Mangmeechai *Sustainable Environment Research* (2022) 32:16
https://doi.org/10.1186/s42834-022-00126-x

Sustainable Environment Research

RESEARCH Open Access

The life-cycle assessment of greenhouse gas emissions and life-cycle costs of e-waste management in Thailand

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Abstract

There is no clear direction in the management of electrical and electronic waste products (e-waste), as there are no regulations on ways to do so. This research attempts to understand the trade-off between the economic value and the environmental effects of the current disposal of e-waste to find ways to optimize waste management, focusing on cellphones, television cathode ray tubes, desktop computers, and air conditioners. A life cycle greenhouse gas and life cycle costs were conducted. Under the e-waste management status quo, most household e-waste is kept in houses because owners do not know where to discard it. In addition, informal sectors, such as domestic farmers or workers, have been actively involved in collecting and dismantling e-waste for more than a decade, leading to poor management standards for both health and the environment. Without e-waste management regulations, informal dismantlers of products gain slight profits by collecting and selling parts and discarding all non-recyclable waste in municipal garbage dumps. The current practice actually adds greenhouse gas to the atmosphere mainly due to improper logistics management and discarding of refrigerants. The logistics are inefficient because the dismantling communities and recycling locations are far apart. Most e-waste is generated, and most recycling industries are located in the central region (the richest areas), while the dismantling communities are located in the northeastern region (the poorest areas). Furthermore, the life cycle of greenhouse gas and the life cycle costs of e-waste are affected by transportation, and not all e-waste parts can be recycled within the country. High-tech mineral extraction cannot be practiced in the country, and thus, circuit boards and batteries are exported for recycling. To promote a circular economy, e-waste management regulations should be implemented, the costs of proper e-waste management should be internalized, and a full recycling industry should be established in the country.

Keywords: Life cycle assessment (LCA), Life cycle costs (LCC), E-waste management, Circular economy

1 Introduction

Thailand has been facing many challenges, as the country lacks accurate information about e-waste, such as the amount of waste generated per year. In addition, the country still has no legislation on e-waste management, and thus, it is difficult to mandate the collection of household e-waste for recycling. Importantly, local authorities are still unready to manage household waste [1, 2].

The amount of e-waste of all types was estimated to be approximately 357, 384, and 421 kt in 2012, 2015, and 2019, respectively, and this trend is likely to increase by more than 40% over the next 10 years [3, 4]. In 2019, the most discarded e-waste product was televisions (99.5 kt or 24%), followed by air conditioners (77.7 kt, or 18%), refrigerators (66.0 kt or 16%), washing machines (62.8 kt or 15%) and computers (59.7 kt or 11%). The rest are VCDs/DVDs, phones and digital cameras (55.7 kt or 16%). The survey of the Pollution Control Department found that most of them came from residential

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houses, accounting for 82%, followed by offices and hotels/apartments, accounting for 14 and 3%, respectively [5].

In addition, according to a survey of household consumers' behavior in dealing with e-waste, the Pollution Control Department [5] reported that 51.3% of e-waste owners sell their devices to secondhand shops, 25.3% keep them at home, 15.6% discard them with general waste, and 7.8% do something else.

Under the current status quo, because no fee is collected from producers or consumers, the market determines the collection system. In addition, informal sectors have been actively involved in separating and dismantling e-waste, which has led to inefficient collection and disposal systems. These informal sectors are scattered throughout the country, particularly in the northeastern region (Daeng Yai and Ban Pao subdistricts, Buriram province). They include approximately 347 families that separate and dismantle 383 tons of e-waste per week [6].

The key to the success of e-waste management is its economic function (cost effectiveness), environmental effects, social awareness, and technological aspects [7]. Importantly, it is impossible to design effective e-waste policies if the government does not have information about e-waste and its distribution flow. Life cycle assessment (LCA) can evaluate the environmental performance, e.g., greenhouse gas (GHG) of e-waste management activities [8, 9], and financial life cycle cost (LCC) is a tool used to analyze the economic effects of an LCA system and can be viewed as an analytic tool parallel to an LCA. The combined use of LCA and LCC is imperative to assess the sustainability of a product or product system in the economy [10].

Accordingly, the objectives of this study are to (1) study and estimate the life cycle of GHG and the LCC of household e-waste, focusing on the top 4 types of e-waste discarded in the country, TV cathode ray tubes (CRTs), desktop computers, air conditioners, and mobile phones, and (2) provide policy recommendations for e-waste management. This study will contribute to understanding the status of e-waste management in Thailand and the trade-off between e-waste's environmental and economic aspects to provide better disposal practices. Hence, the results of this study will be valuable for the entire e-waste treatment industry.

2 Background

2.1 Estimated total amount of e-waste generated in Thailand

Some studies have utilized government agencies, such as the Pollution Control Department and the Department of Industrial Works, for the quantity of e-waste estimates. The estimation of the amount of waste products produced in 2019 was provided in various reports [4, 5, 11, 12]. Each study used different estimation methods, such that the results yielded different numbers. The estimated number of the 4 types of waste products (mobile phones, desktop computers, air conditioners, and televisions) generated in 2019 was approximately 89.5–257.6 kt: of these, (1) 1.3–2.9 kt or 10.7–23.0 million mobile phones; (2) 16.2–58.2 kt or 1.25–4.47 million desktop computers; (3) 34.9–97.1 kt or 0.91–2.54 million air conditioners; and (4) 37.0–99.5 kt or 2.46–6.80 million televisions. The amount of e-waste generated in Bangkok and the provinces had a very strong positive association with household income [6].

