Int J Life Cycle Assess (2016) 21:15–28
DOI 10.1007/s11367-015-0993-5

LCA FOR MACHINES

Life cycle assessment of horizontal-axis washing machines in China

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Received: 20 November 2014 / Accepted: 28 October 2015 / Published online: 6 November 2015

Abstract
Purpose Currently, environmental sustainability of washing machines, one of the most popular household appliances in people's daily life, has gained much attention from governments and suppliers due to resource and energy consumptions as well as emissions in the production, distribution, use, and disposal processes. Therefore, it is necessary to systematically evaluate the environmental impacts from a life cycle perspective to explore the sustainability improvement opportunities of washing machines especially for China, a major producer, exporter. and consumer.
Methods This study is conducted according to the International Organizations for Standardization's 14040 standard series from cradle to grave. The research object is a Chinese-produced horizontal-axis washing machine. The production and recycling data mainly come from field investigations on representative firms, including both household appliance production and recycling firms in China. The use phase data are mainly from 1330 questionnaires about Chinese residents. The secondary data are supplemented from databases, literature, and authoritative technical manuals. The potential environmental impacts are evaluated using the CML2001 methodology built into the GaBi version 6.0 software. The hotspots throughout the life cycle of the washing machine are determined with the impact categories of abiotic depletion, acidification potential, global warming potential, photochemical ozone creation potential, eutrophication potential, and toxicity.
Results and discussion The results show that the production and use phases are the main contributors to the environmental impacts dominated by electronics, plastic components, and electricity consumption as well as the wastewater discharge in use phase which brings eutrophication potential. While, the end-of-life phase brings recycling credits due to the recycling of materials such as copper, steel, and plastics. In particular, aluminum and copper consumption in the electronics, electricity consumption, and plastics used in injection molding of plastic parts, electricity consumption, and detergent use in use phase are the main hotspots based on the results of life cycle impact assessment. The use phase scenario analysis shows that water temperature is the most important factor that decides the environmental impacts because heating water consumes large amounts of electricity.
Conclusions This quantitative life cycle assessment can be a useful tool for decision-makers to understand the life cycle environmental impacts of Chinese washing machines and explore sustainability improvement opportunities, as well as help manufacturers identify priorities for actions from an environmental protection perspective.

Keywords Cleaner production · Consumer behavior · Environmental management · Household appliance · Life cycle assessment · Sustainability · Washing machine

Responsible editor: Chris Yuan

Electronic supplementary material The online version of this article (doi:10.1007/s11367-015-0993-5) contains supplementary material, which is available to authorized users.

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1 Introduction

Washing clothes and other home textiles is a common form of housework. Currently, due to technological and economic development, washing machines have played an important role in people's daily life. China has been a major producer and consumer of washing machines in the world. According to the Chinese Statistical Yearbook (National Bureau of Statistics of China 2013), the yield of washing machines increased by 166 % from 2004 to 2012, reaching 67 million sets in 2012, and the penetrations of washing machines in Chinese urban and rural households were 98.02 and 67.22 %, respectively. However, the production, transportation, and use of washing machines have potential environmental impacts. For example, in the production stage of washing machines, the degreasing and phosphating processes use large amounts of surface treatment chemicals such as bonderite and discharge a significant amount of pollutants into the environment. Chlorinated agents, widely used solvents for metal degreasing process, are considered as the sources of both greenhouse gases and volatile organic compounds (Kikuchi and Hirao 2008). Hence, the government and the enterprises are paying more attention to the sustainable development of washing machine industry. Besides, washing machine operation consumes water, electricity, and detergents at varying degrees depending on the design of washing machines and consumer behaviors (Pakula and Stamminger 2010). Several national standards for washing machines have been enacted in China to save energy and improve water use efficiency in use phase, such as the National Standards for Household Electric Washing Machines (China National Standardization Management Committee 2003), and Maximum Allowable Values of Energy, Water Consumption, and Grades for Household Electric Washing Machines (China National Standardization Management Committee 2013). These regulations have already achieved significant improvements in energy efficiency, but the residents' daily usage habits also have an important effect on the consumption of energy and water. Besides, with the continuous increase of washing machines, large quantities of electronic wastes are produced and discarded every year, and the obsolete washing machines are estimated to be 687 to 708 million sets in 2030 in China (Zhang et al. 2012). For the disposal of washing machines, standardized recycling is favorable to improving the resource recovery and mitigating pollution (Friege 2012; Yu et al. 2014; Zhu et al. 2012), while poor technologies and operations can lead to the waste of resources and negative impacts on human health (Hertwich and Roux 2011). Considering the huge amount of obsoleted home appliance and the poor recycling status at present in China, legislations have also issued to improve the management of waste electrical and electronic equipment (WEEE) in China (Ministry of Industry and Information Technology of the People's Republic of China 2014). Under this situation, more and more used washing machines would have to be collected and recycled, which would require fully understanding their potential environmental impacts (Yu et al. 2014). Therefore, it is necessary to systematically evaluate the environmental impacts of washing machines from a life cycle perspective so as to identify the potential hotspots to improve the sustainability of washing machine industry.

Life cycle assessment (LCA) is an effective tool to evaluate the resource consumption and potential environmental impacts of a product throughout its life cycle (International Standard Organization 2006). For example, the life cycle concept was usually used to explore the design of washing machines, taking the whole life cycle into account and figuring out a way to improve the environmental performance in every life stage (Hou 2012; Xi 2010). But, these studies just stay in life cycle thinking and qualitative description lacking of quantitative environmental impact assessment. The life cycle inventory (LCI) and life cycle cost (LCC) of vertical-axis washers and horizontal-axis washers were established to find when it would be the most economically and environmentally efficient for residents to replace vertical-axis washer with a new horizontal-axis washer (Bole 2006). However, this study was focused on LCI without quantifying the life cycle environmental impact. There are some LCA researches focused on a certain process of washing machine. For instance, the environmental impacts of the end-of-life stage of washing machines were ever assessed using LCA methodology (Menikpura et al. 2014; Nakano et al. 2007). It was found that the washing machine recycling has reduced 3.8E+4 t CO_2eq emissions with the implementation of the Home Appliance Recycling Law in Japan (Nakano et al. 2007). Furthermore, the water and electricity consumption were ever analyzed by quantifying the behaviors such as washing frequency and washing temperature of consumers from 38 countries in use phase of washing machines, but the environmental impacts associated with water and electricity consumption were not involved (Pakula and Stamminger 2010). Some studies were concerned about the whole life cycle of washing machines and environmental impacts. For example, Rüdenauer used LCA and LCC methodologies to determine the optimal life span of washing machines based on situation in Germany with secondary data. But, this study did not analyze the effect of different kinds of washing machines and consumer behaviors on the results (Rüdenauer et al. 2005). In addition, the CO_2eq emissions of washing and drying with heat-pump washer-dryers were ever compared with the conventional washer-dryer (Yamaguchi et al. 2011). But, this study considered only CO_2eq emissions associated with the production phase and did not concern the impacts of recycling of washer-dryers.

