastics such as PUF, comes with a very high initial capital cost.

The emissions from incineration relative to the typical grid mix are significantly worse. The Energy Justice Network (n.d.) summarized data, shown in Figures 3 – 5, from the EPA's 2010 eGRID database (EPA, 2010). The data shows that the amount of pollution per MWh derived from MSW incineration is by far the worst for some of the major emission compounds.

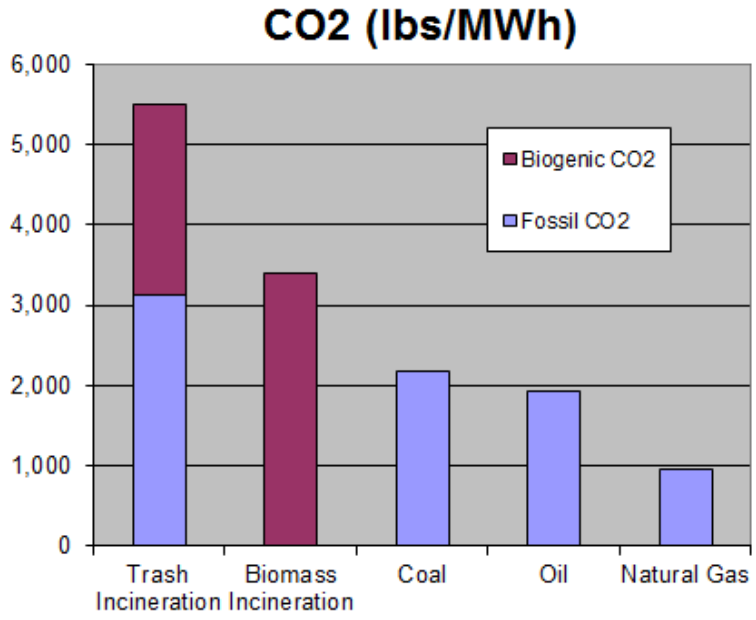

Figure 3. CO_2 emissions by generation method.

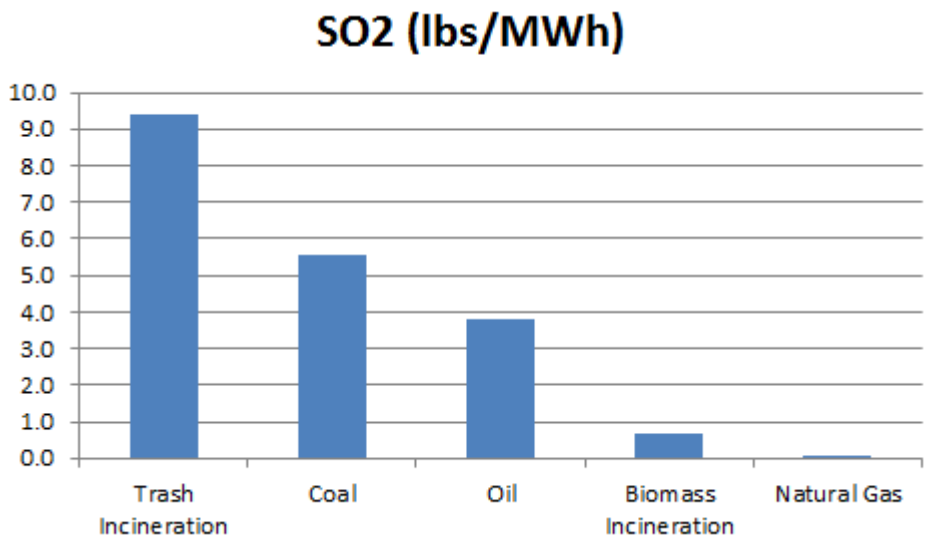

Figure 4. SO_2 emissions by generation type.

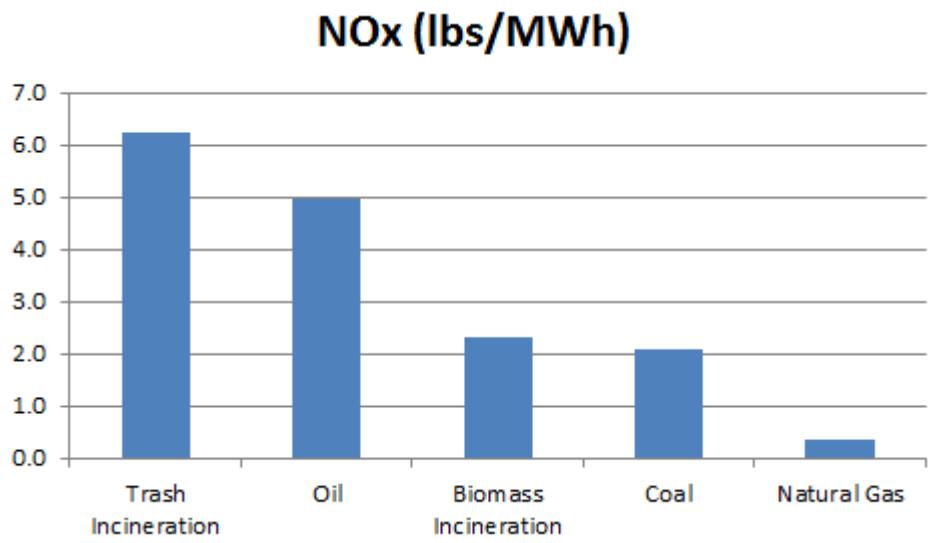

Figure 5. NO_x emissions by generation type.

The conclusion to be derived is that there is a significant body of work defining the total environmental and economic impact in the use of PUF, of which the end of life is a sub-segment of these analyses. There is also a lot of information on the mechanical and chemical processes used to recycle PUF. However, there is no body of work to

define, quantify and contrast the environmental impacts and costs of chemical recycling and incineration.

Research Questions and Hypothesis

There are two main hypotheses for this analysis:

1. Chemical recycling (glycolysis) of fPUF waste will have a lower environmental impact than the alternative of incineration to produce electricity in a Municipal Solid Waste stream. Impact categories utilized by TRACI 2.1 will be used.
    - Which environmental impact categories will glycolysis and incineration perform the best in?
    - Which inputs in the glycolysis process have the largest environmental impact?
2. The total net contribution margin of the glycolysis process will be higher than that of the incineration process.
    - Which step in each option has the largest cost impact?
    - Will incentives be required to make glycolysis an economically sustainable option to manage the end of life of fPUF?

Specific Aims

Significant work must go into collecting environmental and cost data on various chemical processes to give quantitative results for evaluation. The steps required are:

1. Define the reactants and processing conditions of the glycolysis reaction, along with the materials recovered. A literature search will be used to define the optimal synthesis path.

2. Perform a mass balance on the chosen synthesis path which will quantify the inputs, the final reaction products and all the resources such as heat, steam and electricity needed to carry out the reaction.
3. Define and quantify the Life Cycle Inventory for each material input, material output and other in-flows and out-flows in the process in typical terms such as GWP, emissions, ODP, etc. in the glycolysis process.
4. For the WtE option, the amount of energy the incineration of the PUF will generate will be quantified.
5. Perform an LCA analysis, utilizing a 3rd party software tool, on both methods (glycolysis and incineration) to provide a quantitative summary and evaluation of environmental impacts to identify the process with the lowest overall impact and identify impact categories where each option is weak and strong. Utilize a normalization and weighting scheme that is recognized in North America.
6. Define the costs associated with each method (glycolysis and WtE) along with the value of the recovered materials. This should include logistical costs, material costs and benefits (sales/reuse of by-products), processing and labor costs to provide a framework to analyze the cost of each option.

Methods

In order to perform a comparative LCA for managing fPUF waste, the actual processes used for glycolysis and for incineration were defined in detail. Once these processes were defined, GaBi LCA software was used to model the inputs, outputs, wastes and processing burdens for both end of life options for fPUF. ISO 14044:2006 principles and guidelines for analyzing and modeling the processes and results were used.

When performing the economic analysis, the inputs and outputs, including energy and materials used in each process along with the outputs generated, were utilized from the balance used for the LCA analysis. Research was done to quantify the costs or value of each process flow and indirect costs for energy and other processes and a net balance was calculated. A sensitivity analysis was done to define the range of net economical value each process has.

Glycolysis – Selection of Process for LCA Modeling

The scope of this research project did not include conducting lab experiments to determine the optimal glycolysis process. Instead, the optimal glycolysis process was determined though literature review and was modeled in the LCA analysis for comparison to incineration of the same fPUF waste.

The main inputs of the glycolysis process are:

- Glycolysis agent. Typically, a low molecular weight glycol like diethylene glycol (DEG), propylene glycol (PG), ethylene glycol (EG) or crude glycerol

- Catalyst. Typically, diethanolamine (DEA) or stannous octoate
- Flexible PU foam. The material is usually reduced in size to speed the reaction. It is assumed the same size foam particles are used for both the glycolysis and incineration processes.
- Process. Typically, heat and the ability mix the materials are all that is required for glycolysis. The mix ratio of foam to glycolysis agent is critical. Post reaction processes are used to separate and purify the polyols recovered from the reaction.

The main outputs from the process are dependent on the specific material inputs, but can generally be classified as:

- Flexible polyol. This polyol can be used to manufacture flexible foams
- Rigid polyol. This polyol can be used to manufacture rigid foams
- Waste water. From the liquid/liquid extraction and purification process. This is mainly water, but contains some organic and amine compounds

Glycolysis is a well-known process, with one of the first papers published on the topic from Ford Motor Company (Gerlock, J., Braslaw, J., Zinbo, M., 1984). The focus of Ford's research was finding viable options for recycling water blown fPUF foams used in automobiles. The results of this study are consistent with nearly all subsequent studies. The quality of the recovered material (polyol) was poor. It was a mixture of multiple chemical components and the molecular weights of the polyol had a large range. This severely limited the type and quality of foam it could be used to make. Additionally, the glycolysis agents, like DEG, are expensive and are required in large quantities.

Gerlock and team noted the tendency for the recovered material to separate at cold temperature. Further research shows a more effective process called "split-phase"

glycolysis which produces purer recovered polyols. These materials are more valuable as they are less limited in use to make another foam product.

A team of researchers at the University of Castilla – La Mancha (UCLM) in Ciudad Real, Spain conducted significant research on the glycolysis process. It is from this group of studies that I have selected the process which was used for this research paper.

A list of some of relevant published work by UCLM include:

- "Recovery of Polyols from Flexible Polyurethane Foam by "Split-Phase" Glycolysis with New Catalysts" (Molero, C., Lucas, A. de, Rodríguez, J.F., 2006)
- "Recovery of Polyols from Flexible Polyurethane Foam by "Split-Phase" Glycolysis: Glycol Influence" (Molero, C., Lucas, A. de, Rodríguez, J.F., 2006)
- "Purification by Liquid Extraction of Recovered Polyols" (Molero, C., Lucas, A. de, Rodríguez, J.F., 2006)
- "Recovery of Polyols from Flexible Polyurethane Foam by ''Split-Phase'' Glycolysis: Study on the Influence of Reaction Parameters" (Molero, C., Lucas, A. de, Rodríguez, J.F., 2008)
- "Valorization of Crude Glycerol as a Novel Transesterification Agent in the Glycolysis of Polyurethane Foam Waste" (Simon, D., Borreguero, A.M., Lucas, A. de, Rodríguez, J.F., 2015)
- "Glycolysis of High Resilience Flexible Polyurethane Foams Containing Polyurethane Dispersion Polyol" (Simon, D., Lucas, A. de, Rodríguez, J.F., Borreguero, A.M., 2016)

Each study sought to gather information and identify the optimal conditions, material and/or process which delivers the highest quality recovered polyols and the best economic value.

Ultimately, the process and conditions in the "Valorization of Crude Glycerol as a Novel Transesterification Agent…" (Simon, D., Borreguero, A.M., de Lucas, A., Rodriguez, J.F., 2015) was selected for this comparative LCA analysis. One of the reasons was that this study incorporated many of the optimal conditions determined from earlier studies. However, the most important factor in choosing this process was the use of crude glycerol as a glycolysis agent.

Crude glycerol has two key characteristics which make it critical to commercial implementation of glycolysis of fPUF. The first is its very low cost. Crude glycerol is a significant by-product, 10 to 11% by weight, in the production of bio-diesel (Thompson, J.C., He, B.B., 2016). Biodiesel capacity in North America, and globally, has increased substantially in the past 10 years in part due to high fuel prices in 2008 and 2009, but also due to recommendations to use some level of bio-content in diesel fuel in the United States.

As a result, bio-based crude glycerol flooded the market. Prices dropped significantly and many factories manufacturing synthetic glycerol, which is derived from fossil resources, were forced to close (Ciriminna, R., della Pina, C., Rossi, M., Pagliaro, M., 2014).

The second major factor is that the polyols recovered when crude glycerol is used were of much higher quality than DEG. DEG has been investigated extensively and was widely accepted as one of the best glycolysis agents. The team at UCLM found that there

are two molecular weight polyols generated in most glycolysis reactions. The upper phase is a relatively pure polyol. The bottom phase is typically excess glycolysis agent, some polyol and some impurities.

In the case of DEG (Simon, D., Borreguero, A.M., de Lucas, A., Rodriguez, J.F., 2015), the low molecular weight polyol generated during glycolysis is soluble in DEG and hence dissolves in the bottom phase. Its value is decreased as a result. There is also a large amount of DEG in the upper phase. This reduces the quality of the recovered polyol mixture and the foam that can be made from it.

When crude glycerol is used, there is a relatively large difference in polarity between it and the polyols generated in the process (Simon, D., Borreguero, A.M., de Lucas, A., Rodriguez, J.F., 2015). As a result, the high molecular weight polyol does not dissolve into the bottom phase at all while the low molecular weight polyol is dissolved at a very low level when compared to the DEG process. Additionally, the upper phase contains a relatively low amount of crude glycerol, increasing the purity of this material.

This means that the upper phase contains almost all of the high and low molecular weight polyols in a ratio similar to what is used to make viscoelastic foam. It therefore carries a much higher value than when other glycolysis agents are used. The bottom phase is mainly excess crude glycerol and can also be used to make rigid foam. An option not explored by the team at UCLM, nor considered in this research, is to recover the excess glycerol for reuse in the glycolysis process.

After the glycolysis reaction, the mixture is transferred to a decanting tank where the two phases are allowed to separate for a period of a few hours. The bottom phase is pulled from the decanter and can be used directly in rigid foams. The upper phase is

transferred to a liquid-liquid extraction vessel where a rinse with de-ionized water is performed (3 rinses in total) to remove impurities. The output from that process is waste water and a relatively pure polyol mixture which can then be used in flexible foams. Figure 6 depicts the process flow, equipment and mass balance used for the UCLM process

These recovered polyols, from both the upper and bottom phases, can replace virgin polyols that would be used to make foam.

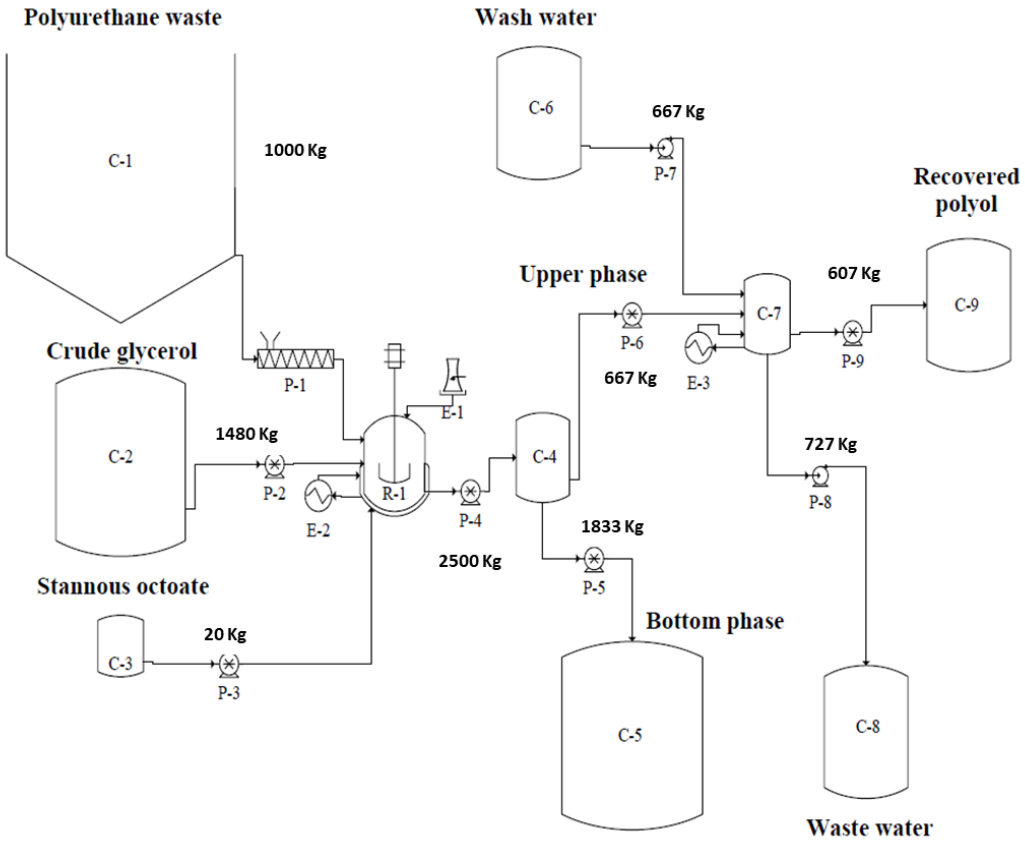

Figure 6: UCLM Glycolysis process for fPUF using crude glycerol (Simon, D., Borreguero, A.M., de Lucas, A., Rodriguez, J.F., 2015)

The feedstock materials used in the 1 liter and 10 liter reactors used by the UCLM team were a water blown viscoelastic foam based on a polyester polyol and Toluene Diisocyanate (TDI) from Interplast (V-50 190), 99% pure glycerol from Panreac, 80% crude glycerol (from biodiesel production) from Biocombustibles de Cuenca, S.A. and stannous octoate from Sigma Aldrich. The 99% pure glycerol was tested to determine if further purification of the crude glycerol would yield higher quality polyols.

Table 3 shows the content of the crude glycerol utilized in the work done by UCLM (A. Borreguero, personal communication, December 20, 2017).

Table 3: Crude glycerol composition used in UCLM research.

Component	Glycerol	Water	Salts	Free Fatty Acids	Gums	Biodiesel
% in Crude Glycerol by Weight	80 – 84	8-12	2-6	1-4	<.82	<.4

The ratio of glycerol to foam was 1.5:1.0. An excess of glycerol is required to achieve a split phase.

Experiments show that the reaction between the crude glycerol and the foam occurs very quickly and the residence time in the reactor is only a few minutes. Figure 7 shows that the concentration of the major components does not change after 10 minutes. The reaction is nearly instantaneous, meaning short processing times are required in the reactor. The short residence times needed in this glycolysis process mean the investment relative to throughput is relatively low.