2.2 E-waste management flow

According to the study of Mangmeechai [6], Fig. 1 shows the flow of the e-waste from industries and households. E-waste from the industrial sector is not a problem because global corporations have very clear protocols for e-waste management. E-waste from these industries is transported to professional dismantling and recycling industries that often have foreign affiliates. The valuable parts, e.g., electronic circuits and batteries, are exported to foreign recyclers; for example, in Singapore and South Korea; the less valuable parts, such as plastic, copper, iron, and aluminum, are recycled by Thai industries.

In contrast, households do not have any directions or guidelines for e-waste. The collection and recycling system is not properly managed and mainly relies on the market demand mechanism. There are four channels for household e-waste:

1. The first channel is e-waste owners selling their obsolescent e-waste products to peddlers who then sell them to e-waste dealers.
2. The second channel is owners donating their obsolescent home appliances to temples or nonprofit organizations or associations.
3. The third channel is to donate to e-waste collection projects conducted by government agencies, e.g., the Electricity Generating Authority of Thailand, universities, or private sector companies such as AIS, a mobile signal provider. However, these projects are just temporary.
4. The fourth channel is to discard e-waste along with household solid waste. According to a survey from the Pollution Control Department, 25% of the owners kept their obsolete electronics at home [5].

The first and second channels, the peddlers and temples or associations, often sell to secondhand markets, where such e-wastes can be reused after simple repairs or upgrades. Due to their lower incomes, rural

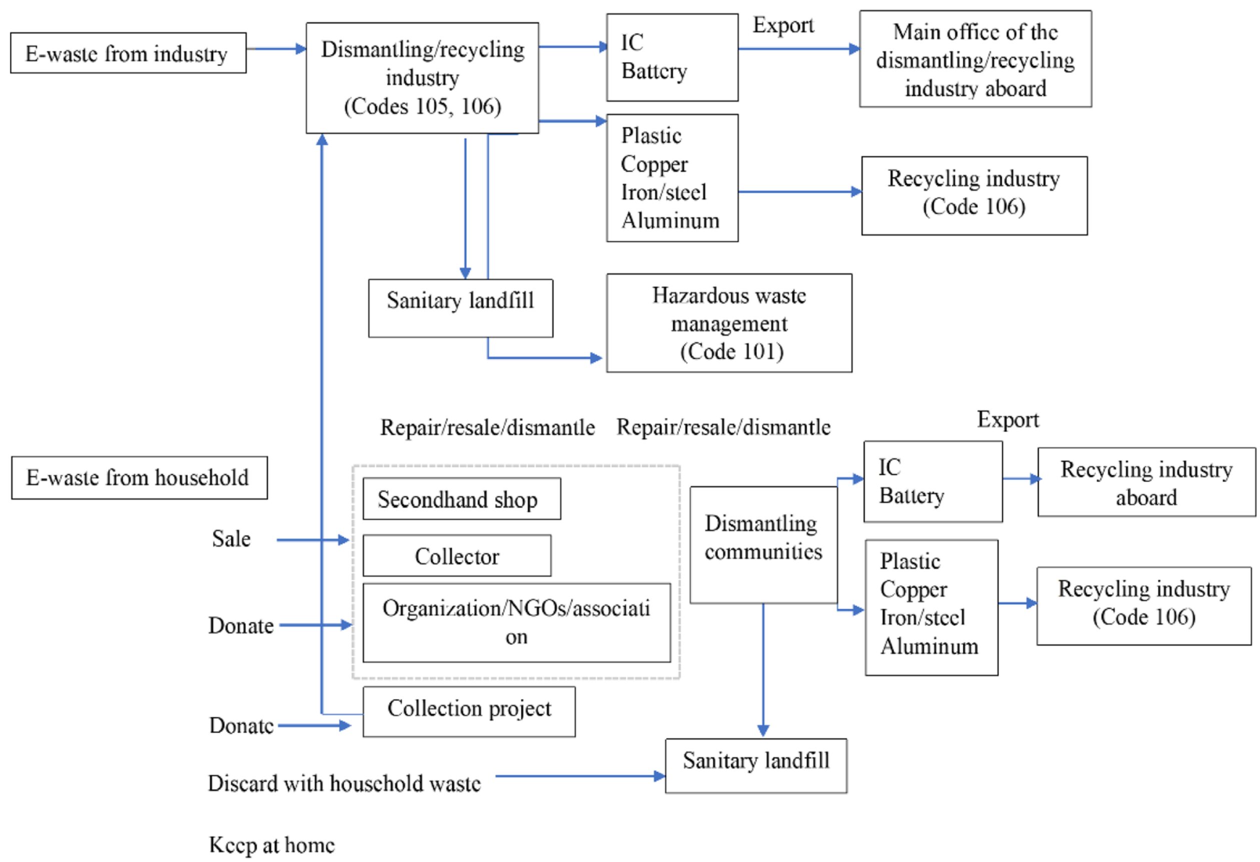

Fig. 1 E-waste flow in Thailand (market driven)

populations are the major consumers for such products. These practices can be considered an extension of the lifespans of these electronic appliances [13]. When devices can no longer be repaired, the waste can be sold to peddlers or dealers again and later shipped to recycling industries. This process might pass through many middlemen before arriving at the recycling industries. Peddlers and dealers collect circuit boards or batteries to sell to Chinese collectors who then export them to China for mineral extraction. Guangdong Province in China has the world's largest recycling center for printed circuit boards. However, because the Chinese government has strengthened controls over the importing of printed-circuit boards, several Chinese firms have recently begun to recycle printed circuit boards in Mong Cai in Vietnam [14].

In the third channel, e-waste is collected and sent to professional dismantling plants (a similar path for industrial e-waste) and recycled as part of corporate social responsibility.

Practices in sorting/dismantling communities, secondhand shops, etc., are not professional, as workers do not have adequate and appropriate knowledge, equipment, and technologies to handle e-waste. After collecting e-waste, they simply employ primitive techniques, including manually dismantling electronic equipment and burning wires for steel and copper.

