Life Cycle of the Electrical and Electronic Equipment Waste. Approach to Circular Economy.

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Abstract.

Electronic and electronic devices - EEE is one of the sectors that has been prioritized in Circular Economic -CE, both at international and national levels, given that they use many resources, have a high potential for circularity, and contain critical materials. Since there is a lack of a systemic and holistic perspective considering the whole life cycle phases and several supply chain actors. With the purpose of knowing what developing countries, such as Colombia, should do to implement extend producer responsibility -EPR and obtain results that are directed to the achievements that it pursues in CE. A system dynamics model is developed to know variables results associated with the material recovered, the WEEE generated and the energy consumed. Policies that are associated with the formalization of the informal sector, allows greater material recovery thus ensures a circular economy. Energy efficiency labels are the instrument, which reduces more energy consumption. However, the scenario where all the policies are placed together is the one that shows the most impactful results over all the variable outcomes of the flow, showing environmental, social and economic benefits.

Key words: WEEE, life cycle, circular economy, system dynamic, scarcity material, sustainability

1 Introduction

The waste electrical and electronic equipment - WEEE are not alien to the global trend, to move from the linear model - take, make, use, disposal- to a circular model, through the Circular Economic - CE, where it is sought that the value of the products, the materials and resources are kept in the economy for as long as possible and the generation of waste is minimized (Ellen Macarthur Foundation, 2012; OECD, 2014; Ghisellini et al., 2016; Lieder & Rashid, 2016; EU, 2016; Parajuly & Wenzel, 2017). Electronic devices - EEE is one of the sectors that has been prioritized in CE, both internationally and nationally, given that they use many resources, have a high potential for circularity, contain critical materials, (EU, 2020), (MADS, 2019). In addition, the rate of recycling through the appropriate channels is only 20% of the 8.9 Mt of generated WEEE is collected and recycled. Additionally, around 4% (1.7 Mt) is thrown into residual waste in higher-income countries. Meanwhile, the fate of the remaining 76% (34.1 Mt) is unknown but is most likely dumped, traded, or recycled under inferior conditions (Baldé et al., 2017).

Extended producer responsibility -EPR is a proposed policy approach to promoting the CE within the European Union (Campbell-Johnston et al., 2021). EPR was proposed as a product-oriented strategy, the first definition Lindhqvist (1992): *EPR is an environmental protection strategy to reach an environmental objective of a decreased total environmental impact from a product, by making the manufacturer of the product responsible for the entire lifecycle of the product and especially for the take-back, recycling and final disposal of the product. The Extended Producer Responsibility is implemented through administrative, economic and informative instruments. The composition of these instruments determines the precise form of the Extended Producer Responsibility*. Lindhqvist (2000) later re-defined EPR as a policy principle to promote total life cycle environmental improvements of product systems. It means, it was conceived as means to incentivize the eco-design, but the EU applications, it focused on the collection and processing post-consumer product, Then, (Campbell-Johnston et al., 2021) have studied how to transform EPR to contribute to EC goals in the Netherlands, which means that EPR can continue to contribute to world goals.

The results of EPR have been differentiated in developed countries and in countries with emerging and developing economies – CEDEs. While in 2016, WEEE generated in the European Union Member States was 14.28 kg/capita, the WEEE collected was 5.6 kg/capita (Eurostat, 2019), (Ylä-Mella & Román, 2019). While in Colombia, WEEE generates is 5.3 kg/capita and WEEE collected is unknown. These data in the EU show that what is collected is only 35% on average of what is generated. However, there are countries like Sweden, Switzerland and Norway that manage to collect 76%, 73% and 67% of what is generated, that is, more than 16 kg/capita. Which have functional and stable systems with great success, from which you can learn (Ylä-Mella & Román, 2019). Lessons that can be more exploited by Latin American countries, which do not have a successful implementation model.

On the other hand, WEEE has been studied at different stages of the life cycle, from the perspective of one or a few value chain actors, but it is said that there is a lack of a systemic and holistic perspective considering the whole life cycle phases and several supply chain actors, (Bressanelli, et al., 2020). For this reason, this study seeks to determine what developing countries, such as Colombia, should do to implement EPR in a way that allows obtaining results that are aimed at the achievements that it pursues in CE, contemplating actions in all stages of the life cycle. of the WEEE, to know the result variables associated with the recovered material, the WEEE generated and the energy consumed.

2 State of the Art

The CE seeks to create closed ties for the phases of the product life cycle through greater reuse, recycling and reuse, in this way it contributes to improving the environment, using resources better and boosting the economy. It is to extend the useful life of the materials through a longer use and a greater use of secondary raw materials (Ellen Macarthur Foundation, 2012; OECD, 2014; Ghisellini et al., 2016; Lieder & Rashid, 2016; EU, 2016; Parajuly & Wenzel, 2017). This process starts in smart product design and production processes can help save resources, avoid inefficient waste management and create new business opportunities (Eurostat, 2019).

