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Review

End of life liquid crystal displays recycling: A patent review

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ABSTRACT

A huge quantity of end-of-life liquid crystal displays (LCD) is collected, every year, around the world. Nowadays, this equipment is disassembled, for the removal of hazardous components (e.g. the backlight fluorescent lamps), and the resulting panel is stored. The reason is the significant content of valuable fractions (e.g. glass, metals and liquid crystals) and the lack of a recycling process, sustainable from an economic and an environmental point of view. Considering the relevance of this critical issue, the scientific community focused on the development of different recovery strategies, summarized in several available reviews. Nevertheless, the literature has not yet dealt with the technological innovation aspect. With the aim of filling this gap, the present review presents the international patents about LCD recycling, from 1999 to 2017, using the Espacenet platform, that has access to all the most relevant patent databases worldwide. The inventions include a first waste disassembling, followed by the classification of the target fractions and the recovery of metal (e.g. indium, indium tin oxide) and non-metal (e.g. glass, polarizing film, liquid crystal) components.

1. Introduction

The last decades were characterized by the liquid crystal display (LCD) technology for several applications (e.g. PC monitors, laptops, tablet PCs, mobile phones, televisions), which caused the production of a huge quantity of waste to manage. The main reasons can be found in the relatively short lifetime, between 3 and 8 years, and the faster and faster technological development (Ma and Xu, 2013). At the end of their life, LCD are classified as waste electronic and electric equipment (WEEE) in the category of *Screens, monitors, and equipment containing screens having a surface greater than* 100 cm^2 (European Commission, 2012). This kind of waste shows a complex structure and a wide range of compounds, including toxic substances, variable on the basis of the technological generation (Ferella et al., 2016). For example, the old equipment includes a backlight fluorescent lamps system, with a mercury content, that requires a specific removal procedure by manual disassembly, recently substituted by light emission diode devices (Amato et al., 2017; Rocchetti et al., 2016). Nevertheless, this critical issue is combined with the presence of valuable components with a significant recovery potential as: plastic, glass, steel, metals and printed circuit boards (Amato et al., 2016a,b, 2017; Rocchetti et al., 2015a). A particular interest is due to the presence of indium, included, with a percentage of 90%, in the indium tin oxide (ITO) film, an optoelectronic material with characteristics of: transparency to visible light, electric conduction and thermal reflection (Li et al., 2011). This metal, mainly mined in China (57% of the global production), was classified by European Commission as critical raw material for Europe for its high supply risk and the significant economic importance (European Commission, 2017). The relevance of indium is also confirmed by a substitution index of 0.94/0.97, proving the difficulty in substituting the material (European Commission, 2017).

In this context, the end-of-life LCD recycling represents a hot topic, extensively discussed in the scientific literature, which reports several approaches carried out at different operative conditions. To have an overview related to the end-of-life LCD, Zhang et al. (2015a,b) collect information about practices and developments for displays recycling, focusing on indium recovery. Furthermore, the paper describes the detail of a combined process which includes physical-mechanical treatment and the exploitation of additional fractions (e.g. liquid crystal, glass, tin). The most recent review presented by Wang et al. (2017), reports processes for several metal recovery from different WEEE, including LCD, using the approach of urban mining in which the waste becomes a source of secondary raw materials. Furthermore, vacuum metallurgical technologies are described within the Zhang and Xu (2016) review about electric and electronic waste recovery. As emerged from the literature, the low concentration of indium in the LCD (about 160 ppm, Amato et al., 2016a,b; Rocchetti et al., 2015a, b) often makes the metal recovery disadvantageous from both the economic and the environmental point of view; for this reason, it is frequently combined with the recycling of other fractions. In this regard, an overview on the

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recycling of non-metallic fractions from WEEE is presented by Wang and Xu (2014), that mainly focuses on plastic and glass. Moreover, Ferella et al. (2016), classified the literature related to the end-of-life LCD processes in four main sections: thermal pre-treatments, mechano-chemical pre-treatments, indium extraction and recovery by hydrometallurgy and recycling of LCD glass.

The many described papers confirm the strong interest for this topic, nevertheless, there is a lack of information concerning the state of art of the technological innovation change, including the inventions designed for the application in a real scale. In this regard, the "innovation" study allows the perception of the new markets based on the adoption and the diffusion of new inventions, defining the most promising field for economic investments (Garcia and Calantone, 2002). For this reason, the present review intends to fill this gap, following the same approach of Archibugi and Pianta (1996), integrating the scientific literature with a deep study of the available patents, an excellent index of the technological activity. The research was updated to October 2017 and it took into account a patent publication period between 1999 and 2017. The free access Espacenet platform was used as the main information source (http://worldwide.espacenet.com) using the "LCD recycling", "LCD recovery", "liquid crystal display recycling", "liquid crystal display recovery", "waste LCD" as keywords for the patents search. This information source, created by the European patent office, ensured a worldwide inventions overview.