2.3 The practice of informal sector and recycling industries

The informal sectors are active in sorting and dismantling activities. They use basic tools such as hammers, wrenches, pliers, screwdrivers, grinding stones, and drills to dismantle the waste. Many workers do not wear personal protective equipment and pay more attention to economic issues than potential health problems. These communities have not yet experienced the adverse health effects of dismantling e-waste, as illnesses from exposure to heavy metals are more likely to present years later than acute sicknesses [15]. However, Amphalop et al. [16] confirmed that e-waste separation activities can elevate the potential ecological risk to these areas, as researchers reported that the soil was highly contaminated with copper and arsenic. One research study confirmed that open burning is a common practice used by informal sectors to separate copper from wires in Thailand. The study found that increased amounts of burnt e-waste significantly influenced the concentrations of coarse and fine particles emitted [17].

In certain countries, workers sometimes heat and remove components from printed circuit boards, cut cables and wires to recover metals, chip and melt plastics, sweep out toners, and recover precious metals through acid leaching [13].

Thus, proper e-waste separating practices, such as operating in a closed-system workshop far from households and vegetation areas and banning open burning, are highly recommended to avoid heavy metal contamination in the soils and high concentrations of fine particles.

The e-waste sorting community does not fall within the definition of an industry since it uses only primitive tools and has few workers (e.g., 1–2 family members). There are e-waste sorting communities in 17 provinces nationwide. Kalasin and Buriram provinces in the northeastern region are the primary e-waste sorting communities and have been involved in this activity for more than 10 years. These communities operate in a way similar to an industry type 105 separation plant or landfill for waste or unused materials. For the most part, these communities' sorting and disassembling activities are just a supplementary occupation or a small business. Thus, there are no major short-term effects on the environment; instead, there are economic and social benefits for poor communities. This is attributable to the fact that poor people undertake informal sorting and dismantling, and thus, the government is unable to impose serious penalties or fines, as they cannot pay them. Open dumping of nonvaluable devices is also common and has caused significant adverse environmental and health effects [1].

Industrial code 105 shown in Fig. 1 licenses the sorting and dismantling of all kinds of wastes. According to the database system of the Department of Industrial Works, Thailand has 43 industries (involved only in e-waste) scattered in 11 provinces (largely in the central region).

Industrial code 106 licenses the recycling of discarded industrial products or waste, including hazardous materials and raw materials or new products. There are 116 industries scattered in 21 provinces. Most are distributed densely in the central and western areas, and only a few are located in the north and south.

Industry code 101 is for companies that treat or eliminate unused materials that are classified as hazardous waste. A 101 plant is a total waste treatment operation that takes one of two forms: 1. A wastewater treatment plant to reduce, remove, and treat pollution contained in wastewater and sludge, or 2. Waste incineration. There are 22 industries with waste disposal facilities involved in e-waste scattered in 10 provinces that are distributed largely in the Central and Eastern regions with a small number in the North and South.

2.4 Electronic waste recovery and recycling processes

Not all e-waste parts in the country can be recycled, and different types of e-waste are transported and dismantled in different areas.

Televisions: Most televisions are sent to waste sorting communities in Kalasin and Buriram provinces that require waste to be transported approximately 31–448 km. Plastic, iron, aluminum, and copper are recycled in the country, and glass is disposed of in municipal landfills. Most of the recycling facilities are located in central areas. The distance between waste sorting communities and recycling facilities is as follows: copper (441–549 km); iron (112–521 km); plastic (31–518 km), and circuit boards (523 km). Circuit boards are exported to recycling industries abroad or burned illegally to extract valuable minerals [6].

Air conditioners: Most households that have air conditioners are located in the central region. Thus, the discarded air conditioners are not transported to other areas for dismantling, and the distance between the waste sorting community and recycling facilities is less than 170 km [6].

Desktop computers: These computers are sent to the Suayai Uthit community (Bangkok), the Daeng Yai Subdistrict (Buriram), and the Khok Saat Subdistrict (Kalasin), and the transportation distance can range widely from less than 100 to 550 km [6].

Cellphones: Phones from all over the country are gathered and dismantled in three subdistricts in the Chiang Yuen District, Maha Sarakham Province. The dismantled parts can be divided into 2 groups: 1. parts that can be sold to foreign recycling companies, e.g., batteries and circuit boards, and 2. parts that cannot be sold and are disposed of later in municipal landfills, e.g., plastic front/back covers, screens, etc. [6].

2.5 E-waste management in Asia

Japan: In 2001, Japan implemented a recycling system for TV sets, refrigerators, washing machines, and air conditioners under the Home Appliance Recycling Law. Consumers pay recycling and transportation fees, and discarded appliances are sent to recycling facilities. The appliances collected under this framework represent only approximately half of the estimated production, suggesting that the remaining half is either exported and/or disposed of domestically [18].

In 2004, there were 41 e-waste recycling facilities in Japan that were financed in part by the ministries, municipalities, or companies that produce electronic products. Many producers have implemented their own business strategies for e-waste management and have their own facilities or collaborate with other producers to create and operate such facilities. E-waste derived from residences is collected when these products are no longer used or when consumers purchase new products. The waste collected is transported to intermediate e-waste collection points (380 points) and eventually to the recycling facilities through a distribution system [19].

Korea: In January 2008, the Eco-Assurance Committee System (ECOAS) in Korea was established to recirculate electrical and electronic equipment and vehicles in joint legislation by the Ministry of the Environment, the Ministry of Knowledge and Economy, and the Ministry of Land, Transport, and Maritime Affairs. According to ECOAS, five product groups and 27 e-waste items, including refrigerators, personal computers, electric ovens, audio equipment, and mobile phones, are controlled to increase the electronic industries' recycling capacity [20].

