

## Methods of material recycling and energy recovery from waste electrical and electronic equipment (WEEE)

## Métodos de reciclaje de materiales y obtención de energía a partir de los residuos de equipos eléctricos y electrónicos

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### Abstract

Waste Electrical and Electronic Equipment (WEEE) currently have generated a great demand for research about the revaluation. The result has been economic sources from the recovery of these waste materials. In Mexico, 56% of states have at least one action for the collection and presentation of WEEE. The main methods for revaluation of WEEE are mechanical and manual. The aim of this study is to describe the different methods of material recovery and energy recovery from WEEE. Developing a descriptive study, using a matrix comparing the different treatment of WEEE. The results allow identifying the feasibility of alternative materials recycling and energy recovery of WEEE. The relevance of this research is to know the various options for recovering materials; new materials identify alternative energy generation, in order to reduce the risk of contamination.

**Recycling of materials, Energy, Electronic waste, WEEE**

### Resumen

En la actualidad los Residuos de Equipos Eléctricos y Electrónicos (REEE), han generado una gran demanda de investigaciones a cerca de la revalorización. La consecuencia se la creación de fuentes económicas a partir de la recuperación de materiales de estos residuos. En México, el 56% de los estados cuentan con al menos una acción para el acopio y revalorización de REEE. Los principales métodos para la revalorización de los REEE son mecánicos y manuales. El objetivo del presente trabajo es la descripción de los diferentes métodos de recuperación de materiales y la obtención de energía a partir de los REEE. Desarrollando una investigación descriptiva, mediante una matriz comparativa de los diferentes tratamientos de los REEE. Los resultados obtenidos permitieron identificar la factibilidad de las alternativas de reciclaje de materiales y recuperación de energía de los REEE. La relevancia de esta investigación es el conocer las diversas alternativas de recuperación de materiales, identificar nuevos materiales de generación de energía alternativa, con el fin de reducir el riesgo de contaminación.

**Reciclaje de materiales, energía, residuos electrónicos, REEE**

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## Introduction

Currently, Waste Electrical and Electronic Equipment (WEEE) has generated a great demand for research into the revaluation of materials. This is a consequence of the dynamic generation scenario due to the unsustainable consumption of sophisticated electronic devices, which due to their demand are easy to acquire and have a programmed obsolescence (Cruz-Sotelo et al. 2013, Ojeda-Benitez et al. 2013.).

Obsolescence occurs when the device is old or provides the user with insufficient performance in its functions. Planned obsolescence arises when a product stop working in a time that benefits the producer, without the consumer losing confidence in the brand. This can be defined as -the consumer's desire to own something a little newer, a little sooner than necessary| (Tobar 2013).

The device when becoming a REEE must be handled properly as they are made up of a complex mixture of different materials. It consists of about 15-30% plastics, 40-50% ceramics and 20-30% metals. However, the composition depends on the age, origin and manufacturer of the equipment (Cui and Zhang 2008, Maurell-Lopez et al. 2011).

In Latin America and the Caribbean, countries such as Argentina, Colombia, Chile, Venezuela, Peru, Costa Rica, among others, are countries that, like Mexico, are part of the Regional Platform on PC e-waste in Latin America and the Caribbean (RELAC), which is an associative project implemented from Santiago de Chile, with the support of the International Development Research Centre of Canada, being an initiative to promote solutions for the prevention, management and handling of the final destination of WEEE (González 2007, Lindhqvist et al. 2008). These regulations imply, in some cases, from the manufacture and design of electronic equipment resulting in a sustainable manufacturing process, although its useful life is a function of the way it is used (Cruz-Sotelo et al. 2013).

In Table I, the useful life of some electronic devices is specified according to their weight, such data were estimated in 2007, although this item may vary due to the versatility of supply and demand, as well as technological advances; for example, a television of ten years ago is different from the current ones both in size and weight, as well as in the material and substances that make it up (Blaser and Schluep 2011, Borraz et al. 2011).