As showed in the review roadmap in Fig. 1, the results were organized on the basis of the target fractions and the possible production of new materials. More in detail, a first group of patents, described in Chapter 2, refers to the mechanical/physical pre-treatment, necessary for the device dismantling and the classification of the obtained fractions. Considering the significant amount of contained glass, many patents deal with this topic, and they are presented in Chapter 3. Such glass can be either recovered as a secondary raw glass or used as ingredient for the production of other materials, such as concrete. Given the important value indium, Chapter 4 describes the available technologies for indium recovery, which also combine the recycling of additional components: glass, liquid crystal and polarizing film recovery, as described in Chapter 5. Moreover, the metal can be recovered, combined with tin, in the ITO compound, avoiding the film decomposition. Finally, Chapter 6 deals with the exploitation of organic liquid crystal, generally extracted before the final disposal.

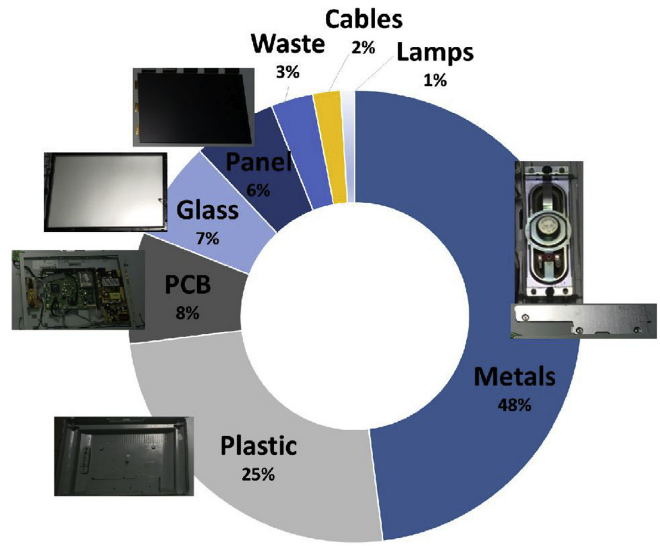

Fig. 2. Average composition of an LCD (adapted from Amato et al., 2017).

2. Pre-treatment for disassembling and classification

As reported in Fig. 2, a typical LCD shows a complex structure, that needs to be dismantled before any recycling treatment.

The choice of an accurate mechanical/physical method, followed by a high efficiency classification of the obtained fractions, represents a key factor in the production of high quality recycled materials.

This chapter covers the patents that deal with the preparation to recycling, excluding the further recovery steps. The main outputs of the treatment are: the LCD panel, printed circuit boards, steel components, glass and organic compounds (Fig. 3). This last fraction is often decomposed to reduce the hazardous level before the disposal.

The considered patents (Table S1), describe both simple methods, carried out by specific dismantling device, and whole treatment chains including thermal treatment and the final degradation of organic compounds. In most cases, the disassembling is either followed (CN104624598, CN101722169, JP2000189939, TW200827051) or substituted (CN104923551, CN204817438, EP2653909, TW536430) by a cutting/crushing with the production of scraps (Bo, 2015; Chen,

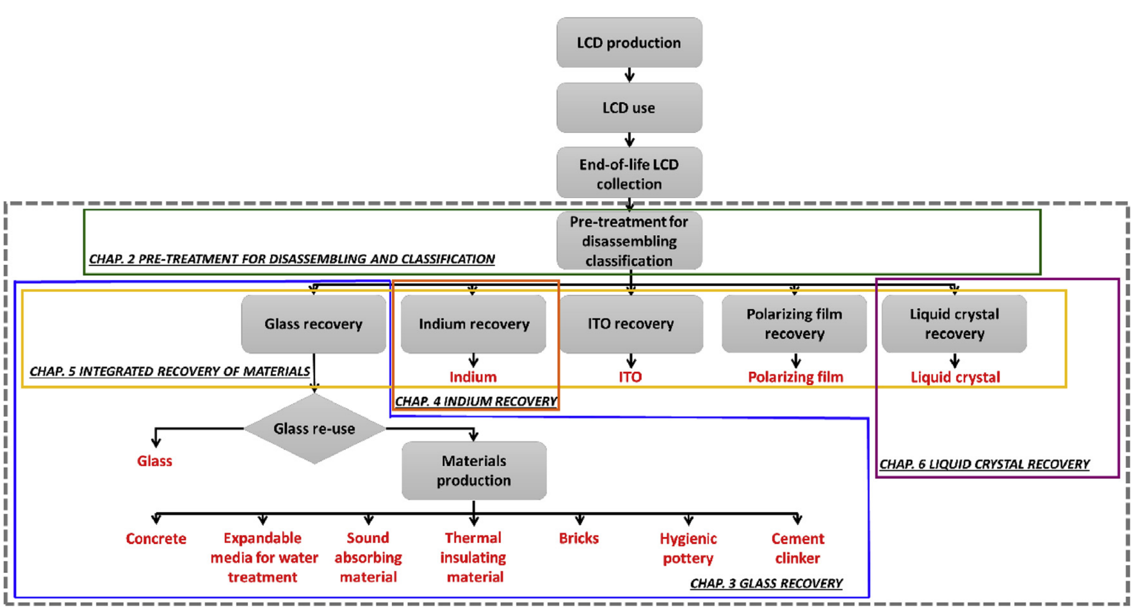

Fig. 1. Roadmap of the present review on end-of-life LCD recycling patents.