India: This country has implemented an extended producer responsibility system since 2012. However, the system did not work because of overlap and lack of a clear target, as well as the lack of a collection system. A new rule issued in 2016 added a deposit and refund system as an incentive to motivate consumers to return discarded electronic devices to their manufacturers. Those who returned their devices claimed some money back with some interest. At this time, each producer was assigned to collect 30% of the electronic devices they sold [21].

3 Methods

3.1 E-waste components

The 4 types of e-waste selected were: (1) TVs with a 51 cm (20-in.) color CRT screen (weight 23 kg), (2) air conditioners, 9000–12,000 BTU (both indoor and outdoor units, weight 31 kg), (3) desktop computers, both the central processing unit (CPU) and 30 cm (12-in.) monitors in models between 2010 and 2018 (weight 24.7 kg), and (4) 4 types of cellphones: 1 feature phone and 3 smartphones (average weight 118 g).

The dismantling process was conducted in the lab guided by experts from the Department of Primary Industries and Mines and informal dismantlers. The methods and steps are as follows: the main parts of the selected e-waste are separated, e.g., plastic cover, yoke, monitor, power supply, hard disk, hot coil, circuit board, motor, etc. Then, each part is weighed to calculate the percentage of the main components.

3.2 Life cycle GHG and LCC of e-waste

The functional units for life cycle GHG and LCC are one unit of 36-cm TV CRT 53 cm screen with weight 23 kg, one unit of air conditioner 9000–12,000 BTU weight 31 kg, one unit of desktop computer 30-cm screen and CPU weight 24.7 kg and one unit of cellphone (smartphone and feature cellphone) average weight 118 g. The units represented are kg CO_{2eq}/unit and THB/unit (32 THB = 1 USD).

A life cycle GHG study followed the international standards of ISO 14040. E-waste management involves collecting, disassembling, transporting, recycling, and disposing of residue [22]. The system boundaries of the life cycle GHG study of each e-waste type are displayed in Fig. 2. This illustrates the e-waste that originates from residences, is transported to informal dismantling facilities, and is prepared for recycling.

The method used was Eco-indicator 99 and allocation default, and unit processes were applied to study the life cycle GHG [23]. Primary data, e.g., e-waste components, transportation distances between stakeholders and secondary data, e.g., SimaPro software (Ecoinvent v. 3 database) were used. Table 1 summarizes the data used for life cycle GHG.

The LCC analysis was followed according to the guidelines from Matthews et al. [25]. The system boundaries of the LCC study of each e-waste type are displayed in Fig. 3. The profits for this can be calculated as profits for informal dismantlers, and profits for Thai and foreign recycling industries. E-waste purchasing costs were received from owners and selling prices were received from interviewing secondhand shops, informal dismantlers, and the recycling industry, and secondary data, e.g., reference prices of rare minerals, transportation costs, and transportation distances, were used (Table 1).

The equations used are as follows:

(costs of purchasing e-waste from owners + transportation costs to dismantling communities + transportation costs to recycling industries) − (profits from selling parts to secondhand shops + profits from selling parts to the recycling industry) = net profits for Thai informal dismantlers (1)

(costs of purchasing parts to the recycling industry + profits from recycling (plastic, copper, iron/steel, aluminum) = net profits for Thai recyclers (2)

(costs of purchasing circuit boards/batteries from dismantlers - profits from rare mineral extraction) = estimated maximum net profits for foreigner recycling industry (3)

The transportation costs for export to the foreign recycling industry and rare mineral extraction costs were not included.

4 Results

4.1 E-waste components

The types and models of e-waste were chosen and dismantled. The separation method followed was according to informal sector practice. The e-waste components are summarized in Table 2.

