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Environmental impacts of reclamation and recycling processes of refrigerators using life cycle assessment (LCA) methods

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ABSTRACT

China has enacted a series of policies and regulations that require manufacturers to reclaim and recycle obsolete refrigerators to mitigate the life cycle environmental impacts and to improve resource efficiency. However, it is not clear whether the environmental benefits of recycling refrigerators can be balanced with the emissions from the reclamation and recycling processes. To address this issue, environmental impacts of recycling refrigerators under different scenarios were quantified through a comparative life cycle assessment. The data were mainly acquired from a large professional refrigerator recycling company. The CML 2001 method built in the GaBi software (Version 6.0) was used to quantify the environmental impacts. The result shows that the environmental benefits brought about by recycling mainly come from the resource and energy savings in the upstream production, such as in the high impact polystyrene recycling (22.17%), the steel recycling (23.94%), and the copper recycling (8.10%) phases. Compared to railway, motor is a more environmentally friendly transportation for refrigerators. Recycling refrigerators increase the ozone layer depletion potential because the crushing process inevitably releases the CFC-11. The environmental impacts of transportation may exceed the environmental benefit of recycling refrigerators. This study will be useful for manufacturers to design new recycling networks from the life cycle and environmental impact perspectives.

1. Introduction

In the past decade, China increased its refrigerator production capacity with an annual growth rate of 5% and produced 93.37 million refrigerators in 2014 alone (National Bureau of Statistics of China, 2014). Consequently, the waste refrigerators also increased greatly and the highly valuable materials in waste refrigerators have stimulated the unregulated recycling activities, which caused severe pollution on the local soil and groundwater. To regulate the reclamation and recycling activities and mitigate the pollution, China has enacted a series of policies and regulations. These legislations led to more environmentally friendly activities within the specific reclamation or recycling stages regarding some environmental impact categories (Zhou and Gao, 2007); however, the question remains as to whether the environmental benefits of recycling refrigerators can be balanced with the emissions from the reclamation and recycling processes.

Most published articles have emphasized the development of disassembly technologies for recovering the materials from waste refrigerators rather than discussing the environmental impacts. For example, Altekin et al. (2008) reported the development of a refrigerator disassembly chain. An environmentally friendly production line was reported in China for recovering the cabinet of waste refrigerators with the recovery rate of 97.6% (Ruan and Xu, 2011). To securely recover valuable materials, Mitsubishi Electric Corporation adopted a disassembling and classification process before throwing waste refrigerators into crushing machines to improve the purity of the recovered materials and to reduce the harm to landfill sites (Kotera et al., 1999). Laner and Rechberger (2007) summarized the European state-of-the-art recycling technologies of refrigerators. These studies considered the efficiency of recycling resources but concerned little about the environmental impacts of recycling systems. Some studies further discussed the economic costs and the environmental benefits to improve the effectiveness of policy-making for recycling waste refrigerators (Lambert and Stoop, 2001; Nicol and Thompson, 2007).

As an effective way to analyze the life cycle environmental performance of products, the life cycle assessment (LCA) was used

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to quantify the environmental impacts of refrigerators (Kim et al., 2006; Gehin et al., 2009). However, these studies either considered only specific processes or stages, or compared the environmental impacts of refrigerators manufactured with different technologies and materials. For example, the phosphating and foaming processes result in environmental pollution. The former discharges wastewater with phosphorus and can eutrophicate local surface waters and the latter emits cyclopentane gas at a rate of 0.03 kg/h and is harmful to human health (Ruan and Xu, 2011; Zhang, 2010; Chen, 2011; Liu, 2011). The energy consumption and greenhouse gas emissions of refrigerators were also compared between two different foamers, HFC-245fa (pentafluoropropane) and pentane, as well as the life-cycle climate performance (LCCP) of different refrigerating fluids based on measured data (McCulloch and Lindley, 2003; Johnson, 2004; Yunho et al., 2007). Considering that the components contain heavy metals, they can pollute air, soil, and water if the waste refrigerator is arbitrarily discarded or sent to landfill directly at the end of a refrigerator's life (Liu and Chi, 2013). The environmental consequences of reclamation and recycling waste refrigerators across different regions still remain unknown. This study aims to quantify the environmental impacts of refrigerator reclamation and recycling systems and to examine the rational reclamation distance in terms of environmental benefits.

2. Methodology

This study does not cover the whole life cycle of the refrigerators, but the same methods used in LCA are used in it. The report was only examined by coauthors and not tested by experts outside. The study is completed with four steps including the goal and scope definition, the life cycle inventory (LCI) analysis, the life cycle impact assessment (LCIA), and the life cycle improvement analysis and interpretation. We also took some methods (Guinee, 2002) to ensure that environmental impacts are assessed within a consistent framework to avoid “problem shifting”.