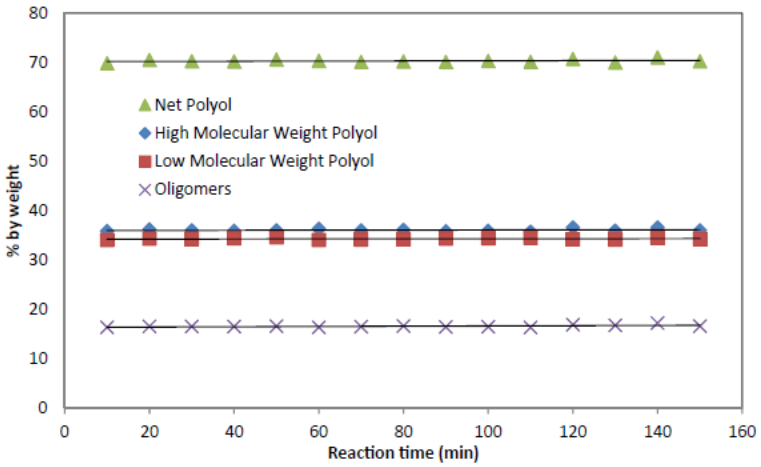

Figure 7. Concentration versus reaction time, UCLM process

The recovered polyols in the upper and bottom phases, using different glycolysis agents, showed the crude glycerol gave the best results.

Table 4. Upper phase recovered polyol molecular weight, various glycolysis agents

Upper phase 150 min	% by weight				
	High Mn polyol	Low Mn polyol	Net polyol	Ratio high Mn polyol/net polyol	Glycolysis agent
Diethylene glycol	51.92	9.39	61.31	0.85	11.75
Glycerol 99% PS	33.50	37.82	71.32	0.47	5.01
Crude glycerol	35.99	34.25	70.24	0.51	2.90

Table 5. Bottom phase recovered polyol molecular weight, various glycolysis agents

Bottom phase 150 min	% by weight	
	High Mn polyol	Low Mn polyol
Diethylene glycol	2.97	17.58
Glycerol 99% PS	0	1.74
Crude glycerol	0	1.76

Table 4 shows the high and low molecular weight polyols in the upper phase for 3 different glycolysis agents – diethylene glycol, 99% pure glycerol and crude glycerol. The highest possible polyol content and the lowest amount of glycolysis agent is desired. The crude glycerol performed well. It has nearly the same total polyol content but nearly

half the glycolysis agent as the 99% pure glycerol. Both glycerol agents were markedly better than the diethylene glycol.

Table 5 shows the quantity of high and low molecular weight polyols in the bottom phase. Ideally, there is no high molecular weight polyol in the bottom phase. Diethylene glycol was by far the worst performer of the three glycolysis agents. The crude glycerol and 99% pure glycerol performed nearly identical.

The data also shows there is not a significant difference in the quality of the recovered polyols when comparing 99% pure glycerol to crude glycerol. Therefore, this confirms that further purification of crude glycerol is not required.

The upper phase polyol mixture recovered from the crude glycerol process was blended with virgin flexible polyol at 12.5% (P87.5-R12.5) and 25.0% (P75-R25) and foam samples were made. The quality of foam was good up to 25% and thus the recovered polyol can substitute 25% of the virgin polyol in a viscoelastic fPUF. Table 6 show the formulation of the virgin flexible foam and the mix ratios tested.

Table 6. Upper phase foam formulations

Chemical	P100-R0	P87.5-R12.5	P75-R25
Raw polyol M_n 3500 (OH = 48)	100	87.5	75
Purified glycolysis upper phase (OH = 84)	0	12.5	25
Hydroxyl number polyol mixture	48	52.5	57
Water	4.60		
Tegoamin 33	0.10		
Niax A-1	0.05		
Silicone L-620 LV	1.40		
Sn Octoate	0.20		
TDI (80:20)	54.58	55.31	56.05
Isocyanate index	105		

The bottom phase consists mainly of excess crude glycerol. Rigid foam was made from this material in ratios with virgin polyol from 25% (P75-BP25) up to 100%

bottom phase (P0-BP100). The quality of the foam with up to 75% bottom phase was very good.

Table 7. Bottom phase foam formulations

Chemical	P100-BP0	P75-BP25	P50-BP50	P25-BP75	P0-BP100
Raw polyol M_n 555 (OH = 455)	100	75	50	25	0
Glycolysis bottom phase (OH = 759)	0	25	50	75	100
Hydroxyl number polyol mixture	455	531	607	683	759
Tegostab B-8404	1.5				
Water	2.5				
Tegoamin BDE	2.5				
PMDI	157.13	176.46	195.80	215.13	234.47
Isocyanate index	106				

Incineration Process – Municipal Solid Waste (MSW) and WtE

Over 256 million pounds of MSW is generated every year in the U.S. Of that, 33.1 million pounds is processed in WtE facilities (Environmental Protection Agency [EPA], 2016). The amount of MSW processed at WtE facilities has actually decreased slightly from 2000 according to the EPA's fact sheet.

Common household plastics, such as low-density polyethylene (LDPE), polypropylene (PP) and polyethylene (PE), are processed at MSW WtE facilities. These materials have high calorific value and are valued products for incineration as a result. fPUF has similar calorific values to these materials and thus are accepted at these facilities. The foam must be reduced to particles at the MSW facility or elsewhere before incineration.

A publication by the Energy Recovery Council (Energy Recovery Council, 2016) notes that there were 77 MSW WtE facilities in the U.S. in 2016. Of these, 60 are mass burn facilities, 14 are Refuse Derived Fuel (RDF) and the remaining 4 are "modular".

Mass burn facilities do little to no sorting or shredding of MSW, making them the least efficient option. RDF facilities separate out non-combustible materials and shred the combustible waste, making them a more efficient generator of energy relative to the Mass Burn process.

The same study shows that there are 3 types of "offtakes" – Electricity (59), Steam Export (3) and Combined Heat and Power (15). For this research, incineration of fPUF at a Combined Heat and Power facility is modeled. This is due to the fact that this process is already modeled in GaBi.

Sustainability advocates are generally opposed to incineration due to the fact it produces a low amount of electricity relative to the amount of waste burned as compared to traditional methods like coal and natural gas. The amount of pollution generated per mass incinerated is thus very relatively high as well. There is also fear that incineration will disincentivize the public to recycle not just foam, but other common plastics.

ISO 14044 Format Report

ISO 14044:20061 methodology was used to conduct the comparative LCA for the end of life options, glycolysis or incineration for energy, of flexible polyurethane foam.

Function and Functional Unit

This study is a gate to gate LCA and economic analysis of handling waste flexible polyurethane foam via glycolysis or incineration for energy recovery. The Functional Unit is 1000kg of waste foam to be processed. The LCI for the same foam was used in both models.

System Boundary

The boundary for the glycolysis process is defined based on the process developed by UCLM. All known inputs and outputs identified in their process have been included, noting that the research was done at lab scale, one liter scaled up to a ten-liter reactor and not in a large-scale manufacturing process. No known inputs, outputs or processes were omitted.

Because this is a comparative study, identical processes preceding and following the boundary of research are excluded.

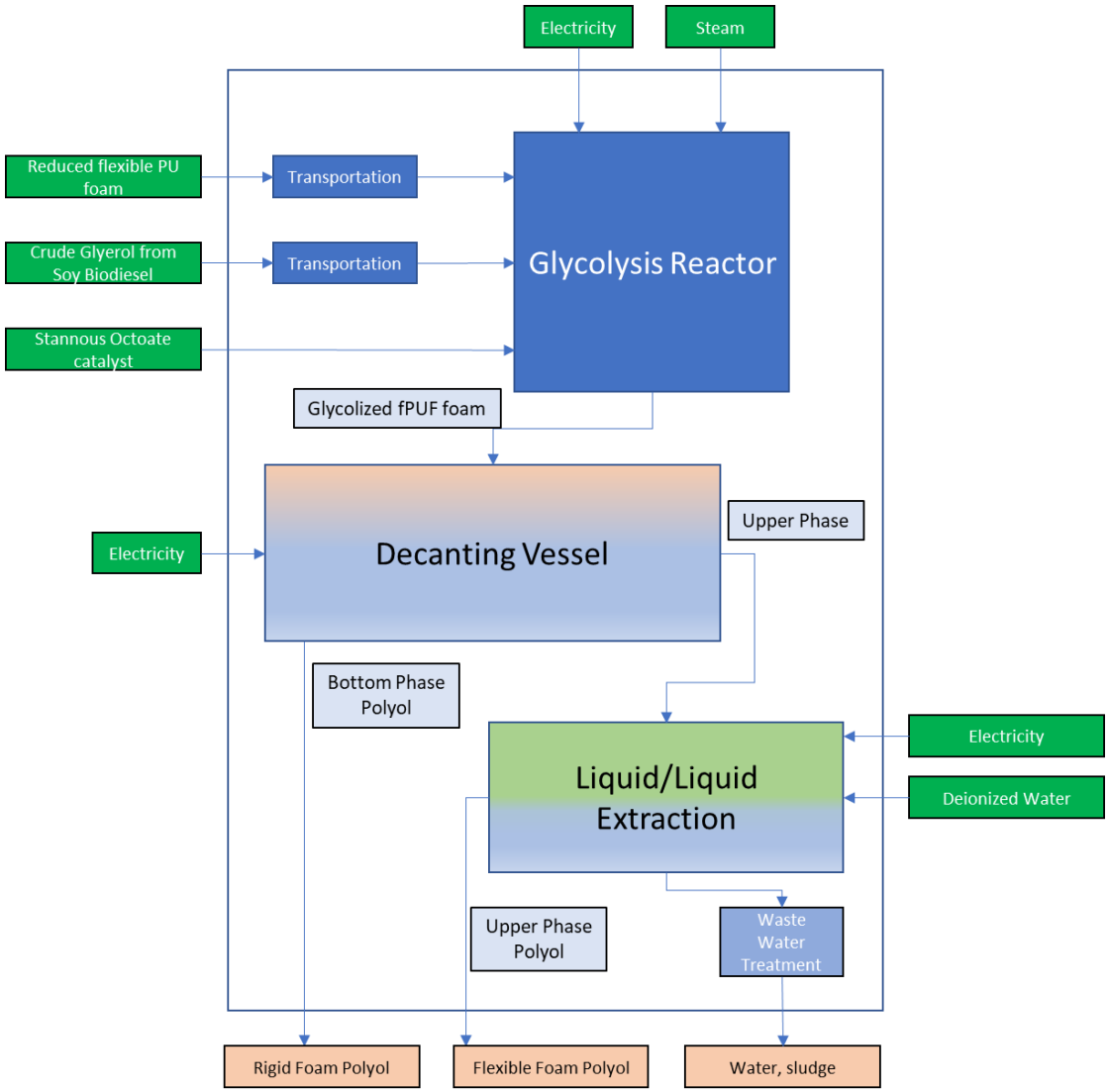

Figure 8. LCA boundary diagram for the glycolysis process

The three main processes used in the study are included.

- Glycolysis reaction where the transesterification reaction occurs between the fPUF and the crude glycerol occurs under agitation and heat (180°C). Small amounts (.8% by weight) of the catalyst stannous octoate are required in this step. Especially due to the fact there is a significantly higher amount of crude glycerol than is stoichiometrically required for the reaction, it is assumed there are no waste products and the foam is 100% converted.

    - Steam and electricity are required to heat the crude glycerol, agitated the material and ultimately pump out the vessel. Credits for heat generated by the exothermic reaction are not being taken.
    - Emissions are assumed to be negligible if the vessel is sealed.
- Decanting is where separation of the bottom and top phases occurs. Energy is required to evacuate the top and bottom phases after separation. No significant air, water or solid emissions or wastes are generated at this step.
- Liquid-Liquid Extraction is done with deionized water. Three equal rinses are done to remove impurities from the upper phase. Electricity is necessary to mix the contents and evacuate the vessel. Waste water is generated and the model includes treatment of this waste water.
- Inputs
    - Crude glycerol as a by-product from the production of soy-based bio-diesel. A plan existed in GaBi for the soy biodiesel process and was used in this model
    - Flexible polyurethane foam is assumed to be already pulverized and ready to be fed into the reactor.

The boundary diagram for WtE is below. This is a very simple process as there is only one unit operation – the incineration of the foam in the MSW mix.

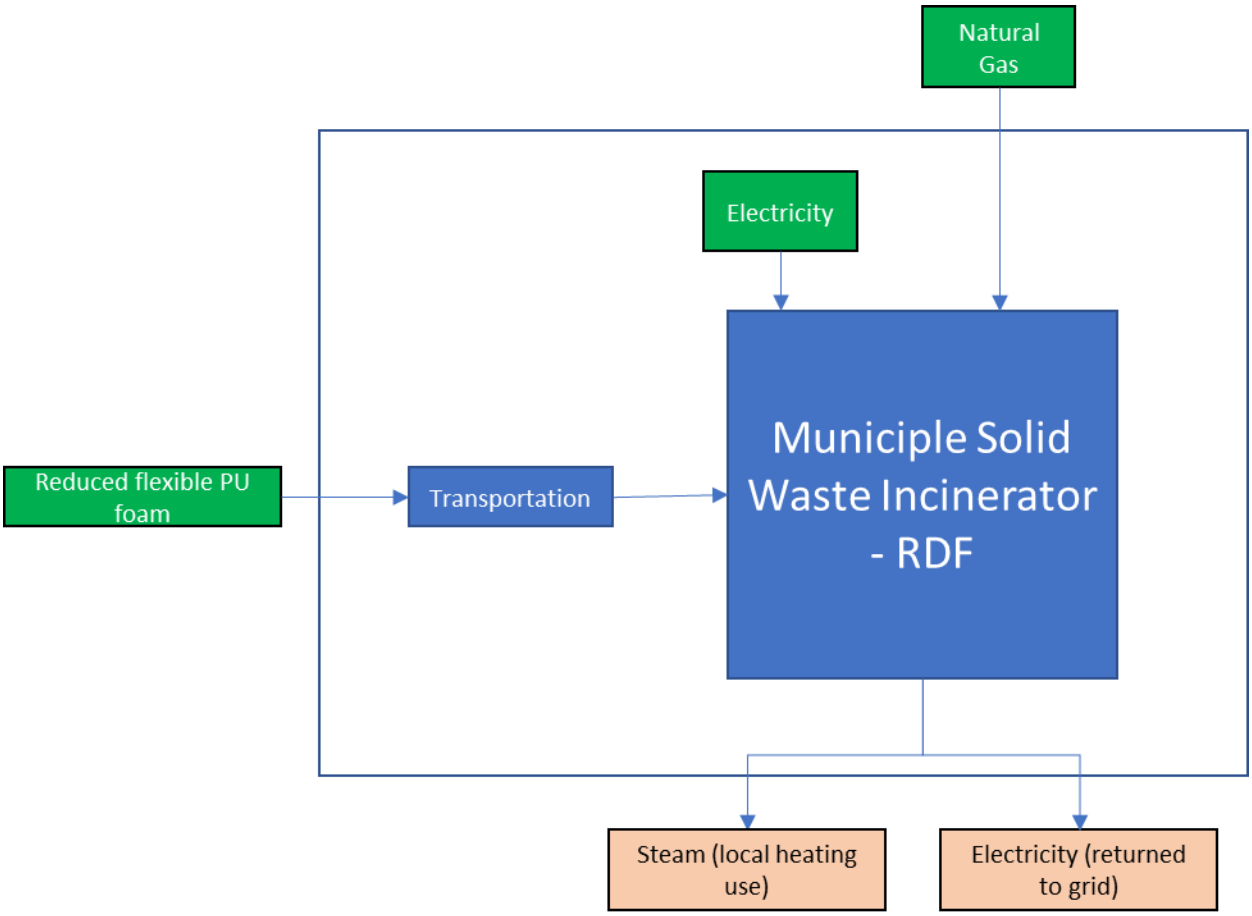

Figure 9. LCA boundary diagram for the MSW incineration process

Inputs and energy use for each end of life option utilized the same Life Cycle Inventory. Trucking, fuel, electrical energy and the fPUF foam all utilized the same LCI profile in GaBi for both options.

Data Sources, Quality and LCI

Data utilized for this study almost exclusively comes from the LCI databases contained in GaBi. With the exception of the processes to make Stannous Octoate, perform the glycolysis reaction and decant and extract the polyols, all processes and plans used within GaBi were existing and used as proxies for the materials used by UCLM in developing their glycolysis process.

A review of each plan and process used within GaBi is below.

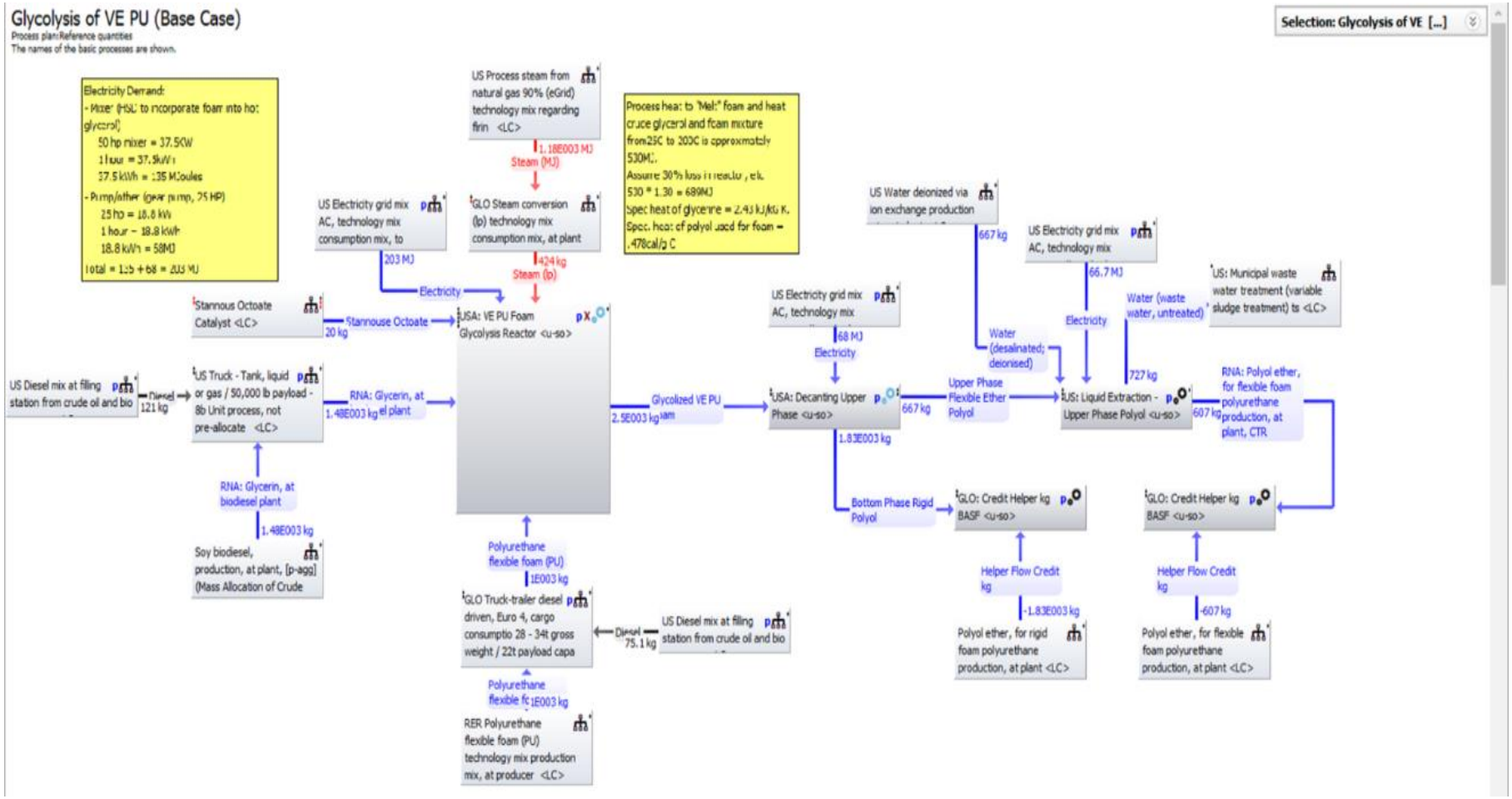

Figure 10. Glycolysis process model in GaBi

Table 8. GaBi glycolysis process/plan description

Description	Source	Inputs/Outputs	Comments
Soy Biodiesel	LCI/NREL	Inputs – Electricity, methanol, natural gas, NaOH, raw soy oil, transport. Outputs – Biodiesel, crude glycerol, fatty acids	No reference year given Cradle to gate, 95% of I/O's covered Mass allocation used in database within GaBi between biodiesel and crude glycerol. Allocation based on calorific value and market price done in scenario analysis
Transport of crude glycerol	GaBi	Diesel fuel & cargo (crude glycerol)	Parameters – distance (2000 miles), utilization ratio (.6 – assumes an empty backhaul). Reference years 2017 – 2020. US Based, US EPA references for emissions. 99% by mass included
PU flexible foam (version 2014)	Plastic Europe		Cradle to gate based on industry consortium data Reference years: 2005 – 2012
Foam Transport	GaBi – Global	Diesel fuel, cargo	Parameters – 2000 miles, 13.8kt payload. Reference years: 2017 – 2020 Cut-off rules: 95% of mass & energy, 98% of environmental impacts
Stannous Octoate	T. McKay	Tin Oxide, 2-ethylhexanoic acid, stannous octoate	Plan created from sub-plans of reactants Tin Oxide & 2-ethylhexanoic acid. Plan includes burdens of these plans, but no process energy, emissions and waste.