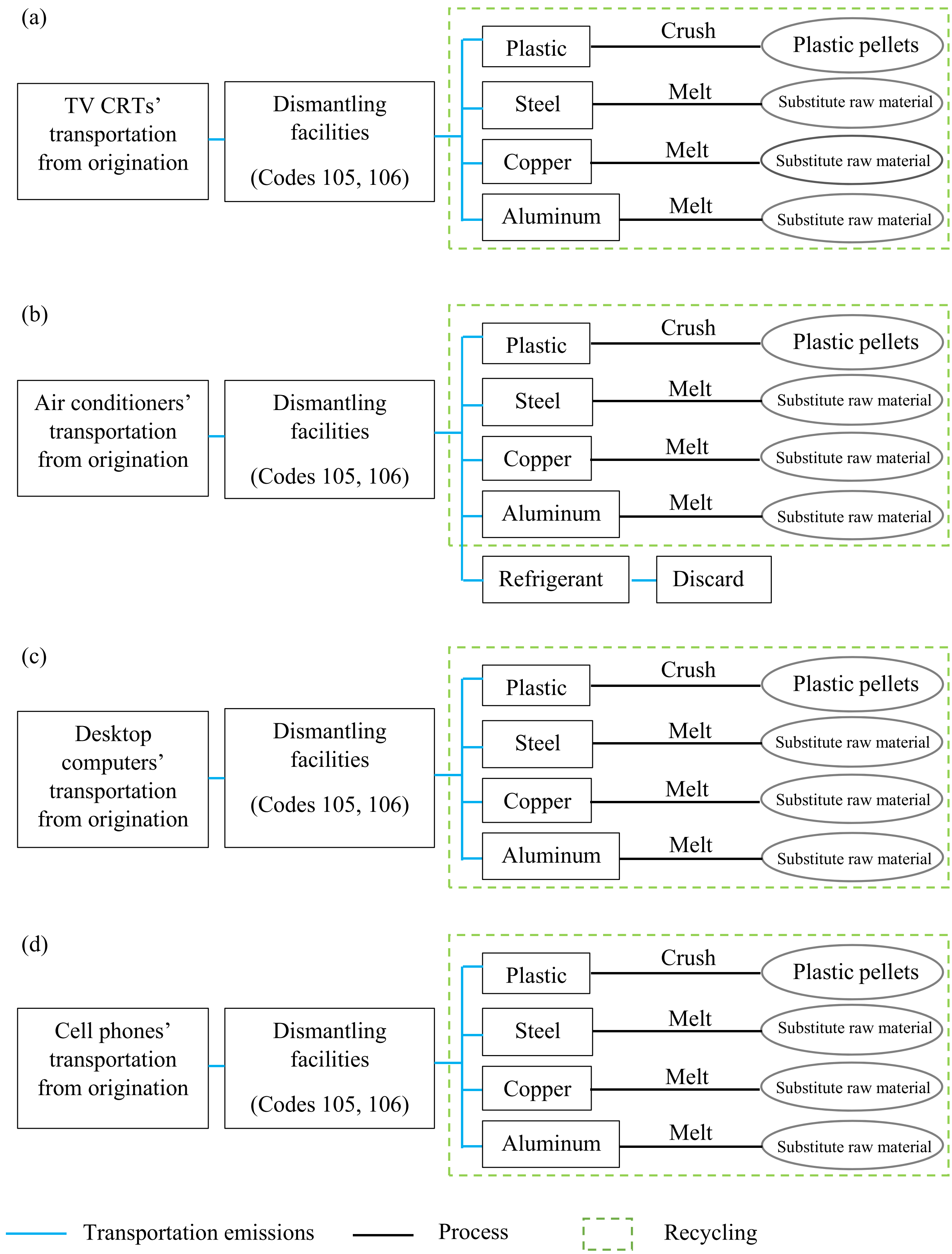

Fig. 2 Life cycle GHG of all four types of e-waste of (**a**) television CRT screens, (**b**) air conditioners, (**c**) desktop computers, and (**d**) cellphones

Table 1 Data sources for life cycle GHG and LCC

	E-waste parts	Primary data/interview	Secondary data/software
Life cycle GHG	Plastic Steel Copper Aluminum Circuit Li-ion Battery		SimaPro 8.3.0.0 (Table S1)
	Refrigerant R32		Table S2
	Transportation distances		GIS data from [6] (Tables S3-S6)
	Transportation emissions		Thai National LCI database/MTEC
LCC	Plastic Steel Copper Aluminum Circuit	- Dismantling communities - Secondhand shops - Recycling industries (Industry code 105 and 106)	Table S8
	Silver Gold Palladium Lead		The London Metal Exchange
	Transportation costs		[24]
	Transportation distances		GIS data from [6]

Most local authorities do not see e-waste in its original form in landfill sites [26]. Copper, steel, aluminum, and plastic can be recycled domestically. Glass from TV and cellphone screens that contain lead and plastic (e.g., cellphone front/back plastic case) are discarded in landfills. Batteries and circuit boards are exported for recycling to other countries, e.g., China, South Korea, and Singapore. The recyclable parts in TVs, air conditioners, desktop computers, and cell phones accounted for approximately 28, 90–98, 45, and 35–50% by weight, respectively. Table 3 shows nonrecyclable e-waste. TV CRTs showed the highest amount of waste, while air conditioners showed the lowest amount of waste, as most of the parts can be sold to recycling firms.

4.2 Life cycle GHG of e-waste

The life cycle GHG of each type of e-waste depends upon transportation distance. The logistical system is inefficient because certain types of e-waste are transported for separation in certain areas and for recycling in another location. Most e-waste is generated in the central areas that have the highest household income and the majority of the recycling firms, while the dismantling communities are located in the northeastern region because this is the poorest sector in the country. Table 4 shows the life cycle GHGs of all 4 types of e-waste. The life cycle GHG is sensitive to transportation.

The country has banned the use of hydrofluorocarbon-R22 (R22) refrigerants in air conditioners nationwide since 2018 and converted to R32, which has less effect on ozone layer depletion [27]. The amount of refrigerant depends upon the compressor size. Normal use is approximately 1–4 kg for air conditioners of 9000–50,000 BTU (data from interviews with air conditioner repair shops). R32 has global warming potential (GWP) of 675 [28]. During the process of dismantling air conditioners, the informal sector allows the refrigerant to evaporate rather than collecting it properly for disposal. Considering the emissions of the refrigerant in R32 air conditioners, it has been found that dismantling air conditioners has a negative environmental effect of (30.1)–(17.3) kg CO_{2eq}/unit if R32 is stored and disposed of improperly. Therefore, to reduce adverse effects on the environment, dismantlers should be encouraged to collect R32 refrigerants rather than allowing them to evaporate.

4.3 LCC assessment of e-waste

The results showed that sorting/dismantling and extracting precious minerals from cell phone waste generates the highest revenue (by weight), followed by desktop computers. The circuit boards of these two types of wastes contain precious minerals/metals, such as silver, gold, palladium, etc. In contrast, CRT televisions generate the lowest revenue because the screen contains lead components that are hazardous substances. Table 5 shows the LCC of e-waste.

