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## Evidence-based integrated environmental solutions for secondary lead smelters: Pollution prevention and waste minimization technologies and practices

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### ABSTRACT

An evidence-based methodology was adopted in this research to establish strategies to increase lead recovery and recycling via a systematic review and critical appraisal of the published literature. In particular, the research examines pollution prevention and waste minimization practices and technologies that meet the following criteria: (a) reduce/recover/recycle the largest quantities of lead currently being disposed of as waste, (b) technically and economically viable, that is, ready to be diffused and easily transferable, and (c) strong industry interest (i.e., industry would consider implementing projects with higher payback periods). The following specific aims are designed to achieve the study objectives: Aim 1 – To describe the recycling process of recovering refined lead from scrap; Aim 2 – To document pollution prevention and waste management technologies and practices adopted by US stakeholders along the trajectory of LAB and lead product life cycle; Aim 3 – To explore improved practices and technologies which are employed by other organizations with an emphasis on the aforementioned criteria; Aim 4 – To demonstrate the economic and environmental costs and benefits of applying improved technologies and practices to existing US smelting operations; and Aim 5 – To evaluate improved environmental technologies and practices using an algorithm that integrates quantitative and qualitative criteria.

The process of identifying relevant articles and reports was documented. The description of evidence was presented for current practices and technologies used by US smelters as well as improved practices and technologies. Options for integrated environmental solutions for secondary smelters were introduced and rank ordered on the basis of costs (i.e., capital investment) and benefits (i.e., production increases, energy and flux savings, and reduction of SO<sub>2</sub> and slag). An example was provided to demonstrate the utility of the algorithm by detailing the costs and benefits associated with different combinations of practices and technologies. The evidence-based methodology documented in this research reveals that it is technically and economically feasible to implement integrated environmental solutions to increase lead recovery and recycling among US smelters. The working example presented in this research can be confirmed with US stakeholders and form the basis for implementable solutions in the lead smelter and product industries to help reverse the overall trend of declining life-cycle recycling rates.

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### 1. Introduction

In today's global economy businesses, consumers and communities are challenged more than ever with the continual significant increase in the costs of, among other things, doing business, daily living and upkeep of societal activities. In this endeavor, the practice of sustainable development becomes integral to maintain the delicate balancing act among the needs of business, society and environment.

This research deals with the environmental management of lead which makes up the largest hazardous waste stream in the US. Approximately 88% of US production is used in the manufacture of lead-acid batteries (LAB) (Smith, 2008). Based on an exploratory study of LAB product lifecycle, Genaidy et al. (2008) found that the recycling rates for lead recovery declined from 1999 to 2006, with a peak of 85.2% in 1999 and significantly dropping to 66% in 2006. According to the authors, the reasons for the decline was attributed to one or more of the following: (a) the amount of lead recovered was virtually unchanged and fluctuating in the range of 10010 and 1060 thousand tons; (b) the amount of lead in domestic battery consumption went up by 18% from 1995 to 2002 at an annual growth rate of 2.25%; and

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(c) the amount of lead in imported batteries increased by 118%, a value much higher than the 37% recorded for lead content in exported batteries. In lieu of the declining recycling rates, the focus of this paper is to explore environmental improvement strategies to increase lead recycling, process efficiency and recovery in order to improve human and environmental health as well as the bottom line of lead smelters, lead-acid battery and other lead product industries.

Environmental management has evolved over the years through a series of successive paradigms: (a) Passive environmental management; (b) Reactive environmental management or end-of-pipe approaches; (c) Proactive environmental management or cleaner production (Hilson, 2003). Passive environmental management included foul and flee (e.g., after contaminating a plot of land, one would abandon the area), dilute and disperse (e.g., the dispersal of waste in the atmosphere or water body, the only waste management practice in pre-industrial society), and concentrate and contain (emerged to address highly toxic wastes such as nuclear waste and spent fuels). End-of-pipe approaches involved the installation of purification and detoxification units at the end of emission pipes and coincided with the implementation of national environmental regulations. The concept of cleaner production has emerged in the past 10–15 years. It embraces waste minimization and pollution prevention at the source, and combines environmental and business concerns.

A comprehensive review of electronic databases suggest general reviews exist on pollution prevention and waste minimization technologies and practices (e.g., Freeman et al., 1992; Chaaban et al., 2001; Moors et al., 2005; Hossain et al., 2008). However, efforts are fragmented on specific technologies and/or practices that address maximum lead recovery at the pre-processing or the in-processing stage (e.g., Reuter et al., 1997; Andrews et al., 2000). Given that the number of secondary lead smelter facilities dropped from 50 plants in 1995 (USEPA, 1995) to an estimated number of 21 plants in 2006 on the basis of data derived from the US Geological Survey (Carlin et al., 2006), there is a need to augment the production capacity of these fewer smelters to reverse the declining recycling rates, yet, to improve the environmental performance of the smelters.

An evidence-based methodology is adopted in this research to establish strategies to increase lead recovery and recycling via a systematic review and critical appraisal of the published literature. In particular, the research examines pollution prevention and waste minimization practices and technologies that meet the following criteria: (a) reduce/recover/recycle the largest quantities of lead currently being disposed of as waste, (b) technically and economically viable, that is, ready to be diffused and easily transferable, and (c) strong industry interest (i.e., industry would consider implementing projects with higher payback periods). The following specific aims are designed to achieve the study objectives: Aim 1 – To describe the recycling process of recovering refined lead from scrap; Aim 2 – To document pollution prevention and waste management technologies and practices adopted by US stakeholders along the trajectory of LAB and lead product life cycle; Aim 3 – To explore improved practices and technologies which are employed by other organizations with an emphasis on the aforementioned criteria; Aim 4 – To demonstrate the economic and environmental costs and benefits of applying improved technologies and practices to existing US smelting operations; and Aim 5 – To evaluate improved environmental technologies and practices using an algorithm that integrates quantitative and qualitative criteria.

## 2. Recovering lead from waste streams

Lead scrap undergoes two stages during the recycling process: physical separation and chemical separation (smelting and refining) (Wernick and Themelis, 1998). Typically, lead scrap comes from

spent automobile and industrial lead-acid batteries (LAB). These spent LABs are drained of the electrolyte and crushed into smaller manageable pieces for further processing using hammer mill and grinding procedures, followed by washing and gravity separation in hydro-separators to isolate the lead-containing components and other materials. There are three streams: lead materials (about 60% lead, 15% PbO<sub>2</sub>, and 12% PbSO<sub>4</sub>), polypropylene scraps, and sulfuric acid (Wernick and Themelis, 1998). The lead materials usually come from grids and posts (lead alloy) and electrode paste (lead oxides and sulfides).

Smelting is the reduction of lead compounds to elemental lead in a high-temperature furnace which operates at higher temperatures (2200° to 2300 °F or 1200° to 1260 °C) than those required for elemental lead (621 °F or 327 °C). Depending on the smelter's practices and process, the recovered lead-containing materials are directly fed to the smelting furnace, or, first desulfurized then fed to the furnace (e.g., blast or electric furnace). The reduction of feed in the furnace yields raw lead product and slag rich (containing 20% to 40% lead) in lead content. The slag is fed back to the furnace for further reduction and lead recovery. The remaining slag is usually discarded as solid waste in landfills or sold to other industries as raw material (e.g., material in Portland cement). Following smelting, the recovered lead is transferred to refining kettles where lead is melted to remove the residual impurities to recover pure lead or to adjust other trace elements to produce alloys as per customer requirements and cast into ingots for shipment.

A simplified flow process diagram is shown in Fig. 1 for secondary lead smelting (USEPA, 1998). The lead recycling process consists of three stages, namely, pre-, in- and post-processing. The physical separation step constitutes the pre-processing stage. The chemical separation makes up the in-processing stage including the smelting and refining processing. It should be noted that the smelting stage consists of charging lead scrap to a reverberatory furnace. Consequently, the reverberatory furnace slag is used as feed material to blast or electric furnace for lead recovery. The third stage consists of post-processing, that is, the application of pollution control technologies.

Fig. 2 presents four possible practices in US secondary lead smelting operations. In the first case, spent batteries are directly fed to the high temperature furnace. The second scenario separates the plastic components from the remainder of spent batteries in which lead scrap and battery paste are fed to the high temperature furnace. The third scenario is a variation of the second case where a drying/roasting unit is introduced between the battery breaking/hydro-separation unit and the high temperature furnace. Lastly, the fourth scenario adds a desulfurization unit to the components in the third scenario for the significant reduction of, among other things, SO<sub>2</sub>.

## 3. Methods

### 3.1. Search strategies

Initially, the search concentrated on in-processing technologies in the US and abroad. However, in light of the application of inclusion criteria such as economic payback and efficiency, the evidence-based research team realized that the search should be extended to environmental technologies and practices at the pre-, in-, and post-processing stages. In addition, we expanded the search to metal recovery at large, that is, it was not exclusive to lead processing. Thus, the redefined target areas in our search were: (a) current environmental practices and technologies adopted by US industries and abroad in the lead recycling process; (b) improved environmental practices and technologies for use in all stages of the lead recycling process; and (c) environmental practices and technologies applicable to pollution prevention and control technologies at the pre- and post-processing stages in the metal recycling process at large.