Based on the review of previous literature, considering the differences of production technologies and consumer behaviors between China and other countries, this study conducted a life cycle assessment of a horizontal-axis washing machine over its entire life cycle based on Chinese situation. In consideration of the importance of first-hand data in LCA study, the main data are acquired from on-field surveys about household appliance manufacturers and recycling enterprises, as well as consumers in China. The study object is selected according to the market share in 2012 (Li 2013), and the horizontal-axis washing machine has become more and more popular among consumers due to its better detergency, less abrasion of clothing, and higher efficiency. The outcome of this study is to offer some practical suggestions on the environmental performance improvement of washing machines in China, and to establish a scientific basis for policy makers to achieve environmental sustainability.

2 Methodology

This study was conducted in accordance with the principles of the International Organization for Standardization's (ISO) 14040 series of standards for life cycle assessment (International Standard Organization 2006). The LCA models for the washing machine are established in GaBi 6.0 software, and the mid-point CML 2001 method (updated Nov. 2010) is used for the impact assessment.

2.1 Description for the manufacturing processes of the washing machine

Four main processes for manufacturing a washing machine are considered in the study: injection molding of plastic parts, stamping and bending of the inner tube and cabinet, powder spraying of the cabinet, and assembly. In the injection molding process, the plastic parts, such as detergent box, outer tub, control panel, and pedestal of a washing machine, are made from plastic granulated using injection machines at a temperature of 200 °C. In the stamping and bending process, the inner tube and cabinet are made from the steel sheets which are firstly stamped to the expected shape by the punch machine and then bended by the bending machine. In the powder spraying process, the cabinet after stamping and bending is hung on the transmission belt, but first, it is degreased to remove the oil on the surface, at a temperature of 55–65 °C. After degreasing, it is rinsed to remove the degreaser. Second, it is given the surface treatment using regulating agents to prepare for phosphating. Third, it is treated by phosphating using sodium dihydrogen phosphate at a temperature of 40–50 °C. After phosphating, it is rinsed to remove the phosphating agents. Next, it is heated at a temperature of 200 °C to dry the components. The last step is to spray in an airtight electrostatic powder plating room, equipped with a spray gun, a powder supplying system and automatic powder recycling system. After spraying, it is roasted at 200 °C. The assembly process uses pipeline operation, and each worker is responsible for only one part of washing machines. All components are assembled and then tested. Finally, products are loaded and stored.

2.2 Goal and scope definition

The specific objective of this study is to evaluate the life cycle environmental impacts by quantifying the consumptions of resources and energy and the emissions of a horizontal-axis washing machine in China. Based on this analysis, we also identify the environmental hotspots and seek opportunities for improving its environmental performance.

2.3 Functional unit and system boundary

This study chooses a horizontal-axis washing machine as the research object, which is produced in China and has a rated capacity of 6 kg and a life span of 10 years, as shown in Table 1. We selected the horizontal-axis washing machine as the study object based on the following two factors: (1) the horizontal-axis washing machine is 50 % more popular than the vertical-axis washing machine in the Chinese market (Li 2013); and (2) the enterprises investigated mainly produce horizontal-axis washing machines. The 10-year life span of a washing machine is based on a literature review and expert estimation (Shen and Mi 2007). The functional unit is defined as "a single horizontal-axis washing machine during its 10-year service life in China", and the amount and frequency of laundry are based on the questionnaires of the Chinese laundry habits.

The system boundary of this study is the entire life cycle of a horizontal-axis washing machine, including raw material extraction and processing, manufacture and assembly, distribution, use, and disposal, as shown in Fig. 1. Specifically, the following modules are considered: (1) raw material extraction and processing of the washing machine, which is based on the data mainly from the Ecoinvent and Gabi database; (2) manufacturing and assembly of the washing machine, which is based on the data from the field investigations; (3) distribution of the washing machine from manufacturers to consumers; (4) washing process in household; and (5) recycling and landfill disposal of the waste washing machine. The collection of used washing machines is excluded in this analysis due to data unavailability. Currently, the used washing machines are mainly collected by thousands of manual workshops in China, and these firms have poor and even no basic informational statistics (Li and Gu 2012). All of these make it difficult for us to acquire data for the collection phase.

2.4 Data collection

The primary data on the production stage are acquired from field investigations at representative enterprises in Shandong Province, Zhejiang Province, and Jiangsu Province, including information on the components of the washing machine and

Table 1 Key parameters of the studied horizontal-axis washing machine

Product	Horizontal-axis washing machine
Rated capacity	6 kg
Washing power	190–230 W
Wash program	Cotton, memory, wool, soak, bulky items, synthetic fiber, quick wash, allergen
Temperature selection	30, 40, 60, 90 °C
Dehydration power	170–220 W
Rated voltage	220 V/50 Hz
Dimensions	664×653×1030 mm
Weight	75 kg

their respective weights and materials, as well as the production processes. Additionally, previous literatures (Rüdenauer et al. 2005; Yamaguchi et al. 2011) provide a compensation for missing data. The LCI of upstream processes of materials originates from the Ecoinvent and PE International professional databases. If unavailable, new LCIs for a few auxiliaries, such as the degreasers and phosphatizing agents, are established with data from technical handbooks, patent reports, and literatures.