CE is applied through approach, methods, models, practices, policy and strategies. CE is focusing in policy and strategies, policy sets the parameters within which it intends to achieve its purpose, while strategy is a design or plan that defines how policy is to be achieved considering the resources, (Davies, 2000). Besides, policy instruments are tools used by decision makers, especially government, to pursue a desired outcome. (Carney, 2013). The implementation of those tools is usually made to achieve policy targets of resource management. However, adjusted to social, political, economic, and administrative concerns, (Ali, 2013). Besides, CE is applied to the whole stage of the life cycle management, which are like the parts of value chain exposed by Kalmykova et al, 2017. It proposed nine parts in the value chain of the resource flow of the circular economy: 1. Materials sourcing, 2. Design, 3. Manufacturing, 4. Distribution & sales, 5. Consumption &Use, 6, Collection and disposal, 7. Recycling and recovery, 8. Remanufacturing and 9. Circular inputs. And in these parts of the value chain different strategies are distinguished, which include theories, politics, case studies, and practice and business case.

If determining the amount of WEEE that is generated is complex, (Baldé et al., 2015); determining the components and materials is even more so. It is necessary to determine a standard equipment model, the average weight and thus determine the materials that compose it. Broadly speaking, most EEE have ferrous metals that make up 50%, non-ferrous (AL, Cu) 13%, plastics 21%, toxic components 3% and others where precious metals are counted (Au, Ag Pd, Pt), among the dangerous ones is chlorofluorocarbons - CFC, mercury and CRT glass, (UNEP, 2007; Oguchi et al, 2011; Oguchi et al, 2013; Wang, 2014; Cucchiella et al., 2015; MADS, 2017). Circuit boards have toxic metal as: Ba Be Cd Cr Pb Sb, base metals like: Al Cu Fe Sn Zn and metal prices like Ag Au Pd, (Oguchi et al, 2013).

Since the goal is to recover the largest amount of valuable material in the highest possible purity, then the value of these materials on the market becomes important. In the table 1 are the value in US $ / kg of the materials that have the highest volume or economic value in the different types of WEEE, this after having consulted different sources in 2020.

Table 1. Material market Price ($US/kg)

Materials	US$/kg	Materials	US$/kg	Materials	US$/kg
Aluminum- Al	1.6	Copper – Cu	6.4	Palladium- Pd	75,309.9
Antimony - Sb	7.60	Gold – Au	67,020.6	Plastics	1.58
Barium – Ba	550.00	Glass	0.05	Platinum –Pt	32,346.2
Beryllium – Be	864.00	Indium – In	550.00	Silver - Ag	799,308.8
Cadmium - Cd	1.50	Lead – Pb	1.8	Steel/Iron	0.30
Chromium - Cr	1.70	Mercury – Hg	124.00	Tin – Sn	17.7
Cobalt- Co	28.5	Nickel – Ni	13.4	Zinc - Zn	2.1

Sources: London metal Exchange.com; Infomine.com; metal-prices.com solostock.com

The materials that have changed the most in value, compared to 2014 values, are Au, Pd and PT (Cucchiella et al, 2015). Gold is used as a store of value, so its fluctuating and growing price is due more to an international political economic environment than to the laws of supply and demand. Its mining production will decrease slightly, the supply from recycling will increase slightly and the demand will also increase slightly (LME, 2019). Since the end of 2018, Palladium has been the most expensive metal, displacing gold, given that supply is not enough to compensate for demand, since its use is mainly in catalytic converters to reduce pollution from vehicles. Platinum has decreased its price, since its demand has fallen, driven by the low demand for catalysts for diesel vehicles, (LME, 2019).

According to the composition EEE can be congregated into groups. Base metal dominant group are large household appliances, small household appliance and luminaries. Precious metal dominant group are IT equipment. Plastics dominant group are small household appliance and IT equipment. Glass dominant group are lamps and CRT monitors and TVs, (Wang, 2014). When considering the potential material value, human toxicity in the end-of life phase the consolidated results are the classification an EEE categories in the new/recast EU WEEE Directive 2012 (Annex III) plus professional equipment as solar panel, central heating systems that require special arrangement, (Wang, 2014). In Colombia, the composition list of the EEE distinguishes 8 materials such as: ferrous metals, Al, Cu, Pb, Cd, Hg, Au, Ag. And these same materials are the ones that are reported as recovered. (MADS, 2017). While in other countries more than 40 materials are considered, including ferrous metals, non-ferrous metals, precious metals, scarce metals, and hazardous materials. Which are were determined in several studies or directives, as ROHS Directive (EU, 2011), recognizing 78 fundamental raw materials (EU, 2016). Especially Co, Ga, In, Ta, Au, Pd, Ag, and REE and whose demand is greater than 30% relative to world mining production, (Zhang et al., 2016), metal has a concentration greater than 0.25g per unit of product, (Cucchiella et al., 2015).

The treatment of WEEE to obtain said materials is affected by two components, 1. Technical (treatment method, machinery and environmental controls) and 2. socioeconomic (collection channels, price of materials, labor and logistics costs, incentives according to technology, environmental standards, recycling facilities for secondary materials, levels of research and development), (Wang, 2014).Three major steps are distinguished in the chain of waste treatment with different alternatives for its execution.1.Removal of material / toxic components, 2. Pre-processing: manual dismantling and mechanical separation or a combination of both, 3. End-processing (thermal, chemical and metallurgical process, which required advanced technologies to reduce impurities and refine materials). is common back yard or low technology process. The grade and quality of the liberated material from preprocessing directly inf light refined efficiency. For example, in PC gold recovery in Austria, manual pre-processing involves 80% recovery vs mechanical pre-processing which involves 51% recovery. Another example, informal processing of circuit boards in India implies 25.5% efficiency, while recovery in China with Trial of PC dismantling in China combined with refining at integrated smelter is 95.3%. This allows us to conclude that the recovery percentage depends on many technical factors. Furthermore, precious and toxic metals should be processed at the same time, the flows of toxic metals will change when treatment processes are modified to recover more resources or for other purposes. This considering the level of toxicity of the materials as a priority criterion. (Oguchi et al, 2013).