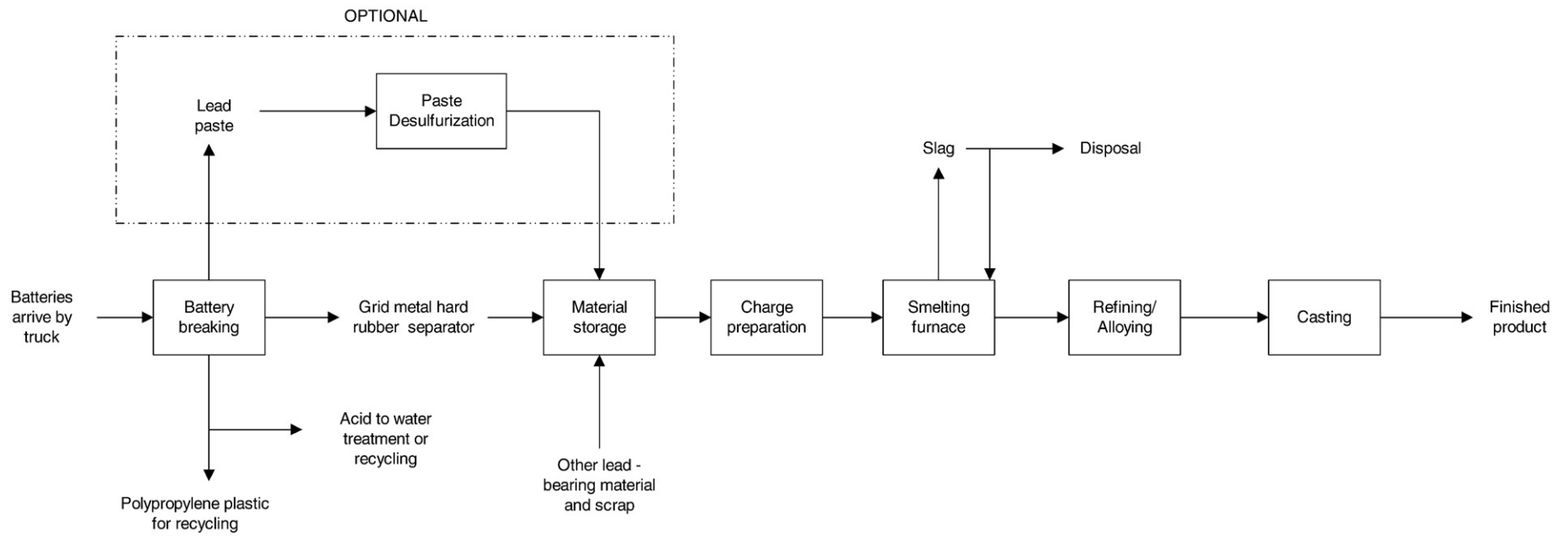
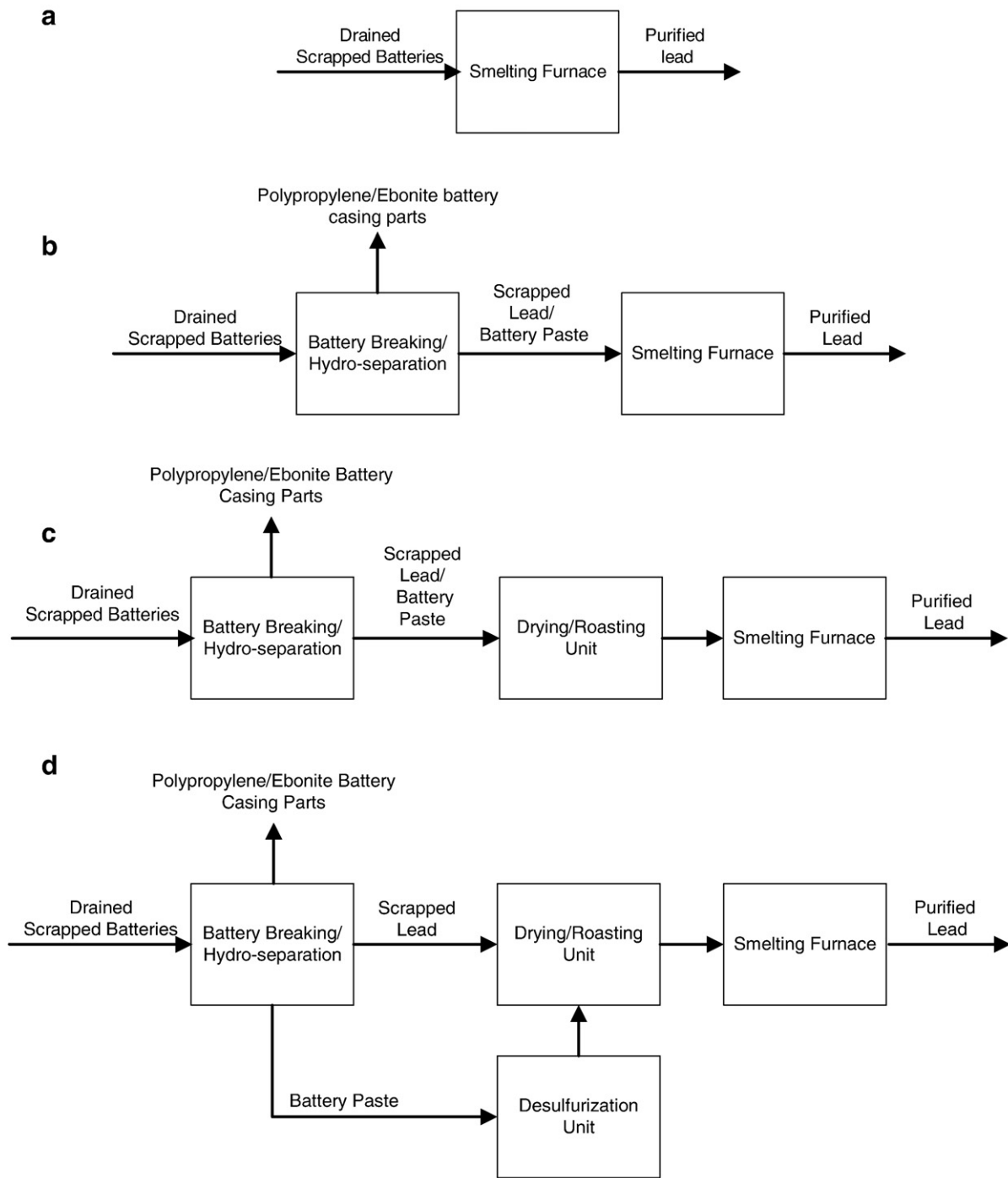


Fig. 1. Simplified flow process diagram for secondary lead smelting process (Adapted from EPA, 1998).



**Fig. 2.** a. Secondary lead recovery with spent batteries directly fed to smelting furnace. b. Secondary lead recovery with battery breaking/hydro-separation unit. c. Addition of drying/roasting unit to set-up in panel b. d. Addition of desulfurization unit to set-up in panel c.

The detail of comprehensive search of electronic databases is outlined below in support of the above target areas.

- For current in-processing practices and technologies in the US and abroad, we consulted the environmental databases of Academic Search Premier and Environetbase and general search engines such as Google and Yahoo with combinations of the following keywords: secondary lead smelting, smelting technologies, lead recycling technologies, and reclaiming and clean technologies. An emphasis was placed on articles emphasizing technologies in terms of efficiency and economic impact.
- For improved pollution prevention and control technologies relevant to all three stages of the smelting operation, specialized

databases were used, namely, Academic Search Premier, Environetbase, Environment Complete and IEEE Electronic Library Online. General purpose search engines were also used including Google and Yahoo. The following combinations of keywords were used: pollution prevention technologies, air emission control technologies, gas emission control technologies, and waste water treatment technologies. Inclusion criteria included efficiency, economic pay-back, and energy expenditures/savings.

- The above databases were also searched for articles on practices and other technologies aiming at improving metal recovery at the pre- and post-processing stages. The following keywords and combinations were used: secondary lead smelting, best practices,

pre-processing technologies, smelter feed, feed preparation, scrap separation, lead scrap treatment. In this light, individual and review articles were included.

### 3.2. Data and information extraction for evidence description

To accomplish Aims 2 and 3, the following items were documented for the evidence description of technologies and practices current and improved for the three stages of secondary lead smelting: (a) Pre-processing – Technology description, efficiency (%), cost-effectiveness (% energy savings or expenditures per ton of metal recovered), payback period (years), environmental benefits (e.g., reduction in slag and SO<sub>2</sub>) and production increases (% increase in throughput); (b) In-processing – Technology description, furnace efficiency (%), cost-effectiveness in terms of energy expenditures per ton of metal recovered (GJ/ton of lead), and effectiveness (purity of metal recovered in %); and (c) Post-processing – efficiency (%), cost-effectiveness in terms of energy expenditures per ton of metal recovered (GJ/ton of lead), payback (yrs), and effectiveness in terms of concentration of contaminant in treated gas or water (mg/Nm<sup>3</sup> for gas flow or mg/l for processed water). Data and information were gathered for each type of technology/practice from one or more articles by one member of the research team and was verified by another member. Any discrepancies were resolved in consensus meetings.

### 3.3. Assessment of economic/environmental cost and benefits for improvement options

To achieve Specific Aim 4, the third scenario shown in Fig. 2c was utilized as the example to demonstrate the economic and environmental costs and benefits of adopting improved technologies and practices. A detailed account of the benefits and costs was presented with respect to changes in production, energy and material inputs, and environmental emissions. The analyses were made with reference to small (production capacity of 10,000 t), medium (i.e., 50,000 t) and large smelters (i.e., 100,000 t).

To achieve Aim 5, a methodology was devised to rank order the different options of bundles of improved environmental technologies and practices. In order to encourage the diffusion of improved technologies and practices, we assumed that the in-processing technologies in secondary smelting are not changing due to prohibitive costs of their replacement. Accordingly, our efforts concentrated on improvement of technologies and practices at the pre-processing stage. To assess the different options, an algorithm was developed which took into account the following criteria: (a) cost of capital investment and (b) benefits from production increases, energy and flux savings, and environmental emission reduction (SO<sub>2</sub> and slag). All benefit indices were estimated in monetary values and were converted into a percentage level relative to the predicted revenues for smelters depending on its size (10,000 t for small smelters; 40,000 t for medium smelters; and 100,000 t for large smelters).