2.1. Functional unit

The functional unit is defined as a “1 kg waste refrigerator made in China.” The direct-cooling double-door waste refrigerator was selected because this type of refrigerator is the most popular, accounting for nearly half of the market share, and because direct-cooling refrigerators hold 90.3% of the market share of double-door refrigerators (Internet Consumer Research Center, 2014).

2.2. System boundary

The recovery and disposal technologies for discarded refrigerators are still being developed in China (Li, 2007). To recover waste refrigerators, private vendors go into communities to collect obsolete refrigerators from the residents with little compensation; the refrigerators are then sold to professional disposal firms which refurbish or dismantle them. We investigated a large professional refrigerator recycling company in Qingdao Shandong province and acquired onsite information about the recycling process. The company was selected primarily based on its scale and technical level which was encouraged and supported by the Ministry of Environmental Protection to be the representative for recycling white appliances. On the other hand, Jiangsu province has a large amount of inventory and scrappage of refrigerator and ranked fourth nationwide below Shandong province, Sichuan province, and Henan province (National Bureau of Statistics of China, 2014).

The choice of the system boundaries is important and affects the LCA results (Guinee, 2002). Based on the research objectives, the system boundary is shown in Fig. 1. The refrigerator is transported from the collection site in Nanjing, Jiangsu province, to the disassembly and recycling plant in Qingdao, Shandong province. In the plant, refrigerants, compressors, and accessories are manually separated firstly, and the compressors are used for direct, second-hand sale. The remaining parts such as the metals and plastics are further separated by follow-on processes. The plastics are granulated and regenerated in the factory, then sold to refrigerator manufacturing enterprises. The recovered metals (copper, iron and aluminum) are sold to metallurgical enterprises. Polyurethane (PUR), a type of hazardous solid waste, is incinerated then transported to a landfill. The recovered energy from gases generated by incineration of PUR is used for upstream production of steel plate. Previous research shows that the recovery and recycling of waste materials and energy brings environmental benefits (Zhang, 2010; Li, 2007).

2.3. Data sources and data quality requirements

2.3.1. Data sources

Types and sources of data may include a mixture of measured, calculated or estimated data. In the first stage of life cycle, the transportation distance of a refrigerator from Nanjing city to Qingdao city is calculated with the assistance of Google Maps. We enter the location names of the departure and the destination, and the distance will be calculated automatically, which is 573 km by road or 884.1 km by rail respectively in the Google Maps. In the second stage of life cycle, we investigated Qingdao Chunqi renewable resources Co. Ltd, a large professional refrigerator

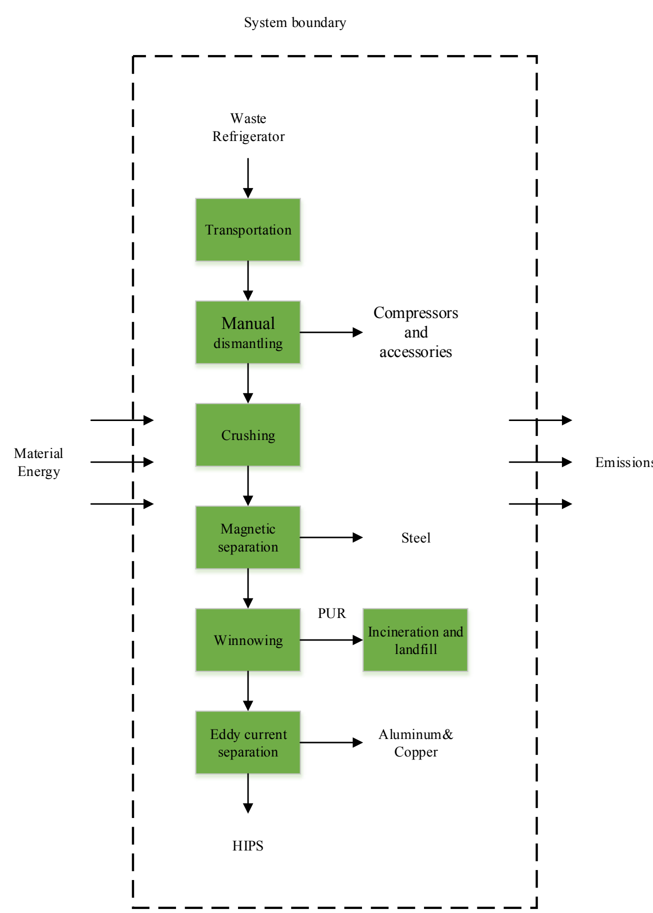

Fig. 1. System boundary for the LCA study.