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ORIGINAL ARTICLE

Processes in informal end-processing of e-waste generated from personal computers in Vietnam

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Abstract Informal treatment of e-waste plays an important role in many countries which have no or weak formal waste management structures. One of the challenges for assessing informal e-waste recycling technologies is to identify their disadvantages and potential technology improvement. The analysis of informal recycling processes starts with a balance of input and output materials for each of the processes. Main obstacles are the fact that in most cases, mixed or variety materials serve as input and, secondly by nature, the informal sector does not systematically measure and monitor the process. This study presents the processes and available data for informal e-waste recycling of desktop personal computer as it consists of components made of plastic and many metals within the Vietnamese context. To identify the most relevant processes, critical flows and technology gap, two scenarios are compared: (1) current situation in which recycling activities are taken in recycling craft villages and (2) appropriately selected BAT. The selected materials from e-waste cover a wide range of recycling processes and technologies: Printed Circuit Board treatment, metal (ferrous metal, aluminum and copper) and plastic recycling.

Keywords Vietnam · e-waste · e-waste from personal computer · Informal recycling · Craft villages

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Introduction

Advanced technologies have led to dramatical demand in electrical and electronic equipment (EEE) but shortened their lifespan as well. Consequently, more waste from electrical and electronic equipment, e-waste or WEEE, is generated. From the global perspective, the total amount of e-waste generated in 2014 was 41.8 million metric tonnes (Mt) and predicted to increase to 50 Mt in 2018 [1]. e-waste contain metals (ferrous and non-ferrous metals) and other materials (e.g., plastics, glass) with full potential to be recycled. Unlike other materials, metals have virtually infinity lifespan and limitless recyclability [2]. Hence, recycling metals (and other materials) can provide numerous to not only environment advantages in terms of energy saving, reduction of waste and emissions but also economic benefits. For example, using scrap iron and steel helps to save 74% of energy, 90% of virgin material use and reduce air pollution, water use, water pollution, mining waste is at 86, 40, 76 and 97%, respectively, compared to primary production. Energy savings from recycled materials over virgin ones are 95% for aluminum, 85% for copper and above 80% for plastics [3].

In Vietnam, with the population is about 91.7 million in 2015 [4], Tran and Salhofer [5] using data from URENCO [6] estimated that e-waste generation from used EEE is roundly 1.9 kg/inhabitant in 2014 and will be increased to 3.7 kg/inhabitant in 2020 [5]. As formal recycling facilities are lacking, e-waste treatment relies on informal sector. Due to the important role of this sector, many researchers have come up with varied definitions of "informal sector". For example, Feige [7] expresses that "the informal economy comprises those economic activities that circumvent the costs and are excluded from the benefits and right incorporated in the laws and administrative rules covering property relationships, commercial licensing, labor contracts, torts, financial credit and social security systems". Scheinberg et al. [8] define the informal solid waste sector as it "refers to individuals or enterprises who are involved in private sector recycling and waste management activities which are not sponsored, financed, recognized, supported, organized or acknowledged by the formal solid waste authorities, or which operate in violation of or in competition with formal authorities". In Vietnam, unlike formal sector which is established from hazardous waste treatment and transportation companies certified by Vietnam Environment Administration (VEA) having e-waste treatment system, informal sector is fast developed with an effective and active system which includes e-waste collection, transportation, trade, dismantling and end-processing. The most remarkable characteristic of the informal sector is the formation of craft villages—villages where residents have involved in industrial activities for their main income [5]. And, informal e-waste recycling has strong involvement of dismantling and recycling craft villages. Although the infrastructure for end-processing is available, large amount of outputs from dismantling process [e.g., ground Printed Circuit Boards (PCBs), capacitors, transistors, plastics] are exported to China because of price and domestic demands. For example, the highest domestic demand is plastic bags made of polyethylene—PE while plastics from e-waste sources consist mainly of acrylonitrile butadiene styrene—ABS, polystyrene—PS. Currently, PCBs are treated to recover copper in one workshop via mechanical processes in Bui Dau village (Hung Yen province). Components with high gold content are treated at few very small-sized workshops scattered in Bac Ninh province and Hai Phong city. Other materials, including ferrous metal, copper, aluminum and plastics, are recycled at craft villages under obsolete technologies. As these technologies pose a high risk for workers and the environment, this paper aims at evaluating the current recycling technologies and identifying the technology gap between the current with better ones.

The selected technologies for reference to the current technologies are best available techniques (BAT). BAT mean "the latest stage of development (state of the art) of processes, of facilities or of methods of operation which indicate the practical suitability of a particular measure for limiting discharges, emissions and waste" [9]. Within the BAT reference documents, techniques to consider in the determination of BAT are provided, from the material storage and handling process, material treatment, processing until waste treatment and/or residue processing. In fact, BAT are normally combined with the term best environmental practices (BEP) which is defined as "the application of the most appropriate combination of environmental control measures and strategies" [9]. It is very common to use BAT/BEP as a target for technology improvement or technology evaluation. Benchmark data on material and energy consumption, and waste generation from BAT and practices from BEP are popular indication for technology gap assessment. Some examples are the Technical booklet "Applying BAT and BEP to eliminate persistent organic pollutants in steel-making process—electric arc furnace (EAF) [10] for Vietnamese steel manufacturers, or BAT for Indian Iron and Steel Sector [11].

In this study, desktop personal computers (PC) waste (without monitors and external accessories: mouse, keyboards, etc.) has been selected as a case study to analyze treatment processes in the context of Vietnam. In terms of product put on domestic market, estimated growth rate of PCs is approximately 20% annually [6]. Moreover, in terms of composition, whole PC consists of various materials: base (e.g., iron, aluminum, zinc), special (e.g., tellurium, selenium) and specious (e.g., gold, silver) metals, plastics, etc. Generally, PC waste can contain more than 69 wt% of iron and steel, non-ferrous metals such as copper (more than 4 wt%), aluminum (more than 5 wt%), zinc, and precious metals (e.g., Au, Ag, Pd) and plastics (e.g., ABS, ABS/PC, PS, PVC) [12]. Thus, outputs from PC dismantling cover comprehensive processing techniques: PCBs are partly treated for copper and gold recovery; metals (ferrous metal, aluminum and copper) and plastics are recycled at craft villages [5, 13, 14].

Materials and methods

A literature review was conducted to describe the complexity of informal e-waste recycling and end-processing in Vietnam. However, there are a limited number of paper that could be found via databases, such as Scopus® or ScienceDirect, specifically addressing this topic in Vietnam. Thus, reports from national projects, studies from other organizations, cleaner production assessment reports, personal communication (e.g., via email, telephone, discussion) and observation during field trips to recycling workshops and craft villages have been utilized for process and data collection. The biggest project focusing on craft villages in Vietnam was the national-level project titled "scientific and realistic basic research for building up policies and solutions for environmental issues in craft villages of Vietnam" in 2005 from Institute for Environmental Science and Technology (INEST). Later, the Ministry of Natural Resources and Environment (MONRE) published the "National state of environment" report with theme "Vietnam craft village environment", together with Vietnam national environment report in 2008. In the Vietnam national environment report 2011, solid waste from those craft villages had been brought up again as a part of national solid waste management system. Evaluation on current situation of technology level and pollution at craft villages has been summarized the report on "National state of environment in the period of 2011–2015" from MONRE which is considered as the most up-to-date source of information. The data referred from these reports have been crosschecked and updated with other studies such as study from Vietnam Steel Association for steel recycling technologies, National Institute for Environmental Studies of Japan (NIES) and INEST on Classification of e-waste processing technology in Vietnam, cleaner production guidebook for metal processing from Ministry of Industry and Trade, and cleaner production assessment reports which are a part of cleaner production—energy efficiency consultancy work of the authors at the Vietnam Cleaner Production Centre for aluminum (e.g., summarization of the implementation of cleaner production assessment and hazardous waste management report at Van Chang craft village, cleaner production assessment report at Quang Dung private manufacturer), steel (e.g., cleaner production assessment reports at Dai Thang Casting Co., Ltd., Viet-Phap Steel Co., Ltd., workshops in Da Hoi craft villages) and plastic (e.g., cleaner production assessment reports at My Hung Co., Ltd., Nguyen Tan Production and Trading Private Enterprise) recycling processes and technologies. Other information has been observed and extracted during the field trips to craft villages such as Ngu Xa (a traditional copper casting village) in Hanoi, Bui Dau (an e-waste dismantling village) and Phan Boi (a plastic recycling village) in Hung Yen province.

As a part of this study is to compare the current recycling technologies with appropriate BAT, the BAT reference documents, or the so-called BREFs by Joint Research Centre of European Commission, together with Ecoinvent report v2.2 (under the license of Institute of Waste Management, University of Natural Resources and Life Sciences, Vienna—ABF-BOKU) have been used as the main information sources.

This study is also used STAN (subSTance flow ANalysis), a freeware developed by Institute for Water Quality, Resource and Waste Management of TU Vienna (Austria) for the flowchart of material flow analysis.

Scenario analysis

The informal e-waste treatment in Vietnam was counted for approximately 30 craft villages handling e-waste recycling [15] out of 90 waste recycling villages mainly from the North in total 5096 craft villages in Vietnam [16]. e-waste treatment comprises four main steps: (1) collection and transportation, (2) reuse and refurbishment, (3) dismantling and pre-processing and (4) end-processing steps [5] as described in the studies of NIES and INEST [13] or Hai et al. [14]. For personal desktop (PC) case, the PC e-waste treatment steps are presented in Fig. 1.

As seen in Fig. 1, features of the first 3 steps (rectangular on the left) have been studied in the work of Tran and Salhofer [5] on how e-waste has been collected, reused parts and refurbished devices, and outputs from dismantling of specific electronic equipment. It is noted that untradeable materials (e.g., plastic foam, hard black plastic) are disposed (then dumped or landfilled) and a part of other components/materials (e.g., PCBs, plastics) are exported. In this study, the focus lies on the end-processing/recycling step (rectangular on the right of Fig. 1). Informal recycling activities involve recycling craft villages where metal and plastic scraps are processed. For PCB treatment, it involves not only the gold and copper recovery but also exportation (or dispose) of other electronic components (such as capacitors, transistors) mainly to China. Due to operating at small size, obsolete technologies and limited capacity for cleaner technology investment and waste treatment facilities [16], negative impacts to environment and human health are inevitable. Those impacts have been investigated by several studies, such as the work of the Vietnam Ministry of Natural Resources and Environment [17, 18], the study of Dang [19] and Dang et al. [16]. To cope with the current situation, local authorities (People's Committee at provincial, district and commune level) have issued several decisions, e.g., Decision number 396/QĐ-UBND of Bac Ninh People's Committee, Decision number 44/2008/QĐ-UBND of Hanoi People's Committee, on planning of industrial clusters and