The materials accounting for 96 % of the total mass of the washing machine, auxiliaries, electricity, steam, compressed air, heavy oil, town gas, and water are considered to be inputs, while the washing machine and emissions are considered to be the outputs. The auxiliaries are used as degreaser, surface treatment agents, and phosphating agents, and water is employed to rinse the component in the powder spraying process. Emissions from washing machine production include wastewater containing chemical oxygen demand (COD), biochemical oxygen demand (BOD), suspended solids (SS), PO_4^{3-}, and exhaust containing non-methane hydrocarbon compounds (NMHC). The plastic parts, inner tube, and cabinet of the washing machine are assessed considering the production of raw materials and processing to finished products, while the other components such as the electronics (including motor of washing machine) and glass door are assessed with only the production of raw materials and processing to semi-finished products. There is little information available for the last manufacturing processes of these components, and the assembly enterprises indicated that these parts are outsourced but have no access to the energy and water consumption data from their suppliers. Under this circumstance, we are only able to take into account the semi-finished products for parts. Table 2 provides the life cycle inventory of production process. The main components include cabinet, inner tub, plastic parts, electronic components, glass door, cable, counterweight, other steel parts, and packaging materials. Furthermore, assembly is comprised in the production process as well. The details about material and energy consumptions as well as emissions of each component or process are shown in Table 2.

The transportation stage of the washing machine contains two phases. The first phase is the transportation of washing machines from manufacturers to wholesalers/retailers, such as supermarkets. The transportation distance of the first phase is calculated theoretically on the basis of the ownership rate of each province and the annual yields and sales of washing machines in China (National Bureau of Statistics of China 2013). For 13 provinces where washing machines are produced (Chinese economic information network data corporation 2012), we assume that the demand of these regions are satisfied first, and the surplus washing machines are exported to other provinces nationwide. Hence, seven output provinces were selected. Then, we use the gravity model (Yang and Liu 2006) to assign the output to each province. The distance between input and output provinces is simplified as the distance

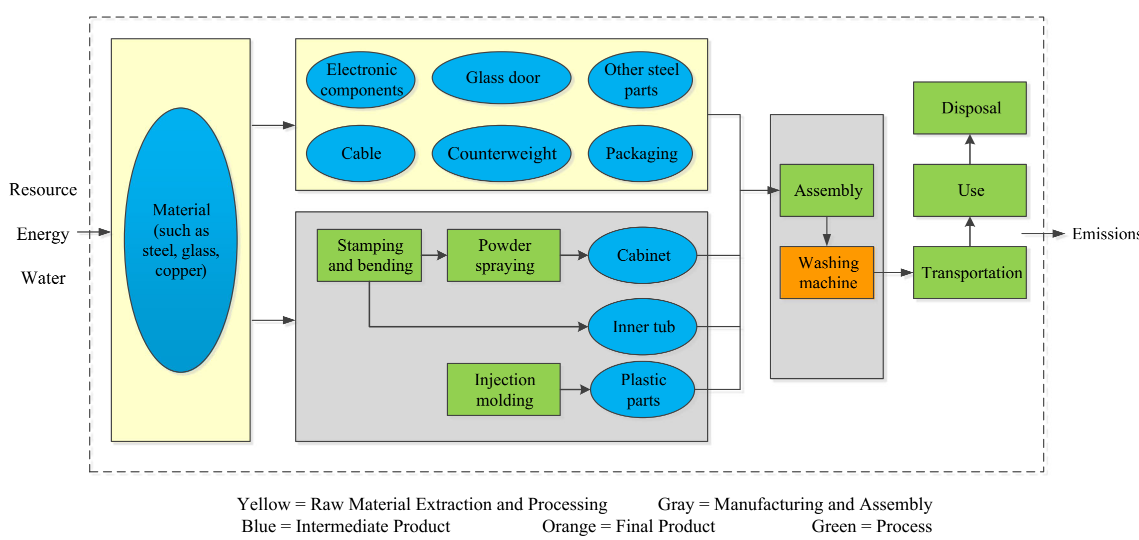


Fig. 1 System boundary for the life cycle assessment of a washing machine

Table 2 LCI of production phase per horizontal-axis washing machine

Component	Material/energy consumption		Emissions		Data source
	Category	Amount	Category	Amount	
Cabinet	Compressed air (m^3)	3.7	Non-methane hydrocarbon (g)	0.33	Field investigation
	Steel (kg)	18.88	waste water (kg)	10	
	Steam (kg)	1.37	SS (kg)	0.005	
	Water (kg)	11.5	COD (kg)	0.006	
	Electricity (kWh)	1.3	Phosphate sludge (g)	0.017	
	Epoxy resin (kg)	0.167	Scrap steel (kg)	0.19	
	Phosphating agent (kg)	0.01			
	Degreaser (kg)	0.0104			
	Surface conditioning agent (g)	0.5			
Inner tub	Steel (kg)	7.879	Scrap steel (kg)	0.079	
	Electricity (kWh)	5.36			
Plastic parts	Electricity (kWh)	116	Scrap ABS (kg)	0.64	
	ABS (kg)	21.25	Scrap PP (kg)	0.22	
	PP (kg)	7.47	Scrap PVC (kg)	0.03	
	PVC (kg)	1.03			
Electronic components	Aluminium (kg)	5.76			
	Iron (kg)	0.92			
	Copper (kg)	1.81			
	Synthetic rubber (kg)	0.88			
	Electricity (kWh)	2.88			
Glass door	Natural rubber (kg)	0.01			
	Glass (kg)	1.8			
Cable	Cable (kg)	0.63			
Other steel parts	Steel (kg)	4.34	Scrap steel (kg)	0.04	
Counterweight	Concrete block (kg)	0.2			
Assembly	Heavy fuel oil (kg)	0.46			
	Electricity (kWh)	8.87			
Packaging materials	Kraft liner (kg)	1.3			Rüdenauer et al. (2005)
	Nylon (kg)	0.1			
	paper (kg)	0.15			
	PE (kg)	0.2			
	PS (kg)	0.5			

LCI life cycle inventory, *COD* chemical oxygen demand, *SS* suspended solids, *ABS* acrylonitrile-butadiene-styrene, *PP* polypropylene, *PVC* polyvinylchloride

between the provincial capitals with the help of Google Map. Based on the above information, the average transportation distance of a washing machine is calculated as 1252 km. The second phase is the distribution of washing machines from retailers to individual families. Generally, commercial groups have set up their logistics networks for household appliance distribution in China, including regional distribution centers, urban distribution centers, and transfer stations. The average distribution radius of retailers is 80–150 km, and so, we take the average distance 115 km as the final value of the second transportation phase. Therefore, the total transportation distance is 1367 km. The LCI data of washing machine transportation is based on Ecoinvent database v2.2: RER: transport, lorry 16–32t, EURO4. We selected these data because the emission standards for trucks started executing "Stage IV" in China from 1 January 2015 (Ministry of Industry and Information Technology of the People's Republic of China 2014), and the fourth stage emission standards are generally based on European emission standards EURO IV.