Socioeconomic factors include collection costs, preprocessing and end-processing techniques which have different start-up costs (for machines), operational costs (labor and energy) and revenues (from different qualities of separation outputs. These costs depend on technology and costs associated with labor that change according to each sociocultural context. This cost is the main barrier in industrialized countries and in some cases an advantage in developing countries. For example, in Ghana and Nigeria, in the refurbishing sector, salaries range between US$ 2.20 and US$ 22 per day, where the highest incomes are achieved by workshop owners, while employees typically earn less than US$ 4.00 per day (UNEP, 2011). They become a factor for not technify the process in developing countries given the high cost of technology vs. low labor costs. When performing an analysis of costs vs. profits, the rem over circuit board metals represents profit €0.31/kg, dismantling €0.25/kg, processing €0.22/kg, where 72% of all profit comes from dismantling, as 40% comes from recovering the valuable materials from the circuit board. The above means, high use of labor in dismantling, (Wang, 2014). While the costs in Brazil are huge and incomparable, they are between 1308 -1606 US$/kg, and include: primary transportation, separation and storage, secondary transportation, dismantling, and administrative. Which are very high and do not include end-processing, since the circuit board is exported. Summarizing, the parts of the value chain associated to the collection and disposal, recycling and recovery, and remanufacturing guarantee the material sourcing and their reincorporation on the chain again.

However, the physical material, it is not the only value, energy one of the most important resource. It is used in the consumption and use, manufacturing and material sourcing part of the value chain. Specifically, about EEE, Geller et al., (2006) present policies, programs and policy instruments intended to increase appliances energy efficiency. For such purpose, they recall strategies that have been successful in countries such as Japan (“Top Runner” and labeling), the United States (EEE efficiency norms, switch to more efficient EEE, federal incentives, federal subsidies and labeling), Western Europe (labeling, voluntary agreements, efficiency norms and financial incentives) and California (EEE efficiency norms and metering to adjust Kwh price to peak time). The use of financial incentives and specific information influence consumer behavior.

Many are the countries that have used the REP as a policy to implement the integral management of WEEE, however, its application is based on different strategies, tools, practices. But what is common are the actors involved in the process. Where producers are distinguished and how many of them have commissioned Organizations that are responsible for the physical and economic flow of WEEE, called PRO.

Table 2. Expecting responsibilities for the EEE life cycle phases actors

Cycle Stage	Producer	PRO	End of life Organization (Use and recycled)	Government and Municipalities	Consumer
Material	-Recycled content in new products.	Recycled material availability. -Material cost.	-	-Recycled content target in new products. -Less raw material. -Competitive industry. -New companies, jobs creation.	-
Design	-Common standards -Avoid toxic materials -Design by 4R-D&R -Cost of 4R-D	-	-	-Common standards -Competitive industry.	-
Production/Commercialization	-Economic and physical responsibility for their products. (Individual or PROs representing different producers) -Common standards -Environmental Reputation -Information about lifespan 4R-D&R -Information about energy efficient	-WEEE register -Setting Advance recycling fees (ARF, ARC)	-	-Freerides follow the EPR policy	-Education and information -ARF visible and differentiated by equipment.
Use	-Availability of spare parts and upgrades.	-WEEE collection points and logistic routes. -Approves diagnostic center for review 4R-D -Approves WEEE treatment operators -Per to per market.	-Warranty on 4R -ARF	- Licensing authority for WEEE treatment for collecting, transporting, repair and recycling. -WEEE collection points -Standards to certify -Available energy for other use.	-Take back the old equipment -Bonus by ARF for new device.
End of life	-Components and Material recycled targets	Approves WEEE treatment operators	-BAT to recover purity materials -Standards compliance -Reporting of collected, recover and sold material and energy recovered	-Proper manage of toxic material -Collection and recovery targets -Standards to certify EoL companies. Operating Licenses for recyclers -Freerides follow the EPR policy	-

Convention: (4R-D&R) repair, refurbish, remanufacturer, disassemble and recycled

PRO are often the ones who approve the companies that carry out end-of-life activities and that work together with the municipalities to establish logistics strategies so that the consumer has different delivery options. In table 2 is the list of actors involved and the responsibilities they must assume in the different stages of the life cycle. This taken from the analysis of the best practices that have been carried out by Switzerland, Norway, Sweden and Denmark. (Ylä-Mella & Román, 2019), as well as studies to improve the application of EPR (Campbell-Johnston et al., 2021), (Park et al., 2018). Where actions like higher collection amounts stand out as well as the quality of WEEE treatment are the most relevant factors connected to the environmental improvement potential of WEEE recovery in the EU (Huisman et al., 2007). The basic feature of the Swedish WEEE system is efficient material flows; recycling operations are centralized, and transportation optimized. El-Kretsen has divided the country into different collection areas based on volume, logistics costs, and the locations of preprocessing plants. The PRO are organizations have established nonprofit-based WEEE management companies with membership fees and payments restricting on the volumes of EEE produced and covering the proper treatment of end-of-life products.