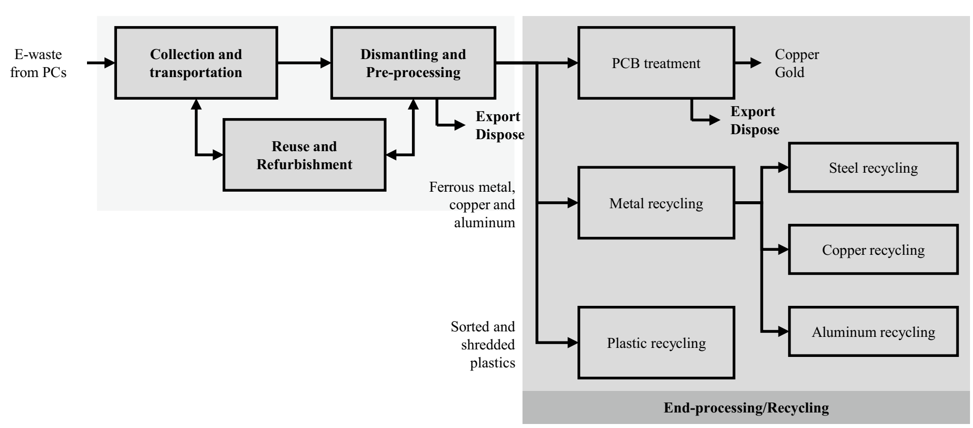

Fig. 1 e-waste treatment steps in Vietnam (adapted from [13, 14])

clusters of producers at craft villages. One important aspect of those plans is that processors at craft villages are supported and encouraged to transfer to centralized workshops with appropriate air and wastewater treatment facilities (e.g., bag filtration, sedimentation, filtration, chemical treatment of wastewater). To analyze the existing technology and to identify improvement potentials, in this study, two scenarios are compared:

- Scenario 1: Current situation. In this scenario, the current situation in which present technologies, input and output data from recycling/end-processing of e-waste has been investigated. Dismantled fractions (plastic, ferrous metal, copper and aluminum) are transported to and recycled at craft villages while PCBs are treated partly for gold and copper recovery. The remaining electronic components (e.g., capacitors, transistors) are exported. Collecting data for this scenario are a challenge as there are very limited number of published articles regarding the informal recycling processes. As stated above in the "Materials and methods", alternative available sources of information have been used. Data on dust, metal fume, other gases (NO_x, SO_2, organic compounds) from melting process are not available as no air treatment facilities are installed and missing of input composition analysis. The only available data are some air quality monitoring reports for craft villages from study of Dang [19], MONRE [17] or Dang et al. [16] but those data were not able to interpolate to air emissions from generated pollution sources. As evaluated by Dang et al. [16], air pollution at craft villages has not been reduced but it tends to increase.
- Scenario 2: Selected BAT. This scenario presents a proposed situation in which, enterprises involved in e-waste end-processing (recycling of metals, PCBs and plastic) are gathered to centralized workshop. Each of them operates separately under selected BAT with BEP by sharing one or more waste treatment facilities. Except for the case of PCB recycling, in which the referred BAT are the current one at Umicore; other selected BAT are based on the following criteria: (1) suitable for recycled materials from e-waste sources; (2) technically upgradable for recyclers/smelters at craft villages; and (3) appropriate for Vietnamese context. The main data sources for selected BATs come from BAT references [20, 21] and data from ecoinvent reports [22–24]. Air emission from melting operations of smelters is available but depending on input materials (feeding capacity, scrap quality), air treatment technologies, air sucking capacity (volume of sucked air per hours). With appropriate treatment facilities, selected BAT and implemented BEP, emission to air, water and soil supposes to be satisfied environmental standards to be discharged into environment.

By comparing both scenarios, the technology gap shall be highlighted. Moreover, it also reveals the potentials such as energy saving, product quality improvement, cleaner technology upgrade, better process control, and good housekeeping. Based on the limited information, together with literature, air pollution, wastewater and solid waste are identified and summarized. Those emissions pose serious problems to not only workers but also residents living in craft villages. Unfortunately, they were not able to quantify. Only equivalent CO_2 emission is calculated as emission to air.

Process and data collection

Dismantling of desktop PC

The informal dismantling processes have been provided in the studies of NIES and INEST [13], Hai et al. [14] with mainly manual works. The outputs include untradeable parts (e.g., foamed plastics, papers, glasses, batteries) which will be dumped or landfilled, metal fractions (copper, aluminum, zinc and ferrous metal), PCBs, plastic and cable fraction. The cables (e.g., power cables, color ribbon cables) are collected for cable treatment (copper and plastic separation). As observed from a workshop at Bui Dau village (Hung Yen province), cables are collected, sorted by diameters and treated by cable treatment machine using blades to strip and cut wires (recent common treatment method) or open-burning (less common practice) for copper extraction. Due to the presence of several types of cables with a high share of color ribbon cables in PCs, the overall copper content extracted from cables is about 13.5 percentage of total weight of processed cables. The rest is a mixture of plastics and other materials (such as fluoropolymers, polyamides [24]). The extracted copper is collected for copper recycling (added to copper proportion) and the rest is transferred to plastic recycling (added to plastic group). Material composition of PCs used in this study has been provided by Peter Beigl from Institute of Waste Management, University of Natural Resources and Life Sciences, Vienna (via personal communication) using the systematic examination of electronic appliances [25]. The output materials are presented in Table 1. As seen in Table 1, the ferrous metal has the highest proportion while copper and aluminum and zinc have the smallest mass percentage.

Energy sources

Energy is very important for end-processing/recycling as most recycling steps demand energy. The most used energy sources are electricity, coal, liquefied petroleum gas (LPG) and wood. This section presents Vietnamese electricity grid, properties of fuels and emissions from using them.

Table 1 Output material groups from manual dismantling work at craft village

Regrouped materials	Mass percentage (%)
Untradeable	4.08
Ferrous metals	76.22
Plastic	8.08
PCBs	9.01
Copper	0.80
Aluminum + zinc[a]	1.80
Total	100.0

[a]Going to aluminum recycling

Table 2 Vietnam power grid in 2014 [26]

Power source	2014 (%)
Hydropower	40
Coal-based thermal	28
Gas turbine	22
Diesel, small-sized hydropower and wind	5
Fuel oil (FO) based thermal	2
Gas-based thermal	1
Imported source	2

For electricity, as of 2014, the main electricity sources were from hydropower, coal-based thermal power and gas turbine power at the rate of 40, 28 and 22%, respectively [26]. A small generated electricity came from wind, Diesel Oil-based thermal power plants and imported electricity (Table 2). The power development program to 2030 mentioned within the National energy development strategy—revision of power master plan VII from General Directorate of Energy showed the change in power generation sector with the major increase of coal based thermal power (58% in 2030 and 60% in 2030) and the significant reduction of hydropower (25 and 12% in 2025 and 2030, accordingly) [26].

To calculate the emission from electricity consumption, only equivalent CO_2 emission is considered as other emissions are not available. The equivalent CO_2 emissions coefficient per kWh of electricity for Vietnamese electricity grid, together with the CO_2 emissions coefficients for coal and LPG, is presented in Table 3.

For fuels, the most common use is coal as observed in the case of copper and aluminum recycling at craft villages. The selected type of coal is lump coal, type 4b at net calorific values of 28 MJ/kg and 78.4 wt% of carbon content [27]. LPG is also used for PCB treatment to recover copper at its net calorific value of 49.5 MJ/kg (propane—LPG). This value is calculated from 90,500 Btu/gal [28] and the density of propane LPG is about 0.51 kg/l [29]. Besides coal and LPG, wood is also used for copper recycling process. Wood in this case is wood residues such as bark, sawdust, chips, wood trim with net calorific values at 10.5 MJ/kg (converted from 4500 Btu/lb [30] for wood residues having moisture content from 10 to 15%). In this study, consumed fuels are provided in converted energy amount (MJ).

Recycling processes and technologies

In this section, both current recycling technologies and selected BAT of PCBs, ferrous metal, copper, aluminum and plastics are presented in detail of processes and input/output tables. The calculation is based on 1 tonne (t) of main input material.

PCB treatment

Current selected techniques The most common practices for PCB treatment at craft villages in Vietnam are (1) to separate and sort electronic components into several categories (ICs, transistors, capacitors) and (2) to shred the remain circuit boards for exporting purposes (mainly to China).

In this study, two current technologies for PCB treatment have been investigated: (1) gold recovery using aqua regia (Fig. 2) and (2) copper recovery using mechanical process (Fig. 3). For the composition of PCBs, data from Le et al. [32] have been used.

For gold recovery, few very small-sized workshops in the north treat high gold-contained parts (central processing units—CPUs and gold-plated connectors) for gold

Table 3 Carbon dioxide emissions coefficients

Energy type	Unit	Equivalent CO_2 emission coefficient	References
Electricity	kg CO_2/kWh	0.4668	[31]
Coal (lump coal, type 4b)	kg CO_2/kg	28.7467	Calculated from the carbon constituent and oxidation reaction of carbon[a] at the assumption rate of 100%
Liquefied petroleum gas (LPG)	kg CO_2/kg	2.86	Calculated from LPG emission factor 12,500 lb/10^3 gal [28]

[a]$C + O_2 \rightarrow CO_2 + \text{energy}$

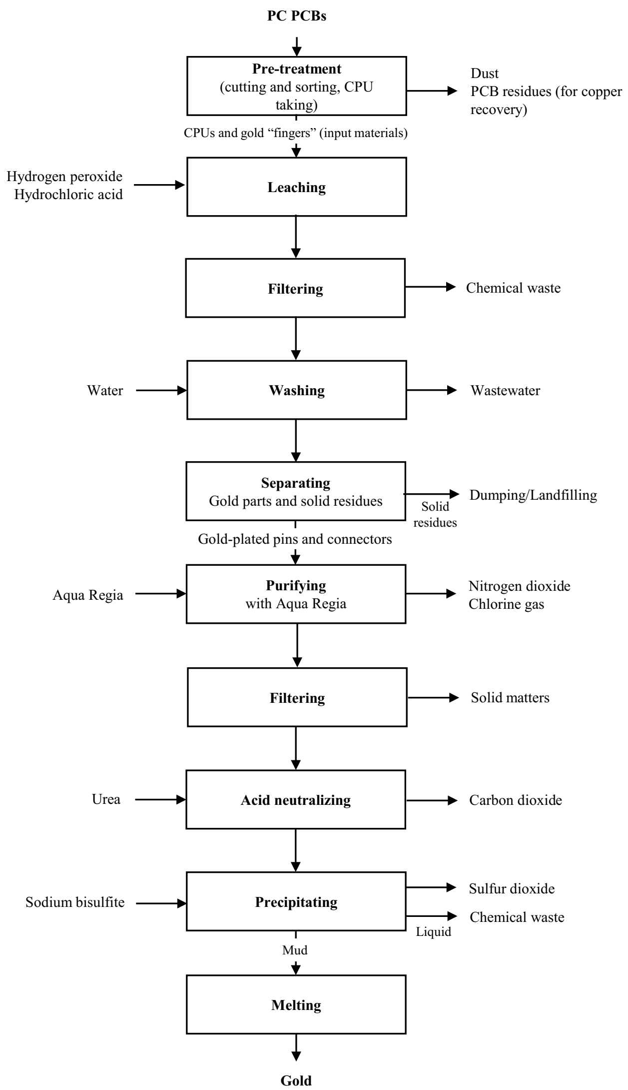

Fig. 2 Flowchart of gold recovery process from gold fingers and CPUs

recovery under acid bathing techniques (e.g., using aqua regia or using other chemicals before using aqua regia or other acid leaching methods) and accessing to these recyclers for information collection is very limited. Generally, the highest gold-contained parts in desktop PCs are CPUs with gold-plated pins but only ceramic types of CPUs have higher amount of gold (e.g., Toshiba, AMD K5, Pentium Pro, Cyrix 586, IBM 686) and they are easy to take out from motherboards by hands or screwdrivers. Other gold-contained parts include random access memory (RAM) modules, peripheral component interconnect (PCI) modules, sound cards, video graphics array (VGA) modules as they have gold-plated connectors. Those gold-plated connectors need to be cut out from boards using cutters or saws. Cut gold-plated connectors are called "gold fingers" as they have the bar shapes. A "good" cut of gold fingers leaves very small area of "green" board. Thus, the quality of gold fingers (how they are cut and thickness of gold-plated layer) is of importance to decide how much gold yield can get after processing. Gold is contained in gold-plated pins as well, such as CPU socket pins, test pins, connector pins and they require other tools to extract (screw drivers, hams).

