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Sustainability Evaluation of Pyrolysis of Waste Mattresses: A Comparison with Alternative End-of-Life Treatments

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Abstract. There is a major push by governments and value chain partners to move towards circular options for difficult-to-recycle post-consumer products such as waste mattresses.[1] In the Netherlands alone ~1.5 million mattresses are discarded yearly, of which majority (>60%) is incinerated.[2] A sustainable solution to recycle waste mattresses is required to enable the Dutch industry meet the circular economy goals set by the Dutch government.[3] This paper shares major findings from the screening level life cycle assessment (LCA) of four End-of-Life (EoL) options for post-consumer mattresses: landfill, incineration with energy recovery, pyrolysis and mechanical recycling using powdering. The LCA was an important work package of a technology development project with the objective to quantify potential sustainability benefits of the pyrolysis of waste mattresses.[4] The emphasis of the pyrolysis process is on product recovery as chemical feedstock. The study showed that pyrolysis is a better option than incineration in terms of greenhouse gases (GHG) and cumulative energy demand (CED) for all the studied cases. Base case analysis showed that pyrolysis of waste mattresses can save approximately 526 kg CO_2-eq. and approximately 5.1 GJ (24% savings) CED per ton waste mattresses compared to incineration. Finally, the study concluded that mechanical recycling can either be better or worse than pyrolysis depending on the processes and quality of recycled material.

1 Introduction

Waste mattress recycling is an important issue considering the volume of the waste disposed on a yearly basis. In the Netherlands alone ~1.5 million mattresses are discarded yearly, of which majority is incinerated. The incineration process has high carbon footprint and the material loss diverges the incineration process from a real circular solution. Due to presence of components such as latex, polyurethane, steel springs and textiles, post-consumer mattresses are interesting waste stream for producing chemical intermediates and products.[5,6] This paper explains major findings from the screening level life cycle assessment (LCA) of End-of-Life (EoL) treatment options for post-consumer mattresses. The

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LCA was performed as a key work package within the PRIMA project, a joint industry project sponsored under the Dutch Top Sector Alliance for Knowledge and Innovation (TKI) program. The four EoL treatment options studied for post-consumer mattresses are landfill, incineration with energy recovery, mechanical recycling using powdering (regrinding) and pyrolysis. In order to study the four EoL options consistently, comparable system boundaries were drawn with common assumptions. Sections 2 and 3 explains the LCA goal & scope, system boundaries, and two mattress recycling technologies, i.e. mechanical recycling and pyrolysis, studied in this work. Section 4 explain the lifecycle inventory used in the study. LCA results and conclusions are covered in sections 5 and 6.

2 Goal and Scope

The goal of the LCA is to assess the environmental impacts of the pyrolysis process for recycling waste mattresses and compare it with alternative end-of-life options. The LCA was performed to gain early sustainability insights into the technology development cycle. A comparison is performed with alternative end-of-life options: 1) landfill, 2) incineration with energy recovery and 3) mechanical recycling with quality reduction. For the pyrolysis process, the emphasis is on recovering chemical feedstocks i.e. pyrolysis oil and gas stream mixture rich in hydrocarbons for mechanical recycling, the product recovery is in the form of lower quality material going into 2nd life.

2.1 Functional Unit, System Boundary & Impact Methods

The functional unit is one ton of waste mattresses sent for EoL treatment in the Netherlands. Fig. **1** shows the system boundaries for the four EoL scenarios for post-consumer waste mattresses discarded in the Netherlands. Mattress manufacturing, use phase and disassembly stages are out of scope. The energy flow method and environmental impacts were assessed using the Cumulative Energy Demand (CED) (MJ) version 1.11 and IPCC 2013 GWP 100a (kg CO_2-eq.) version 1.03, respectively. SimaPro 9.1.0.8 was used to perform the LCA.