<i>Equipo</i>	<i>Peso (kg)</i>	<i>Vida Útil (años)</i>
Televisores	30	10
Computadoras de escritorio	25	5
Computadoras portátiles	11	5
Aparatos de Sonido	12	6
Teléfonos fijos	1.2	6
Teléfonos celulares	0.82	3

**Table 1** Weight and lifetime of some electronic equipment

Due to the increase of these national and foreign economic investments, Mexico is committed to complying with laws that regulate this type of products, ratifying its obligations with the Basel and Stockholm conventions, as well as being part of the RELAC platform project and participating in the trade and environmental agreements of the Commission for Environmental Cooperation (CEC), it acquires the responsibility to continuously evaluate the health and environmental impacts that come from the manufacturing and disposal waste of electronic devices, in order to develop instruments for solutions (Silva 2013).

To this end, the National Institute of Ecology and Climate Change (INECC) and the Ministry of the Environment and Natural Resources Natural Resources (SEMARNAT) have elaborated diagnoses of WEEE generation in the country. country, which are:

Diagnosis on the generation of electronic waste in Mexico, 2006. The objective of this study was to generate information in order to know the state of the generation and management of electronic waste, constituting the generation inventory and its management modalities. The study is limited to six types of electronic equipment: televisions, personal computers (PCs) and laptops, sound devices, fixed telephones and mobile phones, describing the toxic substances they contain and the effects they produce.

The estimated amount of waste generated in 2006 was between 150 and 250 tonnes to be disposed of, which generated an indicator of 1.5 to 1.6 kg/year per capita per year. 1.6 kg/year per capita (Román 2007).

Regional diagnosis on the generation of electronic waste at the end of its useful life in the northeastern region of Mexico, 2008. It estimates the generation of e-waste, the risks associated with its disposal and proposes strategies for the mitigation of these risks in the states of Coahuila, Nuevo León and Tamaulipas. It is based on the Diagnosis on the Generation of Electronic Waste in Mexico and selects televisions, computers, stereos, home telephones and mobile phones as the main sources of electronic waste. The results of the estimated generation of e-waste disposed by state, extrapolating the results of the survey, are 20,835 tonnes in Nuevo León, 12,665 tonnes in Coahuila and 15,749 tonnes in Tamaulipas (Acevedo et al. 2008).

Regional diagnosis of e-waste in two northern border cities in two cities on Mexico's northern border: Tijuana and Ciudad Juárez of Mexico: Tijuana and Ciudad Juárez, 2009. Applying the same methodology designed in the first diagnosis in 2006, the study is based on two main cities, Tijuana and Ciudad Juárez, and on the application of surveys in statistically representative samples for both cities of 384 people in each. The results obtained for the northern border area were between 32,000 and 40,000 tonnes per year respectively (Román 2009).

Diagnosis of electronic waste generation in two cities on the northern border of Mexico: Tijuana and Ciudad Juárez, 2009. Applying the same methodology designed in the first diagnosis in 2006, the study is based on two main cities, Tijuana and Ciudad Juárez, and on the application of surveys in statistically representative samples for both cities of 384 people in each. The results obtained for the northern border area were between 32,000 and 40,000 tonnes per year respectively (Román 2009).

Diagnosis of e-waste generation in the Metropolitan Zone of the Valley of Mexico (ZMVM), 2010. In this study, it was estimated that the amount of electronic waste generated was 13,216,422 devices, equivalent to 112,490 tonnes. Of the total, 53% are discarded or stored because they are considered obsolete (by the user) and the remaining (47%) are reused (Meraz 2010).

Other studies that have been carried out at the national level were:

Evaluation of alternatives for the management of Special Handling Waste, 2007. This study contributed elements to the North American Regional Action Plan (PARAN) on dioxins, furans and hexachlorobenzene (Almada-Calvo 2007).

Life cycle analysis of electronic waste and management proposal in border cities of Coahuila, Nuevo León and Tamaulipas, 2012. In which the impact of e-waste on different natural resources such as water, soil and air is analysed under different scenarios such as the current management of low recycling and deposition in open dumps to an optimal scenario of controlled disposal in landfills (González 2012).