A total of 1330 questionnaires collected by face-to-face interviews and online surveys supplied information on the operation of washing machines. The content of the questionnaire involved the washing load size, washing frequency, program settings, and dosage of detergents, which determine the electricity and water consumption for clothes washing. The program settings of using a washing machine can further be subdivided into the selection of temperatures, water volumes, washing time, dehydration time, and rinsing times. Analysis of questionnaires shows that one family washes 2.6 times per week (133 washes per year) in China, with an average load of 60 % of its capacity. In use phase, electricity, water, and detergent are considered to be inputs, while wastewater containing BOD, COD, NH_3-N, total nitrogen, and total phosphorus is considered to be outputs. Data on the energy for the mechanical actions, water use, and wastewater discharge per wash cycle are calculated using expert estimation and the washing machine instruction manuals. More detailed life cycle inventory of use stage concerning the consumption of electricity, tap water, and detergent, as well as the emissions can be found in Table 3.

For the end-of-life phase, the data are based on a field survey at an appliance recycling enterprise in combination with literature reviews (Liu 2011; Matsuto et al. 2004; Ruan 2012). The considered processes include disassembly, shredding, and separation. Washing machine disassembly is mainly a manual operation. After disassembly and removing the components such as cabinets, the residues are shredded and separated into metals and plastics. The materials that can be recycled include steel, copper, iron, aluminum, polypropylene (PP), acrylonitrile-butadiene-styrene (ABS), and polyvinylchloride (PVC), and all other materials are disposed in a landfill. It is noteworthy that the recycling of steel, copper, iron, aluminum, PP, ABS, and PVC can bring recycling credits, and it is shown as negative value in LCIA results. The total recovered materials are 64.76 kg, occupying approximately 86 % of the total mass of the washing machine. The detailed life cycle inventory data about the disposal process regarding the weight of all kinds of recycled materials and electricity consumption are shown in Table 3.

2.5 Life cycle impact assessment

For the impact assessment, the mid-point CML 2001 method (updated November 2010) is used to determine hotspots throughout the life cycle of the washing machine. The impact categories include abiotic depletion (ADP elements and ADP fossil), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP), photochemical ozone creation potential (POCP), freshwater aquatic ecotoxicity (FAETP), marine aquatic ecotoxicity (MAETP), human toxicity potential (HTP), and terrestrial ecotoxicity potential (TETP).

Table 3 LCI of use and disposal phase per horizontal-axis washing machine

Resource/energy consumption	Amount	Data source
Life cycle phase: use		
Resource consumption		
Water	88,320 kg	Questionnaires, expert estimation and instruction manual
Electricity	517.38 kwh	
Detergents	20.16 kg	
Emission to water		
COD	28.5 kg	Zhao et al. (2010)
BOD_5	12.2 kg	
NH_3-N	0.5 kg	
Total nitrogen (TN)	2.3 kg	
Total phosphorus (TP)	0.4 kg	
Life cycle phase: end-of-life		
Resource consumption		
Steel	−30.17 kg	Liu (2011)
Copper	−1.5 kg	Matsuto et al. (2004)
Iron	−0.91 kg	
Aluminum	−4.76 kg	
Plastic	−27.42 kg	
Electricity	7.23 kwh	Field investigations
		Ruan (2012)
Landfill	6.9 kg	PE professional database

LCI life cycle inventory

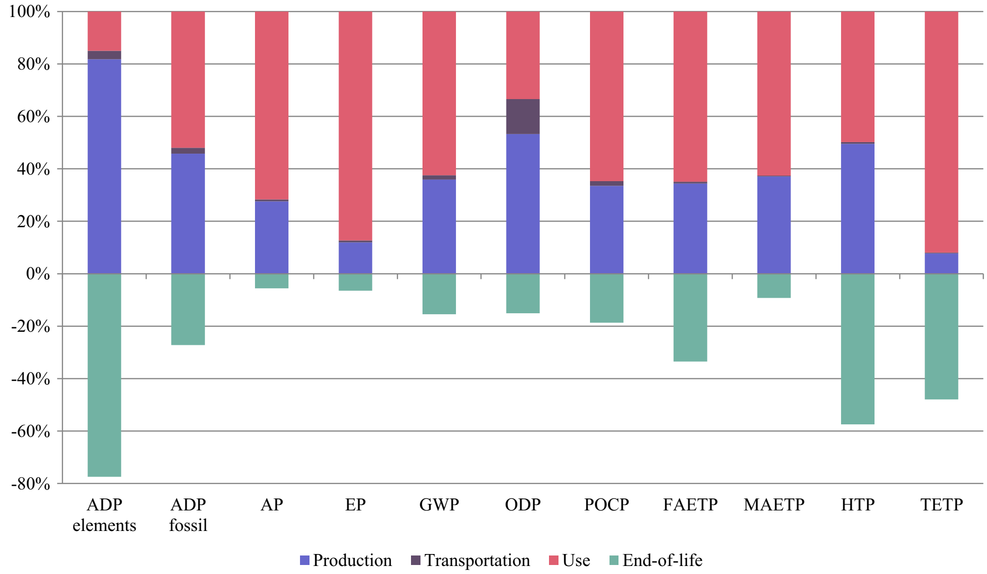


Fig. 2 Relative contributions of the different life cycle stages to each impact category

3 Results

The LCIA results of the washing machine for all selected impact categories are shown in Fig. 2, and the detailed Gabi modeling of different life cycle stages can be found in the Electronic Supplementary Material to help understand the results. The y-axis shows the contribution of each life cycle stage to the whole environmental impacts, and the x-axis shows each environmental impact category. The transportation contributes a little to environmental impacts in the life cycle of washing machines. The end-of-life phase leads to some recycling credits, from 5 to 77 % for the different impact categories. The production and use phases demonstrate significant environmental impacts, which differ a lot among impact categories. The production phase comprises 7.7 % for TETP while contributes 80 % to ADP elements. In general, the use phase is the most important contributor for most impact categories, ranging from 14.8 to 91.8 %, excluding ADP elements and ODP, which are dominated by the production phase.