3 Colombian Context and Scope

Colombia is a country of 50 million inhabitants (DANE, 2020), with a *medium-high* income and a *high* inequality index of 50,4 (World Bank, 2020). In infrastructure, in the country there are 36 companies with an environmental license to take advantage of, treat or dispose of WEEE (MADS, 2017). Of these, 13 companies export the flows of materials, components and parts recovered to China (50%), the United States (9%), Hong Kong (8%), Spain (7%), South Korea (5%), The Netherlands (4%), Taiwan (4%), Belgium (2%) and 27 other countries (11%), (MADS, 2017). The average exports from 2007 to 2011 were 3703 tons/year, a figure that increased 87% in the period from 2012 to 2015 to 6919 tons/year. It is estimated that the installed capacity is 14,000 tons/year, so it is considered enough to process the amount generated. Materials such as: ferrous metals (19%), copper (49%), aluminum (11%) and plastic (9%) are recovered, while that of EEE, parts and components is of 9%. They do not recover, or have not registered, valuable, scarce and hazardous materials. Likewise, eco-design is not a priority, since we are not a producer country, instead of an importer of EEE. As for the legislation, since 2005 the MAVDT has formulated policies that allowed structuring law 1672 of 2013, as they are listed in table 3.

Table 3. Colombian Regulations on WEEE

Regulation	Scope
Resolution 1511 de 2010	The systems for selective collection and environmental management of light bulbs waste.
Resolution 1512 de 2010	The systems for selective collection and environmental management of waste of computers and peripherals.
Resolution 1297 de 2010	The systems for selective collection and environmental management of waste batteries and accumulators.
Law 1672 de 2013	Guidelines for the adoption of a public WEEE management policy under EPR principle.
Decree 2041 de 2014	Environmental license for the construction and operation of facilities whose purpose is storage, treatment, use (recovery, recycling) or final disposal of WEEE. Refurbishment and repair activities of used electrical or electronic equipment were excluded.
Decree 284 de 2018	Integral Management of Waste Electrical and Electronic Equipment - WEEE and other provisions are dictated. Into force in February 2019
Resolution 076 de 2019	Environmental license process for projects for the construction and operation of facilities whose purpose is the storage, treatment, and/or use (recovery/recycling) of WEEE.

Resolution 480 de 2020	Registry of Producers and Sellers of: Electrical and Electronic Devices
Circular Economy Strategic (MADS, 2019)	WEEE is priority project. Circular economy and waste management is part of the regulatory agenda 2019.

Source :(MADS, 2022) (MADS, 2019)

In Colombia, the program Computers to educate-CPE, which allows the provision of technological tools, training and accompaniment to educational communities and environmental management of disused computer equipment. In the period from 2014 to 2017, it retook up 1,679 tons, reaching average annual income, in that period, of $ US 72.6 million ($ Col 218 billion). In addition, 2,571 tons of CO2 e were avoided. The cost benefit ratio was 1.2 on average for said period. (CPE, 2018).

The informal recycling has more preponderance over the formal one, this one manages to collect more WEEE, because it offers money to the end user for the delivery of the EEE and it does not pay taxes due to its informality. Besides, they recuperate the material through technology that is often not appropriate, abandoning the materials hazardous and difficult to recover, thus generating environmental and health implications for waste pickers and the surrounding population. For ordinary waste, Bogota has adopted affirmative actions that facilitate the inclusion of formal organizations of waste pickers in the provision of public cleaner services. This means that they have experience in formalization schemes, (Minvivienda, 2016). Besides, in Colombia, it is believed that UEEE is not received from other countries, however Brazil does receive and be part of the region (Lundgren, 2012), which is why the threat to Colombia is considered latent. Dicha informalidad se asocia a la falta de claridad de las responsabilidades que deben asumir los diferentes actores.

The equipment selected for this study is the refrigerator or refrigerator, the lights responsible for lighting consumption, the television and the sound system. Which are responsible for the highest consumption of electrical energy in Colombian homes, as can be seen in Table 4. This both for 2012 and for 2016, where the variation is given by televisions, since in 2016 93.0% of households had at least one television, 63.8% was a conventional color television and 46.2% was an LCD, plasma or LED television. In addition, the first three pieces of equipment are the ones with the highest penetration in Colombian homes and the last one may represent the equipment that has an average behavior of energy consumption and penetration, specifically the penetration of sound equipment is 53.5%

Table 4. Selection criteria for study devices.

Devices	Energy consumption. UPME 2012	Energy consumption. Urban Residential UPME, 20.16	Penetration/Use in homes (DANE, 2017) Cities
Refrigeration	43,25%	39%	89,9%
Illumination	14,89%	10%	99,8%
Television	13,45%	20%	95,9%
Electric shower	5,71%	6%	10,6%
Others	6,7%	10%	N. A
Total	84%	85%	

Source: (DANE, 2017), (MinEnergia,2019)

4 Methodology

The primary data are taken from the results of surveys applied to citizens and secondary data from government entities, (DANE, 2017; CPE, 2017; UAESP, 2010; ANDI, 2009). These allow feed the variables that are used to describe the management model of WEEE in the stages of material sourcing and production, use and end of life. This contributes to modeling and simulating through system dynamics, a technique that allows determining the feedback cycle between the variables, showing their interrelation, as well as the effects of policy instruments in closed cycles. This being one of the best tools to simulate circular or closed cycle economies.