The overall benefit level was derived using the step-by-step process outlined in Fig. 3. In step 1, production increase is evaluated into one of four levels, namely, very low, low, moderate and high. Both energy/flux savings and environmental benefits are computed in units relative to production increase, that is, no change, increase by 1/2 level, or increase by one level as shown in steps 2 and 3 in Fig. 3, respectively; then, the energy/material savings and environmental benefits are converted into a single score by utilizing the conversion factor in step 4 (Fig. 3). Finally, the overall benefits are determined by integrating the values of production increase and energy savings/environmental benefits (see step 5). For example, if the converter outcome is '1 level' and the level of production increase is 'high', the product will yield a 'very high' overall benefit. The one-time capital cost investment was converted into an annual basis by dividing the value by 4 years to be able to compare it on equal level with annual

benefits (a 4-yr normalization value was selected because it corresponds to the payback period for hydro-metallurgical units as reported in Table A3 in Appendix A). Consequently, the obtained value was converted to a percentage level relative to the smelter's estimated revenues as explained above. The percentage value was transformed into a linguistic descriptor as shown in Fig. 3 (Step 6).

To illustrate the process of converting the numerical value into a linguistic descriptor for a benefit or cost variable, let us assume for example that a production increase in the improved blast furnace system for a small smelter is valued at \$17 M. Relative to the smelter annual revenues (e.g., \$27 M), this is equivalent to 62% of the annual revenues and equates to a 'High' level (see Fig. 3). It should be noted that one cannot easily translate the significant reduction in SO<sub>2</sub> emission into monetary values. Therefore, given that the reduction in SO<sub>2</sub> is comparable to that in slag reduction, the percentage value assigned to the reduction in slag was assumed to be the same as that for the reduction in SO<sub>2</sub>.

Fig. 3 depicts the compatibility function for integrating the costs and benefits into a single index ranging in values from 'Very Low', 'Low', 'Moderate', 'High' to 'Very High'. The compatibility function takes into account not only the payback period for the option at hand, but also, the economic and environmental benefits beyond the payback period. In a way, the compatibility function can be seen as a sustainability index integrating the economic, environmental and societal costs and benefits under one umbrella.

The assessment algorithm is used to calculate the compatibility function in several steps as follows: (1) Production increase is assigned a linguistic descriptor ranging from 'Very Low' to 'High' as shown in Step 1 of Fig. 3; (2) The energy and flux savings are evaluated as reported in Step 2 of Fig. 3 to determine the action required ranging from 'No Change' to 'Increase by 1/2 Level' to 'Increase by One Level'; (3) Step 3 of Fig. 3 calls for a similar action in terms of the added environmental benefits of both SO<sub>2</sub> and slag reduction; (4) The action outcomes from Steps 2 and 3 are added up to obtain an intermediate action for the integration of energy/flux savings and SO<sub>2</sub>/slag reduction ranging from 'No Change' to 'Increase by 1 1/2 Level'; (5) The outcome of production increase obtained from Step 1 of Fig. 3 is modified by an integration of the intermediate action outcome from both the energy/flux savings and SO<sub>2</sub>/slag reduction to arrive at the overall benefit level (step 5); (6) The overall cost is assigned one of five values ranging from 'Very Low' to 'Very High' as demonstrated in Step 6 of Fig. 3; (7) the compatibility function is calculated for a given value of cost and benefit using the table shown in Fig. 3 and is assigned a value ranging from 'Very Low' to 'Very High' (Step 7).

It should be noted that combining energy and flux savings together with environmental emission reduction may lead to improvement in the order of 1/2 units (see footnote in Fig. 3). Thus, one may add a 'somewhat' level between two consecutive descriptors, for example, 'low' and 'moderate' becoming 'somewhat moderate'. Therefore, the benefit scale (i.e., in steps 1, 5 and 7) will consist of the following levels: 'Very Low', 'Somewhat Low'; 'Low', 'Somewhat Moderate', 'Moderate' 'Somewhat High', 'High', 'Somewhat Very High' and 'Very High' (please see a refined table of the compatibility function in the footnote of Fig. 3). The compatibility table was developed using a round table of experts in industrial management.

### 3.4. Identification of studies

#### 3.4.1. Smelting technologies

The search of electronic databases for smelting technologies resulted in 1452 citations (Fig. 4a). Seventy-two abstracts were retrieved after removing repeated abstracts, review articles and abstracts not related to the topic. Upon application of inclusion criteria (e.g., efficiency, cost-effectiveness, output purity), a total of 28 articles were fully examined and twenty-one studies were finally selected for use in our evidence-based methodology (Andrews et al., 2000; Baldock and Short, 2000; Cow-perthwaite et al., 1980; Diaz et al., 2001; Ferracin et al., 2002; Frias



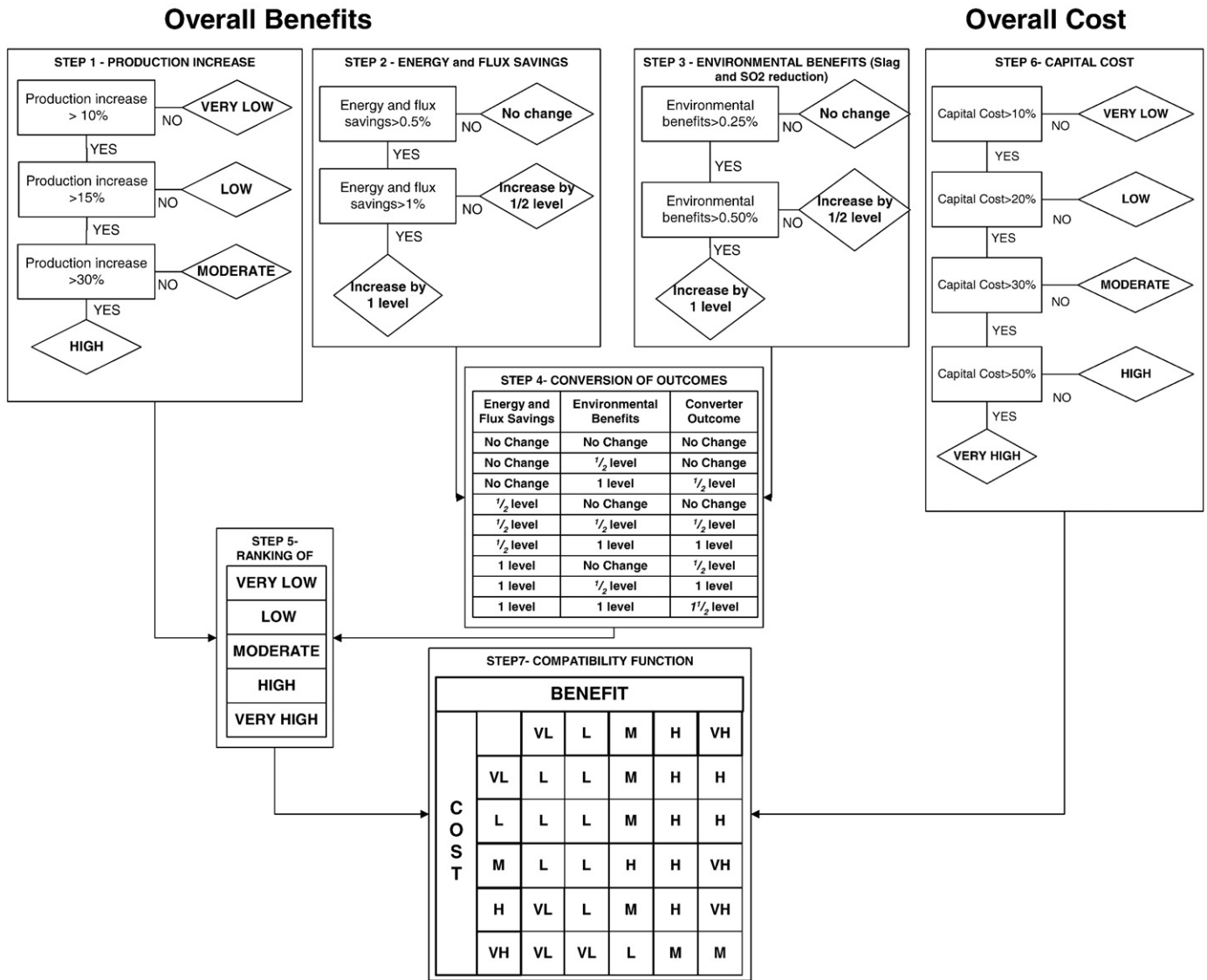


Fig. 3. Calculation of compatibility function. (VL – Very Low; L – Low; M – Moderate; H – High; VH – Very High).