			Goal was to carry burden of materials into LCA, but material is used at .8% of total input materials Quality would be considered low Reference year for Tin is 1996 – 2003, Ecoinvent LCI. BASF Europe LCI used for 2-ethylhexanoic acid
Decanting Process	T. McKay	Glycolized foam, upper and lower phase polyols	Plan created based on process defined by UCLM process Utility demand is a pump @68MJ Bottom phase is polyol usable as is in rigid PU foam w/o further processing Upper phase requires further purification in next step
Polyether polyol	USLCI, GaBi	Bottom phase (credit taken to replace virgin rigid polyol)	Reference year 2003 Limited number of rigid PU foam plans or processes. Alternate foam substituted
Liquid-liquid extraction	T. McKay	Upper phase from decanting, waste water, deionized water, polyether polyol for flexible foam	Plan created based on process defined by UCLM process Power requirements for low horsepower mixer, pump = 68MJ Recovered polyol substitutes virgin polyol for flexible foam
DI Water	GaBi, US based	Water, HCl, NaOH, DI Water	Ion exchange process Reference years: 2017 – 2020 95% of mass and energy covered. 98% of environmental burden

Waste Water	GaBi, US based	Waste water, sludge as fertilizer (60%), sludge landfilled (18%), sludge incinerated (22%), purified water	Reference years: 2017 – 2020 Can be used for low contaminated industrial waste & municipal waste. No credit taken for taken for clean water generated.
Polyester polyol – flexible	GaBi, USLCI	Recovered flexible polyol (credit taken)	Reference dates: 2003 - ? Alternate Polyol substituted as part of scenario modeling
Lupranol 2090	BASF, DE/EU based	Glycerin, propylene oxide (PO), ethylene oxide (EO), potassium hydroxide (KOH), steam, etc.	Alternative flexible polyol for scenario modeling Reference years 2014 – 2014. Verbundsimulator data, emissions from Boustead dataset 6797.
Pluracol SG470	BASF, US based	PO, sucrose, glycerin, dimethyl, ethanolamine (DMEOA)	Alternate rigid polyol for scenario modeling Reference year: 2009
Alternate foam source	GaBi, Europur		TDI/polyether flexible foam, 35 – 40 kg/m3, no flame retardant, water blown Reference years: 2013 – 2023
Alternate glycerin source	GaBi, US Based	Epichlorohydrin, NaOH, Na_2CO_3	Reference years: 2017 – 2020

Electricity for glycolysis reactor: High Speed Disperser + Evacuation pump. Mixer: 50 hp = 37.5kW @ 1 hour = 37.5 kWh = 135 MJ Pump: 25 hp = 18.8kW @ 1 hour = 18.8 kWh = 68MJ Total: = 203 MJ

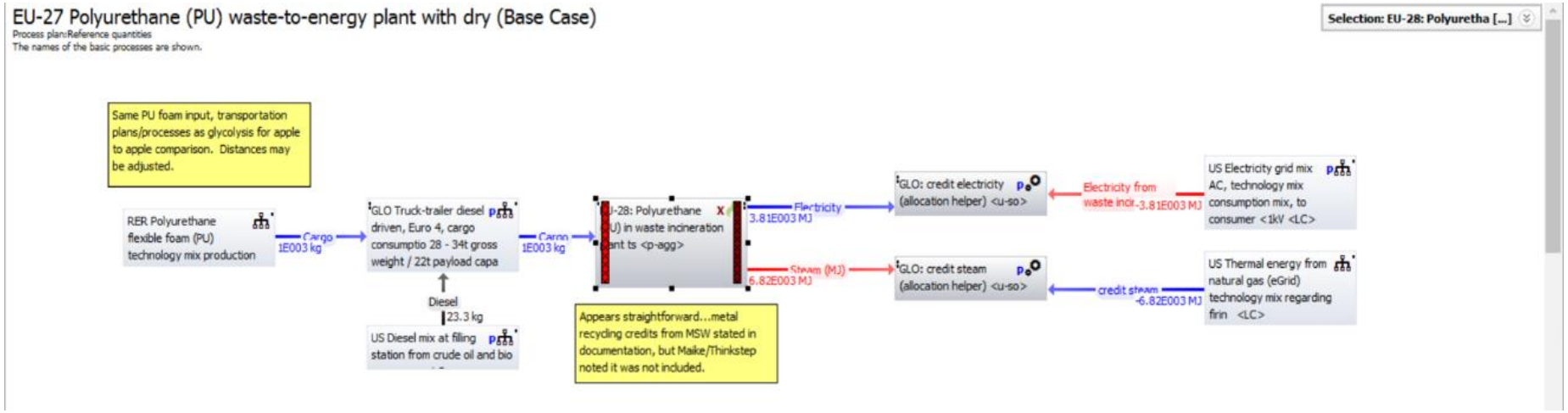

Figure 11. Incineration process model in GaBi

Table 9. Gabi incineration process/plan description

Description	Source	Inputs/Outputs	Comments
PU flexible foam (version 2014)	Plastic Europe		Cradle to gate based on industry consortium data Reference years: 2005 – 2012
Foam Transport	GaBi – Global	Diesel fuel, cargo	Parameters – 2000 miles, 13.8kt payload. Reference years: 2017 – 2020 Cut-off rules: 95% of mass & energy, 98% of environmental impacts
PU in waste incineration	GaBi, Europe based	MSW w/ PU mix	Reference years: 2017 – 2020 Industry average from 231 sites in Europe WtE with dry flue gas treatment, selective catalytic reduction 25.5 MJ/kg calorific value of PU foam Includes disposition of ash and other residues

Allocation Methodology

There was only one allocation utilized in this study. An LCI in GaBi was used for the production of bio-diesel from soy beans. There are (3) material outputs from that process: bio-diesel, crude glycerol and fatty acids. Crude glycerol is one of the main inputs for the glycolysis process and thus needs to have the burdens associated with soy biodiesel production allocated to it.

The “Base Case” scenario utilized a mass allocation methodology between the outputs of the soy bio-diesel process. Additional analyses were performed where calorific values and market price were used to allocate burdens from the bio-diesel process.

The approximate burdens for crude glycerol are 11% for mass allocation, 5.4% for calorific value and 3.6% for market value.

The calculation used to estimate the calorific allocation is (Thompson, J.C., He, B.B., 2016):

- Soy derived biodiesel = 41.2 kJ/g
- Crude glycerol = 19.63 kJ/g
- Calculation of relative energy
    - .893 g biodiesel * 41.2 = 36.79 kJ
    - .107 g crude glycerol * 19.63 = 2.10 kJ
    - TOTAL = 38.89kJ
- Relative values
    - Biodiesel - 36.79 kJ/38.89 = 94.6%
    - Crude glycerol – 2.10/38.89 = 5.4%

The calculation used to estimate the market value allocation is:

- Biodiesel B99/B100 national average is $3.48/gallon, or $.458/lb (at 7.6 lbs/gallon) (U.S. Department of Energy [US DOE], 2018)
- Crude glycerin (approximately 80% purity) market price is $.14/lb (Oleoline, 2017, December).
- Calculation of total value of biodiesel products

  - .893 lb biodiesel * $.458/lb biodiesel = $0.409
  - .107 lb crude glycerin * $.14/lb crude glycerin = $0.015
  - Total = $0.424
- Relative value
  - Soy derived biodiesel - $0.409/$0.424 = 96.5%
  - Soy derived crude glycerol - $0.015/$0.424 = 3.5%

Mass allocation was selected as the base case because that is the LCI that existed in GaBi without the need for modification. The other allocation methods were utilized to understand if they will make a material difference in any of the impact categories when comparing glycolysis to incineration.

LCIA Methodology and Types of Impacts

TRACI 2.1 methodology was used for this analysis. “thinkstep LCIA Survey 2012, North-America, TRACI 2.1, incl biogenic carbon (person equiv. weighted)” was used in weighting the LCI results. “TRACI 2.1, US-CA 2008, incl biogenic carbon (person equivalents)” was used for normalization of the same data.

TRACI impact assessment tool was developed by the U.S. Environmental Protection Agency as a means to incorporate societal opinions and impacts and incorporate regional impacts into the weighting process. The impact categories in the tool are:

- LCIA Survey 2012, NA, TRACI 2.1, (incl biogenic carbon (person equiv. weighted)
- TRACI 2.1, Acidification [kg SO2-Equiv.]

- TRACI 2.1, Ecotoxicity (recommended) [CTUe]
- TRACI 2.1, Eutrophication [kg N-Equiv.]
- TRACI 2.1, Global Warming Air, incl. biogenic carbon [kg CO2-Equiv.]
- TRACI 2.1, Human Health Particulate Air [kg PM2,5-Equiv.]
- TRACI 2.1, Human toxicity, cancer (recommended) [CTUh]
- TRACI 2.1, Human toxicity, non-canc. (recommended) [CTUh]
- TRACI 2.1, Ozone Depletion Air [kg CFC 11-Equiv.]
- TRACI 2.1, Resources, Fossil fuels [MJ surplus energy]
- TRACI 2.1, Smog Air [kg O3-Equiv.]

For this analysis, all categories are considered to meet the goal of identifying, which categories were favored by glycolysis and which were favored by incineration of the fPUF.

It is important to note that an impact assessment for water consumption is not included in TRACI at this time and therefore is not an impact considered for this analysis. The glycolysis process, via the connection to soy bean cultivation, and the incineration processes are both large consumers of water. Water consumption is a very important impact category that should be investigated separately (EPA, 2016b).

Economic Analysis

The formulation used to quantify the economic impacts of each process can be simply defined as:

$$CM = I - (C_v + C_d)$$

where *CM* is defined as the contribution margin and *I* is defined as the income generated from the operation – mainly from the sale of the recovered polyols or electricity and heat. The costs are split into variable costs (C_v) and direct costs (C_d) of the operation. The variable costs are proportional to the amount of functional unit (foam) processed while the direct costs are not. In the chemical and power industries, direct costs are typically referred to as Operational & Maintenance (O&M) costs.

In the glycolysis process the variable costs and income in this process are dominated by commodity materials like the crude glycerol and the polyols. These materials have large swings in their market cost/price based on supply and demand balance, the cost of feedstocks and even natural disasters impacting transportation and capacity. O&M costs tend to trend along with inflation and typically do not vary significantly up or down year over year.

The costs of building a glycolysis facility and an incineration are very different. The capital costs for glycolysis are relatively low compared to incineration, but the throughput is much lower as well.

The capital cost to build an MSW incineration plant with energy recovery varies widely based on the amount of waste it will process. The World Energy Council estimates the cost to be $600 – 900 per metric ton (World Energy Council, 2016). One of the largest MSW incinerators in the world was built in Detroit, MI in 1986. This unit was built at a cost of approximately $1.2 billion and has a capacity of 800,000 tonnes per year (Zero Waste Detroit, n.d.).

It was not the goal of this study to estimate capital costs for the different processes. However, the above information makes it evident that expanding the number

of WtE facilities for MSW capable of processing fPUF will carry very high capital costs and cannot be justified solely for the purpose of incinerating fPUF.

Glycolysis – Variable Costs (C_v)

The costs for commodity chemicals used, and the value of materials recovered, in the glycolysis process were quantified after a search for historical cost/pricing. Services such as ICIS track the current and historical market price of many chemicals and are an accurate and reliable source of data. Where possible, values going back 2 – 3 years were used and an average taken. The minimum and maximum during that period will be used in a sensitivity analysis.

Other variable costs include deionized water, utilities, freight and waste treatment.

Table 10 outlines all of these variable costs and the respective quantities used in the glycolysis process.

Table 10. List of variable costs for the glycolysis process.

Variable Cost	Quantity Consumed	Impact Type (flow type)
Crude Glycerol 80%	1,480 kg	Cost (input)
fPUF for Recycling	1,000 kg	Cost (input)
Stannous Octoate	20 kg	Cost (input)
Rigid Polyol	1,830 kg	Income (output)
Flexible Polyol	607 kg	Income (output)
Electricity	521 kWh	Cost (input)
Natural Gas	656 kWh (equiv)	Cost (input)
Freight	4,917 kg trans	Cost (N/A)
Water	667 kg	Cost (input)
Waste Water Treatment	727 kg treated	Cost (output)

ICIS data (ICIS, 2018) was found for the period of March 2017 through February 2018 for 80% crude glycerol prices. Figure 12 shows the short-term trend has been

upward for this material. The average of $.171/kg, along with the minimum and maximum from this chart, were used in the economic evaluation. A second source, Oleo Online (Oleoline, 2017), was found and gave a spot buy price of $.22/kg for December, 2017. The market price of crude glycerol is highly dependent on the amount of soy biodiesel produced.

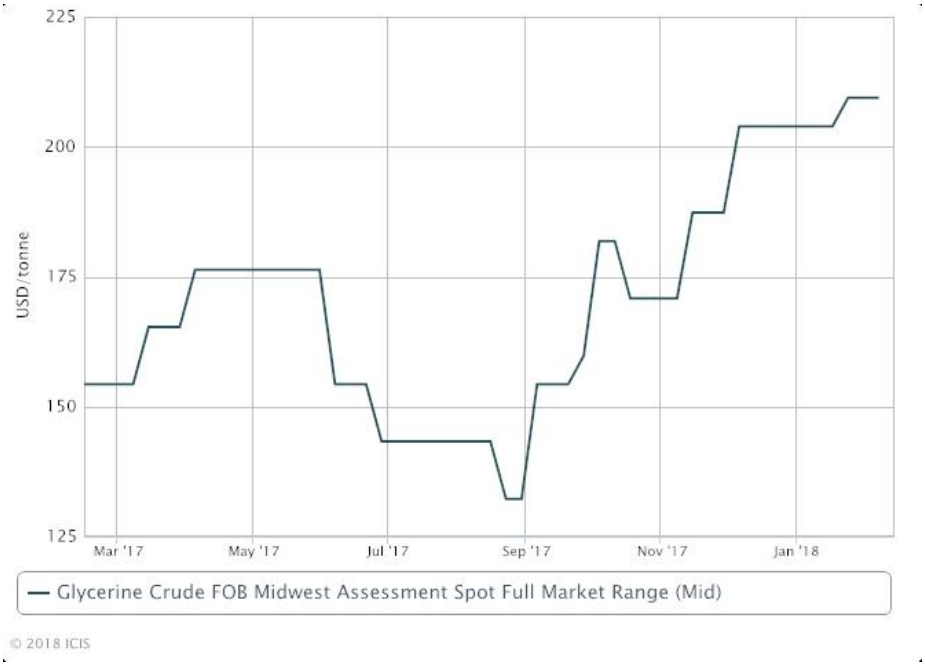

Figure 12. Historical US Crude glycerol prices

The cost of chopped fPUF was difficult to define. Spot prices on websites for waste foam were the only sources found for market pricing making it impossible to review historical data. An average price of $0.33/kg was used based on data from Recycle.Net (The Recyclers Exchange, n.d.).

The price for stannous octoate was found on the Alibaba site. The price will change on a regular basis on this exchange. No historical pricing was found. However, the quantity used is very small (0.8% by weight) and will not have a material effect on the total variable cost of the glycolysis process.

The U.S. government's Energy Information Administration (EIA) was the source for pricing of electricity (US Energy Information Administration [EIA], 2018, May) and natural gas (EIA, 2018, July). Rates for Industrial users were used.

Little data was found on the cost of deionized water. The cost for municipal water (US DOE, 2017) was used and then doubled to account for the cost of the deionization process.

The market price for the rigid and flexible polyols was found on ICIS (ICIS, 2018b) for the period of January, 2017 through December, 2017. Additional data from ICIS, going back 3 years, was used to calculate the average and minimum/maximum values used in the sensitivity analysis. Figure 13 shows the recent trend of rapidly escalating market prices for polyol, whereas 2 years ago the prices were very low. When calculating the income generated from the sale of the recovered polyols, the market price for each type less a discount of 15% was used. The market will require some discount to go through the work of qualifying a recovered polyol that is not 100% virgin material.