3.1 Production

Figure 3 shows the LCA results of various parts and processes in the production phase of a washing machine for the selected impact categories. The y-axis shows the contribution of each part or process to the environmental impacts of production phase, and the x-axis shows each environmental impact category. For ADP elements, it can be clearly observed that the main impact is due to the electronics, accounting for 47 % of the total. The second position is taken by the cable that is responsible for

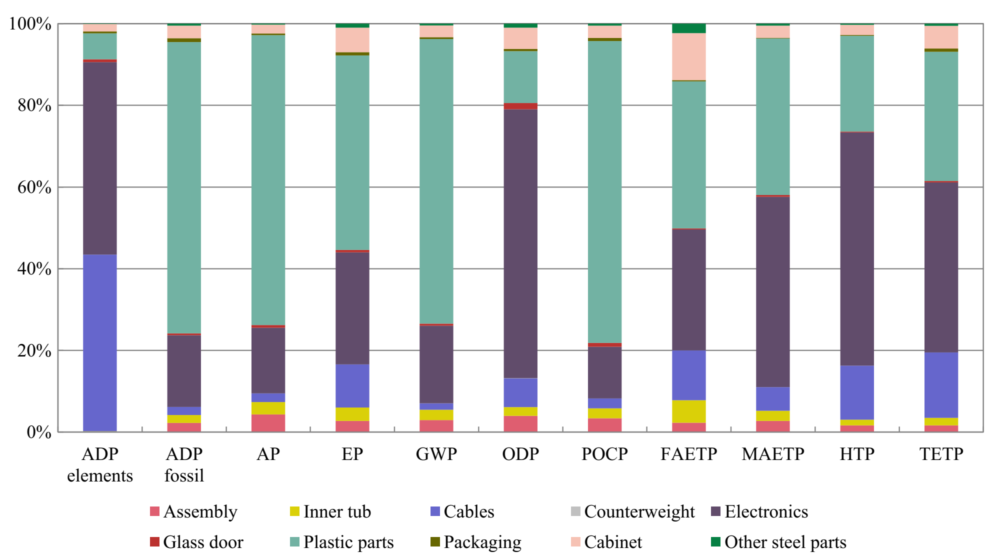


Fig. 3 Relative contributions of production phases to each impact category

approximately 43 %, followed by the plastic parts (6 %) and the cabinet (2 %).

For the ADP fossil, the most important contributor is the plastic parts, with a proportion of 71 %, followed by the electronics (17 %). The plastic parts generate high impacts because of the huge raw material consumption of acrylonitrile-butadiene-styrene, as well as the electricity consumption during the injection molding process. As for the electronics, it is attributable to aluminum usage.

For the AP, the result is similar to ADP fossil, and the plastic parts (71 %) and electronics (16 %) dominate the impact. The significant impact arising from plastic parts is primarily attributable to the electricity consumption during the injection molding process. Aluminum use is another main reason. Additionally, the results of GWP and POCP are similar to that of AP and ADP fossil, respectively.

For the EP, the largest contributor is the plastic parts (48 %), followed by electronics (27 %), cables (11 %), and cabinet (6 %). The reasons for the high EP impact by plastic parts are the electricity consumption and the large amount of ABS used. As for the electronics, it is attributable to copper usage. For the FAETP, the largest contributor is the plastic parts (36 %), followed by electronics (30 %), cables (12 %), and cabinets (12 %). The main impact factors are the electricity consumption for injection molding and copper use in electronics.

For the TETP, MAETP, HTP, and ODP, the results are similar, namely the largest contributor to these impact categories is electronics. It is mainly due to the copper usage in electronics for TETP and HTP. Aluminum usage is mainly responsible for MAETP and ODP. The next largest contributor of TETP, MAETP, HTP, and ODP is plastics, which consume considerable electricity during the injection molding process.

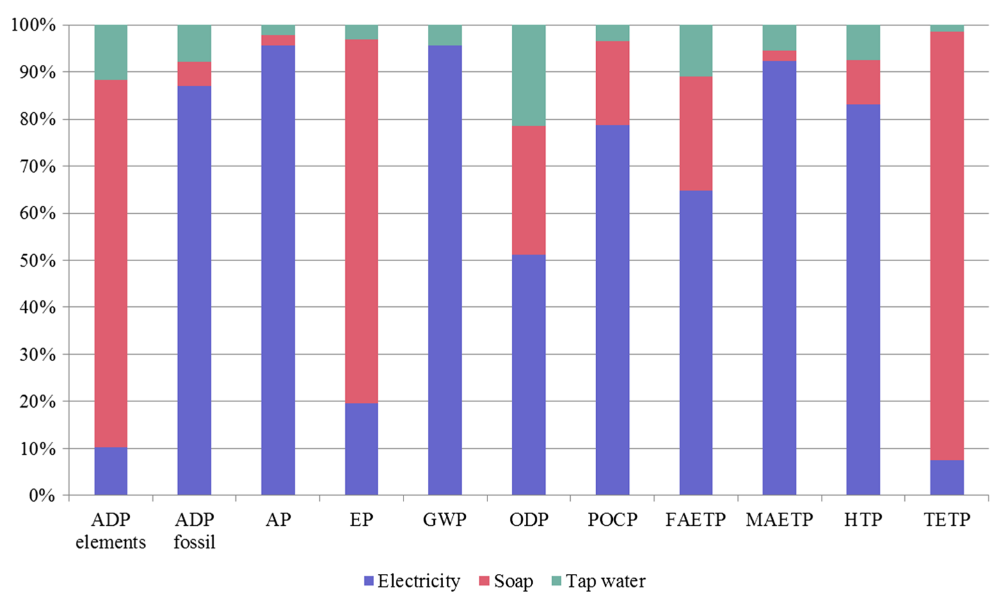
3.2 Use

Figure 4 shows the relative contributions of substance and energy consumption to each impact category. The y-axis shows the contribution of each consumption to the environmental impacts of use phase, and the x-axis shows each environmental impact category. For ADP elements, EP and TETP, the soap use and wastewater discharge dominate the environmental impacts, accounting for 78, 77, and 91 % of the total, respectively. In addition, the environmental burdens of the other impact categories are mainly due to electricity consumption.

3.3 End-of-life

The end-of-life phase does not cause an impact but does have a recycling credit. In Fig. 5, the recycling credits of various environmental impact categories from the end-of-life phase are shown in detail, and the positive value means environmental impacts, while the negative value means recycling credits. The y-axis shows contribution to recycling credits or environmental impacts, and the x-axis shows each environmental impact category. As shown, the largest recycling credits for each impact category are from the large amount of steel and plastic recycling, which contribute more than 50 % to the overall recycling credits. The third biggest contributor is the recycling of copper, and the recycling of iron and aluminum is of minor importance, as it contributes less than 1 % to most impact categories. All the recycling credits are due to the burdens avoided during the production of materials. On the other hand, the electricity consumption for recycling processes and landfill disposal can cause environmental impacts, but they are not higher than 20 % compared with the recycling credits.