For the calculation of the recovered materials, data from Wang, 2014, where the weight in kg of the device studied and the % of the composition appear, taking into account four groups of components: 1. common metals (iron Fe, copper - Cu and aluminum - Al), 2. Precious materials such as Silver-Ag, gold-Au and palladium-Pd, in mg/kg, 3. Plastics and 4. Other materials. Hazardous materials such as CFC, CRT Glass and Mercury Hg. These values were used with the model results through a lookups table, which are output data in accordance with predetermined input values necessary for the simulation, considering the percentage of recovery efficiency if it is done through the informal or formal channel.

The validation of the model was carried out through the verification of the trends of variables such as the number of households, penetration rate of EEE.

5 Model Description

The model presents the different stages of the life cycle of several EEE commonly used in the city of Bogotá by modeling the physical, economic and information flow of these elements over a 50-year horizon. The base year for which the initial values were taken for the model was the year 2001. The four EEE considered in the model are medium-sized refrigerators, CRT, LED and LCD televisions, audio equipment, incandescent, fluorescent and LED bulbs.

The model represents the relationships between energy consumption, generated WEEE and materials recovered from the different EEE in their life cycle, which are affected by consumer decisions regarding purchase, use and end of life. Figure 1 shows the causal diagram that represents the different variables of the system and their interrelations.

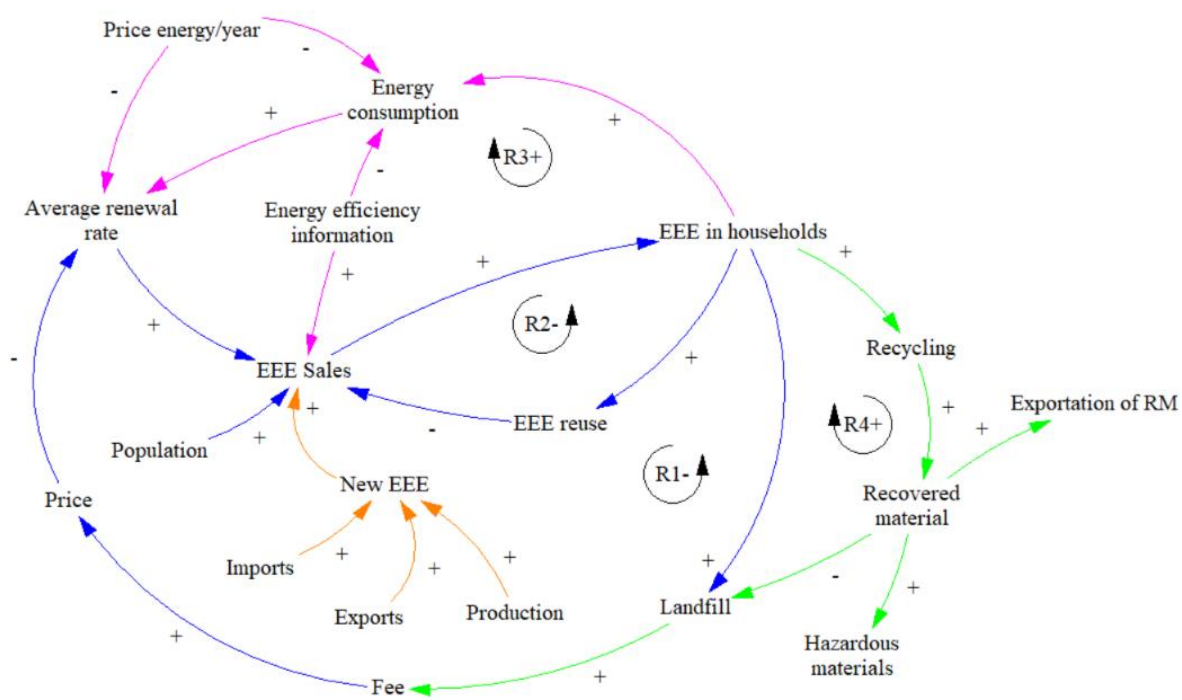

Figure 1. Causal Diagram

5.1 Physical Flow

The physical flow shows the passage of EEE in the stages of production and use, up to WEEE end of life, this last stage includes the recovery of materials that can be incorporated back into the productive cycle, guaranteeing the circular economy at the end of the cycle.

In the production stage, the apparent consumption of each domestic appliance is considered, which includes local production from raw materials and recovered materials, imports and exports. Apparent consumption was estimated from equation 1.

$$Apparent\ Consumption = Production + Importation - Exportation \quad \text{(equition 1)}$$

The amount of EEE in households is directly related to the penetration rate and is determined by the new households that acquire EEE for the first time, by those that renew them due to a change in technology or because the EEE has already reached its useful life. And additionally, those EEE that are repaired or donated to another household are contemplated, thus extending their useful life. The equipment for which the reuse is contemplated in the model are for refrigerators, and televisions, since light bulbs are used until they stop working.

In figures 2 and 3, the amount of EEE in the system for the base scenario is shown. The number of CRT televisions, as well as incandescent and fluorescent bulbs tend to decrease over time because they are technologies that have become obsolete or are not efficient and are being replaced over time.