Footnote:

- Combining energy and flux savings together with environmental emission reduction may lead to improvement in the order of 1/2 units. In this case, one may add a 'somewhat' level between two consecutive descriptors such as low and moderate becoming 'somewhat moderate'. Therefore, the benefit scale (i.e., Steps 1, 5 and 7) will consist of the following levels: VL – Very Low; SL – Somewhat low; L – Low; SM – Somewhat moderate; M – Moderate; SH – Somewhat high; H – High; SVH – Somewhat very high; VH – Very High.
- The final compatibility matrix is shown below while incorporating the 'somewhat' levels:

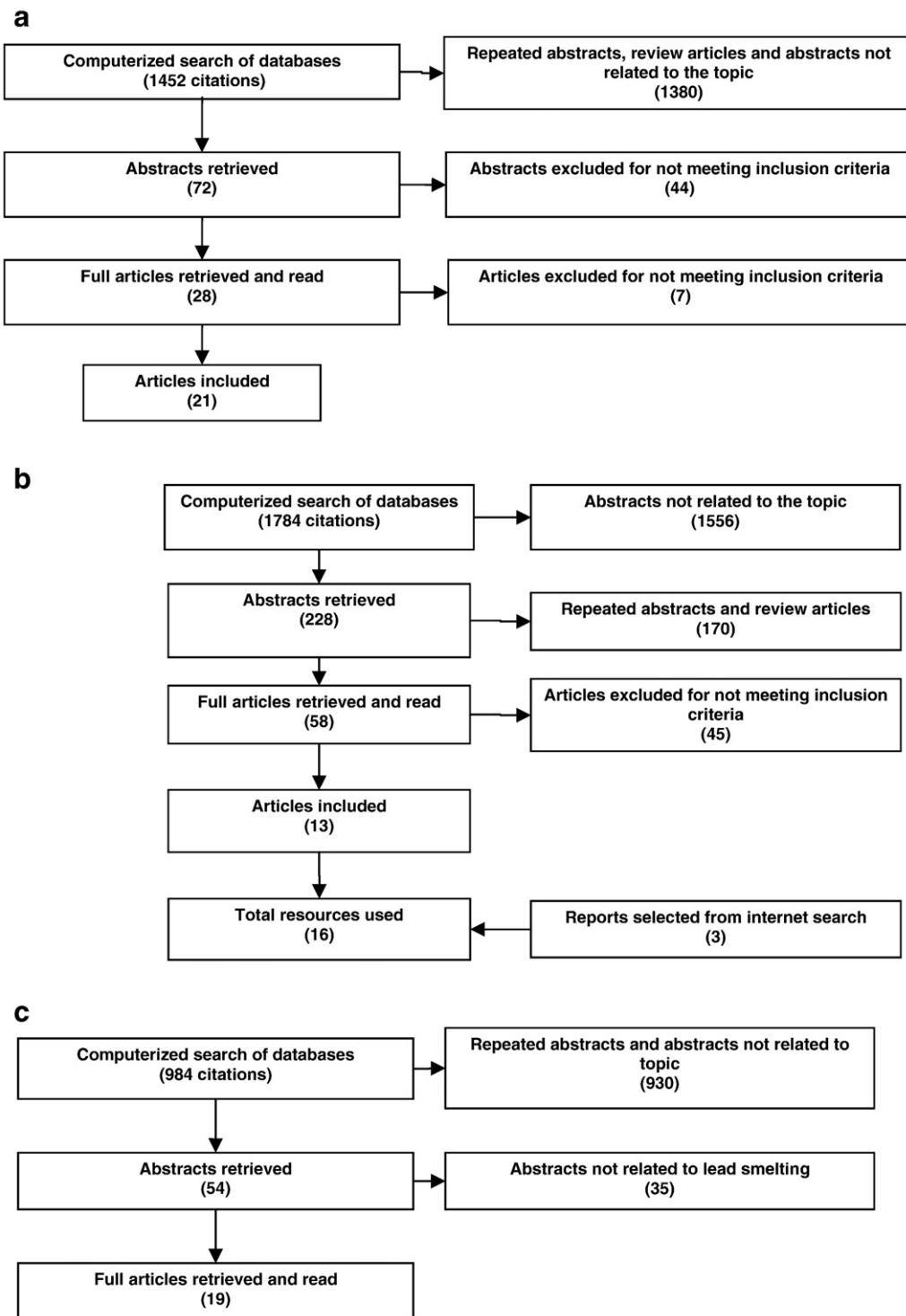
Cost	Benefit									
	VL	SL	L	SM	M	SH	H	SVH	VH	
VL	L	L	L	SM	M	SH	H	H	H	
L	L	L	L	SM	M	SH	H	H	H	
M	L	L	L	SH	H	SH	H	SVH	VH	
H	VL	L	L	SM	M	SH	H	SVH	VH	
VH	VL	VL	VL	SL	L	SM	M	M	M	

et al., 2002; Agrawal et al., 2004; Rabah, 1998; Ramus and Hawkins, 1993; Reddy, 2003; Raghavan et al., 2000; Tianjun and Qichang, 1999; Errington et al., 2005; Arthur and Edwards, 2003; Zhang et al., 2008; Ziebig and Stanek, 2006; Barakat, 1998; Ettler et al., 2005; Ryzhenkov et al., 2006; Socolow and Thomas, 1997; Yender, 1998).

3.4.2. Pollution prevention and control technologies

The electronic search for pollution prevention and control technologies applicable to secondary lead smelting produced 1784

citations of which 1556 articles were eliminated on the basis of irrelevance to the study objective (Fig. 4b). After elimination of review and repeated articles from different databases, fifty-eight articles were short listed and read. Upon screening with respect to technology characteristics (e.g., efficiency), thirteen research papers were deemed appropriate for our study (Freeman et al., 1992; Hilson, 2000; Warhurst and Bridge, 1996; Hilson, 2003; Matheickal and Yu, 1997; De-Bruijn et al., 1996; Jaworek et al., 2006; Mooiman et al., 2005; Moss, 2008; Kreuzsch et al., 2007; Jolly and Rhin, 1994; Hossain



**Fig. 4.** a. Article selection flowchart for in-processing lead smelting technologies. b. Article selection flowchart for pollution prevention and control technologies. c. Article selection flowchart for additional technologies and practices for metal recovery.

et al., 2008; El-Halwagi 1998). Three additional reports were identified and found of use in the present study in light of internet inquiry on general purpose search engines (UNEP, 2003; USEPA, 1998; European Commission – Integrated Pollution Prevention and Control, 2001).

#### 3.4.3. Additional practices and technologies

Fig. 4c provides a summary of the article selection search procedure for additional technologies and practices designed to max-

imize metal recovery at the pre- and post-processing stages during the recycling process. A total of 984 citations were found. Fifty-four abstracts were selected after eliminating repeated abstracts and papers which are not relevant to the study objective. The following nineteen articles were finally used to support the study specific aims (Kang and Schoenung, 2005; Scott et al., 1997; Mesina et al., 2007; van Schaik and Reuter, 2004; Salomone et al., 2005; Vaysgant et al., 1995; Rabah, 1998; Quirijnen, 1999; Nakada et al., 2008; Lewis and



Beautement, 2002; Kinaev et al., 2005; Driussi and Jansz, 2006; De Angelis et al., 2002; Dahodwalla and Heart, 2000; Espinosa et al., 2004; Coxa et al., 2000; Bunge et al., 1996; Bourson, 1995; Zhao et al., 2008; Zabaniotou et al., 1999).

Upon completion of the primary electronic search and evidence-based analyses, the research team conducted another secondary search to fill in gaps found in the tables of evidence-based information discussed in the results section and reported in the [Appendices](#). Additional studies and reports include, among others, the work of Akihiko (2004), Abrams et al. (1999), Hughes (2000), Kenson (2005), Lyakov et al. (2007), Olson (2008), Olympia Resource Limited (2005), Saman and Nutter (1994), Warner et al. (2006), Wolters et al. (2008), and Xstrata (2006).

## 4. Results

### 4.1. Description of evidence

The description of evidence is documented in [Appendix A](#). Tables A1 through A4 provide the description and characteristics of in-processing technologies in typical US secondary smelting plants, improved in-processing technologies (not currently used in US plants), and pre- and post-processing technologies, respectively. The sources of emissions and pollutants during the smelting operations are outlined in [Fig. 5a](#) for typical activities conducted in US recycling plants based on pyro-metallurgical techniques. [Fig. 5b](#) documents the emissions for improved hydro-metallurgical technologies.

#### 4.1.1. Current technologies and practices used by US smelters

The US lead smelting industry uses reverberatory, blast, rotary and electric furnaces for smelting lead scrap to produce refined lead. As a first step, the batteries are broken down by hammer mills or sawing and scrapped lead is separated via hydro-separation. Few of the smelters use desulfurization units to remove sulfur from lead prior to being fed into high temperature furnaces. The recovered lead scrap is dried and mixed with other lead-content materials. Measured quantities of feed are processed with flux and reducing agents in high temperature furnaces, usually reverberatory, to separate elemental lead from other impurities. Soft lead is tapped from the furnace and the generated slag rich in lead content is further reduced in blast or electric furnaces. Thereafter, soft lead is purified or alloyed in kettles and cast to lead billets per customer requirements.

The emissions in the secondary lead smelting process are controlled to meet environmental regulations. Baghouse filters are used to collect the dust produced during battery breaking, drying and feed preparation and smelting. Some smelters process the battery paste directly into the high temperature furnaces, therefore, the plants are equipped with gas scrubbing units to remove the sulfur dioxide produced during the process in the form of sulfuric acid. Other emissions such as carbon monoxide and dioxide, and dioxins are burned with the dust collected in bag filters. Lead dust collected in bag filters is redirected to the furnace for further smelting.

Vast amounts of water are used at different points in secondary lead smelting operations including hydro-separation units, furnace cooling, quenching, and emission control equipment. The resulting contaminated water with lead and lead compounds and other acids and alkalis is collected and treated in tanks and reservoirs to remove contaminants. The treated water is reused in the smelter processes or released into the streams depending on the smelter practices and waste water.

