Renewable and Sustainable Energy Reviews 61 (2016) 433–450

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Chemical recycling of brominated flame retarded plastics from e-waste for clean fuels production: A review

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ARTICLE INFO

Article history:
Received 19 November 2015
Received in revised form
25 February 2016
Accepted 6 April 2016
Available online 22 April 2016

Keywords:
E-waste plastics
Feedstock recycling
Flame retardants
Catalytic hydrogenation
Clean fuels

ABSTRACT

Electronic waste plastics (e-waste plastics) have been one of the emerging and fastest-growing waste streams due to the increasing number of generation in waste electrical and electronic equipment (WEEE). Given that brominated flame retardant (BFR) materials in e-waste plastics have been the major impediment for recycling treatment, chemical recycling has been proposed as an environmentally friendly method of recycling e-waste plastics for clean fuels production or chemical feedstocks. This paper summarized the current techniques of BFR-plastics recycling with a view to solving energy crisis and the environmental degradation of BFR-plastics. Emphasis was paid on the recent chemical treatment of BFR-plastics, including pyrolysis, co-pyrolysis and catalytic cracking, which are yet to be completely feasible in conversion of BFR-plastics for clean fuels production. Hydrothermal treatment is regarded as a novel high-efficiency technology to recycle BFR-plastics, which can be a potential process for the in situ debromination of oil products. An advanced chemical recycling technique, pyrolysis-catalytic upgrading process, is highlighted. The recycling route of pyrolyzing BFR-plastics prior to catalytic upgrading was intended to obtain high quantity oils, and then the upgrading process of pyrolysis oils was conducted by means of catalytic hydrodebromination with the aim of obtaining bromine-free oils for commercial applications. In short, the integration of pyrolysis with catalytic upgrading process can provide significant economic and environmental options in conversion of e-waste plastics into useful and high-value materials. Further investigations are required to develop the pyrolysis-catalytic upgrading process to become sustainable and commercially viable for clean fuels production.

Contents

Abbreviations: ABS, acrylonitrile-butadiene-styrene; BFRs, brominated flame retardants; Br-ABS, acrylonitrile-styrene-butadiene flame retarded with tetrabromobisphenol-A and Sb_2O_3; Br-HIPS, high impact polystyrene flame retarded with decabromodiphenyl ether and Sb_2O_3; CRT, cathode ray tube; decaBDE, decabromodiphenyl ether; DDE, decabromodiphenyl ethane; DDO, decabromodiphenyl oxide; DNA, deoxyribonucleic acid; BDE, brominated diphenyl ether; EEE, electrical and electronic equipment; e-waste, electronic waste; FCC, fluid catalytic cracking; Fe–NZ, iron oxide loaded natural zeolite; Fe–YZ, iron oxide loaded HY zeolite; FR, flame retardant; GC/MS, gas chromatography/mass spectrometry; GPS, global position system; HBCD, 1,2,5,6,9,10-hexabromocyclodecane; HDB, hydrodebromination; HDC, hydrodechlorination; HDH, hydrodehalogenation; HIPS, high impact polystyrene; HIPS/PPO, mixtures of high impact polystyrene and poly(p-phenylene oxide); HFRs, halogenated flame retardants; IQ, intelligence quotient; LED, light-emitting diode; Mt, million tonnes; NZ, natural zeolite; octaBDEs, octabromodiphenyl ethers; OHCs, organohalogen compounds; PA, polyamide; PBB, polybrominated biphenyl; PBDD/Fs, polybrominated dibenzo-p-dioxins/furans; PBDDs/PBDFs, polybrominated dibenzo-p-dioxins/polybrominated dibenzofurans; PBDEs, polybrominated decabromodiphenyl ethers; PC, polycarbonate; PE, polyethylene; PE/Br-ABS, mixtures of high density polyethylene and acrylonitrile-butadiene-styrene copolymer containing a polybrominated epoxy type flame retardant; pentaBDEs, pentabromodiphenyl ether; PET, poly(ethylene terephthalate); POPs, persistent organic pollutants; PP, polypropylene; PPO, poly(p-phenylene oxide); PS, polystyrene; PS/Br-ABS, mixtures of polystyrene and acrylonitrile-butadiene-styrene copolymer containing a polybrominated epoxy type flame retardant; PU, polyurethane; PVC, poly(vinyl chloride); PXDD/PXDFs, polybrominated, chlorinated or mixed brominated-chlorinated dibenzo-p-dioxins/polybrominated, chlorinated or mixed brominated-chlorinated dibenzofurans; Py-GC/MS, pyrolysis-gas chromatography/mass spectrometry; SAN, styrene-acrylonitrile; TBBPA, tetrabromobisphenol-A; WEEE, waste electrical and electronic equipment; YZ, HY zeolite.