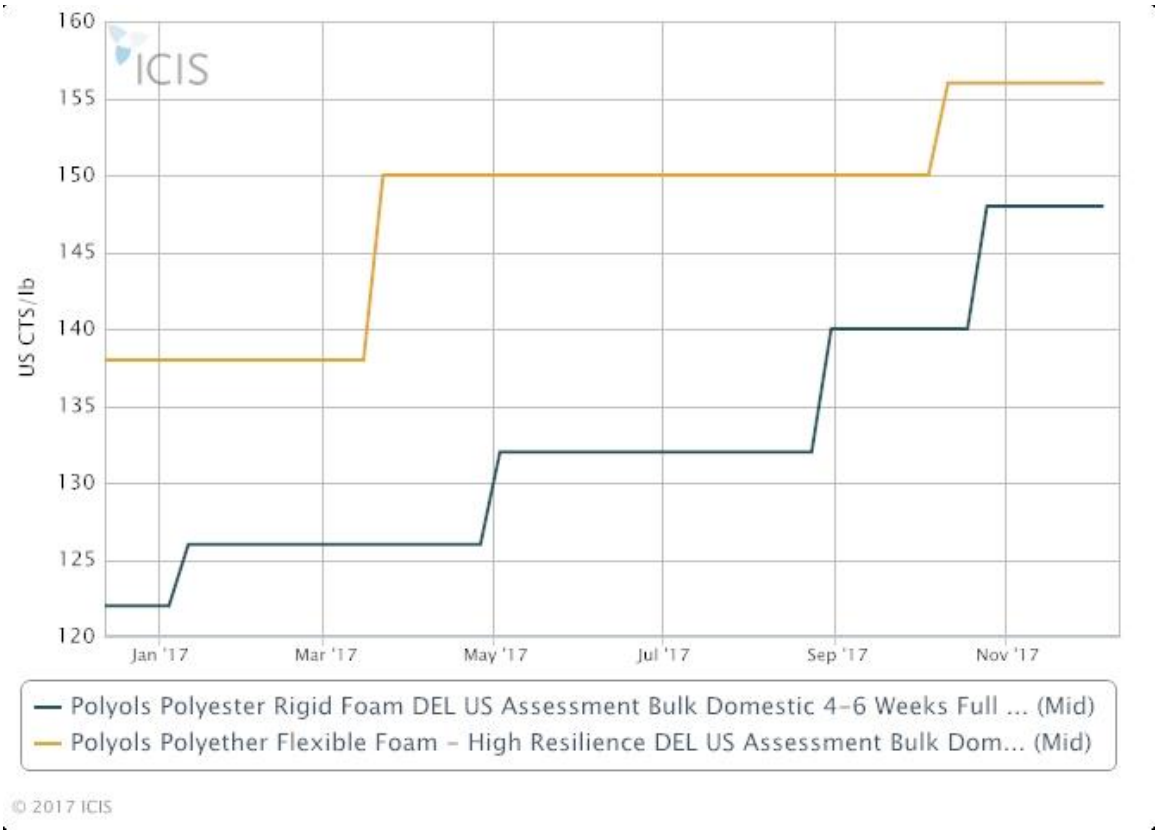

Figure 13: Historical foam polyol pricing.

The costs associated with the treatment of the waste water generated by the glycolysis process was estimated from a U.S. Department of Energy study (US DOE, 2017). Figure 14 shows typical municipal waste water treatment rates for various cities in the U.S. An average of $6.00/1000 gallons was used ($0.0028/kg) in the calculations. A second source, with lower costs and a somewhat different scope, was found and estimated the price to treat black water at $.00069/lb adjusted for 2018 (Morton, J., 2014).

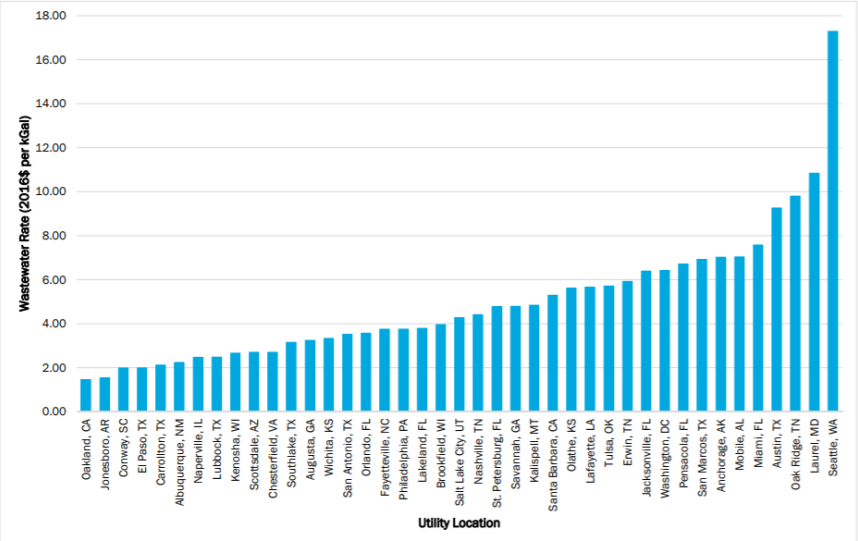

Figure 14. Municipal wastewater treatment rates by city

Glycolysis – Direct Costs (C_d)

O&M costs for a chemical facility are difficult to find in literature. Studies published by the EPA (Katari, V.S., Vatavuk, W.M., & Wehe, A. H., 1987) and Anderson (2009), analyzing incineration and chemical processing facilities respectively, focused on defining the capital costs for a facility and using factors to estimate O&M costs. As stated earlier, it was not the goal to define the capital costs associated with a treatment of the fPUF waste. However, an estimate of capital costs is required to estimate O&M costs.

A paper published estimating the capital and operational costs of a polyether polyol manufacturing facility, as a senior project (Hum, C., Wang, C. & Tassano, M., 2017) at the University of Pennsylvania, very closely approximates the process and equipment needed for a glycolysis facility.

Finally, the author has significant experience in the chemical industry, especially in manufacturing, including a deep knowledge of the O&M costs in these facilities. This experience will be used a reality check to the calculated value.

A reputable source (Seider, W. D., Seader, J. D., Lewin, D.R. & Widagdo, S., 2009) was used by the UPenn team in estimating equipment costs and installation factors. The only modification made was the removal of one reactor because the glycolysis process only needs one.

Table 11 outlines the total cost of equipment ("Total Cost"), which includes the cost of the equipment (C_p), installation and associated equipment factor (F_{BM}) and miscellaneous costs. The total capital cost for a 100 million lb/year facility was estimated to be $5,029,000.

Table 11. University of Pennsylvania capital investment estimate for a polyester polyol facility.

Unit	C_p ($)	F_{BM}	Associated Costs ($)	C_{BM} ($)	Total Cost ($)
Condensers					
COND-01	32,600	3.17	10,300	103,300	113,600
COND-02	107,800	3.17	34,200	341,700	375,900
Decanter					
D-01	64,700	3.05	19,700	197,300	217,000
Heat Exchangers					
HX-01	62,000	3.17	19,700	196,700	216,400
HX-02	55,000	3.17	17,400	174,200	191,600
HX-03	87,900	3.17	27,900	278,600	306,500
HX-04	31,600	3.17	10,000	100,000	110,000
Mixers					
MX-01	48,300	4.16	57,900	201,000	258,900
MX-02	89,000	3.5	7,600	312,000	319,600
Pumps					
P-01	4,600	3.3	2,800	15,000	17,800
P-02	8,400	3.3	4,700	28,000	32,700
P-03	4,200	3.3	2,900	14,000	16,900
P-04	20,000	3.3	11,700	66,000	77,700
P-05	4,200	3.3	2,900	14,000	16,900
P-06	21,000	3.3	12,000	70,400	82,400
P-07	21,500	3.3	9,000	70,800	79,800
P-08	11,000	3.3	6,800	36,200	43,000
P-09	11,000	3.3	6,800	36,200	43,000
Reactors					
R-01	220,000	4.16	165,000	915,000	1,080,000
R-02	255,300	4.16	185,700	1,062,000	~~1,248,000~~
Storage					
STR-01	9,700	3.5	3,400	34,000	37,400
STR-02	113,100	3.5	39,600	395,900	435,500
3 x STR-03	176,100	3.5	61,500	616,200	677,700
Vacuum Pump					
VP-01	112,600	2.15	24,200	242,200	271,100
TOTAL:	**1,580,000**	--	**730,900**	**5,551,000**	~~6,277,000~~

5,029,000

Table 12 shows the actual O&M costs calculated using Anderson's method, assuming 100M lbs/year throughput and $5M capital investment.

Table 12. O&M cost methodology utilized by Anderson for a chemical operation.

Cost Item	$K/year	Anderson Methodology
Operating labor	$ 900	3 people per shift, 4 shifts, $75K/person
Non-operation labor	$ 540	0.6 x Operating labor
Suuplies	$ 270	0.3 x Operating labor
Administration	$ 810	0.9 x Operating labor
Utilities	$ 101	0.02 x Capital
Maintenance	$ 201	0.04 x Capital
Miscellaneous	$ 75	0.015 x Capital
Total	$ 2,897	
Per Unit costs ($/kg)	$ 0.0637	
Per Unit costs ($/lb)	$ 0.0290	

Tables 13 and 14 outline the methodology and actual O&M costs calculated using Katari, et. al's method. This estimates the costs for an incineration operation, but is presented here as a second source of comparison to Anderson's method.

Table 13. O&M methodology utilized by Katari, et. al

Table III. Suggested factors for estimating incinerator annual costs.

Item	Suggested factor
Direct operating costs	
Operating labor[a]	0.5 h/shift
Supervisory labor[a]	15% of operating labor
Maintenance labor	0.5 h/shift
Maintenance materials[a]	100% of maintenance labor
Replacement parts	Thermal incinerators: none Catalytic incinerators: periodic replacement of catalyst, Part I.[b]
Utilities:	
Fuel	The amount of fuel required is calculated from Part I (Table III).[b]
Electricity[c]	Use the following ΔP values in estimating electricity requirements: Thermal incinerators = 4 in. water Catalytic incinerators = 6 in. water Heat exchange of 35% = 4 in. water 50% = 8 in. water 70% = 15 in. water Ductwork and stack = as required
Indirect operating costs	
Overhead	60% of sum of operating, supervisory, maintenance labor and maintenance materials
Administrative charges	$2\% \times TCI$[d]
Property tax	$1\% \times TCI$
Insurance	$1\% \times TCI$
Capital recovery cost[e]	$CRF_s \times (TCI - 1.08 \times C_{cat})$

Table 14. O&M estimate utilizing Katari, et. al methodology

Cost Item	$K/year
Operating & maint labor	$ 900
Superv labor	$ 135
Maint Mat'ls	$ 300
Utilities	$ 101
Overhead	$ 801
Maintenance	$ 101
Property Tax & Insur.	$ 101
Total	$ 2,438
Per Unit costs ($/kg)	$ 0.0536

In comparing Anderson and Katari's results, the typical O&M costs were relatively close – $0.0637/kg and $0.0536/kg respectively.

The author's experience indicates that the cost to operate a glycolysis facility is typically significantly higher than all of the above estimates. In an effort to start at a conservative value, $0.30/kg, or $300/functional unit, O&M costs for glycolysis will be used and a range will be provided for the sensitivity analysis.

Incineration – Variable Costs (C_v)

The variable costs associated with the incineration process are made up of the incoming foam and the electricity and steam sold to the market. A summary of these costs can be found in table 15.

Table 15. List of variable costs for the glycolysis process.

Variable Cost	Quantity Consumed	Impact Type (flow type)
fPUF for Recycling	1,000 kg	Income (input)
Electricity	3,810 MJ	Income (output)
Steam	6,820 MJ	Income (output)

Unlike the glycolysis process, the foam will likely be an income stream for the incineration operation and not a cost. These facilities charge a tipping fee for each load delivered to cover some of the costs of treating and managing that waste.

Tipping fees are typically charged any place garbage, particularly MSW, is dumped. A study published by the National Solid Waste Management Association in 2005 showed the tipping fee for MSW incineration to be approximately $61.67/ton, or

$0.068/kg, in 2004. (Repa, E.W., 2005). When adjusted for inflation at an average of 2.01% between 2004 and 2017, the estimated cost is $0.089/kg.

Ecocycle (2011) stated incineration tipping fees were $92/ton, or $0.101/kg. They referenced the study noted above and an EPA document that is no longer available. Therefore, the tipping fee calculated by the solid waste management association was used in the analysis.

Income derived from electricity generation is assumed to be the same cost as the purchase price for the facility – industrial use rates. There is very little data or information available defining the rates paid to MSW facilities by utilities. Additionally, each state is likely to have different rates at the discretion of the individual State Energy Commissions. One source (Gibson, L., 2018) referenced the 1978 Public Utilities Regulatory Policies Act which requires cogeneration facilities and small generators, which meet certain criteria, be paid a price equal to the utility's avoided cost of energy and capacity. This source stated MSW facilities got a price higher than expected. However, this price was not defined. It only assures that the prices will not be discounted below market price.

The sale of electricity from an industrial scale generator like an MSW operation is complex and can be heavily regulated. The price for electricity is sometimes subsidized through agreements with the municipality it serves. The largest generator in the U.S., located in Detroit, is an example of misguided investment and political mismanagement. The cost to incinerate MSW at this facility ultimately cost approximately $0.187/kg (Jackman, M., 2018) as compared to the average used in the financial calculations of $0.089/kg.

Similar to electricity, it was difficult to find a reliable source for the value of the steam an MSW facility generates in the market. A study published by The World Bank as a guide for parties interested in investing into a MSW facility provided a guideline for income based on calorific value of the waste to be processed (Rand, T., Haukohl, J., Marxen, U., 2000). As seen in Figure 15, the linear plot for the price of electricity and steam in this guideline, for the range of calorific values shown, have approximately the same slope. It is assumed the prices are therefore directly proportional. The ratio of steam price to electricity price is 0.429 to 1.0. Using an electricity price of $0.07/kWh and applying this ratio gives an estimated market price of steam of $0.03/kWh.

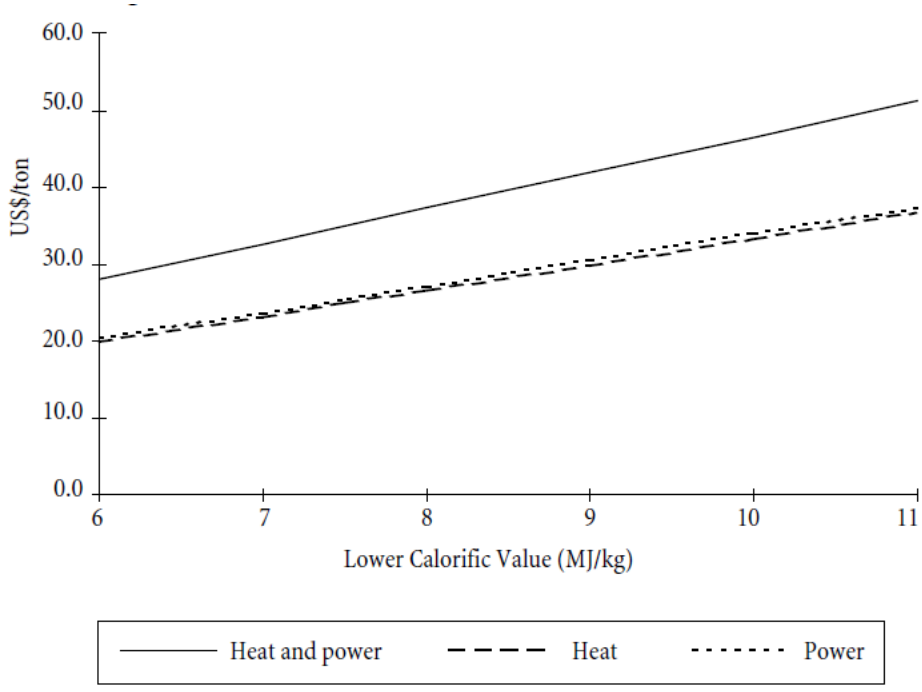

Figure 15. MSW price for electricity and heat.

The LCI used in GaBi for incineration of polyurethane foam contains a generic diagram for MSW incineration with electricity and steam generation. This diagram shows additional outputs of recovered metals such as steel and aluminum along with fly and bottom ash. Within the detailed LCI inventory list, neither steel nor aluminum in any

form are present as a significant output – only as minor quantities in soil, water and air emissions. It was not possible to identify the ash components as waste products were labeled “slag”, “spoil”, “tailings” and “waste” which were identified as “Stockpile” materials. The diagram indicates these residues were deposited in a salt mine. This technique is practiced in Europe (Astrup, T., 2008), which is the source of this LCI.

Thinkstep, the developer of the GaBi software, was consulted (M. Pieper personal conversation, January, 2018) and gave guidance that although the diagram in the GaBi documentation indicates there is a credit for recovered metals, one wasn’t taken in the LCI that was used.

There is likely a cost for depositing the ash components in a salt mine. However, this could not be quantified and was omitted from the economic analysis. Note that bottom ash is sometimes used as a filler in concrete, possibly making it a minor value stream for the incineration process.

The incineration process, like all thermoelectric processes, utilizes a lot of water in the generation of electricity. This is accounted for in the LCI. However, when trying to quantify the amount of water used in the LCI, it was discovered it is not easily broken out. It was also found that most major utilities must get permits and approvals for withdrawals from surface and ground water, but no source could be found to quantify what they pay for those materials. It is likely that beyond permit fees and renewals, the water is free of charge.

Again, thinkstep (Russ, M., personal conversation, July, 2018) was consulted about the fact that there were no individual material streams into or out of the MSW/polyurethane incineration process, other than steam and electricity. It was shared

by thinkstep that water, ammonia, activated carbon and other materials stream are used in the process for cooling and pollution controls, among other things. The environmental impacts are accounted for in the LCI for the polyurethane incineration process and are thus included in the LCIA results. However, the author was asked not to share details of this information because it is proprietary. The economic impact of these additional materials is not included in this analysis but is likely very small relative to other streams.

The typical water consumed for all thermoelectric sites, except nuclear, from the Union of Concerned Scientists database (Union of Concerned Scientists, 2012) is approximately 1,100 gallons per MWh generated. This assumes a recirculating cooling process which reduces withdrawals from surface and groundwater relative to the "once through" process. The total withdrawal amount is approximately 4,275 gallons per MWh generated.

Thinkstep clarified that the typical LCI for MSW incineration, including paper, metals, glass, and organic materials was used in the polyurethane foam LCI. The only modification made was to the calorific value, with polyurethane having a much higher embodied energy than the average MSW mix. Thus, the amount of electricity and steam generated per pound of input is higher for the polyurethane LCI used versus the typical MSW waste profile.

Incineration – Direct Costs (C_v)

Two reliable sources were found for estimating the O&M costs of an incineration facility. The first is European based while the second is published by the Energy Information Administration, which is part of the U.S. Department of Energy.

The European publication "GIZ" (Deutsche Gesellschaft fur Internationale Zusammenarbeit GmbH ("GIZ"), 2017) is a guide published by the German government (GIZ) as a guideline to help developing nations understand all the aspects of an MSW facility installation that is used to recover energy. This publication is "pro" incineration, which is not a surprise since incineration of MSW in Europe is the norm.

They estimated that for a developed country, the O&M costs for an MSW incineration facility in Switzerland would be €180/ton of material processed. Based on the current exchange rate, that equals $.212/kg of foam.

The 2013 publication from the EIA (EIA, 2013) provides both variable costs and direct O&M costs for all of the common sources of electricity generation. Electricity generated from a MSW facility has direct O&M costs of $392.82/kW-Yr, or $0.0448/kWh. Note that this is approximately 26 times higher than the cost of generating electricity using natural gas combined cycle.

The LCI for polyurethane incineration in GaBi indicates that approximately 10,000MJ (2778 kWh) of energy is derived per 1000kgs of foam processed. To estimate the cost per pound of foam, the following conversion was done.

$$\frac{\$394.82}{kWyr} * \frac{1yr}{8760hrs} = \$0.0448/kWh$$

To convert this to a value per pound of foam processed,

$$\frac{\$0.0448}{kWh} * \frac{2778\ kWh}{1000kg_{foam}} = \$0.124/kg$$

Adjusted for 2017 dollars, the O&M costs for incineration is approximately $0.131/kg or $131/functional unit.

The two studies give dramatically different estimates for O&M of an incineration plant - $0.212/kg versus $0.131/kg. Because the EIA data is based on U.S. operation versus Switzerland, this value was selected for use in the financial analysis.