#### 4.1.2. Improved technologies and practices

Improved in-process smelting technologies include both pyro- and hydro-metallurgical processes (UNEP, 2003). Pyro-metallurgical tech-

niques reduce all metallic compounds via chemical methods to their metallic or reduced forms by means of heating and use of fluxing and reducing agents. Prior to smelting, some pyrometallurgical techniques employ desulfurization and neutralization steps. Following smelting, a refining step is required in which specific reagents are added to molten lead at appropriate temperatures. The reagents will remove the unwanted metals.

Hydro-metallurgical technologies reduce all lead compounds to metallic lead electrically via electrolysis that deposits lead on electrodes, which is subsequently shaken off, collected and pressed to form platelets of pure lead. A comparative assessment of hydro- and pyro-metallurgical techniques reveals the following observations:

- Hydro-metallurgical methods are highly effective in producing pure metals. Its efficiency is comparatively higher than that of pyro-metallurgical procedures.
- Hydro-metallurgical processes can be altered to accept a wide range of feed materials with minimally invasive process changes.
- The production output capacity of pyro-metallurgical technologies is much higher than that of hydro-metallurgical processes.
- The points of emissions are significantly less in hydro-metallurgical methods ([Fig. 4b](#)) in comparison to pyro-metallurgical process ([Fig. 5a](#)).

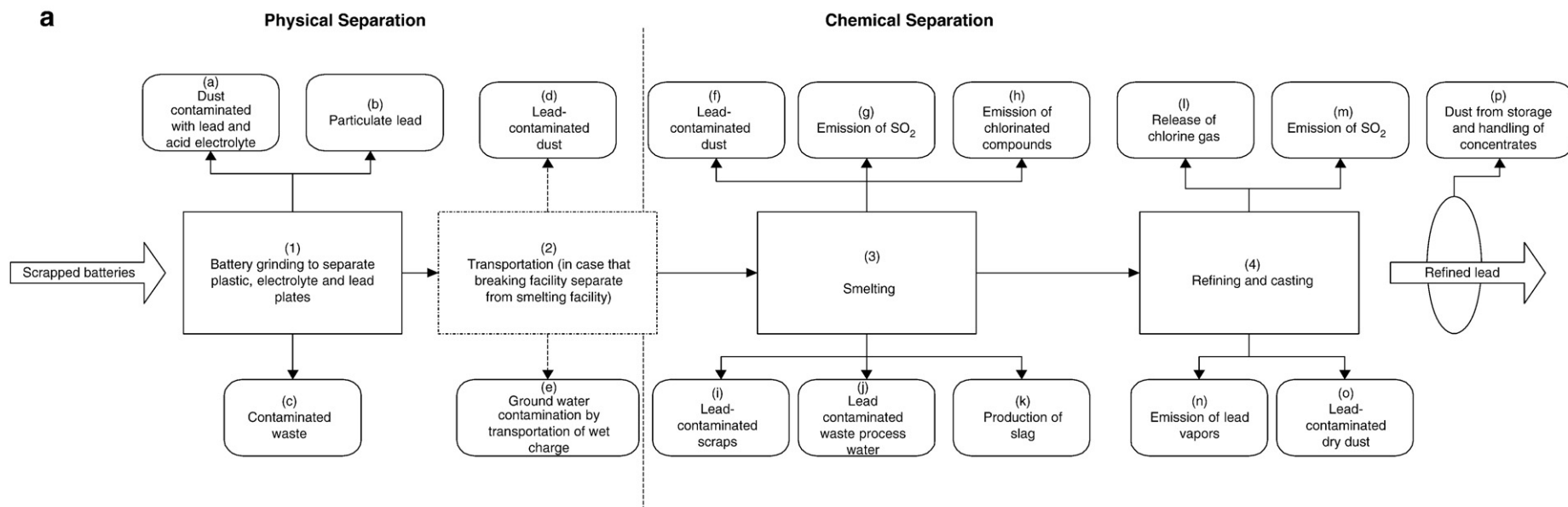
It should be noted that hydro-metallurgical units are produced in various sizes. In this research, smaller hydro-metallurgical units, as shown in a later section, are also presented as viable options in the pre-processing technologies to augment the capabilities of in-processing technologies among US smelters (e.g. pyro-metallurgical units).

In addition to hydro- and pyro-metallurgical techniques, the following observations can be made about pollution prevention and waste minimization technologies and practices which can assist in reducing the sources of emissions during pre- and in- processing activities:

- Baghouse filters with fabric and ceramic filters are best suited for dust abatement with efficiency greater than 99.9%<sup>+</sup>.
- Significant reduction in hazardous gas emissions can be achieved through in- and post-processing after gas burners.
- End-of-pipe control technologies, such as sedimentation, can be used to capture material lost in water and dust during transportation, handling, processing and extraction of lead.
- The recycle and reuse of process/waste/treatment of water has significant economic impact.
- The desulfurization of battery paste prior to in-process smelting significantly reduces the amount of generated slag due to reduction/elimination of iron and savings in coke consumption. The efficiency of smelting operation can increase by 25 to 30% due to the desulfurization activity.
- Battery separation and smelting practices have a significant impact on slag reduction relative to smelting whole batteries (i.e., the whole battery is fed to high temperature furnaces).
- Prior to entry into the smelting phase, drying feed materials can significantly reduce the energy requirements of the furnace.
- The pre-sorting of batteries and lead-containing materials increases the furnace efficiency via increased throughput, and reduced emissions and generated slag.

#### 4.2. Example of economic/environmental costs and benefits for improved technologies and practices

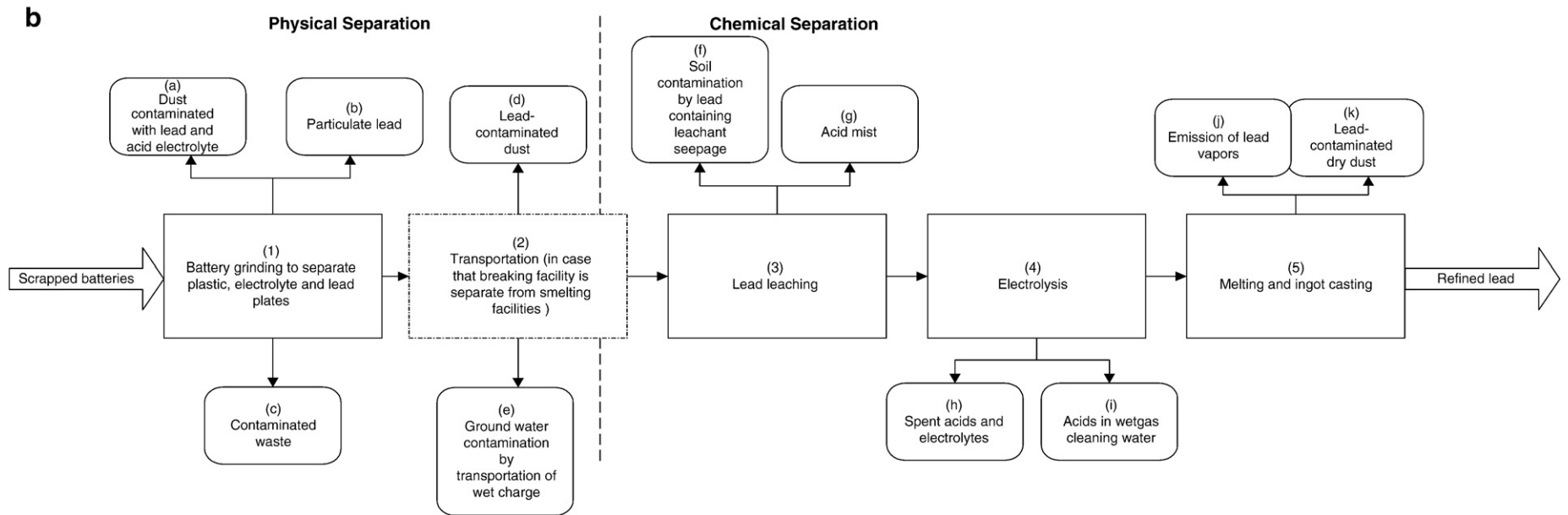
[Appendix B](#) documents the details of costs and benefits of introducing hydro-metallurgical techniques to the third scenario shown in [Fig. 2c](#) so as to improve the environmental practices of US smelters. The details are demonstrated for small, medium and large smelters.