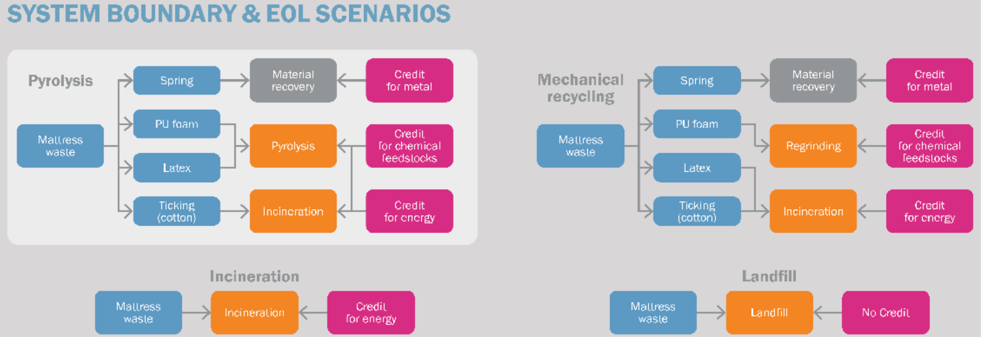

Fig. 1. Four EoL scenarios for waste mattresses and their respective system boundaries.

2.2 Assumptions

Transportation of waste mattresses from the consumer site to the landfill, incineration or to the recycling facilities is neglected. The pyrolysis process is assumed to have furnace efficiency of 70% and energy use of 536.6 kWh/ton. Additionally, the separation of gas phase product stream is modelled using a proxy dataset i.e. ethane separation from natural gas (NGL extraction) and the carbon monoxide formed is assumed to be 100% combusted into carbon dioxide with negligible energy generation. On the other hand, the disassembly, shredding, cleaning, and transportation steps are excluded from the comparative LCA analysis. For mechanical recycling, the quality of recycled PU is assumed to be 80% of the virgin PU quality. It is also assumed that latex and ticking are incinerated (except landfill scenario) and springs are recovered for recycling. Typical waste mattress composition and potential uses of the various components were provided by MRE.

2.3 End-of-Life Treatment Options

2.3.1 *Mechanical Recycling*

In the mechanical recycling process, the mattress is disassembled without any burden and the individual components are treated separately and a credit is given to the recovered components. Details of the studied mechanical recycling process are provided in reference.[7] Mechanical recycling of PU involves two steps: grinding the PU material into a fine powder and mixing powder with polyol component with an optimum concentration of 20 wt% to make new PU foams.[7] In the mechanical recycling model, the polyol production burden is taken into account. In order to achieve a better quality recycled PU, a two-roll mill is necessary to obtain smaller particle size but eliminating this process can save a significant amount of energy. This effect is considered during the analysis.

2.3.2 *Pyrolysis*

Pyrolysis of waste mattresses helps provide valuable feedstock for the chemical industry, thereby contributing towards long-term circular economy ambition of the mattress and PU manufacturers. In the recycling value chain with pyrolysis process, the only post-treatment step is the separation of the gas phase products for use within the petrochemicals industry as chemical feedstock. Methane stream is combusted internally in the pyrolysis process and produces heat equivalent to its calorific value. 70% of this heat is utilized either internally to run the pyrolysis process or externally for heat generation. The remaining 30% of heat is wasted and transmitted to the environment. The main gas fractions are separated and credit is given to the pyrolysis process for these chemical products. The main gas fractions (chemical compounds) are not mentioned here because of project confidentiality constraints.

2.3.3 *Landfill*

For the landfill scenario, the disposed mattress is buried underground or disposed above ground without any credit for energy recovery. There is a very small benefit from methane formation and its use in CHP. This benefit is not accounted in the current landfill model.

2.3.4 *Incineration*

For the incineration scenario, a credit is given to the individual components recovered either as a product or energy. Electricity and heat was generated which replaces the Dutch electricity/heat grid. The efficiency of the electricity and heat production was 17 and 20%, respectively.

2.4 LCA Scenarios

Depending upon the material types and their origin, a mattress can contain significant amounts of fossil or biogenic carbon content. Therefore, two LCA scenario types were defined to study the environmental impacts of the four EoL treatments options and to understand whether pyrolysis is a suitable method for treatment of waste mattresses.

1. **LCA scenario 1:** In LCA scenario 1, we assume that the mattress is made of petrochemicals products – mainly PU and synthetic latex – and has only fossil carbon content. Ticking is also assumed to be of fossil origin.
2. **LCA scenario 2:** In LCA scenario 2, we assume that the mattress has both fossil and biogenic carbon content. PU is of fossil origin. Latex (natural latex) and ticking (cotton) is assumed to be of biogenic origin. We believe that it is the most realistic scenario.

Composition of the mattress material remained the same in the two assessments. We also assumed that there is no change in pyrolysis co-products because of change from fossil to biogenic carbon content of the mattress materials. It must be noted that assumptions on EoL fate for latex and cotton are only for investigating the GWP impacts (fossil and biogenic carbon accounting). For a comprehensive comparison, lifecycle inventories for the four EoL scenarios must be updated to study the other environmental impact categories such as particulate matter, human and marine toxicity etc.