Basic Diagnosis for Integrated Waste Management, 2012. Its objective is to update information on waste management in Mexico up to 2012, to support the National Programme for the Prevention and Integrated Waste Management, as well as to provide elements for the formulation of objectives in the National Development Plan 2013-2018 (INECC-SEMARNAT 2013).

The above shows the growth of WEEE in Mexico, with televisions, computers and audio equipment having a considerable impact. However, there are inconsistencies in the generation indicators due to the versatility of the WEEE design and the problems in obtaining information from the generating sources. Table II shows the WEEE generation trend in Mexico.

Año	Generación (toneladas)	Generación (kg/año per cápita)	Fuente
2006	150 y 250	1.5 a 1.6	Román 2007, Gavilán-García 2007, González 2007.
2010	307, 220	2.7 a 2.5	Ojeda-Benítez et al. 2013a, Benítez et al. 2010, Gavilán-García, 2007.
2012	1,032.74	8.9	STEP 2014, Frey 2012.

**Table 2** WEEE generation trends in Mexico

According to the National Programme for the Prevention and Integral Management of Waste (PNPGIR) 2009-2012, they estimate an annual generation of between 150,000 and 180,000 tonnes of WEEE (Román 2007). They report at least 411 ton/day of WEEE generation; specifying the difficulty of developing information about the management and disposal of WEEE (SEMARNAT 2008).

The main problem is that the toxic materials and substances contained in WEEE are grouped into Polychromated Organic Compounds known as Brominated Flame Retardants (BFR), Heavy Metals and other compounds generated by improper management such as dioxins and furans (Chen et al. 2011, Noel et al. 2013).

Poor disposal has created informal economic sources due to the amount of metals that can be recovered and traded. These economic sources from the recovery of materials from these wastes have evolved, as have the material recovery processes. Denmark, the Netherlands and Norway have since 1999 taken action to minimise their environmental impact with regard to WEEE.

Countries such as Belgium, Sweden and Switzerland have integrated the management of WEEE into their laws since 2002. In Spain, the recycling of electronic equipment began in 2003, with the legal framework regulating electronic waste, known as -tecnobasural (Sáez 2005). One of the metals recovered from WEEE is Copper (Cu). In Spain, its demand has been increasing since 2004, with the most important source of recycled copper coming from products at the end of their functional life (Sáez 2005).

Because of the revaluation of these materials, the volumes of waste to be disposed of at Final Disposal Sites (FDS) are lower, causing collection and disposal costs to decrease (Li et al. 2012, Martínez 2013). The revaluation of a WEEE is 95% of its totality, the remaining 5% of its materials are those that have a negative impact, causing adverse effects on the health of the population and the environment, due to the toxic substances present such as mercury, lead, selenium, bromine and cadmium, among others (Zhang et al. 2012, Labunska et al. 2013).

Mexico is in transition with respect to WEEE. Fifty-six percent of the Mexican states have already taken at least one action to manage WEEE, which allows setting areas of opportunity for the development of specific WEEE management plans (Bautista-Vargas et al. 2014).

In Mexico, the reported formal recycling capacity is 10% of total generation, while non-formal recycling ranges from 10-20%. In other words, there is 70% of WEEE whose final destination is uncertain (Román, 2007).

As mentioned above, the characteristics of the WEEE components are based on toxic materials if they are not disposed of properly, but they are potentially revalued. This is why it is necessary to determine the composition of the materials, their recycling alternatives and energy recovery. Knowing how to recover materials and their revaluation provides an alternative to minimise these impacts. There are few companies in Mexico that carry out WEEE recycling activities, so these are areas of opportunity for the generation of new materials, ecological design and revaluation of materials from WEEE.