**Fig. 5. a.** Sources of emissions in pyro-metallurgical process.

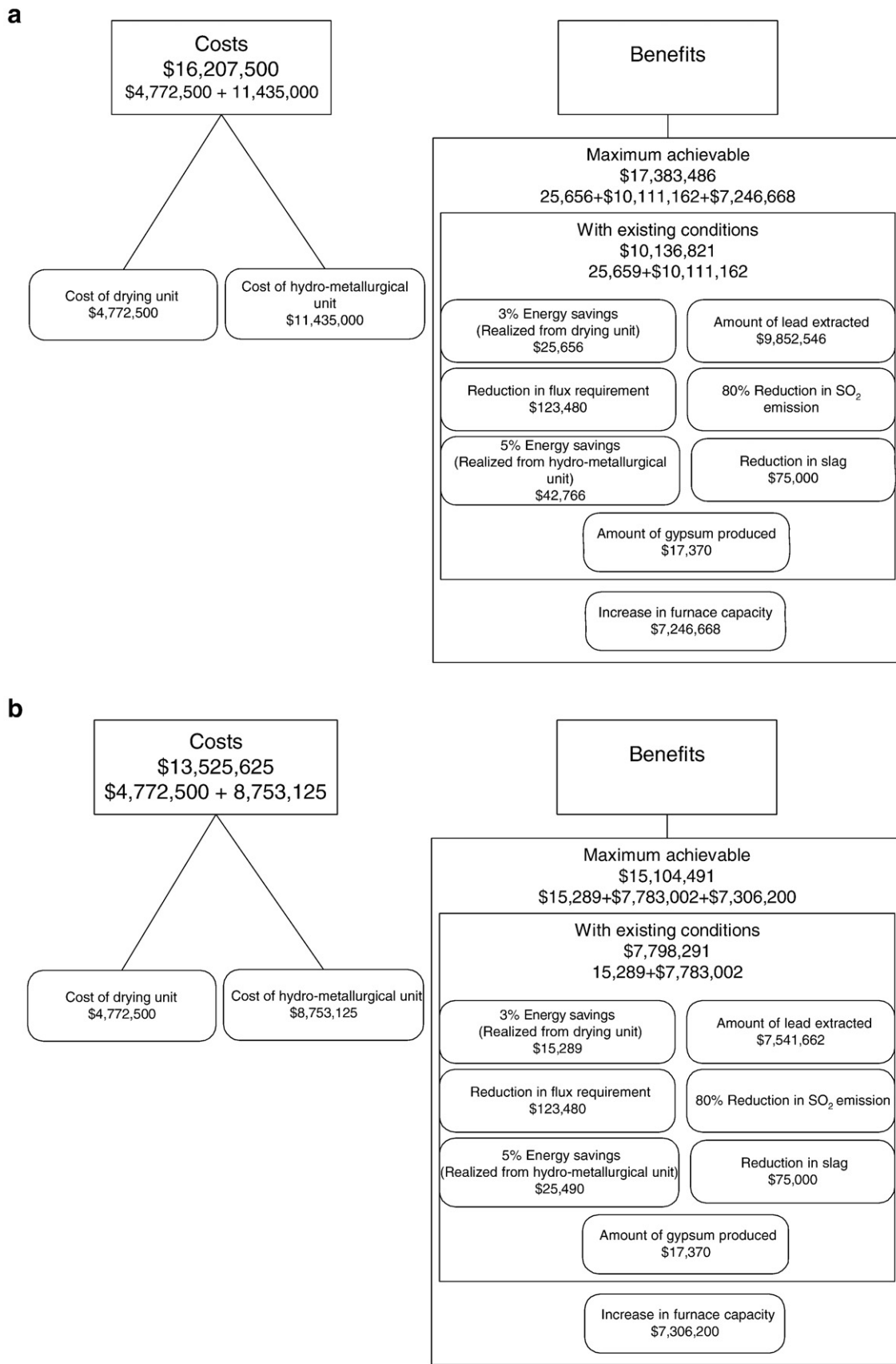
Footnote:

- Grinding of battery to separate plastic, electrolyte and lead plates:
  - Dust contaminated with lead and acid electrolyte
  - Particulate lead
  - Contaminated waste
- Transportation (in the event that a breaking facility is separate from a smelting facility):
  - Dust contaminated with lead particulate and lead compounds
  - Ground water contamination by transportation of wet charge
- Lead reduction in a rotary furnace:
  - Lead-contaminated scrap
  - Lead-contaminated dust (from filters)
  - Emission of SO<sub>2</sub>
  - Emission of chlorinated compounds
  - Production of slag
- Separation of metallic lead from slag and refining:
  - Emission of lead vapors
  - Emission of SO<sub>2</sub>
  - Production and removal of fine, dry dust with high percentage of lead and other metals
  - Release of chlorine gas (Cl<sub>2</sub>)
- Other sources:
  - Dust from storage and handling of concentrates; Leakage from roasters and smelters; Miscellaneous (0.7 t/year)



**Fig. 5. b.** Sources of emissions in hydro-metallurgical process.  
Footnote:

1. Grinding of battery to separate plastic, electrolyte and lead plates:
  - Dust contaminated with lead and acid electrolyte
  - Particulate lead
  - Contaminated waste
2. Transportation (in the event that a breaking facility is separate from extraction facility):
  - Dust contaminated with lead particulate and lead compounds
  - Ground water contamination by transportation of wet charge
3. Lead leaching:
  - Lead containing leachant seepage and contamination of soil in in-situ or dump leaching
  - Dust contaminated with lead while transporting pregnant solution
  - Acid mists (pressure leaching)
4. Electrolysis:
  - Spent acids and electrolytes
  - Acids in water from wet gas cleaning



**Costs**  
\$13,525,625  
\$4,772,500 + 8,753,125

Cost of drying unit  
\$4,772,500

Cost of hydro-metallurgical unit  
\$8,753,125

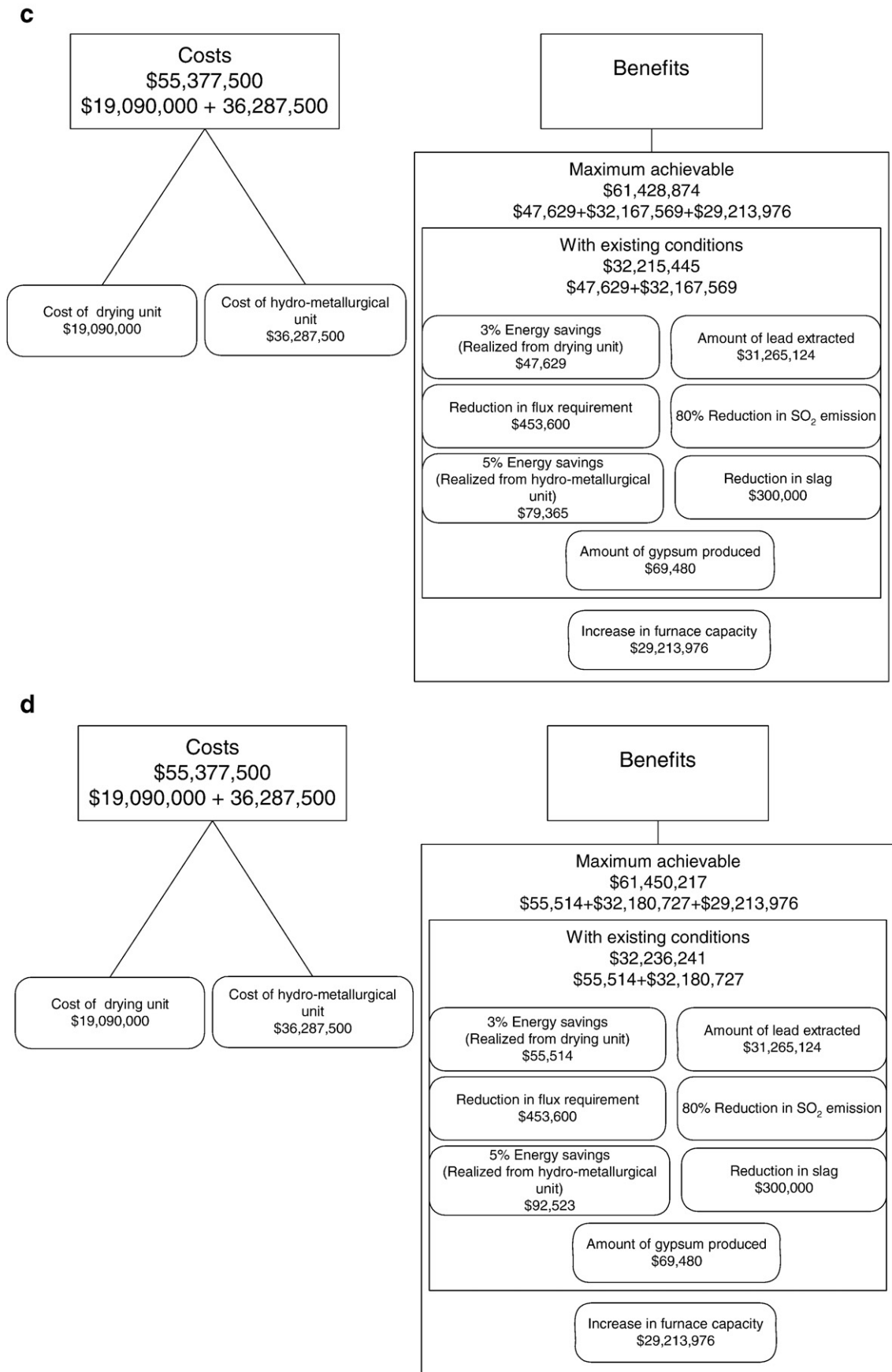
**Benefits**

**Maximum achievable**  
\$15,104,491  
\$15,289+\$7,783,002+\$7,306,200

**With existing conditions**  
\$7,798,291  
15,289+\$7,783,002

<p>3% Energy savings (Realized from drying unit) \$15,289</p>	<p>Amount of lead extracted \$7,541,662</p>
<p>Reduction in flux requirement \$123,480</p>	<p>80% Reduction in SO<sub>2</sub> emission</p>
<p>5% Energy savings (Realized from hydro-metallurgical unit) \$25,490</p>	<p>Reduction in slag \$75,000</p>
<p>Amount of gypsum produced \$17,370</p>	
<p>Increase in furnace capacity \$7,306,200</p>	

**Fig. 6.** a. Summary of costs and benefits for small smelter – blast furnace. b. Summary of costs and benefits for small smelter – electric furnace. c. Summary of costs and benefits for medium smelter – rotary furnace. d. Summary of costs and benefits for medium smelter – reverberatory/blast furnace set-up. e. Summary of costs and benefits for medium smelter – reverberatory/electric furnace set-up. f. Summary of costs and benefits for large smelter – rotary furnace. g. Summary of costs and benefits for large smelter – reverberatory/blast furnace set-up. h. Summary of costs and benefits for large smelter – reverberatory/electric furnace set-up.