3 Lifecycle Inventory

Background datasets for avoided products, mass and energy inputs and treatment of waste streams were from Ecoinvent 3.6, a well-known global LCA database. Foreground data for the pyrolysis process was provided by PRIMA consortium partners. For the pyrolysis process, Waste4ME provided the mass and energy data including, oil, gas, ash and water fractions. TNO conducted laboratory experiments on the composition of gas fractions from Pyrolysis Gas Chromatography Mass Spectrometry experiments. Experimental and pilot datasets from PRIMA project are not reported in this paper due to confidentiality reasons. A short summary on temporal, technological, geographical coverage, and dataset type is listed in Table 1. Simplified mattress composition and component fate are shown in Table 2.

Table 1. Data quality for foreground and background lifecycle inventories.

Life cycle inventory dataset	Temporal Correlation	Technological Correlation	Geographical coverage	Reliability	Reference
Pyrolysis	2020	Laboratory and pilot scale	The Netherlands	Experimental measurements	PRIMA Project 2020 [9], Waste4ME[10]
Mechanical recycling	2020	Literature (laboratory scale)	The Netherlands	Literature	Literature[7]
Incineration with energy recovery	2018	average Swiss MSWI plant adapted to Dutch geography	The Netherlands	Industry average data	TNO model [11], Literature[12], Ecoinvent database [13]
Landfill	2014	Swiss municipal sanitary landfill	Global (excluding Switzerland)	Literature	Ecoinvent database [13]

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Table 2. Simplified mattress composition and fate of each component in the studied scenarios.

Mattress component	Weight percentage (%)	End-of-Life Scenario			
		Pyrolysis	Incineration	Mechanical recycling	Landfill
Ticking (cotton)	21%	Incineration	Incineration	Incineration	Landfill
Latex	16%	Pyrolysis			
PU (foam)	44%			Material recovery	
Spring	19%	Material Recovery	Material recovery	Material recovery	

4 LCA Results

4.1 Global Warming Potential

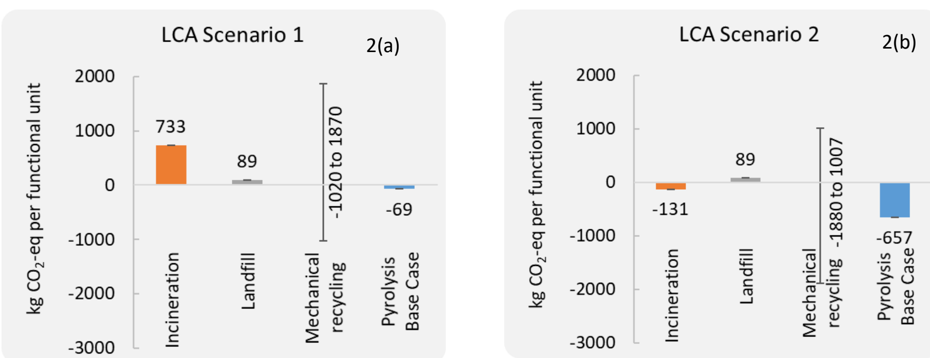

Figure 2 shows comparison of the total GWP impacts of the four EoL scenarios as per LCA scenarios. The most realistic comparison is between incineration and pyrolysis, as currently the majority of mattresses end up in incineration facilities. For the LCA scenario 1, pyrolysis of waste mattress can save approximately 802 kg CO_2-eq per ton mattress compared to incineration with energy recovery. Since the ticking (cotton) and natural latex generate biogenic CO_2 when incinerated, further analysis was carried out to study its effect on the GWP of the four EoL treatment scenarios. Fig. 2 shows the IPCC result for LCA scenario 2. Similar to LCA scenario 1, pyrolysis is a better EoL option in comparison to incineration and landfill. LCA scenario 2 results show that pyrolysis can save approximately 526 kg CO_2-eq per ton of waste fossil based mattress compared to incineration with energy recovery. With 40% mattress weight achieving the same fate, 526 kg CO_2-eq savings for pyrolysis with respect to incineration is considerable. LCA scenario 2 GWP impacts for the four scenarios are significantly lower compared to LCA scenario 1 as carbon ticking (cotton) and latex has zero GWP because of biogenic CO_2 emissions. The negative CO_2 impacts are because of the CO_2 credit received from energy recovery.