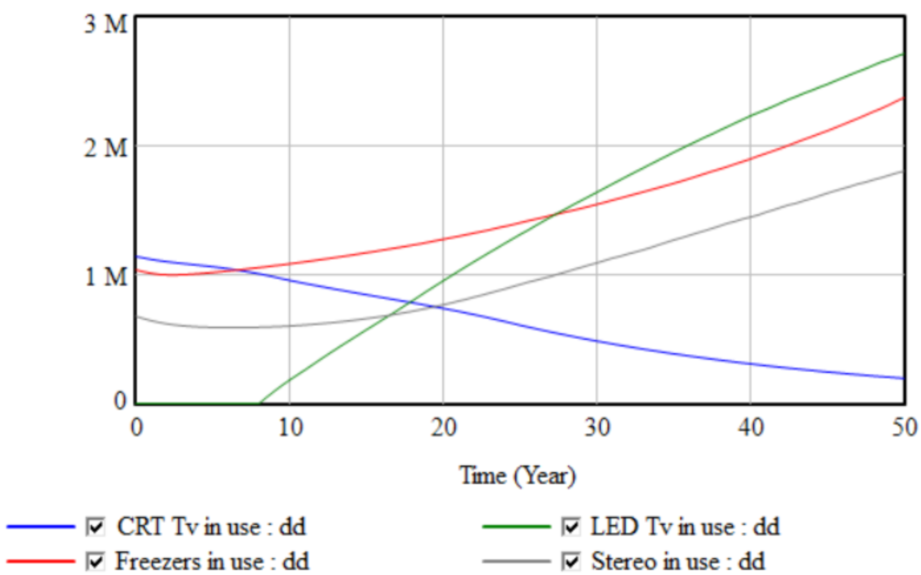

Figure 2. Amount of EEE in use of the baseline scenario across the simulation horizon

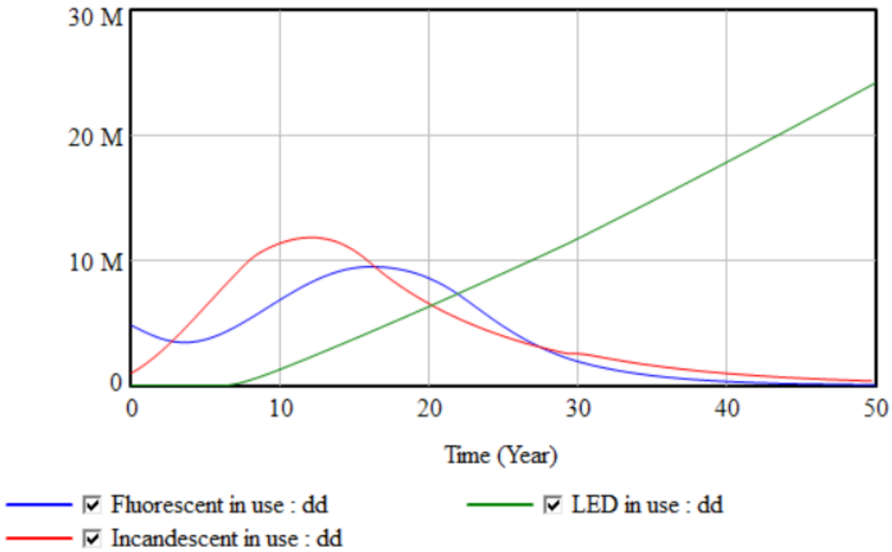

Figure 3. Number of light bulbs in use of the base scenario across the simulation horizon

The base model considers the end of life through two channels: informal channel that deals with 35% of WEEE by means of informal recyclers without any formal training to carry out the work, with a material recovery capacity of 20%. And the formal channel that handles 8% of the WEEE through certified companies that have knowledge of standards and procedures to manipulate waste and with a greater capacity to recover materials (40%). 57% of the remaining waste is deposited directly in the landfill (which has a capacity of 14,076,800 tons). In addition, the companies in charge of the collection of ordinary garbage collect some waste such as screens and CRT glass and are taken to the landfill, (ASOCRIM, 2012).

Some of the recovered materials contemplated in the model and that are the result of formal and informal recycling process are: ferrous materials, aluminum, plastics, glass and hazardous materials such as: CFC, plastics with bromide, mercury, barium, chromium, lead, among others. Recognizing that inadequate management and end of life of WEEE causes negative impacts on the environment and human health.

5.2 Economic Flow.

The economic aspect is considered in the model when calculating the average renewal rate of the EEE, end of life taxes and the price of energy. The renewal of EEE in a household depends on economic variables such as the price of the EEE, the cost of repairing in case of damage, the purchasing power, determined by the level of household income and finally access to financing or discounts that can be come directly from the purchasing establishment or a bank.