**WEEE compounds**

Halogenated Organic Substances such as Polyvinyl Chloride (PVC) and BFRs, such as Polybrominated Biphenyls (PBBs), Polybrominated Biphenyl Ethers (PBDEs) and Tetrabrominated Bisphenol A (TBBPA), which are highly toxic, are used as additives to plastics in TV circuit boards, plastic monitor and TV housings, plastics and circuit boards in Personal Computer (PC) keyboard and mouse, PC plastic cabinet, PC motherboard, PC microprocessor bonding paste, PC memory, video game equipment plastics, video game microprocessor, VCR circuit boards, VCR microcontrollers, VCR housings, among others. (Gavilán-García et al. 2009, Niu et al. 2012). Such toxicity and persistence raises concerns about environmental and public health impacts (Chi et al. 2011, Gaidajis et al. 2011).

Metals such as Cadmium (Cd), Lead (Pb), Mercury (Hg), Chromium (Cr) and Nickel (Ni) are present in batteries, solder, electronic circuits, in Cathode Ray Tubes (CRT) which are part of the kinescopes of televisions and computer monitors. Lead oxide is used in CRT glass, lamps and fluorescent tubes. Copper (Cu), Gold (Au), Aluminium (Al), Iridium (Ir), among other metals are present in mobile phones. Printed circuit boards contain heavy metals such as Antimony (Sb), Au, Silver (Ag), Cr, Zinc (Zn), Pb, Tin (Sn) and Cu (Román, 2007, Chancerel et al. 2009, Chancerel 2010, Kalantzi and Siskos 2011).

However, there are countries that have transformed their economy to recycling WEEE, such as Ghana, India and China, which receive around 70% of all exported WEEE, as do Pakistan, Vietnam, the Philippines, Malaysia and Nigeria. The techniques they use are very rudimentary, leaving them exposed to highly toxic compounds emitted during dismantling and recycling activities (Kong et al. 2012).

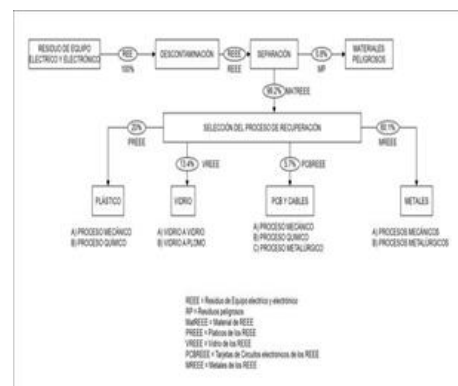
Informal reuse actions are precarious, ranging from burning cables, hammering screens and monitors, where Pb is released from the glass of the CRTs and exposed to the environment and people, electronic cards bathed in acids and other chemicals used to recover valuable metals, as well as contaminated waste materials that are disposed of in an improvised manner (Niu et al. 2012).

Currently, the reuse of materials from WEEE is an economic opportunity that stimulates the revaluation of waste as 90% of the materials can be recovered and recycled.

Of the materials used in electronic devices that can be recycled, 50% is iron and steel, 20% is plastic, 13% is other metals including precious metals and 5% is glass. Approximately 95% of a computer can be recycled in its entirety, ranging from the hard disk and memory to the motherboard and its gold and silver wiring. From mobile phones up to 92.5 % can be recovered, from which precious metals such as silver, gold, palladium, 14 % of other metals such as copper and 80 % of other materials and elements (glass, tin, indium, cobalt and plastic) can be extracted. In both equipment there is 5% of non-recyclable material such as lead, selenium, bromine and other heavy metals, which are considered Hazardous Waste (HW) (Chancerel 2010, Buchert et. al. 2012).

**WEEE material recovery process**

Various processes are used for materials recovery, Figure 1 shows the percentage composition of e-waste. As well as the different material recovery processes that are used for each part that makes up a WEEE. A WEEE contains 0.8% of hazardous materials such as batteries, components with Mercury, among others, which there are specialised managers in the handling of this type of Hazardous Waste (HW). 99.2% of the WEEE is made up of plastics and mixed plastics (20%), glass (13.4%), printed circuit boards and cables (5.7%) and ferrous and non-ferrous metals (60.1%). There are two main trends in the disassembly process of electrical and electronic equipment: Manual and Mechanical.