**Costs**  
\$55,377,500  
\$19,090,000 + 36,287,500

Cost of drying unit  
\$19,090,000

Cost of hydro-metallurgical unit  
\$36,287,500

**Benefits**

Maximum achievable  
\$61,450,217  
\$55,514+\$32,180,727+\$29,213,976

With existing conditions  
\$32,236,241  
\$55,514+\$32,180,727

3% Energy savings (Realized from drying unit) \$55,514	Amount of lead extracted \$31,265,124
Reduction in flux requirement \$453,600	80% Reduction in SO <sub>2</sub> emission
5% Energy savings (Realized from hydro-metallurgical unit) \$92,523	Reduction in slag \$300,000

Amount of gypsum produced  
\$69,480

Increase in furnace capacity  
\$29,213,976

Fig. 6 (continued).

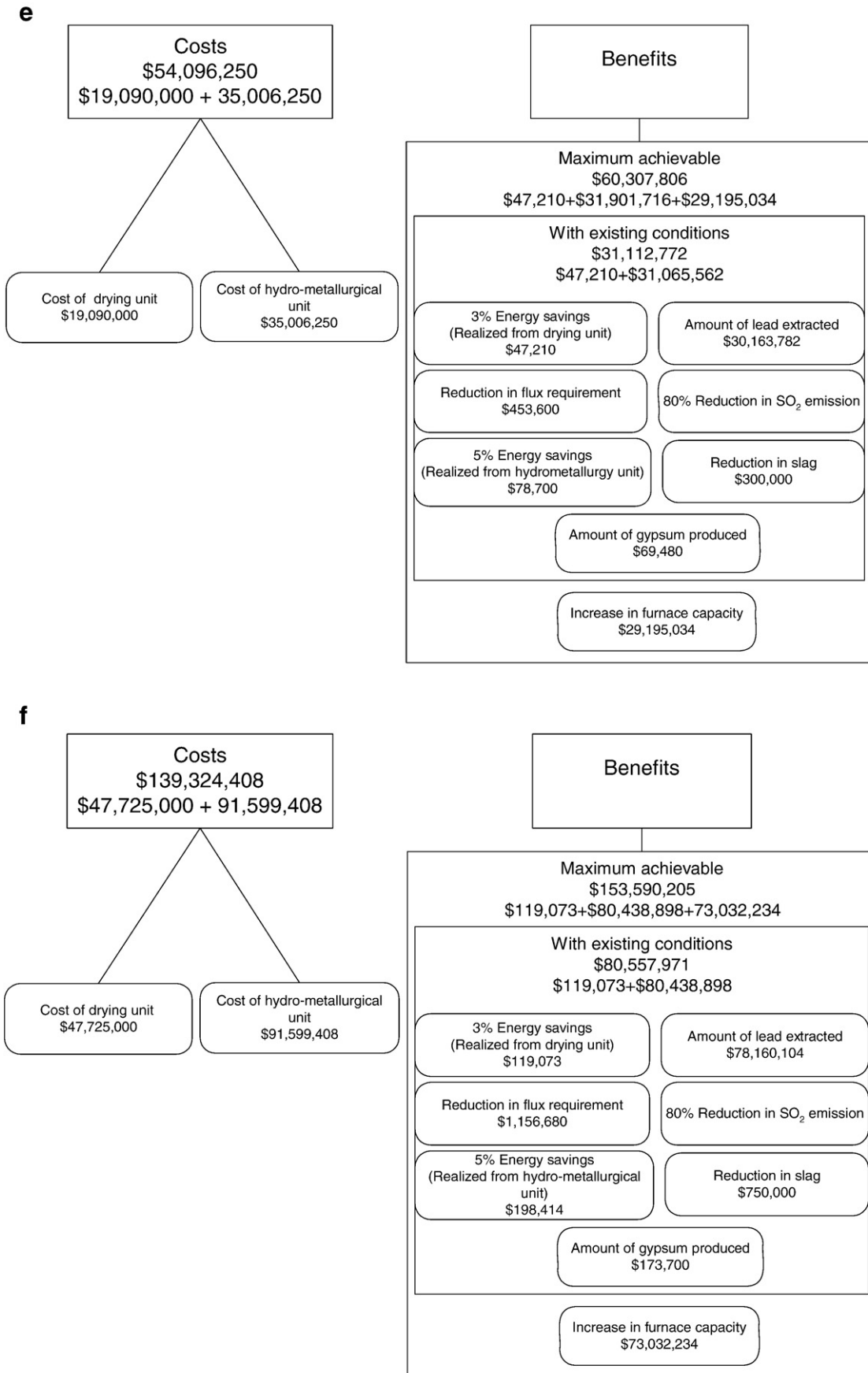


Fig. 6 (continued).



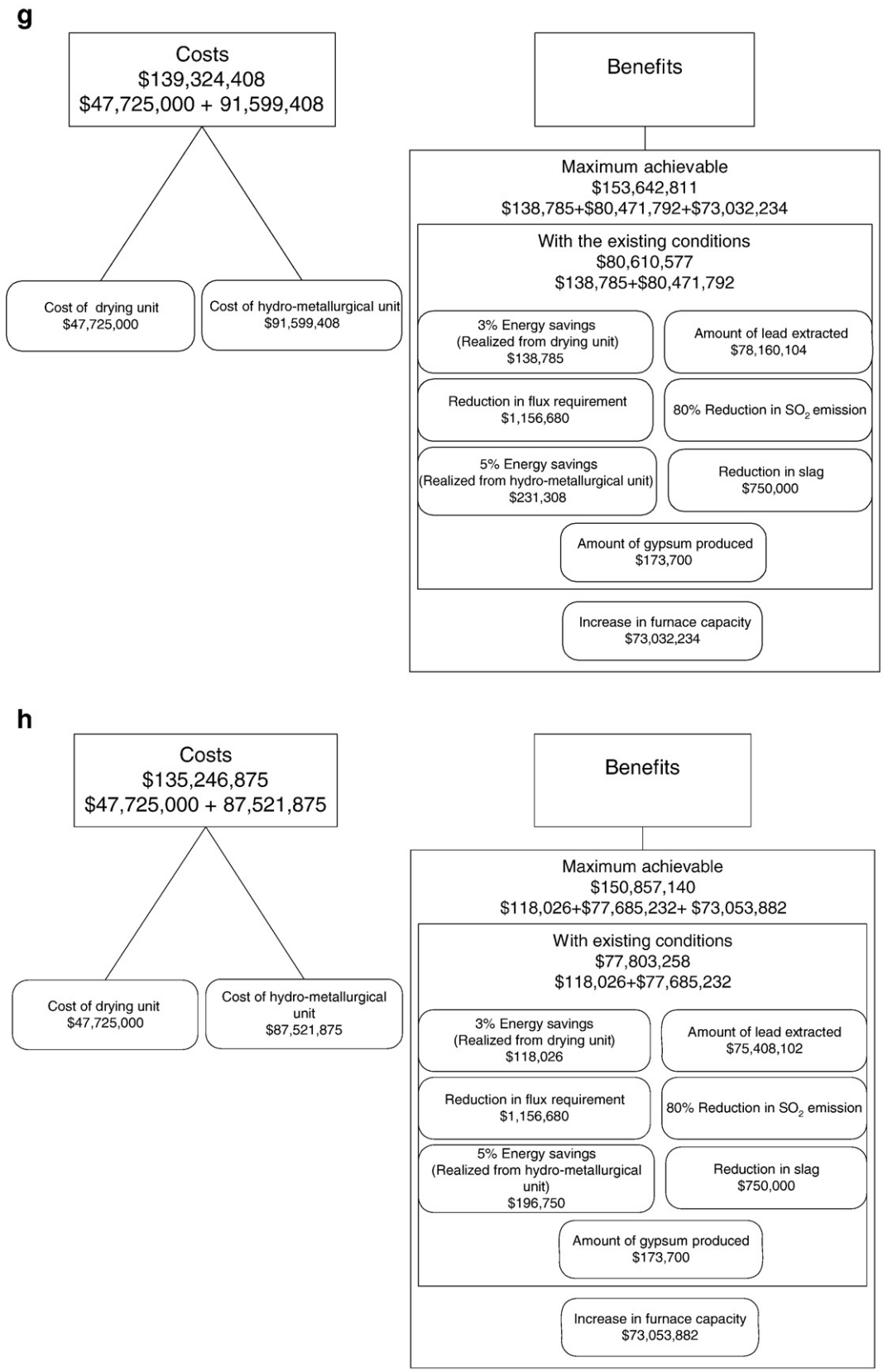


Fig. 6 (continued).

It was assumed that existing in-processing smelting technologies are kept as is for economic reasons. With this in mind, the costs and benefits are outlined for both blast and electric furnaces (small

smelters with a capacity of 10,000 t), and rotary, reverberatory/blast and reverberatory/electric furnaces (medium and large smelters with capacities of 40,000 and 100,000 t, respectively).

Fig. 6 shows a summary of the costs and benefits of the drying/roasting and hydro-metallurgical units for different types and combinations of in-processing smelting technologies. The costs represent the one-time capital investment in improved technologies and practices. On the other hand, the benefits are presented on an annual basis for: (a) increases in refined lead production and creation of gypsum as secondary products accrued only via the hydro-metallurgical unit; (b) energy savings from both units; and (c) reduction in flux usage due to re-routing of battery paste directly to the hydro-metallurgical unit as well as significant reduction in environmental emissions as evidenced by SO<sub>2</sub> and slag removal. For small smelters, the benefits are higher for existing blast furnace set-ups because their efficiency is lower (91%) than that of electric furnaces (99%). Therefore, the full benefits of the hydro-metallurgical unit are realized for the blast furnace. Comparable benefits are achieved for different combinations of high temperature furnaces for medium and large smelters because of the comparable efficiencies of existing furnace set-ups.