The process of collecting and disposing of WEEE at the end of the life cycle requires economic resources, which are generally covered by the government, or come from taxes paid by the manufacturing companies or the consumer as ARF. Currently EPR is not implemented as an economic responsibility yet. The model includes the consumer tax or ARF that is paid when purchasing an EEE through an authorized distributor. The purpose of this tax is to generate awareness in the consumer at the time of the end of life of WEEE to be done properly, to reduce the environmental impact. The tax o AFR is calculated according to the remaining capacity of the landfill as shown in equation 2.

$$taxes = \begin{cases} 5\%, & landfill < 0.25 * landfill\_capacity \\ 10\%, & 0.25 * landfill\_capacity < landfill < 0.5 * landfill\_capacity \\ 15\%, & 0.5 * landfill\_capacity < landfill < 0.75 * landfill\_capacity \\ 20\%, & landfill > 0.75 * landfill\_capacity \end{cases}$$

The price of energy is a factor that affects the purchase decision and consumer habits, because electricity consumption is reflected directly in the bill. When the value of the invoice increases, consumers tend to reduce the time of use of the EEE, such as light bulbs, televisions, entertainment equipment, or try to acquire an EEE with greater energy efficiency that translates into lower consumption of energy and therefore lower cost of the invoice.

5.3 Information Flow

The energy consumption in a household is determined by the EEE usage habits and the energy efficiency of these. So, the information of the parameters associated with energy consumption in an equipment are a determining factor in the purchase decision or change, given that the value to pay by electricity consumption increases with EEE that have a low efficiency, causing more energy to be consumed.

For consumers to make informed decisions when making the purchase an EEE, energy efficiency labels are used as an informative tool. These give detailed information on energy consumption with respect to a scale. In the European Union, it goes from A +++ to C, in accordance with Directive 2010/30 / EU; in North America it is determined by Energy Star (McWhinney, 2005); and in Colombia the scale goes from A (more efficient) to G (less efficient), according to resolution 41012 of 2015 and resolution 40420 de 2021 (MMinas, 2015); (MinEnergía, 2021). For the simulation a scale of 5 categories was defined with reference to an average consumption that corresponds to category 3, as it is observed in table 5.

Table 5. Energy Efficiency Label Scale

Category/Label	**Efficiency**
1	-25%
2	-15%
3	0%
4	+25%
5	+40%

6 Results in different scenarios

According to the model described, several scenarios are simulated to evaluate the effects that are had on the system in terms of EEE in use, Sales of EEE, Energy consumption. In this last part material is contemplated in the landfill, hazardous and recovered material. The scenarios evaluated are show in Table 6.

Table 6. Scenarios Evaluated.

Scenarios	**Description**
E1	Reuse of EEE
E2	End of life taxes o ARF fees
E3	Formalization of recycling
E4	Energy price increase
E5	Energy Efficiency label

The first scenario (E1) simulates the effect of the reuse of some EEE, such as refrigerators and televisions. These have an average lifespan of 11 and 10 years in Europe, but in the case of Colombia, the useful life of these equipment can be extended to 25 and 15 years respectively (Blaser, 2009), (Rodríguez et al, 2010; Rodríguez et al., 2013). Reuse consists of extending the life of an EEE by donating it to another household for its use or by repairing it repeatedly instead of acquiring a new one.

The second scenario (E2) is implemented to observe the effects of applying a tax o ARF policy to end of life according to the level at which the landfill is located. This implies that the lower the capacity of the landfill, the greater the tax o ARF that will be applied on the price of the EEE. See equation 2. This should preferably be at the time of purchase. It should be visible and differentiated according to statistics of reuse, remanufacturing, recovery of each brand. This would motivate companies to carry out end-of-life management.

The third scenario (E3) is simulated to evaluate the effects on the system when formalizing the WEEE end of life, this implies that the formal channel collects 35% of the waste and recovers 60% of the materials and the informal channel collects the 15 % of waste and continues with the same level of recovery described in the base scenario.

The fourth scenario (E4) implies an increase in the base price of energy of 15%, which is initially taken as US$ 0,11 (COP $ 352) per kWh, to observe the response of households in the purchase decision and the effects on the rest of the system.

The last scenario (E5) simulates the effect of energy labels on the purchase decision by having information on the efficiency of the different EEE. These are consulted in the first purchase or in the renewal of the equipment, especially when looking for some more efficient.

To observe the effect of the simulation of each of the scenarios described above, the result variations are calculated, which average throughout the simulation time are. These are: bulbs in use and EEE in use, sale of EEE, energy consumption, material in the landfill, valuable material recovered, and hazardous materials recovered. The results obtained are shown in table 7.

Table 7. Result variables in the different scenarios

Scenarios	**Bulbs in use**	**EEE in use**	**Sales of EEE**	**Energy consumption**	**Material in landfill**	**Valuable material recovered**	**Hazardous material recovered**
E1	0.0%	2.0%	-1.3 %	1.6%	3.3%	4.6%	5.8%
E2	0.0%	-2.5%	-4,3%	-1.6%	-0.5%	-1,6%	-1.7%
E3	0.0%	-3.7%	0.0%	-3.4%	-18.5%	63.6%	35.7%
E4	-3.9%	-1.9%	9.1%	-2.9%	10.7%	11.5%	10.0%
E5	-3.6%	-1.3%	6.1%	-29.1%	7.2%	7.8%	6.7%
E6	-7,6%	-12.6%	10.0%	-36.1%	-3,9%	96.2%	57.0%

To analyze the impact of all the policy instruments on the whole system, they were simulated simultaneously, and the results shown in the last row of table 6 were obtained.

In the scenario (E1) where reuse is present, the changes observed in relation to the baseline scenario are a slight increase of 2% in the EEE in use, and a reduction of 1.3% in sales. It can be caused by the fact that user received an UEEE for use instead of acquiring a new one equipment. Besides, the consumption of energy is increased by 1.6%, which is low and is because there is more equipment in the system. Furthermore, the old equipment can consume more. As there is more WEEE in the system then proportionally there will be more material in the landfill, valuable material recovered, and hazardous material recovered, in a range of 3.3% to 5.8%. The reuse implied other activities as repair, refurbish, remanufacture and repurpose.