Fig. 4 Relative contributions of use phases to each impact category



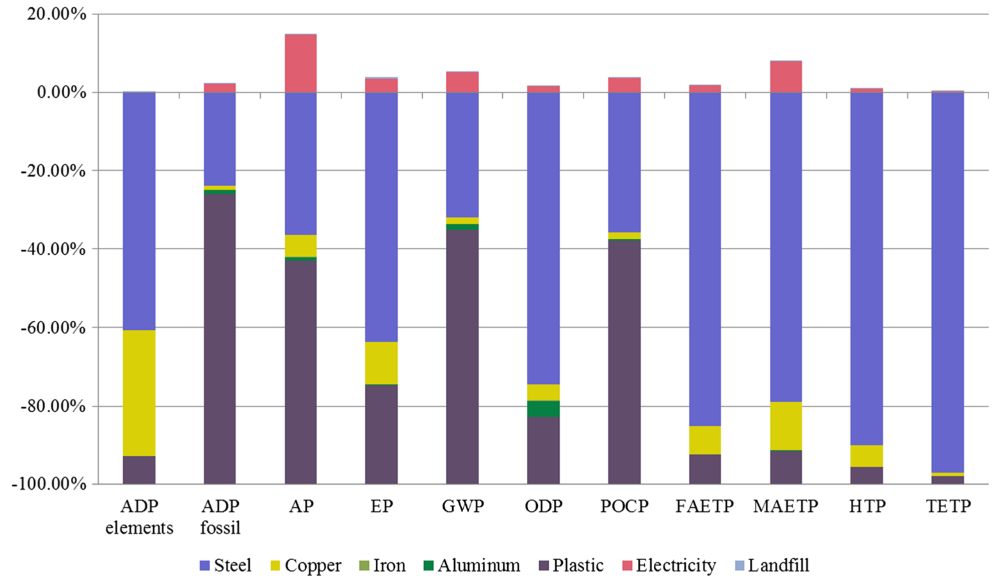


Fig. 5 Recycling credits of the disposal phase to each impact category

3.4 Comparison to the results of other studies

A comparison has been conducted with an existing study (Rüdenauer et al. 2005) to understand the differences between the results and its reliability. Because the impact categories selected in the two studies are different except GWP, here, we just compare the results of GWP. In Table 4, an overview is given concerning the general framework of the studies, and it shows the absolute results of the two studies for each life cycle stage. It can be seen that the values of the two studies show a difference of around 10 % (for the production phase) to more than 90 % (for the transportation phase). The contributions of production phases are consistent with each other, but the differences for other phases are much higher. A possible explanation for the huge difference in transportation phase is the different distribution distances due to the larger geographical area in China. The number of washing cycle is different for the two studies, resulting in different GWPs in use phase. When calculated by per wash cycle, there is no significant difference. For the end of life stage, we take the higher recycling rate of the materials than the ones in the previous study. However, the results of the current study greatly lie within the magnitude of the other result. Compared with other study, the results of our study are reasonable and more representative in China.

4 Discussion

4.1 Potential hotspots

A hotspot is an activity during a phase of a product life cycle that has a potentially significant environmental or social impact as a result of specific mechanisms. In this study, the identification rule is that a human activity is regarded as a hotspot when its environmental impact exceeds 10 % of the whole life cycle impacts in any impact category. We identified possible environmental hotspots through the entire life cycle of a washing machine with specification of their mechanisms and impact groups, as shown in Table 5. These hotspots are areas where improvements can be achieved.

In the production phase, aluminum and copper use in the electronics, ABS use, and electricity consumption in injection molding are the potential hotspots. It reveals that the production of aluminum, copper, and ABS is not environmentally friendly, which emits various contaminants to the atmosphere and water, and consumes fossil resources leading to environmental burdens. In the use phase, electricity consumption is dominant for each impact category, and cleaner electricity is needed in China. The detergent use is quite influential on eutrophication which is caused by washing wastewater containing nitrogen and phosphorus discharged into water.

4.2 Improvement opportunities

An improvement opportunity addresses one or more hotspots by mitigating environmental impacts. Improvement opportunities may include product attribute improvement, manufacture and consumer behavior improvement, or supply chain optimization.

For production process, the key processes are injection molding and powder spraying. On-site management should be strengthened by promoting energy-saving performance appraisal with education and upgrading employee's professional knowledge and skills to reduce the energy and material consumption. In injection molding process, waste heat should be recycled to save energy. Besides, based on practical

Table 4 Comparison with other study from different life stages

Study		Production	Transportation	Use	End of life
Current study	Data	Manufacturer data	1252 km truck	10 years lifespan with 133 washing cycles per year	Credits for recycling of materials
	GWP (kg CO_2-equiv.)	355	16.7	617	−153
Rüdenauer et al. (2005)	Data	Manufacturer data	170 km train 170 km truck	11.4 years lifespan with 175 washing cycles per year	Credits for recycling of materials
	GWP (kg CO_2-equiv.)	312	2	988	−55

production conditions such as mold temperature and injection time, the parameters of main process equipment should be optimized to reduce the defective rate. A high efficiency of dust collection equipment should be installed in powder spraying process which reduces both the production cost and the emissions effectively.

For use phase, on the one hand, the consumers' washing habits can be optimized by environmental education such as selecting normal temperature washing mode in summer, washing more clothes under the premise of no more than the maximum capacity, and adding appropriate amount of detergent and water according to the amount of clothes. On the other hand, the electricity mix can be improved, and cleaner energy such as hydropower and nuclear power can replace thermal power. Furthermore, more municipal wastewater treatment plants should be built especially in villages and