Results

Following the iterative approach supported by the ISO standard, the "Base Case" model for glycolysis was built on the process defined by the UCLM team. The LCIA for this process was analyzed to identify the areas of least and greatest impact. It was discovered that the embodied impacts of the inputs (crude glycerol and flexible foam to be recycled) along with the credits for the flexible and rigid polyols recovered, drove the results in nearly all impact categories. Utilities, transportation and other in-process requirements had minimal impact in the total outcome for any given impact category. For example, 94% of the quantified, weighted impacts for GWP in the base case glycolysis process was accounted for by the recovered polyols, the crude glycerol mass allocation from biodiesel and the fPUF embodied impact. The other factors combined only accounted for 6% of the impacts.

Therefore, multiple scenario analysis were performed utilizing, as a substitute in the base case, different input and output LCIs. This was to determine which materials might have a large and material impact in the glycolysis process LCIA. Additionally, scenarios were run where the impacts for crude glycerol were allocated by calorific value and market value from the biodiesel LCI.

Table 16 summarizes the inputs and outputs of the base case and the scenarios analyzed, highlighting the differences between them. Only one variable, highlighted in red, was changed in the base case to create each scenario.

Table 16. Changes of inputs or outputs for various scenarios analyzed.

Base Case	Crude Glycerol Calorific Allocation	Crude Glycerol Value Allocation	Alternate Foam Source	Alternate Rigid Polyol	Alternate Flexible Polyol	Alternate Glycerol Source
Soy based crude glycerol, mass allocation	Soy based crude glycerol, calorific allocation	Soy based crude glycerol, value allocation	Soy based crude glycerol, mass allocation	Soy based crude glycerol, mass allocation	Soy based crude glycerol, mass allocation	Synthetically derived glycerol
Flexible PUF (Plastics Europe LCI)	Flexible PUF (Plastics Europe LCI)	Flexible PUF (Plastics Europe LCI)	Flexible PUF (Europur LCI)	Flexible PUF (Plastics Europe LCI)	Flexible PUF (Plastics Europe LCI)	Flexible PUF (Plastics Europe LCI)
Rigid Polyol (USLCI)	Rigid Polyol (USLCI)	Rigid Polyol (USLCI)	Rigid Polyol (USLCI)	Rigid Polyol (Pluracol SG470 LCI)	Rigid Polyol (USLCI)	Rigid Polyol (USLCI)
Flexible Polyol (USLCI)	Flexible Polyol (USLCI)	Flexible Polyol (USLCI)	Flexible Polyol (USLCI)	Flexible Polyol (USLCI)	Flexible Polyol (Lupranol 2090 LCI)	Flexible Polyol (USLCI)

Only one scenario for incineration was run because the LCI and plan in GaBi captured this relatively simple process in total and there wasn't an option to vary parameters or input/outputs in a meaningful way.

GaBi LCI's for glycerin, foam, polyol and the incineration process are not parameterized and thus did not allow a sensitivity analysis to be run.

Table 17 displays the LCIA "absolute value" results using TRACI 2.1 impact categories without weighting and normalization (for a functional unit of 1,000 kg fPUF recycle). The various glycolysis scenarios and the incineration process are defined in the columns while the impact categories are defined in the rows. The first seven processes are the glycolysis scenarios described above while the last column is the incineration process. For each impact category, the best performing process is highlighted in green while the poorest performing process is highlighted in red.

Table 17. GaBi absolute values by process and impact category using TRACI 2.1 methodology

Traci 2.1, Absolute Values								
	Base Case (Mass Allocation)	Glycerin Allocation - Energy	Glycerin Allocation - Value	Alt Foam Source	Alt Glycerin Source	Pluriol SG 470 Rigid Polyol	Lupranol 2090 Flexible Polyol	Incineration
TRACI 2.1, Acidification [kg SO2-Equiv.]	-56.1	-62.0	-59.9	**-72.7**	-36.7	-24.3	-35.0	**20.1**
TRACI 2.1, Ecotoxicity (recommended) [CTUe]	-20300	-20700	-19700	**-21000**	-19400	-7940	-14900	**70**
TRACI 2.1, Eutrophication [kg N-Equiv.]	39.9	24.4	18.0	32.3	10.1	25.7	**40.1**	**9.9**
TRACI 2.1, Global Warming Air, incl. biogenic carbon [kg CO2-Equiv.]	**-4630**	-3620	-1590	-2610	**12200**	-1870	-518	5860
TRACI 2.1, Human Health Particulate Air [kg PM2,5-Equiv.]	-2.1	-2.54	-2.38	-4.11	-0.667	**-5.6**	-0.466	**2.2**
TRACI 2.1, Human toxicity, cancer (recommended) [CTUh]	6.23E-06	4.60E-06	4.68E-06	7.41E-06	**1.23E-05**	**-4.74E-06**	1.14E-05	1.10E-06
TRACI 2.1, Human toxicity, non-canc. (recommended) [CTUh]	-4.89E-03	-3.46E-03	-2.72E-03	-4.93E-03	-1.39E-03	**-4.97E-03**	-4.07E-03	**1.32E-04**
TRACI 2.1, Ozone Depletion Air [kg CFC 11-Equiv.]	-3.11E-04	**-3.23E-04**	-3.11E-04	-2.82E-04	-3.21E-04	-1.04E-04	-2.29E-04	**-2.25E-07**
TRACI 2.1, Resources, Fossil fuels [MJ surplus energy]	-8310	**-10100**	-9670	-9540	**18900**	-6740	-9240	9090
TRACI 2.1, Smog Air [kg O3-Equiv.]	-106	-171	-179	-162	**243**	**-502**	-54.1	185
TRACI 2.1, Global Warming Air, excl. biogenic carbon [k	-913	-1650	-2800	**-6510**	**12500**	-4650	-4230	5860

Table 18 provides the LCIA results per TRACI 2.1 using the weighting and normalization factors for that methodology. This is done to arrive at a single score for each process for comparison reasons. As above, the best performing process in a given impact category is highlighted in green while the poorest performing is highlighted in red.

Table 18. GaBi weighted and normalized values by process and impact category using TRACI 2.1 methodology.

Traci 2.1, 2012 Weighted Values								
Impact Category	Base Case (Mass Allocation)	Glycerin Allocation - Energy	Glycerin Allocation - Value	Alt Foam Source	Alt Glycerin Source	Pluriol SG 470 Rigid Polyol	Lupranol 2090 Flexible Polyol	Incineration
thinkstep LCIA Survey 2012, NA, TRACI 2.1, incl biogenic carbon (person equiv. weighted)	-44.3	-39.9	-35.2	**-50.1**	-7.6	-44.0	-32.1	**12.1**
TRACI 2.1, Acidification [kg SO2-Equiv.]	-3.44	-3.80	-3.67	**-4.46**	-2.25	-1.49	-2.15	**1.23**
TRACI 2.1, Ecotoxicity (recommended) [CTUe]	-12.400	-12.600	-12.000	**-12.800**	-11.800	-4.840	-9.090	**0.043**
TRACI 2.1, Eutrophication [kg N-Equiv.]	12.90	7.91	5.81	10.40	3.27	8.30	**13.00**	**3.19**
TRACI 2.1, Global Warming Air, incl. biogenic carbon [kg CO2-Equiv.]	-1.72	-1.34	-1.04	**-2.41**	**4.63**	-1.73	-1.57	2.17
TRACI 2.1, Human Health Particulate Air [kg PM2,5-Equiv.]	-0.47	-0.57	-0.53	-0.92	-0.15	**-1.25**	-0.10	**0.49**
TRACI 2.1, Human toxicity, cancer (recommended) [CTUh]	1.010	0.747	0.761	1.200	**2.000**	**-0.771**	1.850	0.179
TRACI 2.1, Human toxicity, non-canc. (recommended) [CTUh]	-37.1	-26.2	-20.6	-37.3	-10.5	**-37.6**	-30.8	**1.0**
TRACI 2.1, Ozone Depletion Air [kg CFC 11-Equiv.]	-1.11E-02	**-1.15E-02**	-1.11E-02	-1.01E-02	-1.14E-02	-3.70E-03	-8.14E-03	**-8.01E-06**
TRACI 2.1, Resources, Fossil fuels [MJ surplus energy]	-2.66	**-3.23**	-3.09	-3.05	**6.03**	-2.16	-2.95	2.91
TRACI 2.1, Smog Air [kg O3-Equiv.]	-0.51	-0.81	-0.85	-0.77	**1.16**	**-2.39**	-0.26	0.88

Generally, the worst performing processes are incineration and glycolysis where the use of the alternate glycerin source (synthetically derived, high purity) is used. Eutrophication and Human Toxicity – Cancer are the categories where glycolysis using crude glycerol performs poorly relative to incineration.

Crude glycerol from soy-based biodiesel production coupled with the use of some renewable feedstocks used in the production of the foam (i.e. glycerin, castor oil, palm oil or even sugar) are the reasons for the poor performance in the Eutrophication category. The use of fertilizers and other chemicals that run off into waterways and water tables is the main contributor to this poor performance.

Glycolysis' poor performance in the Human Toxicity – Cancer category is mainly caused by the use of Stannous Octoate as a catalyst during the glycolysis process. TRACI 2.1 utilizes the USEtox database of hazardous materials and their relative impacts on Human Health Cancer, non-Cancer and Ecotoxicity. There are three outputs from GaBi using the TRACI weighting for the Human Toxicity – Cancer category: Human Health Cancer Air, Soil and Water.

Figures 16, 17 and 18 show the impacts of each input and output in the three Cancer categories for the glycolysis Base Case. There is a large benefit in the Human Health Cancer Air when glycolysis is used. The large credits for the recovered polyols offset the impacts for the embodied fPUF foam and process burdens. However, in Human Health Cancer Soil and Water, the Stannous Octoate catalyst and crude glycerol from the soy biodiesel process have a large, negative impact.

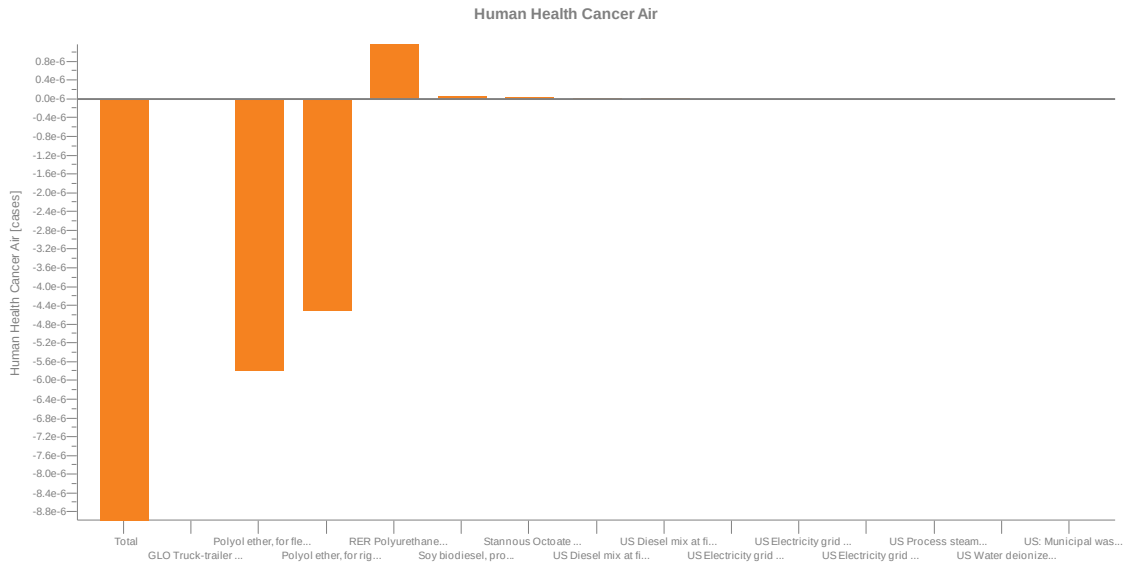

Figure 16. Human Health Cancer – Air results for Glycolysis base case by GaBi defined process

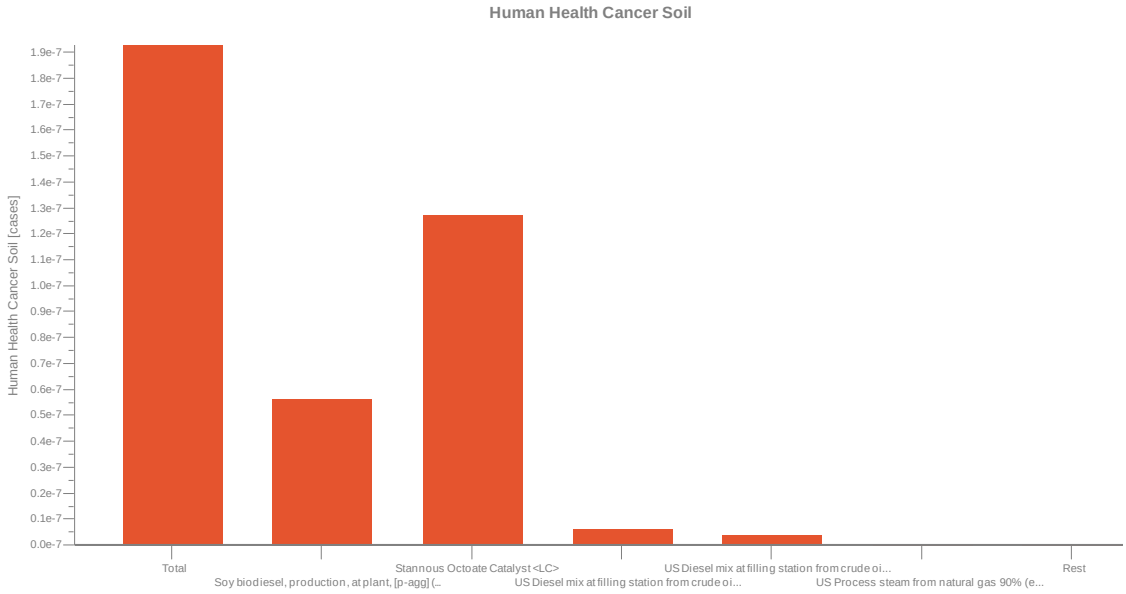

Figure 17. Human Health Cancer – Soil results for Glycolysis base case by GaBi defined process

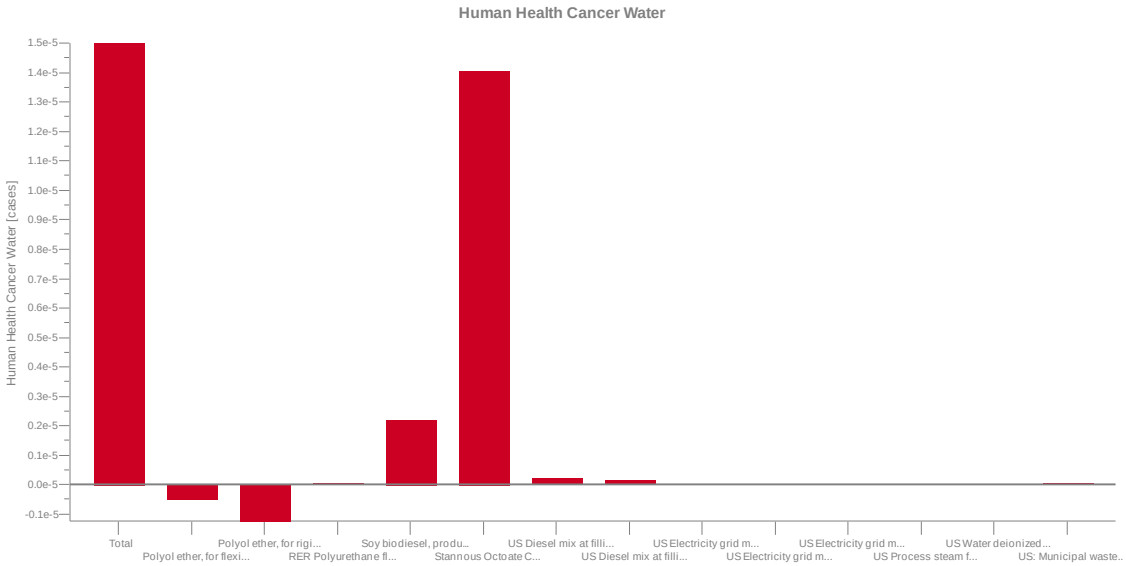

Figure 18. Human Health Cancer – Water results for Glycolysis base case by GaBi defined process

Further analysis, as seen in Figure 19, shows that the production of the Stannous Oxide from tin and ammonia is the driver of the poor performance in Human Health –

Cancer. Note that Stannous Octoate is used only at .8% by weight as a catalyst in the reaction of crude glycerol and fPUF during the glycolysis process. This very small amount has a disproportionally large impact in human toxicity.

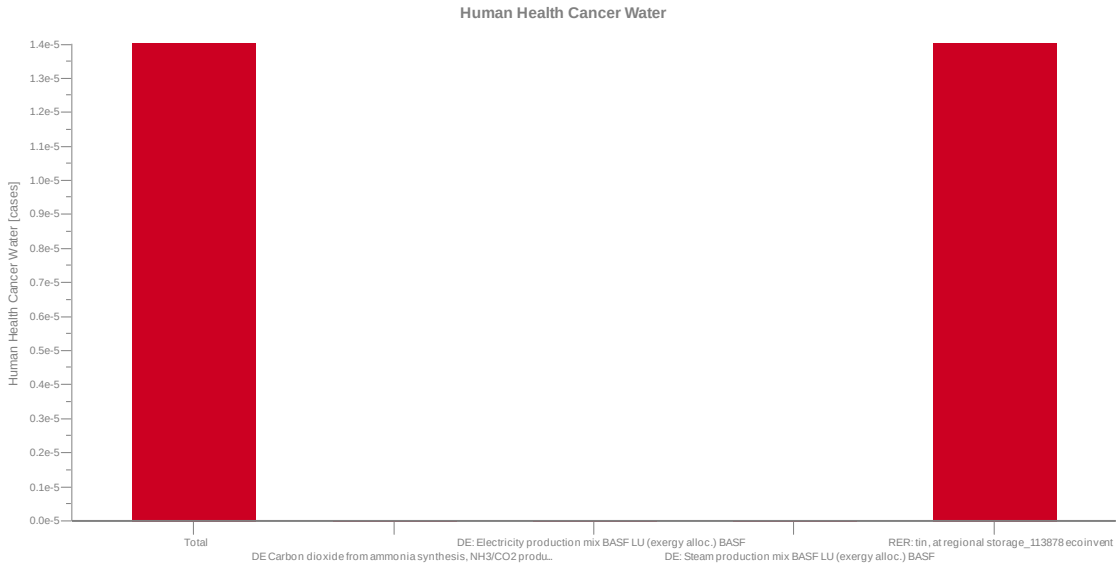

Figure 19. Human Health Cancer – Water results for the production of stannous octoate catalyst by GaBi defined process

The soybean oil (wet mill) production is the main contributor to the poor performance in Human Health Cancer Soil and Water. It is not clear which input or processing step in the creation of soybean oil is contributing to the high burden in this category.

In the case of the alternate glycerin source, the GaBi plan for the synthetic production of glycerin at high purity levels was used. The GaBi plan is a purely synthetic chemical production process which is energy intensive and utilizes other chemicals like NaOH and Allyl Chloride during synthesis.