In the scenario (E2) when the producers/government establishes taxes or ARF for end of life by formal channels. The value of the EEE is increased in the sale, generating that buying are reduced 4.3%. The same effect occurs in the equipment in use, which is reduced by 2.5%. Then the amount of energy demanded is less, near to 1.6%. Besides, it causes a reduction in the valuable and hazardous materials and in the landfill. Which means that people avoid renewing their equipment. But if that tax or ARF were returned in the form of a bonus for the purchase of new equipment, then it would surely stimulate the renewal of equipment.

The scenario (E3) of formalization is the scenario where the application of an individual policy instrument presents the best results. Specifically, the recovered material is increases by 63%, likewise the hazardous material recovered increases by 35.7%, which means that the material that goes to landfill is reduced by 18.5%. Sales are not they vary, but the EEE in use if they are reduced, which may be associated to citizens identify an adequate channel to deliver their WEEE and decide not to keep them stored at home but to deliver them for an adequate disposition. This implies technological changes associated with the recycling process, which favor the recovery of high-purity materials and obey not only demand criteria, but also environmental and health impact criteria. These technical criteria will be established only if there are changes that encourage the modernization of existing companies or the creation of new ones that favor the recovery of materials and the collection, dismantling, recycling and recovery activities in their value chain to achieve it.

In the scenario (E4) where there is a 15% increase in the energy price, Kwh, which is feasible in times of drought, since 70% of Colombia's energy comes from hydroelectric plants. This means, that sales increase by 9.1%, as users will want to acquire more energy efficient EEE. Then, this is reflected in the fact that energy consumption is reduced by 2.9% and appliances in use in 1,9% as well, especially in light bulbs. Where people have as a practice to save energy, because they do not turn on the light bulbs or they use less time them. Nevertheless, as sales increase, then, the material in the landfill increases and the valuable and hazardous material recovered in quantities close to those that increased sales

In the scenario (E5) where citizens acquire more energy efficient products after being informed about it, there are savings in energy consumption of 29.1%, but when replacing old EEE with new more efficient ones, sales increase by 6.1%. Besides, the quantities of material in landfill and recovered increase similar values. As output in the policy of increasing energy price there is a decrease in the use of household appliances and light bulbs in 1.3% and 3.65% respectively.

When performing the simulation using all the instruments at the same time in the E6, the best results are obtained in all the variables, as shown in table 6. Energy is reduced by 36.1% in relation to the baseline scenario, even when the number of household's new ones continues to increase. The valuable recovered material is increased by 96% and the hazardous material in 57%, due to the formalization of recycling and because there are more EEE in use in the system. It is due that energy efficiency labels and the increase in the price of energy cause citizens to replace their EEE before ending their useful life by more efficient ones, which causes sales to increase in 10%. At the same time, the appliances in use is not increased; in contrast, EEE are reduced in 7,6 and light bulbs in 12,6%, possibly because energy efficiency labels make them use only those they need, and the existence of a formal channel encourages the user to want to deliver the WEEE for an adequate channel, without deteriorating the environment and health. A fact that is guaranteed by the taxes paid at the time of purchase, so that the good is disposed of correctly.

7 Conclusions

Currently in Colombia there are two non-existent actors in the WEEE management system, such as the PROs and the municipalities. Likewise, the non-existent responsibilities are the financial responsibility and information responsibility associated with the economic flow and the flow of information that is described in the model. Despite the recent regulations that require EEE producers and sellers to register and recoverees to obtain environmental operating licenses, the missing responsibilities to comply with are those associated with common standards from the design so that the products can be reused, repair, refurbish, remanufacture, and recycle. On the other hand, with the intervention of the municipalities, more collection points would be generated and thus the collection logistics routes could be optimized. This is because the lower costs are generated, the lower the value of the ARF that the consumer must pay.

It is necessary that in each one of the stages of the life cycle, results or benefits are achieved for all the actors and, likewise, the best use of resources is made. Since all the stages are interconnected, action in one stage can generate results in others. In the same way, the interaction of the different authors is what allows the best results to be obtained, for example, if the user is motivated to deliver the product at the end of its useful life, the recover can collect it and carry out a diagnosis of it, to find out if it can be reused, repaired, restored, remanufactured, retrofitted or recycled, but if the user prefers to keep it, none of the mentioned processes in the chain can take place.

The formalization of informality is the most convenient individual scenario, its formalization would imply the creation of a PRO that materializes the physical, economic and informative responsibility of the WEEE as a representative of the producers and importers. These determine the cost or tax to be paid by consumers for the end of life of WEEE. PRO can approve WEEE treatment companies that meet standards that protect the environment and the health of employees. The initial activities of the end-of-life stage being a diagnosis of the state of EEE that allows its repair, refurbish, remanufacturer, disassemble and recycled. The recycling, it must be with the best available technology that allows recovering all the materials, with great purity, so that they reach the highest possible level in the market.

It can be concluded that the synergy of different policy instruments allows obtaining the best result in all the variables. The efficiency instruments, which are informative, allow the achievement of the best results in reduction of energy consumption.

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