The process of gold recovery is briefed in Fig. 2. The highest gold-contained parts after extracting from PCBs are leached in the mixture of hydrogen peroxide (H_2O_2) and hydrochloric acid (HCl) to dissolve copper and release gold-plated connectors and pins. When gold-plated connectors and pins are collected by filtering and washing, they are purified with aqua regia. Only the solution is used to be neutralized with urea. Then, sodium bisulfite is added, mixed and waited to collect the precipitation. The precipitation is melted directly under fire from a gas blowtorch (blowlamps) to get pure gold.

The recovery rate of 25% was taken from studies of Keller [33] and Rochat [34]. A study from Williams et al. [35] summarizes that 58% of total gold remains in the circuit board and 5% of total gold is emitted as dust during separating activities of connectors from boards. During gold extraction from connectors, 5.5% of total gold is lost as scrap metals and 6% of total gold is lost in gas/liquid form [35]. This study provides an evaluation that gold yield from Chinese informal PCB recycling may be higher than that in Indian case but no recovery rate has been given.

By interview, the amount of recovered gold is about 2.5–5.5 g per kg of gold fingers and CPUs depending on their quality. To calculate chemical used for acid neutralizing and precipitating step, gold content in treated gold "fingers" is needed. To do so, the overall gold recovery rate is assumed at 25% (or 20.5 g based on gold content in PCBs is 82 ppm [32]) and each kg of high gold-contained parts treated can achieve around 5.0 g of pure gold. The overall recovery rate is considered a rough assumption. Thus, the amount of high gold-contained parts is about 4.1 kg. Due to no gold concentration data analysis in the input, the gold content is calculated theoretically under some assumptions: high gold-contained materials are gold "fingers", total amount of gold is 82 g per t of PCBs [30], PCBs are made from flame retardant grade 4 (FR4)—a woven glass fabric with epoxy resin with the density of 1.85 g/cm^3, gold-plated layer thickness is at 30 μin [36], thickness of PCBs is at 1.6 mm [37], width of gold-plated connectors is 6 mm, gold-plated connectors cover both sides of boards, they are under a "good" cut, and density of gold is 19.32 g/cm^3. Thus, the gold content in 4.1 kg of gold "fingers" is calculated as 24.5 g.

The informal practices of gold recovering and purifying are varied in quantity of chemical using (ratio of HCl and H_2O_2 can be 1:1, 2:1–3:1), reaction time and temperature. In fact, recyclers observe the appearance of bubbles released, color of solution, gold-plated connectors stuck

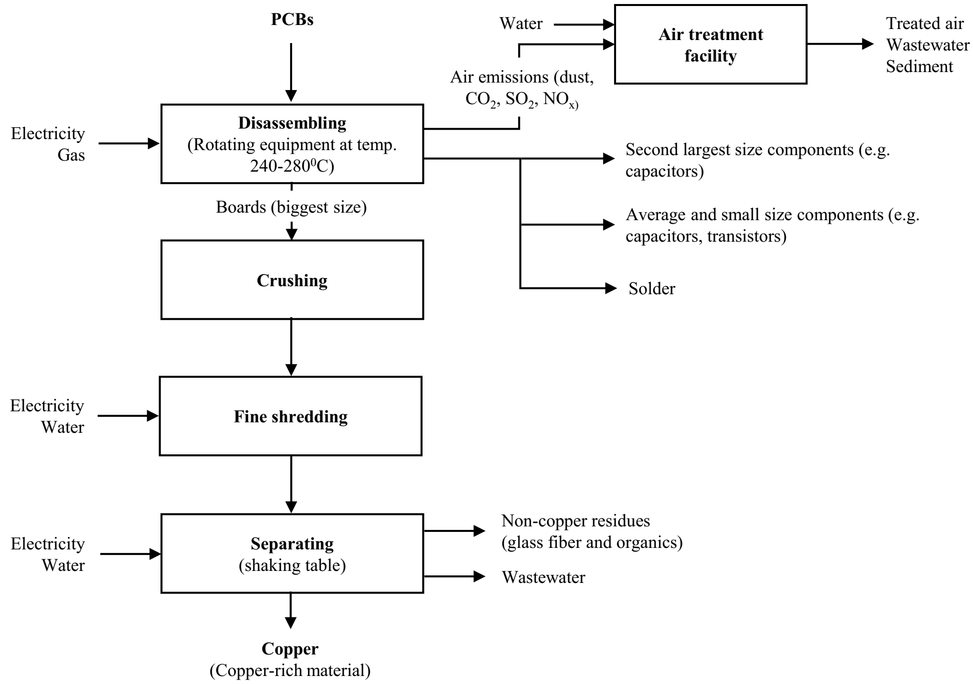

Fig. 3 Flowchart of copper recovery from PCBs under mechanical process

on the "fingers" to adjust the volume of chemicals or reuse them for another batch or re-leach gold "fingers" with fresh chemical solution. No real data on chemical consumption as well as no air emission (release of acid fume, NO_2, Cl_2) have been obtained. The volume of chemicals used to calculate has been collected from the same practices found on Youtube from some recyclers [38–41] and verified with the HCl:H_2O_2 ratio is at 1:1.

Reactions happen during gold recovery and purification, as follows:

$$\text{Dissolving of copper in mixture of HCl and } H_2O_2: \quad Cu + H_2O_2 + 2HCl = CuCl_2 + 2H_2O \tag{1}$$

$$\text{Dissolving of gold in aqua regia [42]}: \quad 2HNO_3 + 6HCl \rightarrow 2NO + 2H_2O + 3Cl_2 \tag{2}$$

$$2Au + 3HNO_3 + 9HCl \rightarrow 2AuCl_3 + 3NOCl + 6H_2O \tag{3}$$

$$HNO_3 + 3HCl \rightarrow Cl_2 + NOCl + 2H_2O \tag{4}$$

$$\text{For calculation}: \quad 2Au + 6HNO_3 + 18HCl \rightarrow 2AuCl_3 + 2NO + 4Cl_2 + 4NOCl + 12H_2O \tag{5}$$

$$2NO + O_2 = 2NO_2 \tag{5*}$$

$$\text{Adding urea to the filtered solution}: \quad (NH_2)_2CO + 2HCl + H_2O = 2NH_4Cl + CO_2 \tag{6}$$

$$(NH_2)_2CO + HNO_3 = (NH_2)_2COHNO_3 \tag{6*}$$

$$\text{Adding sodium bisulfite to the solution}: \quad 2AuCl_3 + 3NaHSO_3 + 3H_2O = 2Au + 3NaHSO_4 + 6HCl \tag{7}$$

$$NaHSO_3 + HCl = NaCl + H_2O + SO_2 \tag{7*}$$

The input and output data for gold recovery from PCBs are present in Table 4.

Besides the extracted gold, this process results in some critical issues from (1) air emission in gold leaching includes several toxic gases (NO_2, Cl_2, NOCl, SO_2 and acid fume). The presence of those gases required good air ventilation and air treatment and protective gears for operators; (2) wastewater consists of hazardous substances (acid, heavy metals). Thus, it needs to be paid attention and treated properly using chemical treatment (for example, using Calcium hydroxide to neutralize residue acids and form precipitation from presence of ion metals); and (3) glass fiber and organics from boards as solid waste stream contains flame retardants.

For whole PCBs, only one workshop in Hung Yen province has a processing line. The detailed process had been described in the study of Tran and Salhofer [5] and illustrated in Fig. 3, in which PCBs are treated under horizontal rotating equipment at temperature from 240 to 280 °C to separate solder, transistors, capacitors and circuit boards. Within this range of temperature, only solders are melt while the rests are restricted weight loss [43]. The outputs per tonne of treated PCBs from this process consist of approximately 44 kg of solder metals, 176 kg of average and small components (e.g., chips, transistors, small capacitors), 100 kg of the second largest size components

Table 4 Consumption data and outputs from treatment of 1000 kg PCBs under current technologies

Gold recovery			
Inputs	Unit	Quantity	Note
Gold fingers and chips	kg	4.100	Calculated with the assumption of overall recovery rate is at 25% and 5.0 g of gold can be extract from each kg of high-gold-contained parts
Hydrogen peroxide 3% (*d* = 1 g/ml)	kg	27.333	
Hydrochloric acid (HCl) 20% (*d* = 1.098 g/ml)	kg	29.520	
Hydrochloric acid (HCl 36%) for aqua regia (*d* = 1.789 g/ml)	kg	1.375	
Nitric acid (HNO_3 68%) for Aqua regia (*d* = 1.405 g/ml)	kg	0.360	
Water for washing	kg	20.000	
Urea	kg	0.584	Calculated from reaction (6) and (6*)
Sodium Bisulfite	kg	0.058	Calculated from reaction (7) and (7*)
Outputs	Unit	Quantity	Note
Gold	kg	0.0205	
Wastewater	kg	80.210	Contains residue acid, salt solution of metals (e.g. Au^{3+}, Cu^{2+}) and is hazardous waste
Solid waste	kg	3.034	
Total air emission	kg	0.066	Summarized from NO_2, Cl_2, NOCl, CO_2 and SO_2 emission calculated from reaction (5), (5*), (6) and (7) (the acid fume is unquantifiable)
NO_2	kg	0.006	Calculated from reaction (5) and (5*)
Cl_2	kg	0.018	Calculated from reaction (5)
NOCl	kg	0.016	Calculated from reaction (5)
CO_2	kg	0.003	Calculated from reaction (6)
SO_2	kg	0.024	Calculated from reaction (7)
Copper recovery			
Inputs	Unit	Quantity	Note
PCBs	kg	995.900	High-gold-contained parts have been separated for gold recovery
Water	kg	5000.000	Water consumption is estimated based on electric pump power (0.37 kW) and its operational time (8 h per day)
Energy			
LPG	MJ	600.030	
Electricity	kWh	165.983	
Outputs	Unit	Quantity	Note
Copper rich material	kg	284.345	Mixture of copper and non-copper materials is at the amount of about 42 wt% of total shredded input and overall copper recovery rate is assumed at 95 wt%. Copper content is roundly 241.32 kg
Solders	kg	44.019	Collected and sold
Transistors, small capacitors	kg	175.278	Average and small size components. Exported
Capacitors and large size components	kg	99.590	Second large size components. Exported
Wastewater	kg	5,000.000	Water can be recycled after treatment. As if, wastewater can be reduced to 1000 kg
Solid waste	kg	392.667	Glass fiber and organics, to be landfilled
Equivalent CO_2 air emission	kg	114.103	Calculated from data provided in Table 3

(e.g., capacitors) and the rest is the largest parts: boards (after removal of components) at the amount of 680 kg. Solder metals are collected for sale. The separated electronic components are collected, shredded (if needed) for exporting. Only the boards are treated at this workshop by mechanical treatment (shredding then separating on shaking table with water flow (Fig. 3) to recover copper. The recycling is done in batch. Each batch, around 500 kg of PCBs is treated. The collected outputs contain copper-rich material (copper mixed with small amount of glass fibers and organics) at the proportion of approximately 42 wt% of input PCBs (interview data) and the rest is glass fibers and organics which is collected for landfilling. The copper content in the output can be calculated from the copper recovery rate. This recovery rate is assumed at 95 wt% based on the same technology from Mt. Baker Mining and Metals (copper recovery rate is higher than 95%) [44].