With the exception of the use of the alternate glycerin source, the glycolysis scenarios that were analyzed have lower impacts in nearly every category relative to

incineration. Differences in the foam type, recovered polyol type and allocation method for the crude glycerol used in the glycolysis scenarios have an impact on the LCIA results relative to the glycolysis base case. However, all the processes using crude glycerol for glycolysis clearly had an overall lower environmental impact when compared to incineration.

Figure 20 shows the output from GaBi for GWP, which indicates that a credit is achieved for the glycolysis process and the opposite is true for incineration. Significant credits are derived in the recovery of the rigid and flexible polyols as well as the use of a bio-based, renewable resource that consumes atmospheric CO_2. The largest impacts come from the embodied burdens of the foam to be recycled and the credits from the recovered polyols. All of the other processes have little to no impact in the overall performance of the glycolysis process. This includes freight, process energy and treatment of wastewater.

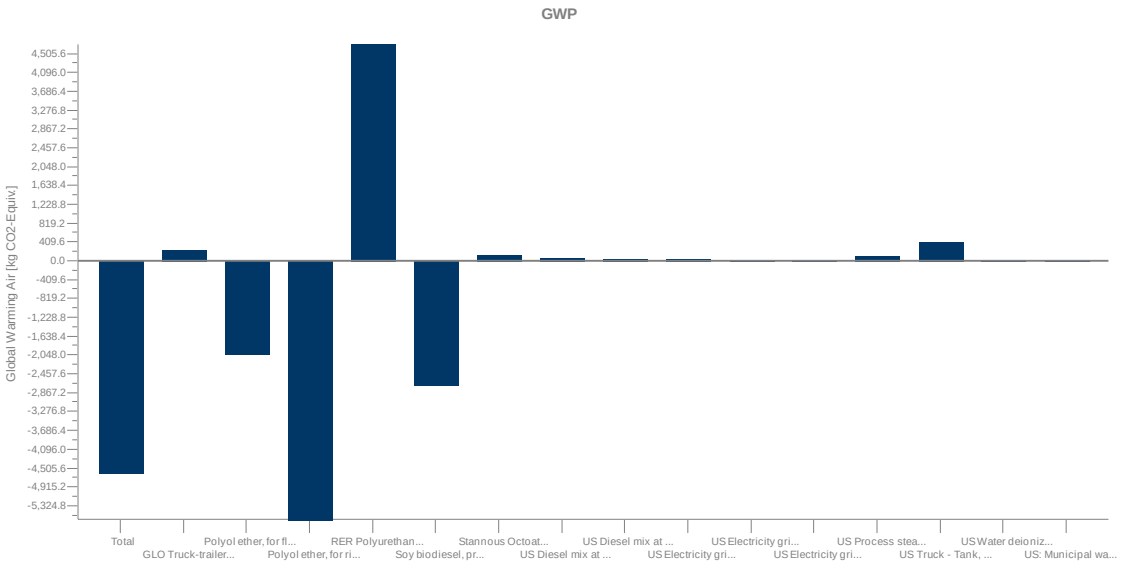

Figure 20. GWP for the base case glycolysis process as defined by GaBi process

The incineration process similarly has a large embodied burden from the fPUF that is being recycled as seen in Figure 21. Credits are apparent from the recovery of electricity and steam but are not significant enough to overcome the burden of the foam. GWP is also impacted heavily by the process of incinerating the fPUF in the form of CO2 emissions.

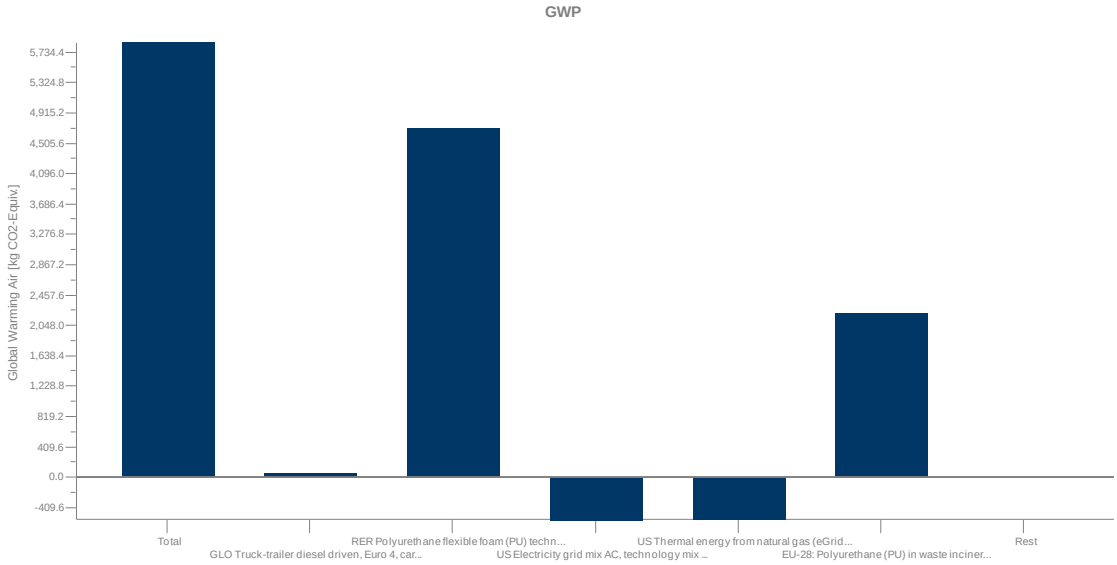

Figure 21. GWP for the incineration process as defined by GaBi process

Similar to GWP, acidification potential (AP) is typically proportional to the energy intensity in a given process. Glycolysis performs well in this area relative to incineration. Figures 22 and 23 show the impacts by process for glycolysis and incineration.

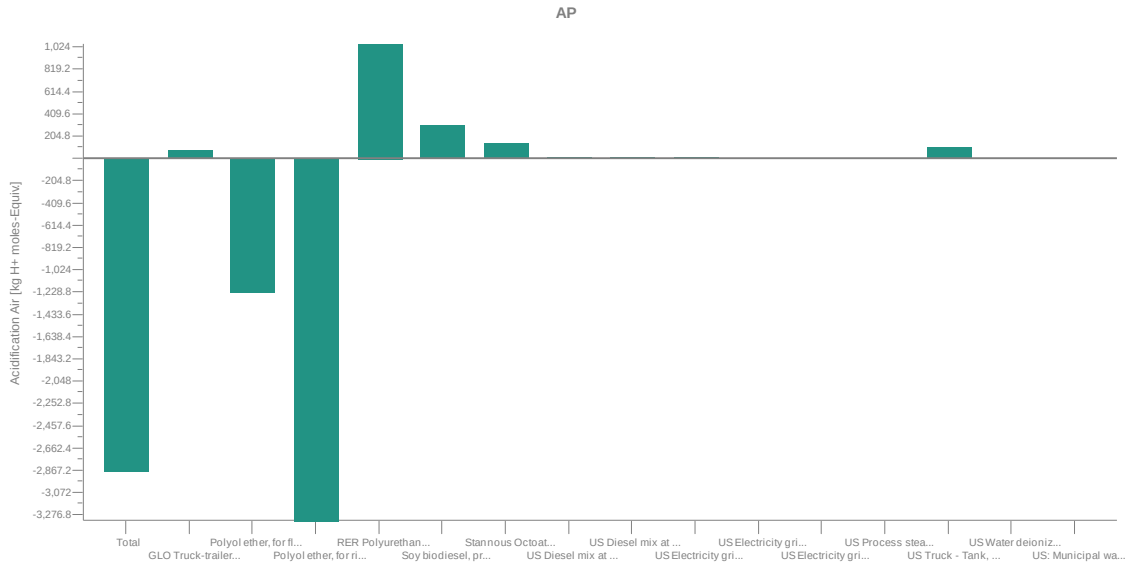

Figure 22. Acidification Potential for base case glycolysis as defined by GaBi process

Incineration performed poorly relative to glycolysis, mainly due to the embodied burden of the foam and the minimal impact of the recovered energy. Energy intensity in the manufacturing of the foam and its feedstocks are the main contributors to AP impact.

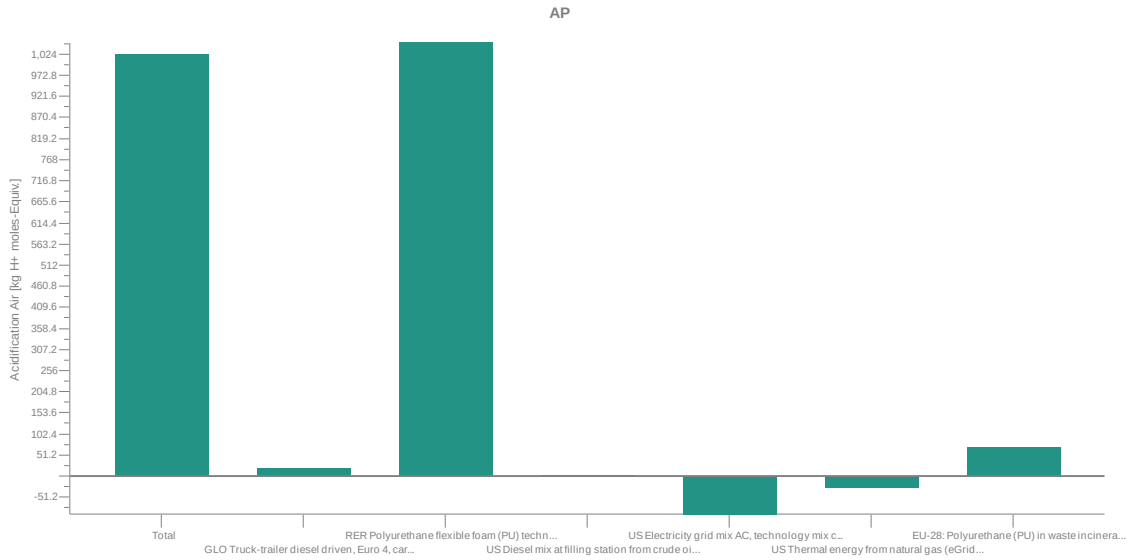

Figure 23. Acidification Potential for incineration as defined by GaBi process

Incineration performed well in eutrophication potential relative to glycolysis. The soy bean oil, as derived from the growth, harvesting and processing of soy beans, is the main cause of the poor performance in this category for all the glycolysis processes using crude glycerol as a feedstock, as seen in Figure 24. The embodied burden of the foam is the only material negative impact the incineration has in this category (Figure 25). Although there is a negative impact in EP from incineration, it is ¼ that of glycolysis.

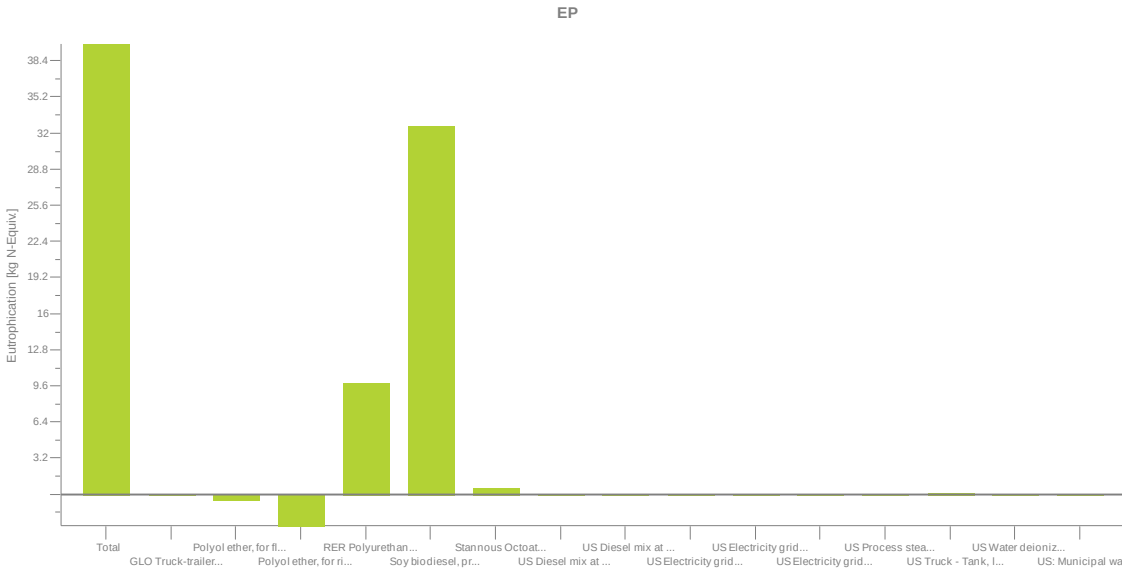

Figure 24. Eutrophication Potential for base case glycolysis as defined by GaBi process

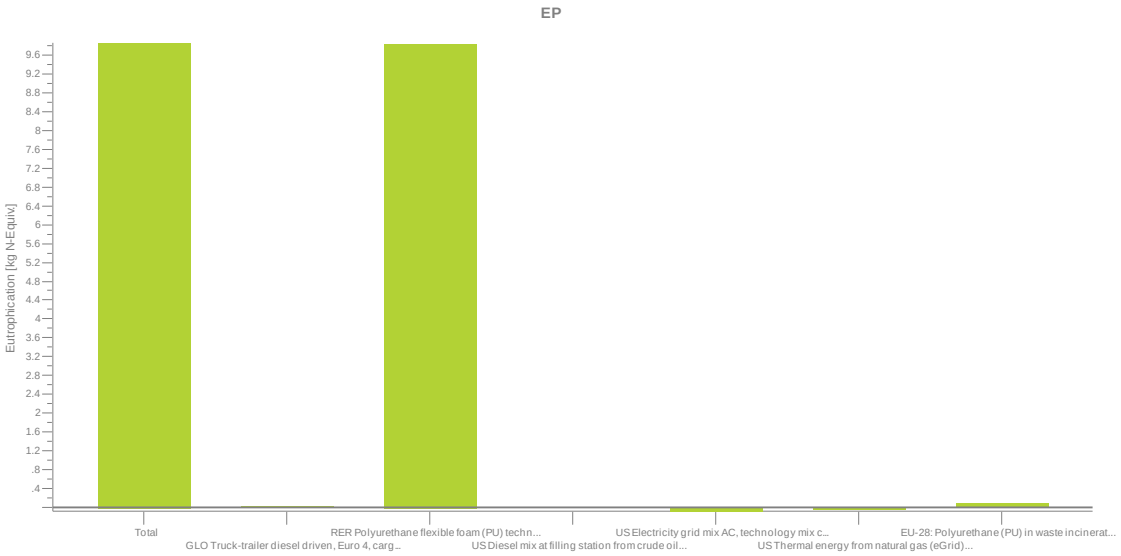

Figure 25. Eutrophication Potential for incineration as defined by GaBi process

The impacts in ozone depletion potential (ODP) for both the glycolysis and incineration processes are relatively small as seen in Figures 26 and 27. The GaBi database does not give much guidance as to the sources that contribute to this category. The polyols contribute the largest credit by far. Blowing agents typically used in foam production, which would be released from the foam when processed, can have a significant impact here. However, it is assumed that the blowing agent for the foam was water and thus there is little to no impact in ODP from the release of blowing agent from the foam.

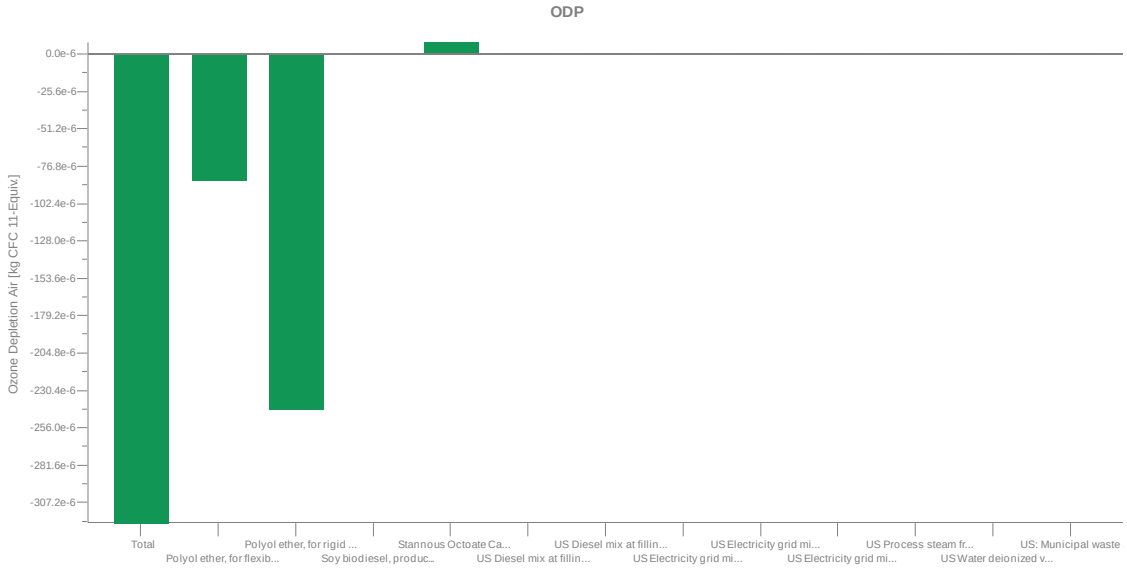

Figure 26. Ozone Depletion Potential for base case glycolysis as defined by GaBi process.

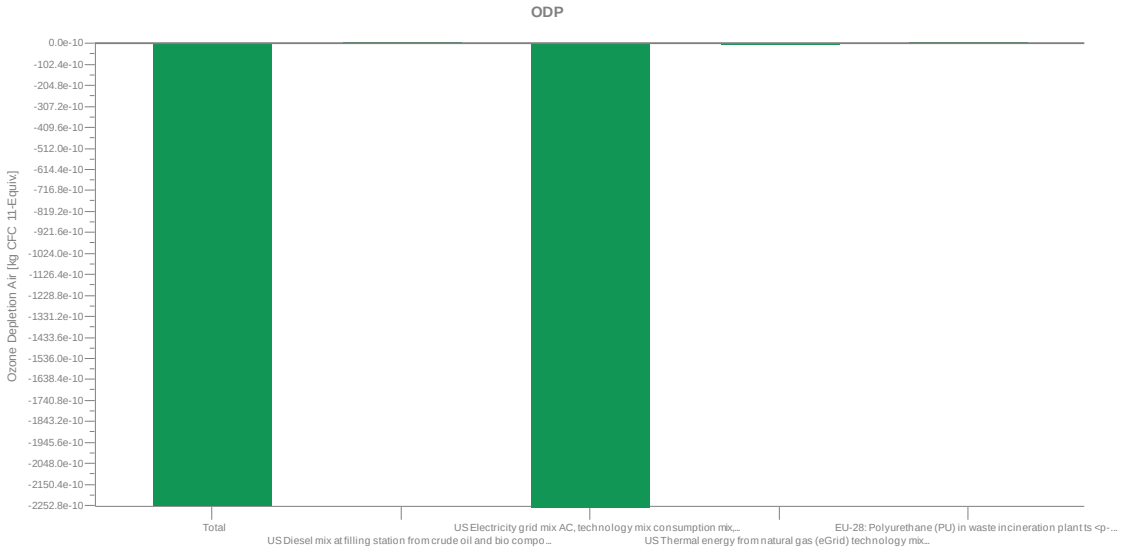

Figure 27. Ozone Depletion Potential for incineration as defined by GaBi process.