Air conditioners yielded the highest profit for Thai recyclers (by unit), followed by computers, TVs, and cell phones. In reality, if the costs of waste treatment (nonrecyclable parts) are included, TV dismantlers would not make any profit. The Khok Sa-at Subdistrict, Kalasin Province area has a large amount of e-waste imported for dismantling in the community. In this area

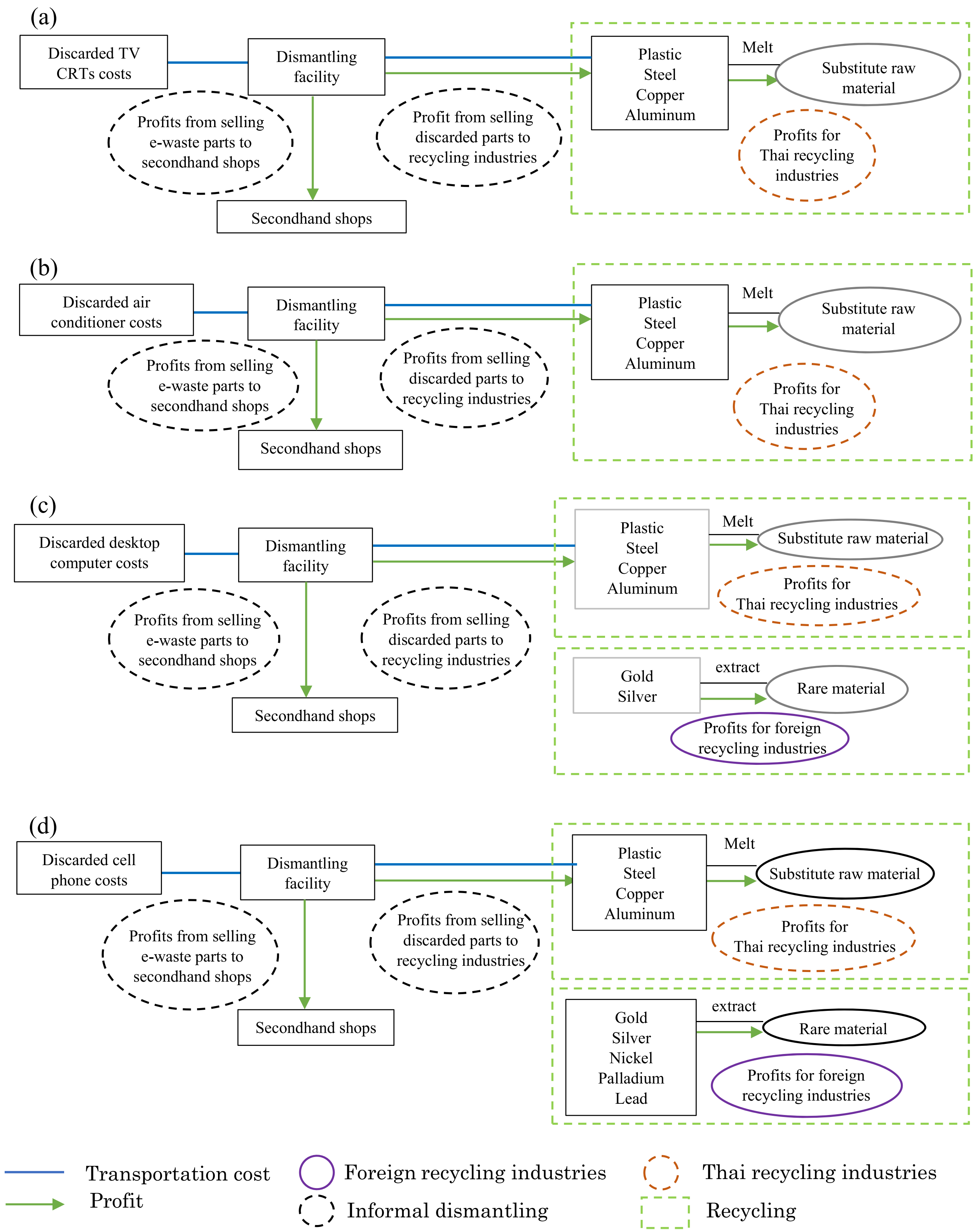

Fig. 3 LCC of all four types of e-waste of (**a**) television CRT screens, (**b**) air conditioners, (**c**) desktop computers, and (**d**) cellphones

Table 2 E-waste components (kg or g per unit)

	Recyclable plastic	Non-recyclable plastic	Glass	Steel	Aluminum	Copper	Circuit board	Carbon	Battery	Other
TV CRT; LG 21″ (23 kg)	3.66	0.08	14.98	2.29	0.03	0.46	0.97	0.27	–	0.26
Air conditioner (31 kg)	7.19	–	–	16.87	2.87	3.65	0.12	–	–	0.44
Computer monitor CRT; 30 cm (18.2 kg)	3	0.2	8.4	3.1	0.1	0.8	1.9	0.3	–	0.5
CPU; (6.5 kg)	0.7	–	–	3.9	0.4	–	1.2	–	–	0.3
Feature cellphone (95.1 g)	–	31.8	6.4	–	11.2	–	15.2	–	21.5	9
Smartphone 1 (124.3 g)	–	17.1	60.3	–	–	–	13.3	–	30.5	3.1
Smartphone 2 (119.5 g)	–	15.5	50.2	–	–	–	14.4	–	34.1	5.3
Smartphone 3 (133.6 g)	–	11.9	59.3	–	–	–	13.9	–	38.8	9.7

(especially for televisions), it was found that the municipality had spent a budget of 3,300,000 THB or US$ 103,100 to eliminate 300 tons of waste in 2018 and 2019. On average, this results in approximately 11 THB kg^{-1} if the dissection community is responsible for the cost of disposal of this waste. It was found that the waste disposal cost of televisions was 182.6 THB/unit, air conditioners 5.5–341 THB/unit, desktop computers 149.6–151.1 THB/unit and mobile phones 0.8 THB/unit. Disposing waste from dismantling TV CRTs costs more than profits gained if the cost of e-waste disposal is included (especially for the treatment of lead-contaminated glass). Similarly, if R32 is collected rather than allowing them to evaporate. Cement kilns can provide a viable technology for destruction of R32. The costs of treatment for 1 haul pickup truck is 8000 THB (or 250 USD) or approximately 10 THB kg^{-1} of R32 or 0.3 USD kg^{-1} of R32 (or 10–40 THB/unit 0.3–1.25 USD/unit). In other words, these are the costs to trade for reducing 675–2700 kg CO_{2eq}/unit.