**Figure 1** Composition of WEEE and recovery processes

*Manual Process*

Manual dismantling is common in WEEE recycling plants. They use flexible tools, planning in advance the most efficient way to dismantle a piece of equipment so that it takes less effort and time. However, it is labour intensive and requires a high degree of training resulting in a costly process. One of the main affecting factors is the design of the equipment that facilitates or hinders disassembly (Cui and Forsberg 2003, Almada-Calvo 2007, Tobar 2013).

Process time is critical to the economic viability of recycling and therefore a dismantling-friendly design is key to making the process cost-effective. This has led engineers and designers to look for new electronic product designs to simplify disassembly.

One proposal is to avoid the use of screws, to make manual dismantling easier, or the use of clear dismantling instructions engraved on the surface of the equipment for the operator to use (Campbell and Hasan 2003, Rios et al. 2003, Williams 2006).

*Mechanical Process*

The initiation of this disassembly process is due to the disadvantages of the manual process, which has led to the development of automated technologies for these processes. One of the obstacles to this process is the diversity of electrical and electronic products which require flexible and intelligent disassembly processes. One of the alternatives is the use of robots with cameras, which can perform simple disassembly operations, whether destructive or non-destructive. By means of artificial intelligence and robots with force sensors, arms and grippers to handle equipment with different characteristics. However, these technologies have not been applied, so manual disassembly is still the most commonly used method (Van Kuren 2002, Cui and Zhang 2008).

*Separation of materials*

The separation of materials is carried out after disassembly, where there are a number of materials that need to be further processed. These materials can be a mixture of plastics, glass and metals or pure streams of materials.

In the case of pure streams of metals, plastics and glass, these are melted down and reincorporated into the life cycle of the materials. Components that are mixtures of plastics, ceramics, semiconductors and metals can be subjected to different separation processes in order to be reused as raw materials.

In which sub-processes are used to obtain these components, which are: Grinding, screening, magnetic separation, thermal conductivity separation and density separation.

*Plastics Recovery*

It is carried out by three different methods:

## a) Mechanical recovery.

The aim of which is to obtain raw material to close the material cycle. An important problem for this type of recycling is the content of paints and coatings, because if they are not removed before recycling, the quality of the product can be affected.

## b) Chemical recovery.

This aims to recover the main chemical components to be used in other applications. Such recovery can be of two types: (1) recovery of monomers by depolymerisation or (2) conversion of the plastic to pure carbon, so that it can be used in metallurgical processes as a reducing agent.

## c) Energy recovery in incinerators.

Plastics have a higher calorific value than coal. According to the United States Geological Survey (USGS), one tonne of plastic can replace 1.3 tonnes of coal. Incineration of these plastics is a fairly common practice, in 2002, Switzerland and Denmark incinerated 70% of the plastic from electronic waste and in 2003 Europe recovered the heat energy from 23% by weight of all discarded plastics.

*Recycling for glass*

There are two recycling methods for glass from Cathode Ray Tubes (CRT), which are:

## a) Glass to glass.

This consists of reusing the glass from the CRT for the construction of more CRTs. In this method it is necessary to completely separate the glass from the other electronic components, plastics and metals. Normally, after disassembly, it is subjected to grinding to obtain a uniform and pure glass mixture. The mixture is then melted and molded into the new CRT.

## b) Lead glass.

In this method, glass from CRTs is used as raw material for the manufacture of lead. The aim is to recover the lead, while the glass is lost in the process. As in the previous process, the CRT is separated from the other components, however in this process the purity of the glass is not relevant, it is subjected to grinding and then used directly in the lead smelter. The glass serves as a fluxing agent, which helps to lower the melting point and density, making the process more efficient. In the production of primary lead, silicon dioxide is used as a flux. Compared to both processes, the Glass to Lead method is more cost efficient, as the process is more automated. However, it detracts from the value of the CRT glass, as it is only used as a raw material for lead.