Further, in incineration and pyrolysis EoL scenarios, only 60% weight fraction of the mattress changes its EoL fate. The rest 40% of the material, springs and ticking made of synthetic fibres, have the identical fate. In both pyrolysis and incineration scenarios, springs go for material recovery whereas ticking goes for incineration. Comparing pyrolysis with the landfill scenario can imply that pyrolysis is a better EoL option. This effect manifests itself in mechanical recycling scenario as well because it was assumed that latex and ticking fractions were sent to incineration with zero emissions. However, in the pyrolysis case only ticking is sent to incineration. Therefore, biogenic carbon accounting has less impact on incineration GWP impacts in the two LCA scenario types.

GWP impacts of mechanical recycling depends on the recycling process used and the trade-off between quality and energy consumption to achieve a specific quality for recycled material. Two options were studied for mechanical recycling, with or without two-roll mill, which shows considerable variation in the GWP impacts of mechanical recycling. The use of the two-roll mill provides a smaller powder size and therefore a higher surface area to react with polyol end-groups, leading to a better and more uniform reaction. However, this improvement in the quality comes with the expense of environmental burdens assigned to the two-roll mill process. In Figure 2, large uncertainty or range in the CO_2 emissions is a result of mechanical recycling steps where injection moulding and two-roll mill processes are used. For mechanical recycling, substitution ratio of 0.8 is a major influencing parameter for GWP impacts. Further, recycling of latex and ticking fractions (that are now assumed to be incinerated) and improved regrinding technology could lead to better performance of mechanical recycling. Therefore, mechanical recycling can be both better and worse than pyrolysis, landfill and incineration as an EoL option.

4.2 Cumulative Energy Demand

The energy demand using CED method is depicted in Fig. 2 and is the same for LCA scenarios 1 and 2. The current pyrolysis process seems not to outperform incineration in terms of energy demand as the values are in the same order of magnitude. The two-roll mill process in the mechanical recycling scenario is an energy demanding step and its avoidance can lead to a significant saving in cumulative energy demand. Landfill shows the worst performance with insignificant overall energy consumption.

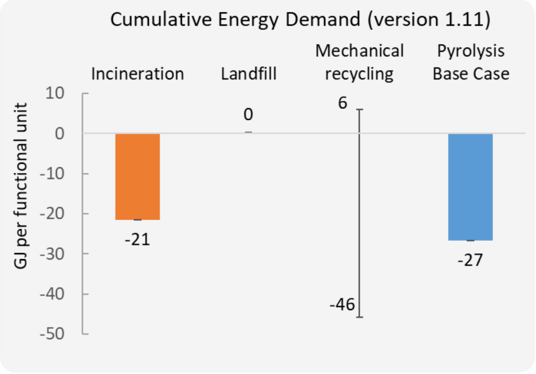

Fig. 2. CED comparison of the four EoL options.

5 Conclusions

This paper explains major findings from the screening level LCA for the post-consumer mattress performed within the PRIMA project. Using the IPCC GWP and CED impact assessment methods, we concluded that in comparison to incineration as the current EoL option, both pyrolysis and mechanical recycling seem to be a suitable option. Pyrolysis of waste mattress can save approximately 526 kg CO_2-eq per ton mattresses compared to incineration. The CO_2 savings are higher at 802 kg CO_2-eq per ton mattresses when organic components of the mattresses are assumed to be 100% fossil based. Pyrolysis of waste mattresses can save approximately 5.1 GJ (24%) cumulative energy demand per ton mattresses compared to incineration. The CO_2 savings will slightly reduce if the ticking was pyrolyzed as well, instead of being incinerated. On the other hand, mechanical recycling can be a better or worse option depending on the technology used and quality of the recycled material. Mechanical recycling can save up to 1749 kg CO_2-eq per ton mattress compared to incineration. Although, this value varies significantly depending on the technology used. Furthermore, we recommend further investigation and comparison of mechanical recycling option with pyrolysis to quantify the environmental savings and circularity potential of the two recycling solutions. Finally, we recommend the use of other environmental impact assessment methods because a single impact assessment method does not provide comprehensive understanding of lifecycle impacts of landfill as EoL. Other impact categories such as fossil resource or eco-toxicity using impact methods such a ReCiPe 2016 will be more reflective of the total environmental damages associated with the landfill scenario.

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