Table 6 shows a comparison of GHG emissions, net profits, and waste generated from the collection, dismantling communities, recycling, and transport of the 4 e-waste products. Given the total e-waste generated in 2019, if all of it had been discarded and collected for recycling under the status quo, then the emissions and value-added would be as summarized in Table 7.

Similar results were reported in that the life cycle GHG study showed that recycling is not as environmentally friendly as expected, particularly with regard to the effect of fossil fuels used in transportation and refrigerants [29].

The trade-off between life cycle GHG and profits for Thai informal dismantlers and recyclers was 2.4–79 g of CO_{2eq}/THB for TV CRTs, 1750–5930 g of CO_{2eq}/THB for air conditioners, (46)–11 g of CO_{2eq}/THB for desktop computers, and 281–706 g of CO_{2eq}/THB for cellphone.

5 Discussion and conclusions

Management of e-waste is clearly ineffective and is determined by the market mechanism. In addition, workers in the informal sectors lack knowledge and tools, yet they are the main group active in sorting and dismantling waste. Thus, the e-waste management system does not meet the standard of waste dismantling practices under the status quo. This research attempted to understand the trade-offs among the economic value and environmental effects of the current e-waste management system.

The study focused on four types of e-waste discarded in 2019: cell phones, desktop computers, air conditioners, and televisions. The e-waste estimates reported above can be divided into three categories according to the value of their parts: (1) waste or nonrecyclable materials. For example, nonrecyclable materials are glass with lead content (TV screens), plastic, etc. which accounted for 24% of the total e-waste generated; (2) recyclable parts within the country, e.g., plastic, iron, copper and aluminum, which accounted for 70%; and (3) recyclable parts outside the country, e.g., circuit boards and batteries, which accounted for 6% of the total waste.

Based upon the life cycle GHG and LCC assessment results of the 2019 waste products, it was found that air conditioner recycling management showed the largest

Table 3 Discarded waste from e-waste separation and dismantling

	TV	Air conditioner	Desktop computer	Cell phone
Waste (kg/unit)	16.56	0.5–3.1	- CRT 9.4 - CPU 4.2–4.4	0.07
% by weight	72	2–10	55	50–65

Table 4 Summary of life cycle GHG of e-waste (kg CO_{2eq}/unit)

E-waste type	Area	Transportation	Recycling	Total
Television	Kalasin	0.42–4.12	(0.20)–(0.19)	0.2–3.9
	Buriram	2.5–7.0		2.3–6.8
Air conditioner	Suayai Uthit	1.1–3.4	(31.18)–(20.68) Refrigerant 675–2700	645–2683
Desktop computer	Kalasin	1.8–6.3	(5.46)–(5.43)	(3.68)–0.82
	Buriram	2.7–9.0		(2.8)–3.5
	Suayai Uthit	0.3–0.4		(5.1)
Cell phone	Maha Sarakham	2.7–9.0	0–(0.12)	2.7–8.9

amount of GHGs throughout the life cycle, although it provided the highest revenue (per unit) for dismantlers and Thai recyclers. However, air conditioner waste management could help reduce life cycle GHG emissions if refrigerants are disposed of properly. The main factors that affect life cycle GHG are the transportation distances from waste generation to dismantling areas and recycling firms. Without proper organization between the life-cycle stages, the emissions from transportation contribute a significant portion. This result is similar to that in Jaunich et al. [22], who state that the decline in using fossil fuel-powered personal vehicles is a key factor in costs and carbon dioxide emissions.

With respect to the LCC assessment, it was found that dismantling and recycling all four types of e-waste in 2019 resulted in net benefits in the range of 202–1399 million THB (6.8–45 million USD). The net benefits from the extraction of precious minerals from circuit boards and batteries was in the range of 587–3010 million THB ($19–97 million USD). Although the amount from parts that are exported to foreign recycling industries is small, it has a high value after the precious metals are extracted. The extraction and recycling of circuit boards and batteries generated higher net benefits than Thai recycling industries.

He et al. [30] showed that the LCCs of recycling one discarded feature phone and one discarded smartphone in China are approximately USD 2.3 and 6.6, respectively. The LCCs of extracting high-tech minerals, such as cobalt and palladium, from one discarded feature phone are USD 6.04 for 1 g of cobalt and US$ 0.014 for 1 g of palladium. The LCCs of extracting 1 g of cobalt, palladium, antimony, beryllium, neodymium, praseodymium, and platinum from one discarded smartphone are USD 10.11, 0.024, 0.14, 0.005, 0.08, 0.016, and 0.006, respectively. The total net benefits from recycling and extracting minerals fall within the same range as that in Thailand.

It appears that the dismantling communities can earn profits from this practice; however, the reason that they gain only a slight profit is because they do not pay a landfill fee or a waste disposal fee. The local municipality

Table 5 LCC of e-waste

	Dismantling areas	E-waste costs	Profit from selling as second-hand part (Dismantler)	Transportation costs (Dismantler)	Profits from selling parts to recycler (Dismantler)	Transportation costs to recycling industry (Transporter)	Profits (Thai recycler)	Profits from rare mineral extraction (Foreign recycler)
Television THB/unit	Kalasin	20–130		0.5–4.3	106.8–132.5	0.1–3.2	86	
	Buriram			1.4–9.9		1.3–3.2	82	
Air conditioner THB/unit	Central region	300–1000	753.9–1375.3	0.3–2.4		1.3–4.3	368.6–452.3	
Computer THB/unit	Kalasin	100–180	231.1–493.2	0.2–4.6	127.3–306.9	2.0–7.5	111.8–312.7	470.2–621.0
	Buriram			1.5–10.6	125.8–296.2	1.9–9.0		
	Sua Yai Uthit					0.5–0.7		
Cell-phone THB/100 unit	Maha Sarakham			0.2–18.3	961.5–1264	1.4–2.2		13,089