From Fig. 2 and Table 4, the PCB treatment for copper extraction includes waste flows: (1) air emission containing NO_x, SO_2 from gas combustion which is collected by a sucking fan and released into environment through a chimney; (2) wastewater from process water using during shredding and separating which is collected at a sedimentation tank then discharged; and (3) solid waste which are glass fiber and organics with flame retardants from boards.

As observed from Table 4 for gold recovery, the appearance of toxic gases poses health problem to workers and suggests that protective equipment (mask) needs to be used by workers, a ventilation and air treatment system should be considered. The wastewater stream in which contains not only residue chemicals (hydrochloric acid and hydro peroxide) but also copper (Cu^{2+}) at the amount of 1.05 kg by dissolving 4.1 kg of high gold content pieces from 1 t of treated PCBs has a high potential for recovery and a treatment system needs to build. For copper recovery process, water using can be recycled but it is needed to invest for wastewater treatment facility (additional filtration step).

Selected BAT Using copper smelters and integrated smelters-refineries is considered as BAT for PCB treatment for copper and other precious metal recovery [45]. The most modern technologies can be found in Europe at Umicore (Hoboken, Belgium), Boliden (Rönnskär, Sweden) or Aurubis (formerly Norddeutsche Affinerie in Hamburg, Germany) [24]. Detailed treatment processes have been described by Isaksson and Lehner [46] for Boliden in Rönnskär and Hagelüken [47, 48] for Umicore in Hobroken. In this study, selected BAT is the metallurgical process applied in Umicore. Under Umicore's technology, the main processes include IsaSmelt smelting, copper leaching and electrowinning, and precious metal refinery [49]. Recovered metals consist of Au, Ag, Pt, Pd, Rh, Ir, Ru (precious metals), Pb, Cu, Ni, Sb, Sn, Bi, Se, In, Te, As (base and special metals) [47, 48]. The metal recovery rate is above 95% [48, 50]. Plastic and organic fraction from feed materials is used as a reducing agent and fuel substitute. The energy content exceeds energy demand for smelting and refining [48]. Other by-products of the plants are sulfuric acid (from off-gas purification) and slag (containing aluminum and iron oxides) that are used as construction material and in the concrete industry. Off-gas emission and wastewater are treated under highly efficient treatment systems to "comply with the strictest environment standards" [50]. The off-gas treatment process installed at IsaSmelt furnace can be seen in the study of Hagelüken [47]. The outputs from treatment of 1 t PCBs under this technology is provided in Table 5 with assumption that the recovery rate of metals is at 95%. Energy consumption is marked with minus (-) as the recycling and refining process produce energy. Other emission load can be referred at Umicore Environmental statements [51], such as 14.544 t of metal emission to air; 1,19 t of SO_x emission; 45 t of NO_x emission; 714,225 t of equivalent CO_2 emission in 2015.

Table 5 shows a large gap between recovered metals between 2 scenarios. Together with Table 4, it is clear that Umicore has treated PCBs under advanced technology: recovering and refining metals at high rate and quality, more recovered metals, no energy needed, and advanced waste treatment technology. The recycling processes under current technologies generate approximately 395.701 kg of solid waste; 5000 kg of wastewater from copper recovery with high recycling potential; 80.210 kg of wastewater containing hazardous substances (acid, heavy metal) with copper recover potential and required treatment before discharging to environment; and 114.103 kg of equivalent CO_2 emission from electricity and LPG consumption. The exported components to China are considered as the material loss under current context.

Ferrous metal recycling

Current technology In Vietnam, the most common technologies for steel production are electric arc furnace (EAF) (for large manufacturer), induction furnace (IF) (for small and medium sized enterprises) and basic oxygen furnace (BOF). 95% of big manufacturers in Vietnam are using EAF [10]. Since 2009, many large steel manufacturers in Vietnam installed and used big capacity IF smelters (5–50 t) and their designed capacity gains up to 20% total steel-making capacity of the nation [52]. At craft villages, such as Da Hoi (Bac Ninh province), Tong Xa (Nam Dinh province), ferrous scraps are recycled under medium-frequency IF technology with a capacity of 0.5–1 t per batch. Ferrous recycling villages contribute a large amount of steel products to domestic market. For example, smelters in Da Hoi village

Table 5 The input and output data from treatment of 1000 kg PCBs between current technology and selected BAT

Per 1000 kg of PCBs from waste desktop PC					
	Unit	Current operation		Selected BAT	
		Quantity	Note	Quantity	Note
Inputs					
PCBs	kg	1000.000		1000.000	
Chemicals	kg	59.231			
Water	kg	5020.000			
Energy				–	The energy content exceeds energy demand for smelting and refining
Electricity	kWh	165.983			
LPG	MJ	600.030			
Recovered metal outputs					
Gold		0.0205		0.078	
Copper rich material	kg	284.345	In which, the copper content is 241.257 kg	242.250	
Solder metals	kg	44.019			
Other metals	kg	–		62.316	Other metals include precious metals (Au, Ag, Pd), base and special metals (Ni, Sn, Sb)
Total recovered metals	kg	285.299	Without non-copper materials in the mixture output from copper recovery (43.088 kg)	304.654	
Other fractions/streams					
Exported components	kg	274.868		–	
Burned fraction for energy recovery	kg	–		512.400	
Solid waste	kg	395.701		–	
Metal in slag and other waste streams	kg	–		182.945	Metal in slag is used as construction material and in the concrete industry
Copper content in wastewater from gold recovery	kg	1.05	Copper salt solution	–	

produce 12,000–15,000 t of steel billets; 450,000–500,000 t of steel sheets per year [53].

Producing 1 t of final products (steel billets) needs to consume 1.05–1.08 [52] or 1.25–1.3 [54–57] t scraps, 750–1300 kWh of electricity [54–58] and 0.2–0.3 t coal for annealing as seen at several smelters [19]. Besides, flux (lime/dolomite) (10–15 kg per t of product) and auxiliary (7–10 kg per t of product) (interview data) are added to melting process. Water is used for cooling purpose and can be recycled after cooling. Volume of wastewater without recycling is in the range of 5–7 m^3 per t of final product [54, 55, 57]. Waste streams consist of solid waste (slag is 20–25 kg (interview data) or 45 kg [55] per tonne of steel billets and it depends on scrap quality; impurities (soil, paper, plastic) are approximately 12.5–14 kg per tonne of steel billets [59]; and metal granule from scattering and surface cutting is around 13 kg per tonne of steel billets). Molds for casting are made from clay or sand, but the most popular ones are from iron. If molds are metallic type, they are reused for other batches. If molds are made of sand, sand can be recycled partly. Metallic molds, most popularity is iron molds, are now used very common to produce steel billets. Sand molds are used to cast parts of mechanical equipment. In this case, molds need to be prepared before casting. Materials for sand molds making mainly consist of sand, clay, water and coal powder. The amount of sand can be recycled after mold dismantling is about 80 wt% [54]. Detailed data for steel recycling under IF technology are provided in Table 6.

The recycling process selected in this study is summarized in Fig. 4. Firstly, steel scraps are classified. At this step, impurities (soil, plastics, etc.) are sorted out and collected for dumping or landfilling and other non-ferrous metals are collected for sale. If the width of scraps is exceeded 20 cm, they need to be cut into smaller pieces. Then, the prepared scraps are transported to the furnace, charged into it and melted. Metal slag is removed during melting periodically.

Table 6 The input and output data from recycling of 1000 kg steel scraps between current technology and selected BAT

Input	Unit	Current technology		Selected BAT	
		Quantity	Note	Quantity	Note
Steel scraps	kg	1000.00		1000.00	
Flux (lime/dolomite)	kg	9.26		9.52	
Auxiliary	kg	9.26	FeMn80 and FeSi75	6.67	
Refractory—ceramic powder	kg	3.70		3.81	
Cooling water	kg	6481.48	Without water recycling	380.95	Added water or lost water by evaporation
Electricity	kWh	925.93		550.00	
Output	**Unit**	**Quantity**	**Note**	**Quantity**	**Note**
Product	kg	925.93		952.38	
Total solid waste	kg	46.76		21.81	
Solid waste—impurities	kg	11.57		–	
Solid waste—metal slags	kg	23.15		15.00	
Liquid metal scattered during pouring and metal residues from steel billets (recyclable)	kg	12.04		–	
Refractory waste	kg	3.70		3.81	
Dust collected from air treatment facility	kg	–		3.00	
Wastewater	kg	4629.63		–	
Equivalent CO_2 emission	kg	432.27	Calculated from data provided in Table 3	256.77	

After casting molten iron into iron molds, molds are cooling by natural air. Later, still billets are removed from molds (mold disassembling step) and molds are reused for another batch. At some smelters, steel billets or casted products can be annealed under heat generated from coal combustion.

Ferrous recycling process results in several critical issues. As seen from Fig. 4, air emission flow is the most serious one. Dust generated from cutting step consists of metal dust and ferrous rust. When charging scraps into furnace, especially the cold charge (for example, the first charge of the day) [60], high emission (mainly particles from rust, dust) is released into environment. During melting process, gaseous emission is formed which may contain metal and metal oxides, organic compounds from the incomplete combustion of impurities and coating layer of scraps, and other gases such as CO, NO_x. During casting step, metal and metal oxide particles are generated; other volatile compounds may emit from burning of additives (e.g., coal powder, sand). If coal is used for annealing, its combustion generates dust, SO_2, NO_x. Moreover, dust can be released during removal of steel billets out from molds. Thus, it is considered that gaseous emission release is general issue in all steps of ferrous recycling. However, studies focusing on air emission from ferrous recycling workshops at craft villages are missing leading to impossibility to quantify air pollutants.

Besides air waste flow, solid waste is considered as another issue with the presence of impurities from scraps,

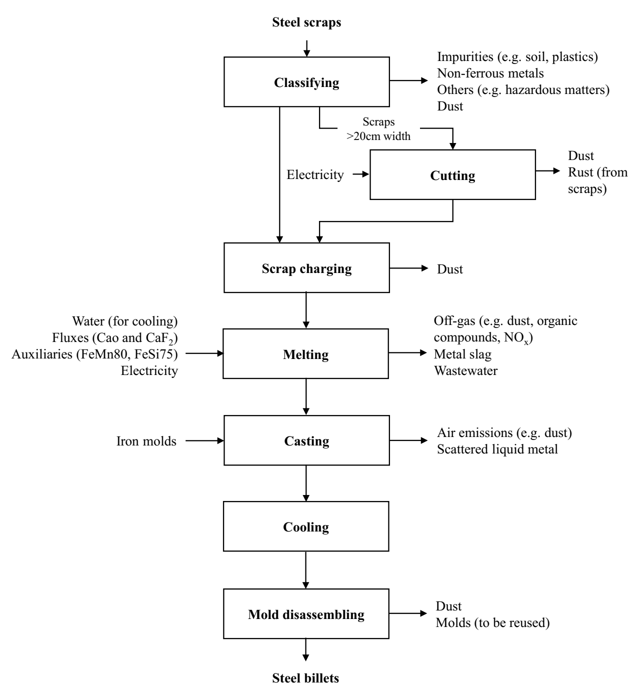

Fig. 4 Flowchart of ferrous metal recycling at craft villages

slag waste, and refractory waste generated from periodically repairing/preparing furnace lining layer. Only solid metal formed from liquid metal scattered on the floor and metal residues from steel billets can be recycled directly. Slag waste is noticeable by high chemical complex as it contains various contaminants such as metal oxides, melted refractories and other metals (e.g., lead, cadmium, chromium) from steel or non-ferrous metal components.