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http://dx.doi.org/10.1016/j.rser.2016.04.020
1364-0321/

1. Introduction

Due to the rapid expansion of electronic inventions, manufacturing innovations, and ever-shortening product lifespans, the electronics industry has become one of the fastest-growing sectors in the world. Subsequently, large amounts of waste electrical and electronic equipment (WEEE) are generated, which have posed a serious challenge to waste management in developed and developing countries. Meanwhile, WEEE has attracted significant interest globally because of its unique combination of characteristics, including threats to the environment and human health and potential opportunities to retain valuable resources by closing the loop of material flows [1,2]. Fossil fuels, which have been heavily exploited and utilized as the only large and cheap source of energy in nearly all activities, are expected to be depleted in a foreseeable future; thus, alternatives with economic benefits are needed to increase the involvement of resource utilization of wastes, which contain large potential secondary energy resources. The total quantity of e-waste generated globally in 2014 was 41.8 million tons (Mt) and it is forecasted to increase to 50 Mt in 2018 at an annual growth rate of approximately 5 wt% [3]. China, as one of the largest electronics manufacturing countries and one of the emerging economies in the world, is rising up as the second largest WEEE generator next to USA [4]. From 1998 to 2013, the amounts of major household electronic and electric appliances in China increased rapidly, as shown in Fig. 1 [5]. The estimation and forecast of e-waste quantities in China show that the total weight of e-waste generated was approximately 5.52 Mt in 2013, which is expected to reach about 20 Mt in 2040, indicating a large increasing potential of e-waste generation in the future [6].

WEEE is highly inhomogeneous and complex in terms of the materials and components. Many of the materials are highly toxic, such as heavy metals, brominated flame retardants (BFRs), refrigerants and fluoride foaming agent, which requires safe handling and recycling to avoid environmental contamination and detrimental effects on human health [7,8]. By contrast, WEEE also contains a variety of valuable materials, including metals, glass, plastics and other materials that can be recovered from WEEE [9]. The rapid emergence of the e-waste problem has motivated EU nations and some developing countries to solve this great challenge. Consequently, international initiatives and regulations have been issued successively, such as Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, Directive on Waste Electrical and Electronic Equipment (WEEE Directive), Restriction of Hazardous Substances Directive (RoHS Directive) and the Waste Framework Directive [10–13]. The Chinese government also issued a variety of environmental laws, regulations, standards, and technical guidance for the e-waste recycling to satisfy the principles of sustainable development [14,15]. All of these regulations require that pollution prevention principles should be adopted during the whole life-cycle of e-waste management so that negative environmental impacts can be minimized. The Waste Framework Directive introduces a five-step waste hierarchy where prevention is the best option, followed by re-use, recycling and other forms of recovery, with disposal such as landfill as the last resort (seen in Fig. 2), aiming to reduce negative environmental and health impacts and create an energy and resource-efficient economy [16].

Therefore, research on recycling WEEE has far-reaching significance in the environmental and energy crises faced by our current societies. Thus far, extensive works have been devoted to recover and reuse the valuable materials of e-wastes, such as metallic fractions [17–21]. However, WEEE plastics, as the main component of WEEE taking up approximately 10–30% [22], were mostly treated with incineration or landfill in the past [23].

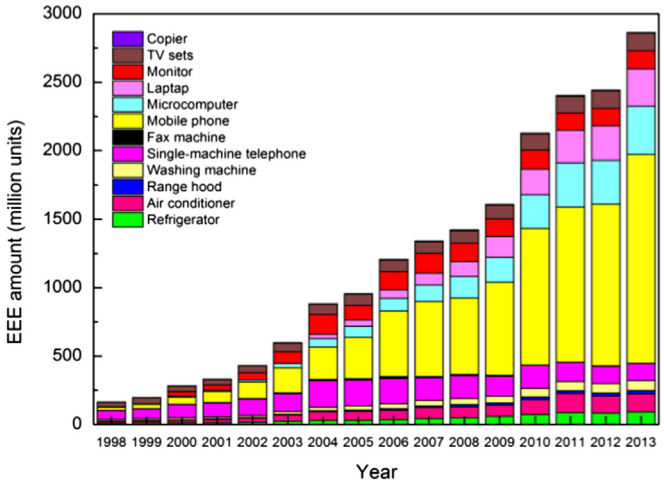

Fig. 1. E-waste generation amounts in China [5].