Note: Labor costs, utility bills, cost of equipment, and transport for recycling abroad are not included

Table 6 Life cycle GHG and LCC assessment results for each type of e-waste from households to dismantling locations and recycling firms

	Type of e-waste (per unit)			
	CRT televisions	Air conditioners	Desktop computers	Cell phones
GHG over life cycle (kg CO_{2eq}/unit)	0.2–6.8 **	645–2683 *	(5.1)–3.5 ****	2.7–8.9 ***
Net profits (THB[a]/unit)	82–86 *	368.6–452.3 ***	111.8–312.7 - Extraction of precious minerals: 470.2–621.0 ****	9.6–12.6 - Extraction of precious minerals: 130.9 **
Waste (kg/unit)	16.6 *	0.5–3.1 ***	- CRT 9.4 - CPU 4.2–4.4 **	0.07 ****

[a]32 THB = 1 USD
* = Poor, ** = Medium, *** = Good, **** = Excellent

covers these costs. In fact, dismantling TV CRTs costs more than its profit if the cost of e-waste disposal is included (lead contained in TV screens). Therefore, existing e-waste management systems should be revised to internalize disposal costs in the economy [31].

Changes in the attitudes of governments, appropriate legislation that specifically addresses e-waste, control of dumping electronic waste, implementation of extended producer responsibility, and technology transfer for the sound recycling of e-waste are the keys for effective e-waste management [32]. The Thai government has taken more than a decade to draft “The Electrical and Electronic Equipment Waste Management Act”. At present, it is still in the drafting process and cannot be implemented anytime soon. Certain e-waste types may need to be charged a waste management fee because collection and recycling have more embedded costs and cannot rely solely on market determinants.

A better e-waste collection system is required, and collection guidelines and collection points will affect both profitability and GHGs. Therefore, collection, sorting, and dismantling centers by region (North, Central, West, Northeast, East and South) need to be established between dismantling facilities and recycling plants. Furthermore, the transportation distance between each facility should not exceed 400 km. This e-waste should be considered an opportunity to recycle or recover valuable metals (e.g., copper, gold, silver, and palladium), given their significant content of precious metals compared to mineral ores [33]. In addition, a full high-tech recycling plant in the country should be developed to achieve the complete extraction of precious minerals.

Ending informal dismantling and recycling sectors should be one of the high-priority policy objectives for governments. Many research articles that have studied this issue have also raised this point [34, 35]. The informal sector should apply the best affordable technologies and upgrade and qualify low- and medium-skilled laborers [36]. In addition, the practical feasibility of circular economy approaches and the development of community commitment through stakeholders’ active engagement should be promoted [37, 38].

Finally, considering the public’s awareness of the human risk undertaken during e-waste recycling activities would be beneficial for organizations with respect to reducing potential adverse effects on society. Incentives may be needed to encourage people to discard e-waste at collection points and not discard together with their solid household waste [39]. The possible introduction of a carbon tax was also found to significantly reduce the cost disadvantage of recycling rather than landfill disposal [10]. Given the high level of environmental load associated with landfilling and the potential introduction of carbon taxes, the circular economy could be seen as a strategy to achieve appliances’ sustainability. Future studies of consumers’ e-waste disposal behavior and awareness could be helpful to devise inclusive e-waste management strategies to address the current challenges [40].

Table 7 Life cycle GHG and LCC assessment results of end-of-life products in 2019

	CRT televisions	Air conditioners	Desktop computers	Cell phones
GHG (tons CO_{2eq})	0.49–46.2	598,175–6,830,918	(22822)–15,662	29,009–204,700
Net profits (million THB[a])	202.4–584.8	337–1151	139–1399 - Extraction of precious minerals: 587–2778	74.1–285.2 - Extraction of precious minerals: 1406–3010

[a]32 THB = 1 USD

6 Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42834-022-00126-x.

Additional file 1. Table S1. Emissions factors from 1 kg of e-waste part. **Table S2.** Global warming potential (GWP). **Table S3.** Flow of discard television (km). **Table S4.** Flow of discard air conditioner (km). **Table S5.** Flow of discard computer (km). **Table S6.** Flow of discard cell phone. **Table S7.** Summary of emission factors. **Table S8.** Purchasing price of parts from discarded television. **Table S9.** Selling price of computer parts. **Table S10.** Selling price of air conditioner. **Table S11.** Selling price of cellphone. **Table S12.** Transportation costs.

Acknowledgments

This research was supported by Thailand Science Research and Innovation Grant number 4450.

Author's contributions

Field data collection, processing the software, writing the whole paper. The author read and approved the final manuscript.

Funding

Fully funded by the Thailand Science Research and Innovation Grant number 4450.

Availability of data and materials

The online version contains supplementary material available at. Additional file 1 Supplementary materials. Table S1 Emissions factors from 1 kg of e-waste part. Table S2 Global warming potential (GWP). Table S3 Flow of discard television (km). Table S4 Flow of discard air conditioner (km). Table S5 Flow of discard computer (km). Table S6 Flow of discard cell phone. Table S7 Summary of emission factors. Table S8 Purchasing price of parts from discarded television. Table S9 Selling price of computer parts. Table S10 Selling price of air conditioner. Table S11 Selling price of cellphone. Table S12 Transportation costs.

Declarations

Competing interests

No.

Received: 12 October 2021 Accepted: 17 February 2022
Published online: 14 March 2022

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