Selected BAT In this scenario, each smelter invests for better technology matching with their own production capacity to improve product quality while increasing operating efficiency. Thus, the selected BAT to compare with current technology is also IF technology. Compared to EAF technology, IF technology shows some advantages which are suitable for smelters at craft villages, such as lower environmental burden generated from furnaces and needs little maintenance [20] while the electricity price per kWh in Vietnam is relatively lower than that in other Asian countries [52]. The furnace capacity is in very wide range, from 0.01 to 30 t per batch [20]. To produce steel billets (as final product), steel scraps are needed, together with carburizing agents or flux, water for cooling and electricity (550–650 kWh/t of metal charge can be achieved) [20]. The best achieved energy consumption is 538.1 kWh per t of crude steel [11]. The emission from this technology has slag (10–20 kg per t of metal charge) and dust (0.04–3 kg per t of metal charge) [20]. Cooling water can be recycled about 90% [61] with the overall water consumption is ranging from 1.6 to 3.3 m^3 per t of steel [61]. The water is lost by evaporation.

Detailed inputs and outputs of selected BAT for steel recycling are presented in Table 8, together with the current technology.

As seen from Table 6, the most significant improvement coming from selected BAT is the reduction of electricity consumption (1.7 times). Moreover, air treatment facility has been installed and cooling water is recycled. It is suggested that new smelter with higher energy efficiency should be invested. Better scrap quality management contributes to the reduce of solid waste, such as sorting, applying "first in, first out" principle in which the scrap should be melted in the same chronological order with the time when it is bought to prevent loss by oxidation. Water cooling tower might be used for water recycling. Air emission collection (e.g., suction hood above smelter) and treatment system also need to consider.

Plastic recycling

Current technology Plastic fractions from the dismantling of e-waste contain many types of plastics (15 or more) [62] in which the highest amounts are accounted for acrylonitrile butadiene styrene (ABS), polystyrene (PS), polypropylene (PP) at 70–80% of the total [45, 62]. Plastic separating and sorting are a big challenge as the complexity of different types of electronic equipment from different producers or different product series is high [63]. Thus, plastics as output from the shredding process are a mixture of many types of plastics with look-alike colors. After manual separating and sorting, plastics are shredded under wet or dry technology. Electricity needs for this step is about 17 kWh/t. Shredded plastics are mainly recycled by two technologies: (1) extrusion and (2) injection molding. Both technologies are suitable for ABS recycling [64]. At craft villages (such as Minh Khai, Trieu Khuc in Hanoi, Phan Boi in Hung Yen province) and other small and medium sized enterprises in Vietnam, the extrusion technology is used more commonly to produce secondary plastic pellets or recycled products. Depending on the types of plastics, the products are varied (such as bags, weaving fabric, thread, containers, chairs, basins, etc.).

The plastic recycling from shredded plastics consists of 2 main processes: (1) making secondary pellets and (2) making products from a mixture of primary and secondary pellets. In this study, the first process: making secondary plastic pellets is investigated as shown in Fig. 5. In which, clean and shredded plastics are mixed by putting them in a cone-shape funnel, then fed into the extruder with heat generated from electricity. After extruding, plastic strands are cooled in water and cut into pellets (cold cut).

Data collected from SMEs and workshops at craft villages in Vietnam show that the capacity for shredder is 200–300 kg per h [19]. Producing each tonne of secondary plastic pellets needs 1.03–1.07 t of plastic scraps [65, 66], approximately 350–400 kWh of electricity for 100–250 kg of secondary plastic pellets per hour [65, 67]. With considering to production size of recyclers at craft villages for plastic pellets from e-waste source, the selected product capacity is approximately 100 kg/h and the electricity

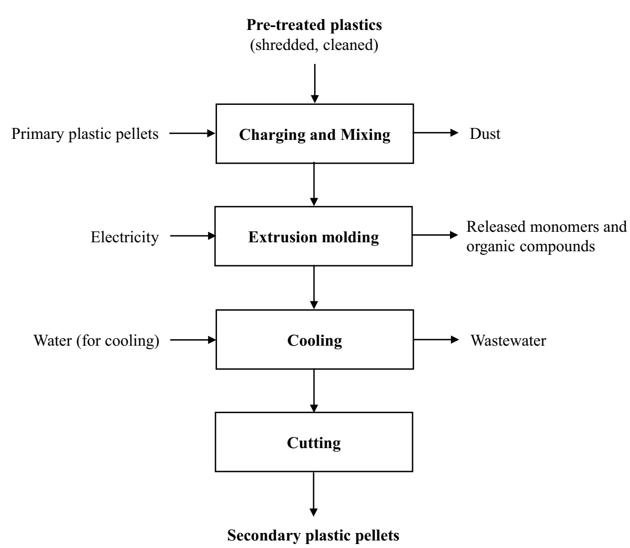

Fig. 5 Flowchart of making secondary plastic pellets at craft villages

consumption is 0.35 kWh/kg. Water for cooling purpose without recycling is about 21.7 m^3 as observed from a small-sized company [66] up to 51 m^3 as provided in the study of Dang [19] per tonne of products.

Out of secondary plastic pellets, plastic recycling includes several waste flows. Air emission is the most critical concern during charging of shredded plastics into cone-shape funnel as dust may be formed and, especially during extruding of plastic as air pollutants (e.g., monomers, or other organic compounds) are generated. It is possible that acrylonitrile monomer is released into the air resulting from thermal degradation of ABS while acrylonitrile is dangerous to exposed workers' health (for example, possible carcinogen to humans, increased lymphocyte counts, severe liver damage, lung cancer, chromosomal aberrations) [68]. In case of melting of polystyrene, released styrene can cause cancer to workers, or act as an endocrine disrupter [68].

This recycling process generates wastewater from cooling of plastic wires that can be recycled and solid waste which includes mainly impurities such as soil, paper is in the range of 8–11 kg/t [59] and plastic pellets scattered on the floor which are collected together with products about 37–40 kg/t [66, 69]).

Selected BAT As stated in the previous section, the selected BAT is the same with the technology in the current scenario: extrusion technology. The consumed plastic scrap is assumed at 1.03 t per t of secondary plastic pallets. The energy consumption and volume of cooling water are considerably variable as they are affected by process types, production mix, etc. [70]. Energy consumption is depended on process load [71] or production capacity (kg/h). Data for energy and water consumption are obtained from the manufacturers' technical data sheets (e.g., BKG). Energy consumption per kg of pellet output is approximately 0.2 kWh for each kg of plastic pellets at capacity of 100 kg per h [67]. Crosschecked with the energy consumption for extrusion process with the same capacity, the energy consumption is calculated as 0.18 kWh [71]; the electricity consumption proposed for calculation in BAT is 0.2 kWh per kg of plastic pellets. In selected BAT/BEP, water using for cooling purpose is recycled and only water is loosed by evaporation. Thus, there is no wastewater. The water flow for output capacity in the range 2–500 kg/h is 15 m^3/h (maximum flow) [72]. Water needed is roundly 30 m^3 per t of products. The solid waste stream counts for impurities at the amount of 11 kg per t of products (8–11 kg/t [59]).

Detailed inputs and outputs from plastic recycling under selected BAT in comparison with current scenario are presented in Table 7.

Table 7 shows the saving potential between 2 technologies in which the electricity consumption in the first scenario is higher than that for the second at least 1.7 times. It leads to the reduction of equivalent CO_2 emission. To improve energy efficiency, extruders with higher energy efficiency can be invested or better process control should be implemented (e.g., running at its most efficient speed, controlling electric motor to match the torque). It is necessary to reduce water consumption by recycling cooling water, so it contributes to not only water saving, but chemicals and energy for water treatment and pumping. Better ventilation system can help to reduce significantly concentration of pollutants.

Table 7 The input and output data from recycling of 1000 kg plastic scraps between current technology and selected BAT

	Unit	Current technology		Selected BAT	
		Quantity	Note	Quantity	Note
Input					
Plastic scraps	kg	1000.00		1000.00	
Cooling water	kg	20,280.37		14,563.11	
Electricity	kWh	327.10		194.17	
Output					
Product	kg	934.58		970.87	
Total solid waste	kg	47.66		10.68	
Solid waste—impurities	kg	10.28		10.68	
Solid waste—scattered pellets (recycled)	kg	37.38		–	
Wastewater	kg	18,411.21	Without water recycling	–	Cooling water is recycled. Water is lost by evaporation at small volume
Air emission (dust, smoke)	kg	–		–	
Equivalent CO_2 emission	kg	152.71	Calculated from data provided in Table 3	90.65	

Aluminum recycling

Current technology Aluminum is recycled at craft villages (such as Man Xa village in Bac Ninh province, Binh Yen village, Tong Xa village, Van Chang village in Nam Dinh province) from aluminum scraps (such as aluminum gears and frames, cooler, plates, wires, aluminum cans, old basins and cookware). Some types of scrap are contaminated from coating layers, oil, paint (e.g., cans, machinery parts). Recyclers at craft villages produce a large amount of products. For example, recyclers in Man Xa village produce about 200–250 t of aluminum products per year or in Van Chang village; the total amount of products from aluminum and steel making is roundly 17,000 t per year [53]. The main scrap sources come from aluminum cans, old aluminum basins and cookware, aluminum frames and machinery parts while aluminum scrap from e-waste source is at a small proportion.

The scrap from aluminum cans is normally melted separately from other scrap sources. The other scrap sources may need to cut into smaller pieces and mixed from several types during charging into smelter—small coal furnace. At smelter, aluminum scrap is melted. Metal slag is removed during melting process. Molten aluminum can be processed under two common stages: (1) casting for aluminum ingot products and making products from ingots under mechanical processes or (2) casting for products (cookware, basins, motorcycle parts). In both cases, molds (made of metal, sand or clay) are used. After cooling, molds are dissembling to get ingots or semi-products. Metal molds can be reused for other batches or mold materials can be recycled. If products are made from ingots, aluminum sheets are formed by mechanical steps (rolling, milling, cutting), then hydraulic pressers are used to form semi-products. From semi-products, residues are removed and collected for recycling. If producing cookware, support grips are attached. Then, products are passed through surface treatment (oil removal, water cleaning, Chromic acid treatment) for better appearance (Fig. 6). Normally, all steps are done at the workshop, except for sheet making steps which is mostly outsourcing at few larger workshops. As observed at some aluminum casting craft villages, aluminum in discharged metal slag can be recovered by manually separating/washing in water at ponds, drainage system. Aluminum is then collected and sold to smelters.

Melting of aluminum scrap is in batch operation. Each batch, approximately 200 kg of scraps is used to produce 170 kg of aluminum ingots [13] or 1.18–1.25 t scraps and 0.47–0.9 t coal are needed for each tonne of final products (motorcycle parts, cooks) [19, 73, 74]. Additionally, water for cooling is needed at the volume from 13 to 21 m^3 per t of final products [13, 56, 73, 74]. This volume of water has high potential to be recycled after cooling.