*PCB recycling processes*

Printed circuit boards (PCBs) are the main component of almost all electronic devices. They are found in almost all electronic equipment and expire at the same or faster rate than the equipment itself. PCBs are basically composed of organic matter, metals and ceramics. The organic matter consists of paper, plastics and flame retardants. The metals are mostly copper, iron and aluminium, and to a lesser extent valuable metals such as platinum, gold, silver and gallium and toxic metals such as chromium VI, lead and mercury. The ceramics are silicon dioxide and aluminium dioxide (Hong-Chao et al 2006, Li et al 2007, Cui and Zhang 2008, Zheng et al 2009). The recycling processes for PCBs are as follows:

## a) Mechanical process.

This consists of shredding the boards as finely and homogeneously as possible, so that the metal, ceramic and plastic parts that were originally glued together are separated. Different methods can be used to separate metallic and non-metallic particles. The difference in densities, or the difference in electrical properties can be exploited (Peng et al. 2004).

## b) Chemical processes.

Sulphuric acid is used to solubilise copper and other metals. The cards are soaked for several hours in the hot acid and then the cards are removed, which no longer have any metals attached to them. Then, either by an electrochemical process or another chemical reaction, the copper is precipitated and sold. This technology is used to directly recover the metals without sending them to smelters.

The major drawback of this process is that it uses acids that have to be treated to avoid the release of heavy metals into the environment.

## c) Metallurgical process.

This process directly uses the cards to be used in copper smelters. It takes direct advantage of the metal content, however strict control of emissions is needed, as the polymers and flame retardants present when burned can produce toxic substances such as dioxins and furans (Zhang and Cui 2008, Maurell-Lopez et al. 2011).

**Methodology**

As mentioned above, a descriptive investigation was carried out in the present work, using a comparative matrix of the different WEEE treatments.

The Comparative Matrix tool focused on the criteria that manage each alternative for the recovery of materials, contrasting with the environmental and technical aspects of WEEE management. The development stages consisted of:

- Description of the materials containing WEEE identifying the approaches on which it is based and the specific parameters in reuse.

- Selection of treatment alternatives and material recovery criteria.
- Elaboration of a double-entry Comparative Matrix showing the information in a summarised and concentrated form on the characteristics of the material recovery treatments.
- Analyse the results by correlating the aspects obtained, identifying the relevant aspects.

**Results**

On analysing the recycling processes, the following descriptive and comparative matrix of the WEEE material and energy recovery processes was obtained. Table 3 shows a summary of the material recovery processes and their relevant characteristics. It can be seen that the processes for the recovery of plastics, metals and glass are the main materials to be processed and reincorporated into the life cycle. Energy recovery from WEEE comes mainly from plastics which have a calorific energy generation of 23% by weight and from PCBs which need electrochemical processes for metal recovery.

The recycling of PCBs requires three processes which are pre-treatment, physical recycling and chemical recycling. All these processes are reduced to physical and chemical methods and it appears that there are no modern technologies available to replace both methods effectively (Hadi et al. 2015).

Parte de REEE	Tipo de proceso	Características relevantes	Recuperación		Observaciones
			Material	Energía	
1	Manual	Herramientas flexibles, se requiere mucha mano de obra y un grado elevado de capacitación	Plástico, vidrio, partes electrónicas.	No	Afecta es el diseño del equipo que facilita u obstaculiza el desarmado.

2	Mecánico	Tecnologías automatizadas, uso de robots con cámaras. inteligencia artificial y robots con sensores de fuerza, brazos y pinzas	Plástico, vidrio, partes electrónicas.	No	La diversidad de los productos eléctricos y electrónicos los cuales requieren procesos flexibles e inteligentes de desensamblado
	Corrientes puras	Metales, plásticos y vidrio	Metales, plásticos y vidrio	No	Fundidos y reincorporados al ciclo de vida de los materiales
3	Componentes que son mezclas	Plásticos, cerámicas, semiconductores y metales	Metales	Si	Molienda, cribado, separación magnética, separación por conductividad térmica y separación por densidad
	Mecánico	Materia prima para cerrar el ciclo de materiales	Plástico	No	Problema para este tipo de reciclaje, es el contenido de pinturas y recubrimientos
	Química	Recuperar los componentes químicos principales	Plástico	No	Recuperación de monómeros por despolimerización y Conversión del plástico a carbón puro
	Energética en incinerador	plásticos tienen un poder calorífico mayor al del carbón	no	Si	La energía calorífica del 23% en peso de todos los plásticos desechados