Table 5 Potential hotspots through the life cycle of a washing machine

Potential hotspots	Mechanism	Impact category	Impact percent
Aluminum use in the electronics	Upstream aluminum production emits trichlorofluoromethane and dichlorotetrafluoroethane to the air.	ODP	27.80 %
	Upstream aluminum ingot production emits hydrogen fluoride and dioxins to the atmosphere.	MAETP	12.10 %
		HTP	11.90 %
Copper use in the electronics	Upstream copper production consumes resources of copper and molybdenum.	ADP elements	35.20 %
	Upstream copper production emits heavy metals, including arsenic, cadmium, and nickel to the environment.	HTP	15.60 %
Electricity use in injection molding of plastic parts	Upstream electricity production consumes fossil resources and emits various types of pollutants to the environment, causing resource depletion, climate change, acidification, photochemical smog, toxicity, etc.	ADP fossil	10.30 %
		AP	15.70 %
		GWP	13.60 %
		MAETP	13.30 %
		POCP	11.40 %
ABS use in plastic parts	Upstream ABS production consumes fossil resources.	ADP fossil	16.90 %
Electricity use in use phase	Upstream electricity production consumes fossil resources and emits various types of pollutants to the environment, causing resource depletion, climate change, acidification, photochemical smog, toxicity, etc.	ADP fossil	44.50 %
		AP	67.90 %
		EP	17 %
		GWP	59 %
		ODP	15.60 %
		POCP	49.50 %
		FAETP	41.90 %
		MAETP	57.70 %
		HTP	41.30 %
		TETP	83.50 %
Detergent use in use phase	Upstream detergent production consumes element and fossil resources and emits cypermethrin to agricultural soil and carbon monoxide and non-methane volatile organic compounds to the atmosphere, causing FAETP and POCP; washing wastewater containing nitrogen and phosphorus is discharged into water, causing eutrophication.	ADP elements	11.50 %
		EP	66.90 %
		POCP	11.30 %
		FAETP	15.70 %

ADP abiotic depletion, *AP* acidification potential, *GWP* global warming potential, *MAETP* marine aquatic ecotoxicity, *POCP* photochemical ozone creation potential, *EP* eutrophication potential, *FAETP* freshwater aquatic ecotoxicity, *HTP* human toxicity potential towns aiming at reducing the emissions of COD, nitrogen, and phosphorus to the environment.

4.3 Use phase scenario analysis

The results of this study show that the use phase contributes the majority of environmental burden in the life cycle of washing machines. In the use phase, 15 washing scenarios are considered regarding water level, temperature, electricity, and water consumption as well as the wastewater discharge per wash cycle based on the different options for the cotton program, presented in Table SI 4 (Electronic Supplementary Material). So it is necessary to discuss how user behaviors affect the LCA results. We choose seven scenarios considering the differences of water level and temperature, and the LCA results are shown in Fig. 6. The y-axis shows the contribution of use phase to the whole environmental impacts, and the x-axis shows each environmental impact category. The scenario analysis shows that the use phase contributes more than 90 % to TETP in all the scenarios, and the water temperature is the most contributor to all environmental impact categories excluding ADP (elements) and EP because heating water can consume a high amount of electricity. For example, the use phase contributes 88 and 47 % to GWP, respectively, under the same volume of water with 90° centigrade (S7) and normal temperature without heating (S1). The use phase contributes to more than 90 % of AP and TETP when water temperature is heated to 90 °C. Nevertheless, the options of water level have little effect on the LCA results because the variation (20 %) of water consumption is much less compared with the variation (89 %) of electricity consumption from 90 °C to normal temperature.

4.4 Limitations

There are several limitations in this life cycle assessment. First, some components of the washing machine, such as the electronics and glass door, are outsourced, and the data on their manufacturing are unavailable in the enterprises we investigated. Therefore, we only take into account the material consumption for these components and cannot capture the impacts from their manufacturing, thus leading to an underestimation of the environmental burdens in this stage. Besides, we have tried our best to build the LCI of horizontal-axis washing machines with enterprises investigation and questionnaires. Considering the LCIs of many raw materials and energy have been examined and included in existing databases, such as steel, copper, and electricity, it is not necessary for us to build the upstream LCI for all these raw materials and energy. Therefore, we built the LCI of some raw materials such as bonderite and borrowed some from the Ecoinvent or PE professional database considering the data background, which may bring uncertainty to the results. For example, the upstream LCI of electricity is from Ecoinvent database: "CN: electricity, production mix CN" which is based on Chinese situation.

Second, for the use phase, to simplify the washing process, we calculate only the energy and water consumptions under the conditions of the most commonly used program (cotton) of a horizontal-axis washing machine. This approach may have a large difference with the actual operation.

Third, for the end-of-life phase, the available first hand data are limited. Although we investigated the disposal enterprise, most data are acquired from literatures. Furthermore, the recycling rates of a washing machine used in this paper seem to be higher than the actual rates in China, and the collection