Glycolysis performed well relative to incineration in the smog generation category. Figure 28 shows that the foam and soy biodiesel processes had a negative impact in glycolysis while the credits received for the polyol contributed significant

credits. Figure 29 shows that the foam and incineration processing were significant negative impacts and recovered electricity and steam contributed only small credits.

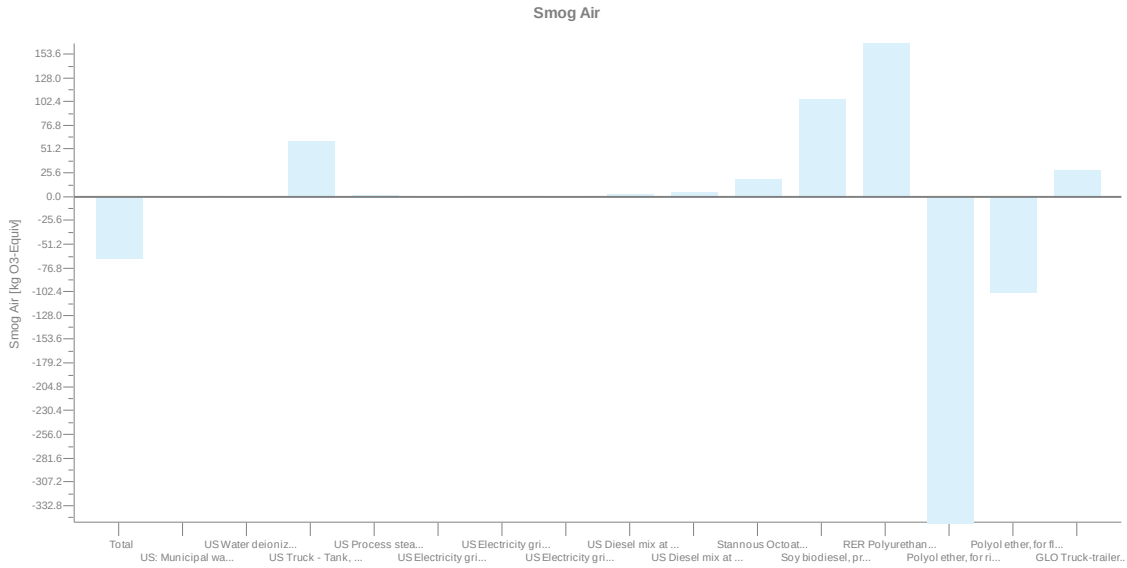

Figure 28. Smog Generation for base glycolysis as defined by GaBi process.

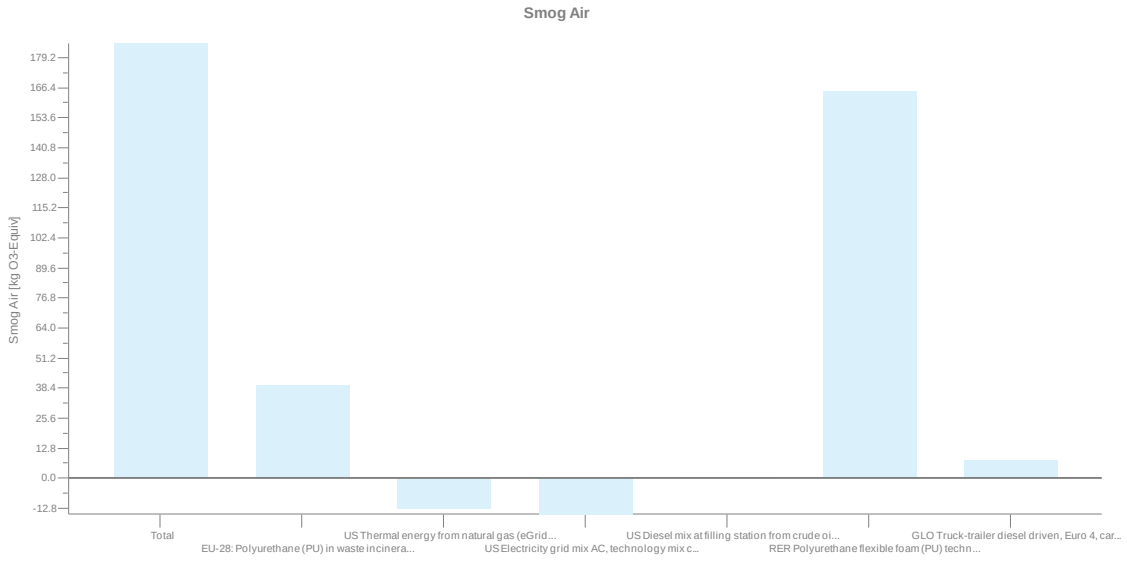

Figure 29. Smog Generation for incineration as defined by GaBi process.

Glycolysis Scenario Analysis

The Base Case for glycolysis utilized crude glycerol that was produced as a co-product of soy-based biodiesel production. The plan for soy biodiesel product allocates the burden of that process based on mass (approx. 11% for crude glycerol). Plans which allocated burdens based on calorific value (5%) and market price (3.6%) of the biodiesel and crude glycerol were created and substituted in the Base Case for the glycolysis process to quantify the change in the impact category values.

Generally, there is not a significant difference in the results between the different allocation methods. The weighted and normalized single score in TRACI ("Person Equivalent Weighted") for each method is -44.3, -39.9, and -35.2 for mass, calorific and market price allocations respectively. This is compared to 12.1 for the incineration process. Table 19 shows the output for all impact categories.

Table 19. Crude glycerol allocation method GaBi results comparison

Impact Category	Base Case (Mass Allocation)	Glycerin Allocation - Energy	Glycerin Allocation - Value
thinkstep LCIA Survey 2012, NA, TRACI 2.1, incl biogenic carbon (person equiv. weighted)	-44.3	-39.9	-35.2
TRACI 2.1, Acidification [kg SO2-Equiv.]	-3.44	-3.80	-3.67
TRACI 2.1, Ecotoxicity (recommended) [CTUe]	-12.400	-12.600	-12.000
TRACI 2.1, Eutrophication [kg N-Equiv.]	12.90	7.91	5.81
TRACI 2.1, Global Warming Air, incl. biogenic carbon [kg CO2-Equiv.]	-1.72	-1.34	-1.04
TRACI 2.1, Human Health Particulate Air [kg PM2,5-Equiv.]	-0.47	-0.57	-0.53
TRACI 2.1, Human toxicity, cancer (recommended) [CTUh]	1.010	0.747	0.761
TRACI 2.1, Human toxicity, non-canc. (recommended) [CTUh]	-37.1	-26.2	-20.6
TRACI 2.1, Ozone Depletion Air [kg CFC 11-Equiv.]	-1.110E-02	**-1.150E-02**	-1.110E-02
TRACI 2.1, Resources, Fossil fuels [MJ surplus energy]	-2.66	**-3.23**	-3.09
TRACI 2.1, Smog Air [kg O3-Equiv.]	-0.51	-0.81	-0.85

A scenario was run where the fPUF that was recycled in the Base Case was replaced by a different flexible foam to be recycled. The embodied burdens of the foam are the only difference versus the base case as the glycolysis process is not expected to differ, especially the ratio of glycolysis agent (crude glycerol) and foam.

The LCI for this alternate foam is from the GaBi database and is based in Europe. It has a more recent reference year, but as noted in the GaBi documentation, foam production is a mature process and significant advances have not been made. Because the LCI for Toluene Diisocyanate (TDI) is common between the Base Case foam and the alternate foam, the difference in category impacts would come from the polyol. The LCI documentation in GaBi doesn't provide any transparency on the formulation. The basic ingredients are ethylene oxide, propylene oxide, glycerin (optional), castor oil (optional) and refined sugars (optional). The differences in the LCIA are likely the basic materials of the different polyols used.

The results in Table 20 show that the fPUF used in the Alternate Foam scenario performed better than the Base Case and other glycolysis processes. This scenario had the lowest single score rating in the weighted and normalized TRACI category. The difference in values shows different foam inputs will have an impact in the LCIA results. However, when compared to incineration, both the alternate foam scenario and the base case are star performers.

Table 20. Alternate foam source comparison to base case – GaBi results

Impact Category	Base Case (Mass Allocation)	Alt Foam Source
thinkstep LCIA Survey 2012, NA, TRACI 2.1, incl biogenic carbon (person equiv. weighted)	-44.3	**-50.1**
TRACI 2.1, Acidification [kg SO2-Equiv.]	-3.44	**-4.46**
TRACI 2.1, Ecotoxicity (recommended) [CTUe]	-12.400	**-12.800**
TRACI 2.1, Eutrophication [kg N-Equiv.]	12.90	10.40
TRACI 2.1, Global Warming Air, incl. biogenic carbon [kg CO2-Equiv.]	-1.72	**-2.41**
TRACI 2.1, Human Health Particulate Air [kg PM2,5-Equiv.]	-0.47	-0.92
TRACI 2.1, Human toxicity, cancer (recommended) [CTUh]	1.010	1.200
TRACI 2.1, Human toxicity, non-canc. (recommended) [CTUh]	-37.1	-37.3
TRACI 2.1, Ozone Depletion Air [kg CFC 11-Equiv.]	-1.110E-02	-1.010E-02
TRACI 2.1, Resources, Fossil fuels [MJ surplus energy]	-2.66	-3.05
TRACI 2.1, Smog Air [kg O3-Equiv.]	-0.51	-0.77

The most extreme scenario looked at substituting the crude glycerol derived from biodiesel production in the base case with a synthetically derived glycerol. The LCI for synthetic glycerol is from GaBi's database. This option was a poor performer in many impact categories, especially resource use and GWP (Table 21). The purity of the glycerol is higher than crude glycerol from biodiesel production, but this increased purity added cost and environmental burden but did not deliver an improvement in the process or quality of recovered polyols. The LCIA for glycolysis using synthetically derived glycerol isn't much better than incineration, with a single score equivalent of -7.6 compared to 12.1 for incineration. Therefore, the use of crude glycerol is a prerequisite for the good environmental performance of glycolysis.

Table 21. Comparison of GaBi results – base case versus use of synthetic glycerol

Impact Category	Base Case (Mass Allocation)	Alt Glycerin Source
thinkstep LCIA Survey 2012, NA, TRACI 2.1, incl biogenic carbon (person equiv. weighted)	-44.3	-7.6
TRACI 2.1, Acidification [kg SO2-Equiv.]	-3.44	-2.25
TRACI 2.1, Ecotoxicity (recommended) [CTUe]	-12.400	-11.800
TRACI 2.1, Eutrophication [kg N-Equiv.]	12.90	3.27
TRACI 2.1, Global Warming Air, incl. biogenic carbon [kg CO2-Equiv.]	-1.72	**4.63**
TRACI 2.1, Human Health Particulate Air [kg PM2,5-Equiv.]	-0.47	-0.15
TRACI 2.1, Human toxicity, cancer (recommended) [CTUh]	1.010	**2.000**
TRACI 2.1, Human toxicity, non-canc. (recommended) [CTUh]	-37.1	-10.5
TRACI 2.1, Ozone Depletion Air [kg CFC 11-Equiv.]	-1.110E-02	-1.140E-02
TRACI 2.1, Resources, Fossil fuels [MJ surplus energy]	-2.66	**6.03**
TRACI 2.1, Smog Air [kg O3-Equiv.]	-0.51	**1.16**

The last two scenarios involved substituting different recovered polyols from the glycolysis process. In the first option, a rigid polyol supplied by BASF U.S., Pluriol SG 470, was substituted for the ether polyol used in the base case. The LCI for Pluriol SG 470 was created by BASF. It was selected because it has a significant number of renewable feedstocks in the formulation.

The LCIA is very favorable for this scenario, having the best performance in the Human Health Particulate, Cancer, non-Cancer and Smog categories (Table 22). It scores slightly lower than the base case scenario which utilized a rigid ether polyol LCI generated by the USLCI/NREL.

Table 22. Comparison of GaBi results – base case versus use of an alternate rigid polyol

Impact Category	Base Case (Mass Allocation)	Pluriol SG 470 Rigid Polyol
thinkstep LCIA Survey 2012, NA, TRACI 2.1, incl biogenic carbon (person equiv. weighted)	-44.3	-44.0
TRACI 2.1, Acidification [kg SO2-Equiv.]	-3.44	-1.49
TRACI 2.1, Ecotoxicity (recommended) [CTUe]	-12.400	-4.840
TRACI 2.1, Eutrophication [kg N-Equiv.]	12.90	8.30
TRACI 2.1, Global Warming Air, incl. biogenic carbon [kg CO2-Equiv.]	-1.72	-1.73
TRACI 2.1, Human Health Particulate Air [kg PM2,5-Equiv.]	-0.47	**-1.25**
TRACI 2.1, Human toxicity, cancer (recommended) [CTUh]	1.010	**-0.771**
TRACI 2.1, Human toxicity, non-canc. (recommended) [CTUh]	-37.1	**-37.6**
TRACI 2.1, Ozone Depletion Air [kg CFC 11-Equiv.]	-1.110E-02	-3.700E-03
TRACI 2.1, Resources, Fossil fuels [MJ surplus energy]	-2.66	-2.16
TRACI 2.1, Smog Air [kg O3-Equiv.]	-0.51	**-2.39**

The last scenario substituted a flexible polyol from BASF, Pluracol 2090 manufactured at BASF Belgium for the base case scenario which utilized a polyol with an LCI created by USLCI/NREL. This scenario was an average performer without providing any major advantages over the other glycolysis scenarios using crude glycerol. The exception, as can be seen in Table 23, is that it had the highest Eutrophication potential of all scenarios, albeit not by much.

Table 23. Comparison of GaBi results – base case versus us of an alternate flexible polyol

Impact Category	Base Case (Mass Allocation)	Lupranol 2090 Flexible Polyol
thinkstep LCIA Survey 2012, NA, TRACI 2.1, incl biogenic carbon (person equiv. weighted)	-44.3	-32.1
TRACI 2.1, Acidification [kg SO2-Equiv.]	-3.44	-2.15
TRACI 2.1, Ecotoxicity (recommended) [CTUe]	-12.400	-9.090
TRACI 2.1, Eutrophication [kg N-Equiv.]	12.90	**13.00**
TRACI 2.1, Global Warming Air, incl. biogenic carbon [kg CO2-Equiv.]	-1.72	-1.57
TRACI 2.1, Human Health Particulate Air [kg PM2,5-Equiv.]	-0.47	-0.10
TRACI 2.1, Human toxicity, cancer (recommended) [CTUh]	1.010	1.850
TRACI 2.1, Human toxicity, non-canc. (recommended) [CTUh]	-37.1	-30.8
TRACI 2.1, Ozone Depletion Air [kg CFC 11-Equiv.]	-1.110E-02	-8.140E-03
TRACI 2.1, Resources, Fossil fuels [MJ surplus energy]	-2.66	-2.95
TRACI 2.1, Smog Air [kg O3-Equiv.]	-0.51	-0.26

Economic Value

The methodology for defining the economic value of each process was defined by the following equation

$$CM = I - (C_v + C_d)$$

The income and variable costs for the glycolysis process are identified in Table 24.

Table 24. Variable costs for the glycolysis process

Cost factor	Unit Value	Quantity Consumed	Extended Cost ($)	Extended Value ($)
Crude Glycerol (80 - 85% pure) ($/kg)	$ 0.1710	1480	$ 253	
Delivery of Crude Glyerol ($/kg)	$ 0.1760	1480	$ 260	
Flexible PU Foam (shredded & baled) ($/kg)	$ 0.3300	1000	$ 330	
Delivery of fPUF ($/kg)	$ 0.1100	1000	$ 110	
Stannous Octoate ($/kg)	$ 4.9500	20	$ 99	
Electricity (consumed) ($/kWh)	$ 0.070	521	$ 36	
Natural Gas (hot oil for reactor) ($/kWh)	$ 0.0188	656	$ 12	
Deionized Water ($/kg)	$ 0.0028	667	$ 2	
Rigid Polyol ($/kg)	$ 2.4796	1830		$ 4,538
Delivery of Rigid Polyol ($/kg)	$ 0.1760	1830	$ 322	
Flexible Polyol ($/kg)	$ 2.5614	607		$ 1,555
Delivery of Flexible Polyol ($/kg)	$ 0.1760	607	$ 107	
Waste Water (incl treatment) ($/kg)	$ 0.0016	727	$ 1	
Total Income Generated ($ per functional unit)				$ 6,092
Total Variable Cost ($ per functional unit)			$ 1,533	

The glycolysis process base case generates an income stream of $6,092 per 1000kg of fPUF processed from the polyols generated and carries a cost of $1,533. This results in a net variable income stream of $4,559.

O&M costs for the glycolysis process are estimated to be $300 per 1000kg of fPUF processed.

The Contribution Margin of the glycolysis process per 1000kg of fPUF processed is

$$CM_{glycolysis} = \$6,092 - (\$1,533 + \$300) = \$4,259$$

Income and variable costs are indicated in Table 25 for the incineration process.

Table 25. Variable costs for the incineration process.

Cost factor	Unit Value	Quantity Consumed	Extended Cost ($)	Extended Value ($)
Electricity (sold) ($/kWh)	$ 0.070	1058		$ 74
Steam ($/kWh)	$ 0.0300	3788		$ 114
Tipping fees	$ 0.0890	1000		$ 89
Total Income Generated ($ per functional unit)				$ 277
Total Variable Cost ($ per functional unit)			$ -	

There aren't any variable costs associated with the analysis since the incinerator is paid to receive the waste (tipping fees). Inputs proprietary to thinkstep could not be shared and thus couldn't be quantified or estimated in this paper. These inputs will carry some minor costs but would not be expected to sway the results dramatically.

Similar to other thermoelectric power plants, water is also withdrawn in large quantities, but no source can be found to confirm that typical MSW incineration facilities actually pay for it.

The Contribution Margin to operate an MSW incinerator is thus

$$CM_{incineration} = \$277 - (\$0 + \$131) = \$146$$

A Monte Carlo analysis was performed on the Contribution Margin calculations based on an estimate of the fluctuations of all unit costs. Tables 26 and 27 show the base case value and ranges for each variable used in the Monte Carlo Analysis for glycolysis and incineration.