					plásticos y metales
	Vidrio a Plomo	Vidrio proveniente de los TRC como materia prima para la fabricación de plomo	Plomo	No	Es la recuperación del plomo, mientras que el vidrio se pierde en el proceso.
5	Mecánico	Triturar las tarjetas de la manera más fina y homogénea	Partes metálicas, cerámicas y plásticas	No	Aprovechar la diferencia de densidades, o la diferencia de propiedades eléctricas, para la separación de metales
	Química	Ácido sulfúrico para solubilizar el cobre y otros metales, por medio de un proceso electroquímico u otra reacción química	Metales	No	Inconveniente de este proceso es que se utilizan ácidos que tienen que ser tratados para evitar la liberación de metales pesados al medio ambiente.
	Metalúrgico	Proceso utiliza directamente las tarjetas para ser usadas en fundiciones de cobre	Cobre	No	Necesita un control estricto de las emisiones, ya que pueden producir sustancias tóxicas como las dioxinas y furanos

**Table 3** Description and comparative matrix of WEEE material and energy recovery processes

Among the treatments for PCBs, they contain environmental and human health risk factors, as they produce air, water and soil contamination.

Rapid cryogenic treatment of PCBs minimises the impact of PCB treatment. Another treatment is pyrolysis, which can be considered as an alternative method of recycling PCB waste, because the organic materials are decomposed into low molecular weight products in liquid and gas phases (Khanna et al. 2014, Hadi et al. 2015).

Published results of this type of treatment process for PCBs indicate that the metals contained in the WEEE have a catalytic role for the vapour gasification of plastic components that can improve the hydrogen production performance in the vapour gasification of WEEE as well as nickel dust (Salbidegoitia et al. 2015). However, metals oxidise at high temperature decreasing their catalytic power. To carry out an efficient gasification process, e-waste must be mixed with metal powder recovered from the same e-waste and gasified with water vapour at low temperature around 823K (Zhang et al. 2012, Salbidegoitia et al. 2015).

One of the WEEE recycling processes is the use of steam gasification to obtain clean hydrogen.

Another alternative is to carry out hydrogen production by pyrolysis and steam gasification. Both techniques produce hydrogen, however steam gasification is the more viable option for H<sub>2</sub> production from e-waste as it produces more moles of H<sub>2</sub> than pyrolysis. However, steam gasification has a disadvantage that it produces a considerable amount of CO<sub>2</sub> and this could cause an environmental impact because CO<sub>2</sub> is a gaseous pollutant (Zhang et al. 2012).

## Conclusions

This research has presented a descriptive and comparative analysis of the different treatment processes for the recovery of matter and energy from WEEE.

The results obtained allowed to identify the feasibility of alternatives for material recycling and energy recovery from WEEE. Identifying the type of revalorisation of each part of the WEEE. Plastics and PCBs are sources for energy production. The feasibility of the processes depends on the degree of contamination arising from the process.

In Mexico there are few companies that carry out WEEE recycling activities, only 56% of the states have collection and recycling activities, so these are areas of opportunity for the generation of new materials and eco-design from WEEE. Similarly, formalising this type of process will reduce informal recycling and the environmental and health impacts that it entails.

The relevance of this research is to know the different alternatives of material recovery, to identify new materials for alternative energy generation, in order to reduce the risk of contamination.

There is an important tendency to continue with research into new recycling processes and the generation of clean energy from WEEE. These results also allow us to advance in the knowledge of WEEE treatment.

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