Besides aluminum ingots, this recycling process creates waste streams which are influenced by types and quality of scraps [21] and comprise air emission, wastewater (cooling water and wastewater from surface treatment) and solid waste. The most critical issue is the dust released into environment from all "dry" steps: classifying, cutting, charging, melting, mold dissembling, sheet making, and residue cutting. Especially, generated dust during charging contains metals, soil and released dust during melting consists of metals and metal oxides from the presence of other metals, organic contaminants from incomplete combustion of organic matters, other gaseous pollutants (e.g., CO, SO_2, NO_x) from coal burning. The most common practice to cope with the air emission issue is to dilute pollutant concentration by constructing some high chimneys. There is no update study available to identify the concentration of metals and organic compounds in air from those recycling villages. But, statistical data on disease of residents living within the recycling villages are accessible. Taken Man Xa village as one example, approximately 50.2% of Man Xa residents have related respiratory diseases (pharyngitis, bronchitis, pneumonia) [53].

For wastewater, the main source of wastewater is from cooling water and surface treatment. Moreover, aluminum recycling villages are facing with the problem of wastewater containing toxic chemicals from surface treatment (e.g., metal, chromic acid, sulfuric acid or sodium hydroxide). Aluminum recovery activity from metal slag by washing/separating it in water from ponds or drainage channels, together with metal slag gathered at unplanned open dumping sites may poison water bodies. The study of Nguyen [53] shows that the concentration of zin, chromium, nickel, lead in wastewater from two recycling workshops in Man Xa village, is higher than Vietnamese National Technical Regulation on Environment for discharged wastewater—QCVN 40:2011/BTNMT (the values in brackets are allowed-discharge pollutant concentration in wastewater regulated by QCVN 40:2011/BTNMT) from 3.18 to 4.72 (3 mg/l), 2.02–3.27 (1 mg/l), 2.95–4.49 (0.5 mg/l), 2.68–4.29 times (0.5 mg/l), respectively (sample taken in 02/2014). Aluminum concentration in wastewater of recycling workshop is from 2106 to 112,045 mg/l (sample taken in 02/2014).

Solid waste is another serious issue which includes impurities (e.g., soil, rubber, etc. at around 5 wt% of scraps) that can be sorted out [19], coal slags (15–20 wt% of consumed coal [57, 75–77]), metal slags (approximately 5–8 wt% of scraps [19, 78]), dust sedimentation from air emission and small pieces of aluminum or aluminum granulate generated during mechanical processes. Metal slags from aluminum recycling have high potential to be recycled by making other products (by-products) (e.g., aluminum sulfate) as it contains 28–45 wt% of aluminum [78]. Another source of solid waste is refractory waste

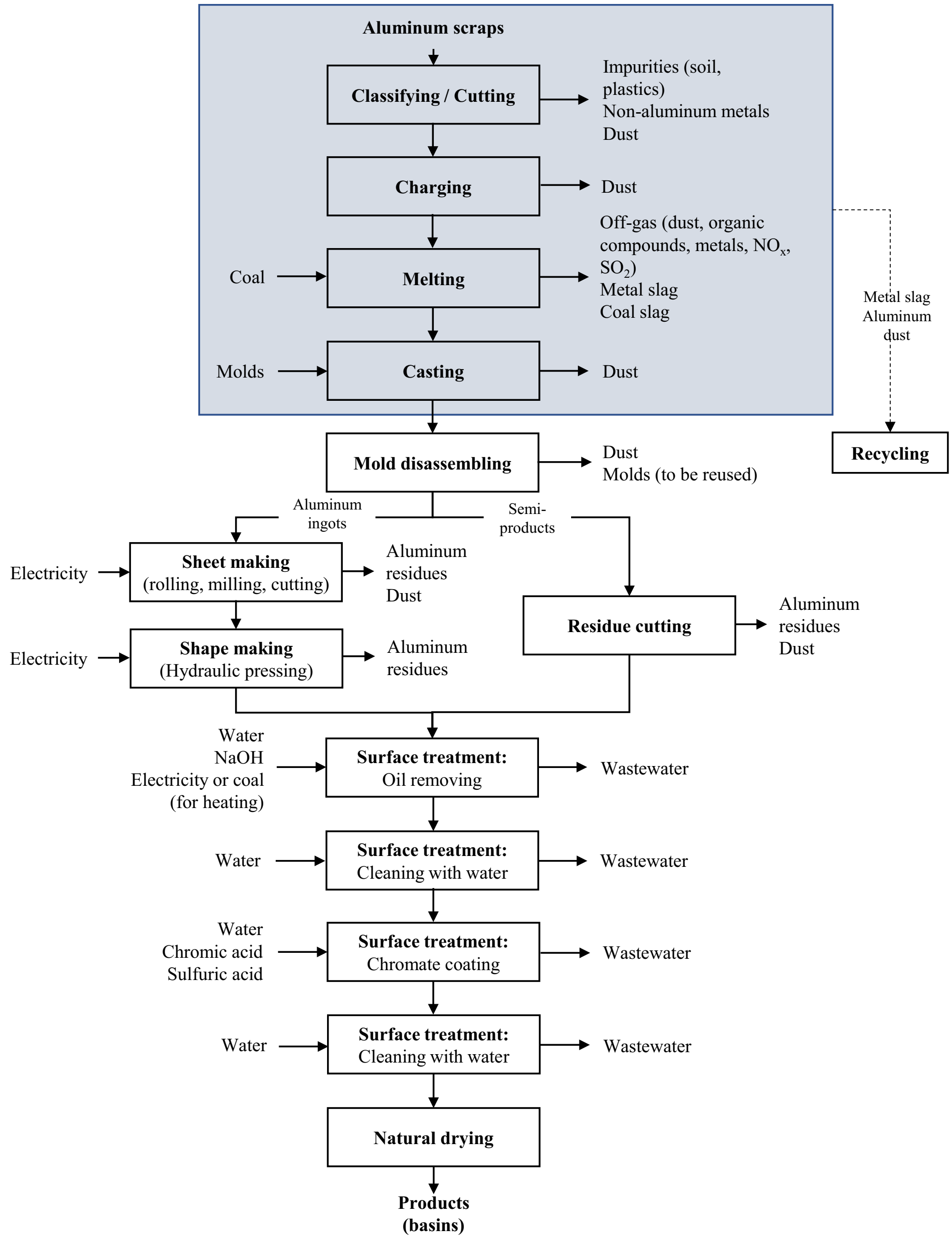

Fig. 6 Flowchart of aluminum recycling at craft villages

from preparing/preparing of smelters. Currently, solid waste has not treated properly. It ends up in unplanned open dumping sites: gardens, ponds, etc.

In this study, selected current practice for aluminum recycling is that ingots are made, then products (basins) are produced from aluminum ingots. The selection is based on the fact that aluminum ingots are considered as products from recycling business. Detailed inputs and outputs from current recycling technology are presented in Table 8.

Selected BAT With small to medium production capacity and aluminum scrap types at craft villages, the most appropriate technology selected for secondary aluminum production from various types of scrap is reverberatory furnaces. The preferred fuels are vary (LPG, natural gas, extra-light fuel oil) and optimal energy consumption is in the range from 2.4 to 4.4 MJ per t of metal [21]. Highly contaminated aluminum scrap can be pretreated by removing oil or other organic compounds before melting stage so air emission from melting step can be reduced. Some pre-treatment technologies (e.g., centrifugation, drying using a rotary dryer) are presented in BAT reference document for non-ferrous metals industries [21]. Data obtained from ecoinvent for "aluminum, secondary, from old scrap, at plant" show to make 1 t of aluminum ingots; 1.03 t scrap is needed [22].

Table 8 The input and output data from recycling of 1000 kg aluminum scraps between current technology and selected BAT

	Unit	Current technology		Selected BAT	
		Quantity	Note	Quantity	Note
Input					
Aluminum scraps	kg	1000.00		1000.00	
Water (for cooling)	kg	12,378.69		282.78	
Water (for surface treatment)	kg	2063.11		2356.49	
NaOH	kg	8.25		8.95	
$NaNO_3$	kg	8.25		9.43	
Chromic acid	kg	2.06		0.71	
Sulfuric acid	kg	0.76		0.87	
Electricity	kWh	31.36	Electricity consumption for mechanical processing	36.89	Electricity consumption for mechanical processing
Fuel	MJ	13,867.10	From coal	4271.84	From preferred fuels (e.g. natural gas, LPG, etc.)
Output					
Products	kg	825.25		942.60	
Total solid waste	kg	251.46		119.26	
Coal slag	kg	99.03		–	
Metal slags	kg	74.27	Estimated 7.5 wt% aluminum scraps [19] and aluminum content is from 28 to 45% [78]	–	
Metal waste (during mechanical process) (collected for recycling)	kg	24.76		28.28	
Impurities in scraps (paper, plastic, stone, rubber)	kg	50.00	Estimated 5 wt% of aluminum scraps [19]	–	
Furnace lining (refractory waste)	kg	3.40		3.88	
Skimming or dross when cleaning of furnace	kg	–		77.67	
Filter dust	kg	–		9.43	
Total wastewater	kg	14,461.13		2659.22	
Wastewater (from cooling)	kg	12,378.69		282.78	
Wastewater (from surface treatment)	kg	2082.44		2376.44	

The solid waste stream has been grouped into metal slag, refractory waste, filter dust and skimming or dross during cleaning of smelters. Data on water using for cooling are 0.15–0.3 m^3 per t of aluminum ingots [21]. After making ingots, mechanical processes are taken place to produce basins as final products. For surface treatment process, some BEP, cleaner production options will be implemented, such as switching from fully manual to semi-manual operation, better process control. Thus, the potential chemical reduction is approximately 70 wt% for chromic acid and 5 wt% for sodium hydroxide [74].

Detailed input and output data for aluminum recycling are shown in Table 8 in putting side by side with the current technology.

Table 8 presents the differences side-by-side between both scenarios. In selected BAT, more yield is produced and with that, water consumption and generated waste are reduced. It is obvious that aluminum loss in waste stream is reduced. New compared technology requires different types of energy so it is provided in energy unit (MJ) but it shows that significant reduction in energy consumption (roundly 3 times). To reduce the gap between two scenarios, new technology smelter suitable for old scrap types (e.g., reverberatory furnaces) might be necessary. Other solutions can be applied such as scrap sorting, better coal quality to reduce generated waste, better process control to improve energy efficiency (e.g., scrap cutting, better insulation, material charging process) and to improve surface treatment steps: water and chemical saving (e.g., applied reverse-order washing principle in which water is supplied only at the cleanest tank (the last one) and run over the previous tank, dripping time increase for products after taking them out from surface treatment tanks), water cooling tower for water recycling, air emission collection and treatment system and solid waste management program.

Copper recycling

Current technology Copper is recycled at traditional craft villages in Vietnam, such as Ngu Xa (Hanoi), Dai Bai (Bac Ninh province), Long Thuong (Hung Yen province), Phuoc Kieu (Quang Nam province) from copper scraps (mostly copper wires and other copper-contained parts: gears, locks, water faucets, disposed copper products, etc.) [13]. Each year, 1000 t of copper products are made from recycled copper. For example, one craft village, Dai Bai village, has produced 300–400 t products annually [53]. Before 2009, when PCBs were used directly in copper smelters, Quang et al. [79] estimated that approximately 30–50 wt% of copper scraps came from e-waste sources. Currently, there is no estimation on that amount, but it is insignificant [5] as PCBs are no longer used straightly in the smelters as concerning about product quality and air pollutants (such as metal fume, organic compounds) during melting process.