Table 26. Variables and ranges used in the Monte Carlo Analysis for glycolysis

Cost factor - Glycolysis	Base Case	Min	Max
Crude Glycerol (80 - 85% pure) ($/kg)	$ 0.1710	$ 0.14	$ 0.21
Delivery of Crude Glyerol ($/kg)	$ 0.1760	$ 0.015	$ 0.025
Flexible PU Foam (shredded & baled) ($/kg)	$ 0.3300	$ 0.198	$ 0.396
Delivery of fPUF ($/kg)	$ 0.0110	$ 0.090	$ 0.015
Stannous Octoate ($/kg)	$ 4.9500	$ 4.000	$ 6.000
Electricity (consumed) ($/kWh)	$ 0.070	$ 0.068	$ 0.090
Natural Gas (hot oil for reactor) ($/kWh)	$ 0.0188	$ 0.0152	$ 0.024
Deionized Water ($/kg)	$ 0.0028	$ 0.002	$ 0.005
Rigid Polyol ($/kg)	$ 2.4796	$ 2.2814	$ 2.8798
Delivery of Rigid Polyol ($/kg)	$ 0.1760	$ 0.015	$ 0.025
Flexible Polyol ($/kg)	$ 2.5614	$ 2.3000	$ 2.9172
Delivery of Flexible Polyol ($/kg)	$ 0.1760	$ 0.015	$ 0.025
Waste Water (incl treatment) ($/kg)	$ 0.0016	$ 0.0010	$ 0.0030
Glycolysis O&M ($/kg)	$ 0.300	$ 0.100	$ 0.400

Table 27. Variables and ranges used in the Monte Carlo Analysis for incineration

Cost factor - Incineration	Base Case	Min	Max
Electricity (sold) ($/kWh)	$ 0.070	$ 0.068	$ 0.090
Steam ($/kWh)	$ 0.0300	$ 0.0200	$ 0.050
Tipping fees	$ 0.0890	$ 0.0890	$ 0.125
Incineration O&M ($/kg)	$ 0.131	$ 0.120	$ 0.250

Excel was used to run a simulation on 10,000 iterations of the Contribution Margin calculation for each process and a histogram and basic statistical data were analyzed. Table 28 and Figure 30 show the data and histogram from the glycolysis analysis while Table 29 and Figure 31 show the results for the incineration process.

Table 28. Statistics from Monte Carlo Analysis on the glycolysis contribution margin analysis

Glycolysis Monte Carlo Analysis	
Mean	$ 5,205
Standard Error	3.53
Median	5206
Mode	#N/A
Standard Deviation	353
Sample Variance	124293
Kurtosis	-0.82
Skewness	0.011
Range	1831
Minimum	4297
Maximum	6128
Sum	52047610
Count	10000

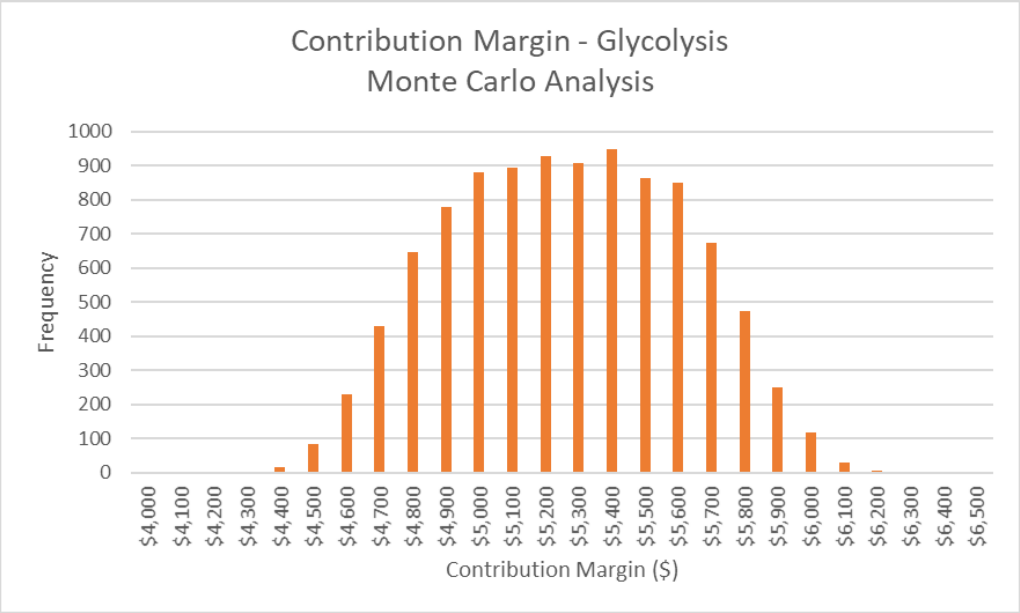

Figure 30. Histogram of Monte Carlo Analysis on the glycolysis process.

Table 29. Statistics from Monte Carlo Analysis on the incineration contribution margin analysis

Incineration Monte Carlo Analysis	
Mean	$ 139
Standard Error	0.52
Median	139
Mode	#N/A
Standard Deviation	52
Sample Variance	2670
Kurtosis	-0.54
Skewness	-0.019
Range	274
Minimum	-1
Maximum	274
Sum	1386346
Count	10000

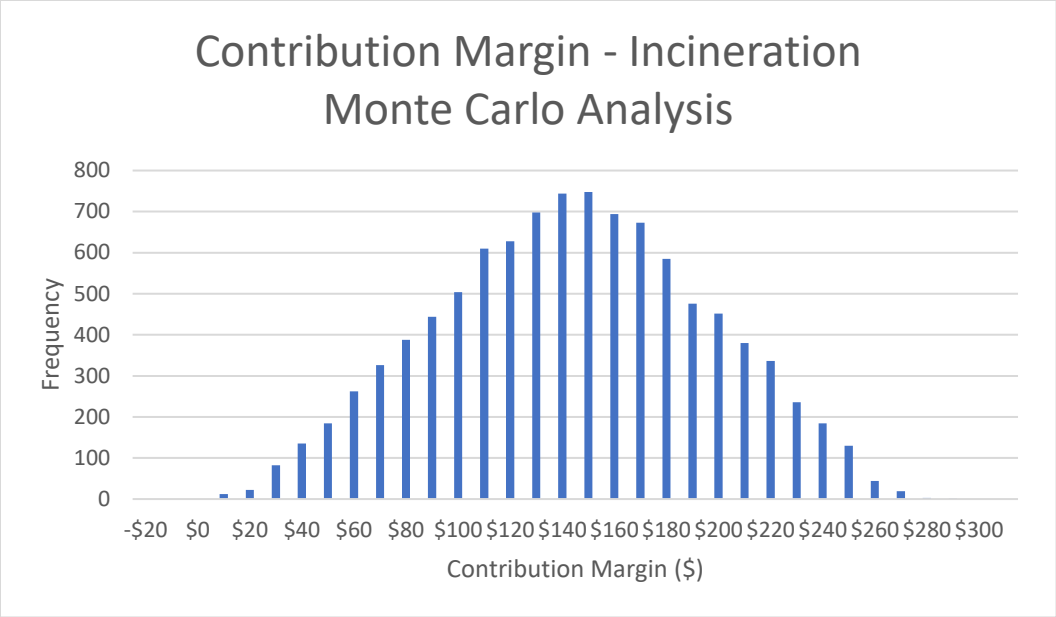

Figure 31. Histogram of Monte Carlo Analysis on the incineration process.

The standard deviation for glycolysis ($353) is 7% of the mean while the standard deviation for incineration ($52) is 37% of the mean. This shows there is considerably more variation in the incineration data. The "minimum" value for incineration goes into negative territory while the minimum for the glycolysis process remains well above negative territory at $4,297.

Discussion

A comparative LCIA analysis, using GaBi modeling software, was conducted on two potential recycling options for flexible polyurethane foam – glycolysis and incineration. The results provided data to answer this project's hypothesis questions. Each question will be reviewed and answered based on the data collected.

Figure 32 graphically depicts the outcome of the LCIA and economic analysis for all the glycolysis scenarios and incineration. The size of the bubbles indicates the economic value of the option. All of the glycolysis processes which use crude glycerol add essentially the same value ($4,259 per 1000 kg fPUF processed). The process using synthetically derived glycerin has a lower value and the value of incineration is the smallest of all options ($146 per 1000 kg fPUF processed).

The environmental impact is shown on the y-axis. The smaller the number, the better. All the glycolysis processes using crude glycerol are very favorable relative to the incineration and glycolysis with a synthetically derived glycerin source. The variations show that the source of the inputs and outputs to the glycolysis process will have an impact on the overall environmental impact. However, all options are far superior to incineration.

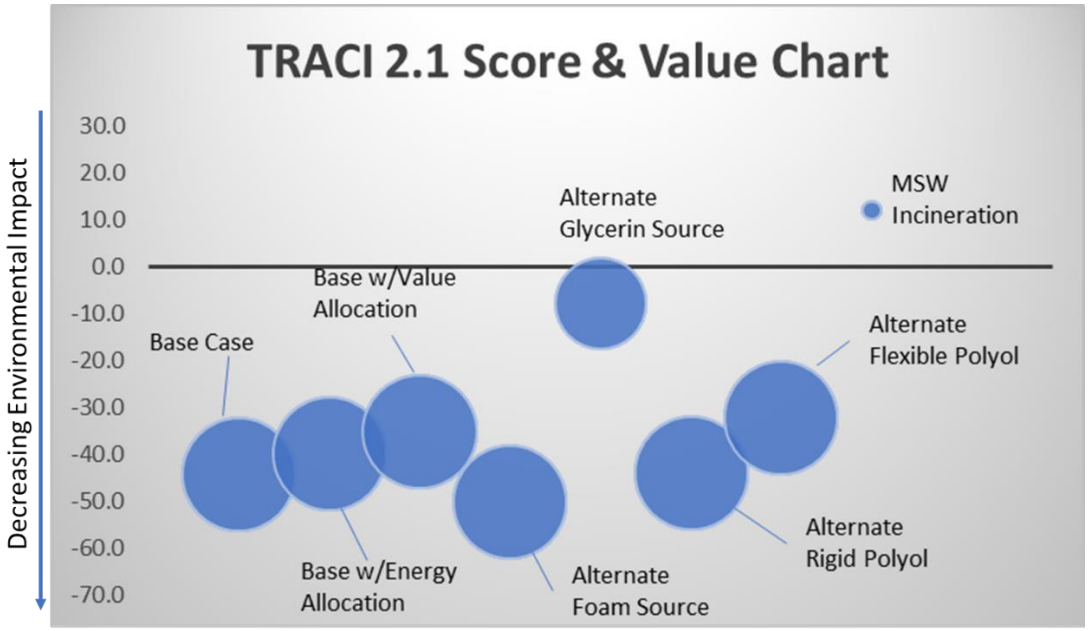

Figure 32. TRACI 2.1 single score and economic value.

Environmental Impacts

The first hypothesis stated that the glycolysis process would have a lower environmental impact, based on TRACI 2.1 methodology, than incineration of the same quantity of flexible polyurethane foam.

Based on the weighted and normalized TRACI 2.1 methodology, this hypothesis is confirmed. The Base Case glycolysis method had a "thinkstep LCIA Survey 2012, NA, TRACI 2.1, incl biogenic carbon (person equiv. weighted)" value of -44.3, a net reduction in environmental impact versus 12.1 for the incineration process.

However, when doing a comparative LCA analysis, rarely is one process superior in every impact category. This was the case for this analysis. The TRACI 2.1 weighting and normalization considers the critical factors and societal influences in the U.S. to generate "single scores" noted above. However, it is critical to understand the key trends and focus regionally to determine which process is best.

If the "Alternate Glycerin" process is removed as an option because it doesn't use crude glycerol, the incineration process had higher impacts in every category except Eutrophication and Human Toxicity – Cancer.

Table 30. TRACI 2.1 weighted values for glycolysis scenarios except synthetic glycerol use and incineration

Traci 2.1, 2012 Weighted Values							
Impact Category	**Base Case (Mass Allocation)**	**Glycerin Allocation - Energy**	**Glycerin Allocation - Value**	**Alt Foam Source**	**Pluriol SG 470 Rigid Polyol**	**Lupranol 2090 Flexible Polyol**	**Incineration**
thinkstep LCIA Survey 2012, NA, TRACI 2.1, incl biogenic carbon (person equiv. weighted)	-44.3	-39.9	-35.2	**-50.1**	-44.0	-32.1	**12.1**
TRACI 2.1, Acidification [kg SO2-Equiv.]	-3.44	-3.80	-3.67	**-4.46**	-1.49	-2.15	**1.23**
TRACI 2.1, Ecotoxicity (recommended) [CTUe]	-12.400	-12.600	-12.000	**-12.800**	-4.840	-9.090	**0.043**
TRACI 2.1, Eutrophication [kg N-Equiv.]	12.90	7.91	5.81	10.40	8.30	**13.00**	**3.19**
TRACI 2.1, Global Warming Air, incl. biogenic carbon [kg CO2-Equiv.]	-1.72	-1.34	-1.04	**-2.41**	-1.73	-1.57	**2.17**
TRACI 2.1, Human Health Particulate Air [kg PM2,5-Equiv.]	-0.47	-0.57	-0.53	-0.92	**-1.25**	-0.10	**0.49**
TRACI 2.1, Human toxicity, cancer (recommended) [CTUh]	1.010	0.747	0.761	1.200	**-0.771**	**1.85**	0.179
TRACI 2.1, Human toxicity, non-canc. (recommended) [CTUh]	-37.1	-26.2	-20.6	-37.3	**-37.6**	-30.8	**1.0**
TRACI 2.1, Ozone Depletion Air [kg CFC 11-Equiv.]	-1.110E-02	**-1.150E-02**	-1.110E-02	-1.010E-02	-3.700E-03	-8.140E-03	**-8.010E-06**
TRACI 2.1, Resources, Fossil fuels [MJ surplus energy]	-2.66	**-3.23**	-3.09	-3.05	-2.16	-2.95	**2.91**
TRACI 2.1, Smog Air [kg O3-Equiv.]	-0.51	-0.81	-0.85	-0.77	**-2.39**	-0.26	**0.881**

Table 30 summarizes the results with the Alternate Glycerin process removed. The data highlighted in brown were the worst performers for a category in the Alternate Glycerin process and are now reassigned to the next worse. This is typically Incineration.

The Alternate Glycerin process did not utilize crude glycerol from soy biodiesel production. The glycerin, at high purity levels, was derived from fossil resources and utilized a much more intensive chemical process in its synthesis. This shows that the use of crude glycerol is critical to not only the strong economic performance of the glycolysis process, but is also key in providing the lowest possible environmental impact relative to incineration.

Eutrophication is defined as "excessive plant and algal growth due to the increased availability of one or more limiting growth factors needed for photosynthesis"

that results in a decrease of biologically available oxygen and the death of fish and other species relying on dissolved oxygen in the water
(Chislock, M. F., Doster, E., Zitomer, R. A. & Wilson, A. E., 2013). It also results in algal blooms, contaminated drinking water supplies and reduced recreational activities in ponds, lakes and rivers.

The run off from industrial processes, sewage and the most important factor, agricultural operations, is the cause of eutrophication. Future technology which can somehow remove the contaminants that cause eutrophication in the cultivation of soy beans will likely improve the performance in this impact category for the glycolysis process.

Stannous octoate was found by the team at UCLM to be the most effective catalyst for the glycolysis process. However, it had a sizable influence in the Human Health – Cancer impact category. This came from the mining of the tin and the creation of the Tin Oxide used to make stannous octoate.

The plan in GaBi for stannous octoate was created by the author and only included the material inputs necessary to make the material. It did not include any processing requirements (steam, electricity, etc.) nor did it include any waste products created by the process. Therefore, the impacts are likely worse that what the study indicated. Other catalysts such as diethanolamine, titanium butoxide, potassium octoate and calcium octoate could be used (Molero, C., Lucas, A. de, Rodríguez, J.F., 2006). However, the quality of the recovered polyols may not be of the quality as when stannous octoate was used. This would require an LCA comparing the overall impacts when the different catalysts are used.

This study also sought to understand which material flows or processes had the largest environmental impact. The contributions to the major impact categories in the GaBi output for TRACI 2.1 can be found in Table 3. This data is based on the functional unit of 1000kg fPUF. The quantity of crude glycerol and stannous octoate are 1480kg and 20kg respectively.

Green highlighted data points note the lowest impact and red highlighted data points note the highest impact.

Table 31. Impact by category for material inputs to the glycolysis process.

Impact Category	Unit	fPUF (1000kg)	Stannous Octoate	Crude Glycerol
Global Warming Potential	kg CO2 equiv	4710	119	-2680
Acidification Potential	H+ mole equiv	1050	130	305
Eutrophication Potential	kg N2 equiv	9.84	0.535	32.6
Ozone Depletion Potential	CFC 11 equiv	0	8.03E-06	2.90E-08
Human Health Cancer Air	Cases	1.16E-06	3.20E-08	5.00E-08
Human Health Cancer Soil	Cases	0	1.27E-07	5.60E-08
Human Health Cancer Water	Cases	3.40E-08	1.41E-05	2.20E-06
Smog	kg 03 equiv	165	1.85E+01	1.04E+02

The results indicate that crude glycerol has a large positive impact on global warming potential relative to the other material inputs because it sequesters CO_2. Depending on whether the new flexible foam is recycled again, this part of the carbon is effectively sequestered infinitely. The rigid foam made from this material will typically have a very long life, but will likely be incinerated or landfilled 10 – 50 years out. The crude glycerol has a large negative eutrophic impact. This is expected since this material is derived from soy beans. Stannous octoate, at a very small relative quantity, has a large impact in ozone depletion potential and human health cancer soil and water. The embodied impacts of the fPUF are most severe in global warming potential, acidification potential, human health air and smog.

The ability to change the impacts of crude glycerol is difficult. If no fertilizers were used, yields would decrease and values in other impact categories would likely increase. The same is true for stannous octoate – other catalysts will likely bring their own unique burdens.

The virgin materials used to manufacture fPUF today contain a large amount of non-renewable, fossil-based materials like ethylene oxide, propylene oxide and diisocyanates. Therefore, a process like glycolysis creates a circular material supply where the recovered materials are used to make new foam and virgin petroleum feedstock use is diminished. The use of crude glycerol is critical for this process to be economically feasible and have the lowest possible overall environmental impacts.

Economics

Like the LCIA impacts of glycolysis versus incineration, the economic evaluation heavily favored glycolysis. The second hypothesis stated that the total net marginal income of the glycolysis process would be higher than that of the incineration process. This data shows this to be overwhelming true.

The average net income generated per functional unit of fPUF processed (1000kg) via glycolysis was $4,259 versus $146 for the incineration process. The recovery of high value polyols, even taken at a 15% discount relative to virgin polyols, coupled with the very low cost of the crude glycerol as a glycolysis agent are what drive the high value generated in this process.

For the glycolysis process, the burden of the process itself, both economically and environmentally, had a minimal impact. The key factor enabling these positive results is

the use of crude glycerol as a feedstock material. Because it is a byproduct in the production of soy biodiesel and supply grossly outstrips demand, it carries a very low cost and low environmental burden in most impact categories.

For the incineration process, the incoming polyurethane carried the biggest burdens environmentally while the operations and maintenance cost for this type of facility had the largest economic impact.

Defining variable costs and income streams was relatively straightforward. Reliable sources were found in most cases. However, the use of water, natural gas and other materials used in pollution control in the incineration process were not be well defined in the LCI for polyurethane incineration within GaBi.

Operations and Maintenance costs were estimated from literature as well. The quality of these values is likely good.

Although incineration has a net positive marginal income, the Monte Carlo analysis indicates that there is a lot of variability, with some scenarios approaching $0 net marginal income. The income generated from electricity and steam, along with tipping fees, is relatively small. Conversely, the O&M costs for incineration are the highest among all options for generating electricity. This is not likely to change under current conditions of low natural gas prices and the fact the renewable energy from wind and solar, even without incentives, are at or below that of natural gas.

In summary, glycolysis using the process defined by UCLM with crude glycerol and the boundary conditions defined by this research project, clearly outperform incineration at MSW facilities in the end of life treatment of flexible polyurethane foam. Economically, glycolysis also outperforms incineration by a wide margin.

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