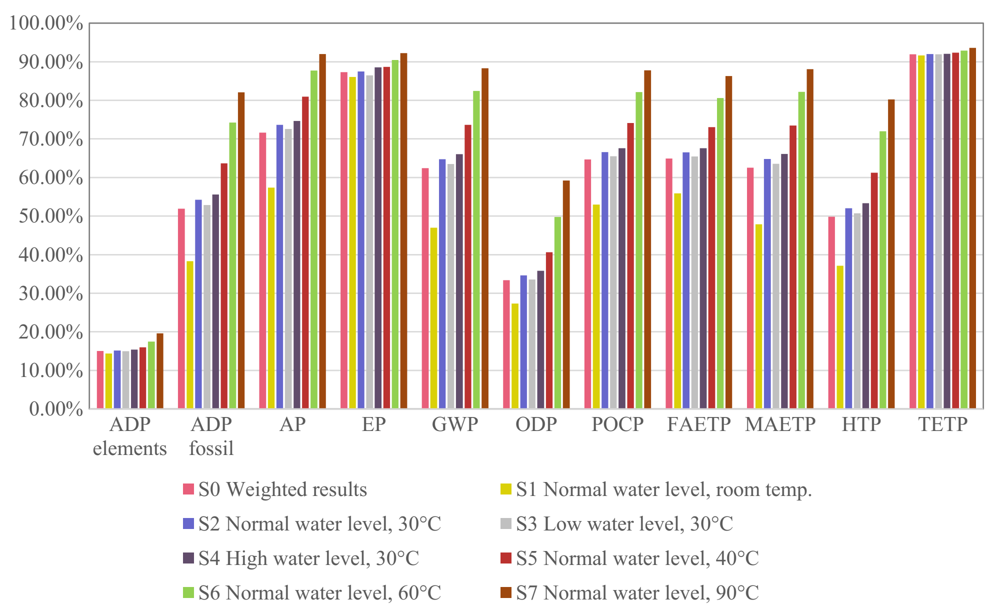


Fig. 6 LCA results of use phase scenario analysis

Table 6 Sensitivity analysis results—percent change from base case

Process	Production						Transportation		Use		End-of-life		
Parameter	P1		P2		P3		P4		P5		P6	P7	P8
Variation	−10 %	10 %	−10 %	10 %	−10 %	10 %	−10 %	10 %	−10 %	10 %	−10 %	−10 %	−10 %
ADP-e	−0.05 %	0.01 %	−0.69 %	0.61 %	−0.03 %	<0.01	−0.31 %	0.31 %	−1.25 %	1.29 %	0.58 %	2.49 %	4.72 %
ADP-f	−0.36 %	0.35 %	−0.03 %	0.02 %	−0.58 %	0.56 %	−0.22 %	0.22 %	−2.61 %	2.39 %	2.06 %	0.03 %	0.67 %
AP	−0.23 %	0.22 %	−0.06 %	0.05 %	−1.17 %	1.13 %	−0.07 %	0.07 %	−2.17 %	1.91 %	0.37 %	0.04 %	0.24 %
EP	−0.04 %	0.03 %	−0.23 %	0.22 %	−0.35 %	0.35 %	−0.07 %	0.07 %	−1.19 %	1.03 %	0.17 %	0.07 %	0.43 %
GWP	−0.37 %	0.37 %	−0.02 %	0.02 %	−0.90 %	0.87 %	−0.17 %	0.17 %	−2.48 %	2.22 %	1.06 %	0.03 %	0.52 %
ODP	−1.47 %	1.37 %	−0.08 %	0.06 %	−0.19 %	0.17 %	−1.17 %	1.14 %	−2.26 %	2.18 %	0.27 %	0.07 %	1.14 %
POCP	−0.19 %	0.17 %	−0.06 %	0.04 %	−0.80 %	0.77 %	−0.18 %	0.18 %	−2.41 %	2.17 %	1.21 %	0.04 %	0.70 %
FAETP	−0.02 %	<0.01 %	−0.61 %	0.57 %	−0.65 %	0.62 %	−0.07 %	0.07 %	−2.40 %	2.17 %	0.27 %	0.26 %	2.91 %
MAETP	−0.77 %	0.75 %	−0.28 %	0.28 %	−0.85 %	0.83 %	−0.03 %	0.03 %	−2.48 %	2.22 %	0.09 %	0.12 %	0.80 %
HTP	−0.61 %	0.59 %	−0.81 %	0.77 %	−0.49 %	0.47 %	−0.06 %	0.06 %	−2.60 %	2.41 %	0.26 %	0.33 %	5.23 %
TETP	−0.12 %	0.10 %	−0.15 %	0.12 %	−0.16 %	0.13 %	−0.03 %	0.03 %	−0.79 %	0.70 %	0.17 %	0.13 %	4.74 %

P1 aluminum consumption of electronics, *P2* copper consumption of electronics, *P3* electricity consumption in injection molding, *P4* distance of transportation, *P5* use frequency in use-phase, *P6* recovery rate of plastics, *P7* recovery rate of copper, *P8* recovery rate of steel, *ADP* abiotic depletion, *AP* acidification potential, *GWP* global warming potential, *MAETP* marine aquatic ecotoxicity, *POCP* photochemical ozone creation potential, *EP* eutrophication potential, *FAETP* freshwater aquatic ecotoxicity, *HTP* human toxicity potential, *TETP* terrestrial ecotoxicity potential, *ODP* ozone layer depletion potential of waste washing machines is excluded in this study due to unavailable data. Hence, the recycling credits generated from this phase may be overestimated.

4.5 Sensitivity analysis

Although we have made reasonable assumptions to acquire the distance data of washing machine transportation, as well as use-phase data, there exist a number of uncertainties related to the distance calculations and the questionnaires. In addition, the production data may have uncertainties considering the production technologies may differ among household enterprises. Therefore, the sensitivity analysis, an important uncertainty analysis tool, was conducted to examine the effects of varying the base case for these parameters. We selected eight parameters and examined their changes on contributions to environmental impacts, which include aluminum consumption of electronics, copper consumption of electronics, electricity consumption in injection molding, transportation distance, use frequency in use phase, recovery rate of plastics, recovery rate of copper, and recovery rate of steel. Each parameter was examined by varying ±10 % from its base value excluding recovery rates of plastics, copper, and steel. The recovery rates of plastics, copper, and steel were examined by varying −10 % from their base values. Each parameter was changed independently of all others so that the magnitude of its effect on the base case could be assessed. Sensitivity analysis results are shown in Table 6. The results show that excluding TETP, the contributions of use phase to all impact categories are sensitive to use frequency, which indicates that clean energy could largely improve the environmental impacts, and the operating behaviors of the washing machine also affect the environmental performance indirectly. While, the contributions of washing machine transportation to all impact categories are not sensitive to distance excluding the ODP. The changes of aluminum consumption of electronics mainly affect the contribution of production process to ODP. The most sensitive parameter for the ADP (elements), HTP, FAETP, and TETP is the recovery rate of steel. Additionally, recovery rate of plastics is sensitive for ADP (fossil) and POCP, and recovery rate of copper is sensitive for ADP (elements).

5 Conclusions

In this study, a cradle-to-grave LCA of a horizontal-axis washing machine was conducted to evaluate its environmental impacts. The results show that the production and use phases are the main contributors to the environmental impacts which are dominated by electronics, plastic components, and electricity consumption as well as the wastewater discharge in use phase. Some feasible measures were provided to reduce the environmental impacts of these hotspots such as recycling waste heat to save energy in injection molding process. Based on practical production conditions, the equipment parameters should be optimized to reduce the defective rate. A high efficiency of dust collection equipment should be installed in powder spraying process. In use phase, the consumers' washing habits can be optimized by environmental education such as selecting normal temperature washing mode in summer, washing more clothes under the premise of no more than the maximum capacity, and adding appropriate amount of detergent and water according to the amount of clothes. The end-of-life phase brings recycling credits due to the recycling of materials such as copper, steel, and plastics. The standardized recycling system should be built up in China to recycle useful resources from waste household electrical appliances and decrease the life cycle environmental impacts of washing machines. This quantitative life cycle assessment can be a useful tool for decision-makers to understand the life cycle environmental impacts of Chinese washing machines and explore sustainability improvement opportunities, as well as help manufacturers identify priorities for actions from an environmental perspective.

Acknowledgments This research was financially supported by the Sustainability Consortium and the Natural Science Foundation of China (41222012). We would like to thank the household appliance enterprises that provided information and data for this research.

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