The main products are decoration products (copper lotus flowers and leaves, statues, flower vases), products for worshiping purposes (incensories, candle stands), instrument (bells, gongs, drums). The products are made by smelting copper scraps in smelters, then casting in prepared molds. At copper casting craft villages, products are various in colors, shapes and sound. Different properties are resulted from different mixtures of copper with other metals (Pb, Zn, Pd, Ni) and final mechanical processes (polishing, inlaying with other metals). For example, half-length statues have the mixture of 92 wt% of copper, 5 wt% of tin and 3 wt% of lead while outdoor statues can have a mixture from copper, tin, lead, zinc and nickel at the proportion of 85, 9, 3, 2 and 1 wt%, respectively (interview data). Each smelter has different know-hows on metal combinations and processes that are usually transferred from one to another generation to make dissimilar types of products of their own and of with other smelters. Many smelters operate in workshops with no air treatment facility or sometimes in open space.

With the selected final products, half-length statues, the producing process includes 2 different steps (Fig. 7). The first step is mold preparation in which clay is mixed with water and after a day, the mixture is used for mold making. Molds can have 2 parts: outer and inner part and can have a cover layer with rice husk, paper, coal powder or biochar. Mold must be dried and heated before pouring liquid copper to prevent breaking or cracking. The second step is copper melting in furnace with some additional metals. After copper is melted, it is pouring into heated prepared molds. After cooling, molds are destroyed to collect casted products and clay from molds is recycled. Casted products are processed at the final mechanical step to form final look. Brief process is shown in Fig. 7.

The common smelters are traditional furnace using coal or fuel oil or combination of fuels (e.g., coal and wood). Generally, consumption data on producing 1 t of final products consist of 1.05–1.18 t copper scraps [13, 19, 79], 1.0–1.2 t coal and 1.5–1.8 t wood [13, 79] or 2.52 t coal [80], 5–6 t clay for molds, and approximately 3 m^3 of water during mold making process (interview data). Energy is needed for 2 steps: (1) mold heating and (2) smelting and

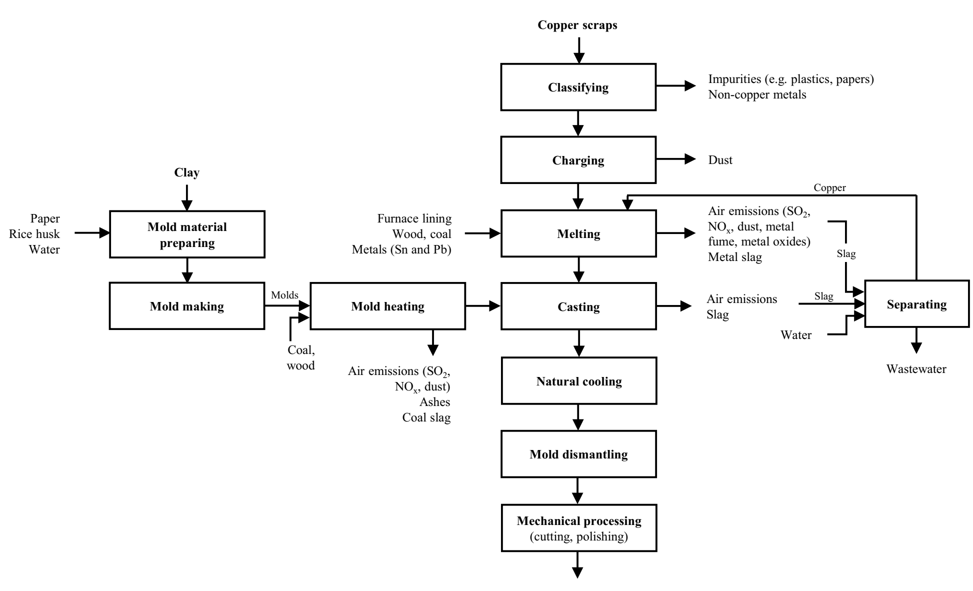

Fig. 7 Flowchart of copper recycling at traditional craft village

holding. Depending on the products, molds can be heated 2 times with different temperatures: 500 and 700 °C, or until 1000–1200 °C. By calculating theoretically needed heat for clay-mold heating and copper smelting, it is estimated that about 80% of total energy has been used for mold heating. The rest is for smelting of copper.

Copper recycling process leads to several serious problems from waste streams. Air emission is the most critical issue as dust is generated in most all steps of recycling process. During scrap charging into the smelters, dust containing metals, soils are released into environment. Especially, during melting process, dust with fume metals and metal oxides, organic compounds from partly burned impurities, CO_2, CO, NO_2, SO_2 from burning of wood and coal is formed and emitted. Casting step with burning of materials from mold cover layer generates dust, CO_2, CO, etc. Dust is also caused from mold dismantling and from mechanical process. Moreover, during mold heating, the combustion of wood and coal is the source for air emission (dust, volatile ash, CO_2, CO, NO_2, SO_2, etc.).

Copper recycling is considered a "dry process" but the metal slag cleaning/separating step (Fig. 7) to recover partly metals results in pollution (metals, sediment) to water bodies (ponds, drainage channels) where metal slag is washed out. This practice is similar to the case of aluminum recovery from aluminum slag at aluminum casting craft villages.

Another waste stream is solid waste with impurities from sorting of scraps (about 1 wt% of scraps), coal slags (15–20 wt% of consumed coal [57, 75–77]), metal slags (dross) (10–15 wt% of scraps [13] or 2–5 wt% of final products [19] and it depends on the quality of copper scraps) that can be recycled after washing with water, metal particles from mechanical processes (0.5 wt% of final products [19]) and mold materials (clay). 90–92 wt% of used clay can be recycled. In case of preparation or maintenance of smelters, refractory waste is appeared.

To calculate, we assume that the finished products are half-length statues with the final mixture of copper, tin and lead with the rates which have been provided above. With this combination, it forms bronze, a type of copper alloys [20]. The energy used for mold heating, copper smelting and casting is generated from coal and wood, in which the energy for smelting and holding is presumed from combustion of coal while wood is used for mold heating purpose. The data on inputs and outputs of copper recycling are shown in Table 9.

Selected BAT There are several technologies for secondary copper, such as blast, Mini Smelter, reverberatory or rotary furnace. The most appropriate technology for small size production/recycling is IF as this type of furnace is commonly used to produce copper alloys [21] due to high melting temperature and a wide range of melting capacity. Recyclers at craft villages can possibly upgrade to this technology. With selected BAT, some data are available. For example, residues from remelting processes consist of dross (or metal slag) (8–15 kg per t of copper product), flue dust (4–7 kg per t of copper product) and refractory lining (2 kg per t of copper product) [21]. The operating data for crucible induction furnace for the production of copper alloys [21] are used to compare with the current scenario with melting capacity which is 2.4–25 t per h; energy consumption is from 900 to 1600 MJ per t of copper ingots. Furthermore, the data for metals given in Ecoinvent [22] are used in which 1 wt% of metals are lost during melting and 0.1 wt% of Sn and Pb input are lost in metal fume. This assumption is also applied to the current situation case. The difference between current process and selected BAT is that the selected BAT focuses on the melting and holding steps. To match both scenarios, energy consumption for the case of applied BAT is added with energy generated from coal and wood combustion (same amount of wood for current technology) for mold heating with presupposition of 7% energy reduction (as evaluated by energy efficiency experts from VNCPC) by applying some cleaner production options such as installed better isolation layer for heating chamber, better process control. Clay used for mold making is remained the same.

Table 9 presents the differentiation between 2 technologies. It is visible that the energy consumption for current situation is higher than that of selected BAT, especially for the melting and holding steps. Selected BAT shows the significant reduction of solid waste stream as well. Due to the energy demand for molding preparation, energy consumption in the case of selected BAT is still high compared to the current situation. It shows the special case for copper recycling in Vietnam: making products instead of producing copper ingots. The proposed improvement potential options might be applied including new technology smelter (e.g., IF), scrap sorting, better process control to improve energy efficiency (e.g., scrap cutting, better insulation, material charging process), air emission collection (e.g., suction hood above smelter) and treatment system, water cooling tower for water recycling and solid waste management program.

Results for desktop PC recycling

Summarization of critical flows

From the analytic for each recycling process which includes process and data, the critical flows and some improvement potentials are summarized in Table 10. Determining critical flows are based on some aspects, such as their quantity, potential to be collected by formal waste

Table 9 The input and output data from recycling of 1000 kg copper scraps between current technology and selected BAT

	Unit	Current technology		Selected BAT	
		Quantity	Note	Quantity	Note
Input					
Copper scraps	kg	1000.00		1000.00	
Sn	kg	52.50	Calculated based on the assumption of 1 wt% metals lost during melting and 0.1 wt% metals lost in air emission.	54.35	Calculated based on the assumption of 1 wt% metals lost during melting and 0.1 wt% metals lost in air emission
Pb	kg	31.50		32.61	
Energy for mold heating, smelting and holding	MJ	46,032.72		37,139.14	
Energy for smelting and holding	MJ	9223.84		1704.95	Manual casting
Clay (recycled)	kg	5095.76		5274.68	
Clay (new)	kg	566.20		586.08	
Water	kg	3088.34		3196.77	
Output					
Final Products	kg	1029.45	Half-length statues (as a bronze type) with Copper, Sn and Pb at the proportion of 92, 5 and 3%, respectively	1065.59	Half-length statues (as a bronze type) with Copper, Sn and Pb at the proportion of 92, 5 and 3%, respectively
Pb, Sn in air emission	kg	0.08		0.09	
Equivalent CO_2 emission	kg	2959.31	Calculated from data provided in Table 3. The CO_2 emission from wood burning is not counted as a biomass source	2030.53	Calculated from data provided in Table 3. The CO_2 emission from wood burning is not counted as a biomass source
Total solid waste	kg	882.08		740.79	
Coal slag and ashes	kg	205.89		125.89	
Dust from filter to recycling	kg	–		10.71	With air treatment facility (filter bags)
Metal slags	kg	100.00		15.98	
Refractory lining waste	kg	–		2.13	
Solid waste (impurities such as paper, plastic, rock)	kg	10.00		–	
Solid waste (clay as mold materials)	kg	566.20		586.08	
Clay (to be recycled)	kg	5095.76		5274.68	
Copper loss in mechanical processes (cutting, polishing) to recycling	kg	5.15	Approximately 0.5 wt% output metal [19]	5.33	Approximately 0.5 wt% output metal [19]

collection, potential to be collected by informal waste collectors for recycling, recycling practices, availability of waste pre-treatment/treatment facility (e.g., sedimentation tanks, air sucking system). Some practical improvement potentials have been suggested based on cleaner production assessment reports from metal and plastic recycling sectors (see "Materials and methods"). More improvement potentials can be retrieved from BAT reference documents.

As seen from Table 10, the most serious issue is air emission from most of recycling processes but there are no available data for pollutant concentration. Gaseous emission consists of not only CO_2 and other gases (NO_x, SO_x, etc.) from fuel combustion but also metal and metal oxide fumes and organic compounds from contaminated scraps or from formation of monomers under pyrolysis of plastic. Wastewater with heavy metals and chemicals from gold recovery and surface treatment of aluminum products requires special treatment. Moreover, metal recovering activities from metal slag in case of aluminum and copper recycling by washing metal slag in water lead to critical problem of water pollution to water received bodies such as ponds, lakes, water channels. Solid waste stream is an issue relating to copper recovery from PCBs as it contains flame retardants while metal slags from metal recycling might contain heavy metals and other compounds.

Table 10 Summarization of critical flows from recycling processes

Critical flow	Air emission	Wastewater	Solid waste	Improvement potential
PCB treatment				
Gold recovery	*Toxic gases from acid leaching reactions such as NO_2, Cl_2.*	*Wastewater (approximately 0.08 m^3 for 4.1 kg of high gold-contained parts from 1 t of treated PCBs) with residue acids, other chemicals, heavy metals. Especially, high copper content in wastewater*	Solid residues consisting of glass fiber and organics (3 kg per 4.1 kg of high gold-contained parts from 1 t of treated PCBs)	Protective equipment (mask) for workers Ventilation and air treatment system for acid leaching spots Solution with high copper content can be collected for further copper extraction. Wastewater collection and treatment system. For example, using Calcium hydroxide solution for residue acid neutralization and metal ion precipitation
Copper recovery	Exhausted gas from gas combustion containing NO_x, SO_2 which is sucked by an electric fan and released into environment though a chimney	Wastewater (about 5 m^3/t of treated PCBs) from water used for fine shredding and separating which is passed through sedimentation tank before discharged	*Non-copper residues containing glass fiber and organics (392.7 kg/t of treated PCBs)*	Wastewater collection and treatment for recycling purpose
Ferrous metal recycling	*Dust consisting of metal dust and ferrous rust from cutting step* *High air emission (dust, rust) from charging scraps into furnace* *Gaseous emission containing metal and metal oxides, organic compounds and other gases such as CO, NO_x during melting process* *Dust released during removal of steel billets out from molds*	Wastewater from cooling water (5–7 m^3/t of steel billets)	Impurities from scraps (12.5–14 kg/t of steel billet) Slag (20–25 or up to 45 kg/t of steel billets) Refractory waste	New smelter with better energy efficiency Potential to improve operation efficiency and minimize emission (scrap management options: scrap sorting; "first in, first out" principle, etc.; melting process control options: scrap size, material charging process, etc.) Water cooling tower for water recycling Air emission collection (e.g. suction hood above smelter) and treatment system
Plastic recycling	*Dust formed during charging of shredded plastics into cone-shape funnel* *Air pollutants (e.g. monomers, or other organic compounds) generated during extruding*	Wastewater from cooling water (21.7–51 m^3/t of secondary plastic pellets)	Impurities (8–11 kg/t of secondary plastic pellets) Plastic pellets are scattered on the floor (37–40 kg/t of secondary plastic pellets)	Extruders with higher energy efficiency Better process control to improve energy efficiency (e.g. running at its most efficient speed, controlling electric motor to match the torque) Water cooling tower for water recycling Better ventilation system

Table 10 (continued)

Critical flow	Air emission	Wastewater	Solid waste	Improvement potential
Aluminum recycling	*Dust generated from all "dry" steps: classifying, cutting, charging, melting, mold dissembling, sheet making, and residue cutting* *Air emission consisting of metals and metal oxides, organic contaminants from incomplete combustion of organic matters during melting step* *Other gaseous pollutants (e.g. CO, SO_2, NO_x) from coal combustion*	*Wastewater from cooling water (13–21 m^3/t of final products, such as cookware, basins)* *Wastewater from surface treatment contains toxic chemicals (e.g. metal, chromic acid, sulfuric acid or sodium hydroxide)* *Wastewater bearing metals and other compounds from aluminum slag washing/separating to recovery metals in aluminum slag*	*Impurities (5 wt% of scraps)* *Coal slags (15–20 wt% of consumed coal)* *Metal slags (approximately 5–8 wt% of scraps* *Refractory waste*	New technology smelter suitable for old scrap types (e.g. reverberatory furnaces) Scrap sorting Better coal quality to reduce generated waste Process control to improve energy efficiency (e.g. scrap cutting, better insulation, material charging process) Better process control to improve surface treatment steps: water and chemical saving (e.g. applied reverse-order washing principle in which water is supplied only at the cleanest tank (the last one) and run over the previous tank, dripping time increase for products after taking them out from surface treatment tanks) Water cooling tower for water recycling Air emission collection and treatment system Solid waste management program
Copper recycling	*Dust containing metals, soils during scrap charging into smelters* *Fume metals and metal oxides, organic compounds, CO, NO_2, SO_2 during melting process* *Generated dust, CO, other compounds from burning of materials from mold cover layer* *Dust from mold dismantling and from mechanical process* *Dust, volatile ash, CO, NO_2, SO_2, etc. from wood/coal combustion during mold heating process*	*Metals and other compounds polluted water bodies (ponds, water channels) from metal slag cleaning/separating activity to recovery metals in metal slag*	*Impurities from sorting of scraps (about 1 wt% of scraps)* *Coal slags (15–20 wt% of consumed coal)* *Metal slags (dross) (10–15 wt% of scraps or 2–5 wt% of final products)* *Metal particles from mechanical processes (0.5 wt% of final products)* *Mold materials (clay)* *Refractory waste*	New technology smelter (e.g. Induction furnaces) Scrap sorting Process control to improve energy efficiency (e.g. scrap cutting, better insulation, material charging process) Air emission collection (e.g. suction hood above smelter) and treatment system Solid waste management program Water cooling tower for water recycling

The text in Italics indicates critical flow

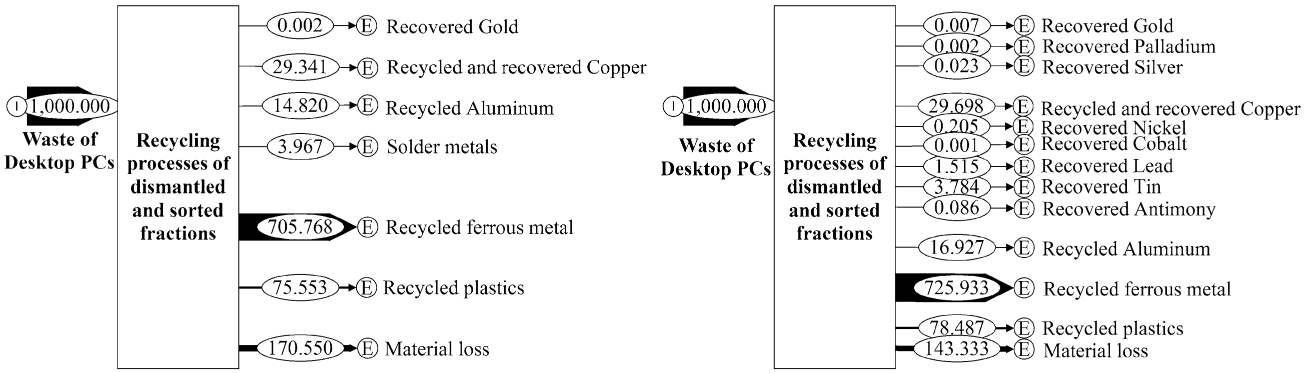

Fig. 8 Recovered and recycled materials (kg) from recycling processes of waste PC under current technologies (left-hand side) and selected BATs (right-hand side)

Table 11 Comparison between current technologies and selected BAT under energy consumption and waste streams

	Unit	Current technologies Quantity	Selected BAT Quantity
Energy consumption			
Electricity consumption	kWh	747.731	439.387
Fuels (coal, LPG, wood)	MJ	672.554	361.110
Waste stream			
Wastewater (total)	kg	5743.700	47.754
Solid waste (total)	kg	127.581	66.409
Equivalent CO_2 emissions	kg	401.689	239.988

Comparison between two scenarios

Using Tables 1, 2, 3, 4, 5, 6, 7, 8 and 9 to apply for 1 t of waste from desktop PC, the main outputs from recycling processes in terms of recovered and recycled of metals and plastics are presented in Fig. 8. As seen from Fig. 8, more precious, base and rare metals are recovered in the case of BAT compared to the current technologies. It is noted that the material loss consists of many metals containing in electronic components from PBCs (capacitors, transistors) that are exported to China for further treatment. The material loss is not much different in weight as the highest fractions are ferrous metals and plastics that are recycled within the territory of Vietnam.

The selected BAT include the energy recovery from burning of non-metal fraction of PCBs and the appearance of by-products from PCB treatment under Umicore's technologies for construction materials (both non-metal fraction and metals in by-products appear in the material loss). The loss of materials is in the form of solid waste, wastewater (metal loss from gold recovery process in the first scenario under acid leaching) and air emissions (dust, metal fume, organic compounds).

As shown in Table 11, the current technologies have higher energy consumption than that of selected BATs. Thus, more equivalent CO_2 emission is emitted. Solid waste in the first scenario contains the organic fraction from PCB treatment for copper recovery and it is possible to contain other metals. It is important to emphasize that air emission is just quantifiable or calculable proportion while more air pollution from melting (and casting) of ferrous metal, copper, aluminum and plastic are not able to calculate because of missing information.

Conclusion

The study focuses on the process and data collection phase for desktop personal computer recycling processes under 2 proposed scenarios: (1) current technologies in which outputs from dismantling processes are passed through the gold and copper recovering, and metal and plastic recycling at craft villages in Vietnam, and (2) appropriate BAT (or Best Available Technologies). Only for the case of Printed Circuit Board treatment, the selected BAT are technologies that cannot be implemented locally. The rest (metal and plastic recycling) of the selected BAT are considered suitable to be implemented at craft villages in terms of production capacity, fuel sources.

The informal end-processing/recycling of desktop personal computer waste includes Printed Circuit Board treatment, metal recycling (ferrous metal, aluminum and copper) and plastic recycling. Each recycling process has been described that consists of inputs and outputs and the data on the quantity of inputs (scrap, energy, water and other materials) and outputs (final products and waste streams).

Especially, the most critical issues have been analyzed. Unfortunately, data on air emission are missing for all recycling processes as lacking of studies on generated pollutants from informal recycling practices. Thus, those missing data should be measured.

In comparison between 2 scenarios, it is visible that selected Best Available Techniques are more advanced compared to the current technologies in both recovered and recycled amount of metals and plastic, water and energy consumption, and waste generation. Electricity and fuel consumption for the current technologies are higher than those of selected BAT about 1.7 and 1.9 times, respectively. Wastewater containing chemical and liquid metal salt from gold recovery using acid leaching needs to be treated properly or collected for further copper (and other metal) extraction. A large volume of water using for cooling purpose has high potential to be recycled. Without recycling, the quantity of water and wastewater for current technologies is 120 times higher compared to the selected BAT. The amount of solid waste from the first scenario is generated at 1.9 times higher than that from the scenario.

This study is an initial and necessary step for building up Life Cycle Inventory for informal e-waste recycling in Vietnam. With further studies focusing on air emission from end-processing of e-waste, Life Cycle Assessment shall be calculated and the comparison between current situation and BAT/BEP in terms of life cycle indicators shall be drawn. Those figures could support decision makers in supporting the informal sectors in several ways, for example, supporting the technology upgrading individually or consolidating the current trend which is to gather processers into centralized workshops with treatment facilities, etc. Obviously, this study is limited in air emission data. In the first scenario, environmental monitoring data are available in some studies but impossible to calculate the air emission as the melting practices are without air treatment facilities. In the second scenario, the air pollutant concentration after treated at appropriate air treatment facilities but the sucked air volume is not available for specific recycling process (such as scrap quality, production capacity, air treatment technologies). More importantly, input analysis (organic matters, metal content) is needed for better calculation but there are no data available. From these limitations, it is suggested that further studies are needed to fulfill the requirement for technology assessment and for an e-waste recycling inventory in informal sector in Vietnam.

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