#### 4.3. Options for integrated environmental solutions for secondary lead smelters

Appendix C provides an analysis of the different options in terms of costs and benefits for pre-processing technologies and practices. There are three pre-processing technologies and practices which can be adopted by US secondary lead smelters without significant changes. These include: (a) drying feed material prior to entry into high temperature furnace, (b) desulfurization of battery paste and slag, and (c) hydro-metallurgical processing of battery paste and slag. Air- and hydro-separation are the choices for physical separation or presorting lead scrap. The selection of presorting methods is dependent on the smelter's acceptance of its raw materials. The processing of a mix of lead-containing materials (e.g. printed circuit boards in addition to LAB) can benefit from air separation units for feed enrichment. Finally, pollution control technologies for air emissions and waste water treatments are mature methods and there is a wide selection to choose from.

Table 1 provides a comparative assessment of different bundles of pre-processing pollution prevention technologies used to improve the performance of existing in-processing smelting technologies. The following observations can be made from this table.

- A drying unit is almost required in any bundle because it significantly reduces the energy requirements of high temperature furnace via removal of moisture and pre-heating the furnace charge.
- When added to an existing pyro-metallurgical smelting operation, a hydro-metallurgical unit significantly increases the metal recovery efficiency by extracting the metal content lost in slag and sludge generated from other pollution control devices.
- Although the rate of reduction in environmental air emissions, particularly SO<sub>2</sub>, is almost the same for both hydro-metallurgical and desulfurization methods, hydro-metallurgical methods use less energy than desulfurization units. In essence, pyro-metallurgical

techniques require further processing of desulfurized paste, hence, higher energy requirements.

- The reduction in slag generated through the use of desulfurization or hydro-metallurgical units is attributed to the reduction in flux required to extract pure lead from sulfurized lead.

In light of the above, it appears that a bundle consisting of dried and hydro-metallurgical units considerably enhance the performance of existing pyro-metallurgical-based smelting plants from the standpoint of production, energy/material savings, and environmental emission reduction. Plants with added desulfurized units (see Fig. 2d) will achieve very high performance by adding the hydro-metallurgical unit. For small smelters, this option will close the gaps between blast and electric furnaces. For medium to large smelters, this option provides the best performance to a rotary furnace or a combination of reverberatory and electric/blast furnaces.

## 5. Discussion

In recent years, sustainable industries determined that conventional end-of-pipe environmental systems are not effective at damage remediation and are costly to operate and maintain (Hilson, 2000). It was concluded that the solution to these problems is to replace the conventional end-of-pipe equipment with cleaner technologies (i.e. equipment that emits little or no hazardous material or that tackles pollution at the source rather than after it is discharged) and to implement cleaner production practices as part of daily business operations. With the above in mind, the research reported herein deals with lead which makes up the largest hazardous waste in the U.S. and still presents a significant source of pollutants (Gearhart et al., 2003). In light of recent declining rates for metal recovery in the LAB product lifecycle in the US market (Genaidy et al., 2008), the focus of this study was to identify integrated environmental strategies to increase lead recycling, process efficiency and recovery in order to improve human and environmental health as well as the bottom line of secondary lead smelters, LAB and other lead product industries.

Typically, a secondary smelting operation consists of three stages: pre-, in- and post-processing. The in-processing stage is at the core of the smelting operation. From a smelter perspective, we assumed that one cannot replace the in-processing equipment given the high capital investment. Therefore, we concentrated our efforts on improving the operation at the pre-processing stage. An evidence-based methodology was deployed through a systematic review and appraisal of the scientific literature with an emphasis on solutions that can lead to recovery and recycling of the largest quantities of lead currently being disposed of as waste subject to technical and economic viability and strong industry interest. A comprehensive search of electronic databases and general purpose search engines was conducted to retrieve relevant articles and reports to the present research. The required data and information was extracted for the purpose of improving the operation of secondary lead smelters. Following data search and

**Table 1**  
Summary of implementation priorities of suggested bundles.

Furnace type	Pre-processing improvement practices			
	Drying unit only	Drying + desulfurization units	Drying + hydro-metallurgical units	Drying + desulfurization + hydro-metallurgical units
Blast (small smelters)	Low	Somewhat Moderate	Very High	Very High
Electric (small)	Low	Somewhat Moderate	High	Somewhat Very High
Rotary medium to large)	Low	Somewhat Moderate	High	Somewhat Very High
Reverberatory + blast (medium to large)	Low	Somewhat Moderate	High	Somewhat Very High
Reverberatory + electric (medium to large)	Low	Somewhat Moderate	High	Somewhat Very high

Appendix C shows the details of rank ordering of different bundles of environmental improvement technologies.

extraction, the description of evidence was presented for current practices and technologies used by US smelters as well as improved practices and technologies at the pre-, in- and post-processing stages.

Indeed, primary barriers to implementing improved environmental technologies and practices are economic factors (Hilson, 2000). Thus, an algorithm was developed to assess the economic and environmental performance of suggested bundles of improved technologies and practices. The assessment criteria were based on capital cost and benefits (i.e. production increases and generation of by-products, savings in energy and flux materials, and reduction in SO<sub>2</sub> and slag). These criteria were formulated through the use of a multi-step procedure incorporating quantitative and qualitative evaluations. In essence, these bundles were rank ordered on the basis of the assessment algorithm in terms of potential improved environmental and economic performance as a function of smelter size (small, medium, large) and existing furnace type (reverberatory, blast, electric, and rotary high temperature furnaces). We compared four types of bundles for inclusion at the pre-processing stage, that is, (a) drying unit only, (b) drying and desulfurization units, (c) drying and hydro-metallurgical units, and (d) drying, desulfurization and hydro-metallurgical units. Typical practices in secondary lead smelting operations involve drying units at the pre-processing stage and to a lesser extent both drying and desulfurization units. As documented in Table 1, the drying unit added little improvement from both economic and environmental standpoint. The desulfurization unit contributed marginal improvement. The addition of hydro-metallurgical unit to drying significantly improved the bundle performance to a 'high' level for different furnace set-ups across all sizes of smelters and even to 'very high' level for the blast furnace set-up for small smelters.

As a significant cleaner technology, a hydro-metallurgical unit is highly efficient and produces significantly less amounts of emissions compared to pyro-metallurgical systems. The use of a hydro-metallurgical system results in increased lead production, energy/flux savings as well as significant reduction in SO<sub>2</sub> and slag. This was evident for all smelter sizes and different types of high temperature furnace set-ups. The addition of desulfurization unit to the drying/hydro-metallurgical combination marginally increased the performance to 'somewhat very high' (except for a blast furnace set-up for a

small smelter). Therefore, it appears that the adoption of cleaner technologies at the pre-processing stage in secondary smelter operations can significantly improve the smelter performance from both economic and environmental perspectives. Consequently, future research should pursue these options among U.S. secondary lead smelters.

The limitations of this study should be acknowledged. First, the knowledge presented in this study is based on an evidence-based methodology. Although it is largely relying on the scientific literature and the experience of the authors, there is a need to further validate the findings with stakeholders in the universe of US secondary lead smelters. Second, we presented a model to integrate the criteria of cost and benefits in a single sustainable index. Although the outcomes of this index are consistent with the general views in the published literature, further validation is required on scientific grounds. Perhaps additional elements should be added to capital cost such as operating costs, an issue that will be examined in future research. Nonetheless, it seems a promising approach for managing complexity and comparing the performance of integrated environmental solutions for different options.

## 6. Concluding remarks

One can deduce from the findings of this study that it is technically and economically feasible to implement integrated environmental solutions to increase lead recovery and recycling among US smelters. The working example presented in this research can be confirmed with US stakeholders and form the basis for implementable solutions in the lead smelter and product industries to help reverse the overall trend of declining life-cycle recycling rates.

## Acknowledgments

This study was supported by a grant from the US Environmental Protection Agency. This paper has not been subjected to the Agency's internal review. Therefore, the research results presented herein do not, necessarily, reflect the views of the Agency or its policies. The authors are indebted for the helpful comments made by the anonymous reviewers.

## Appendix A. Description of evidence for in-, pre- and post- processing technologies for secondary lead smelters

**Table A1**

Description of evidence for characteristics of in-processing technologies in US recycling plants.

Type of technology	Type of furnace	Technology description	Furnace efficiency	Cost-effectiveness (energy expenditure) (GJ/t of lead)	Effectiveness (purity of metal recovered)
Pyro-metallurgical techniques	Blast furnace	• Extracting lead via reaction of lead scrap and coke, and subsequent oxidization <sup>1</sup>	91–94% <sup>a</sup>	5 –11.86 <sup>b</sup>	82–94% depending on charge and reaction gases <sup>b</sup>
	Electric furnace	• Extracting lead via melting and reaction of lead scrap, fluxes and coke • An electric arc produced between two electrodes is used to heat the mix to the reaction temperature <sup>b</sup>	>99% <sup>b</sup>	2.98 <sup>c</sup>	>99.5% <sup>b</sup>
	Rotary furnace	• Extracting lead via reaction of lead scrap and coke, and subsequent oxidization of coke with introduction of fuel gases through tuyeres or burners <sup>d</sup>	98% <sup>e</sup>	2.32 <sup>f</sup>	94–98% <sup>e</sup>
	Reverberatory furnace	• Extracting lead by reaction of lead scrap and flux by introduction of reaction gases, fuel and fine materials through top or wall mounted tuyeres <sup>f</sup>	75–80% <sup>d</sup>	2.13 – 2.47 <sup>g</sup>	92–96% <sup>f</sup>

Cost effectiveness is calculated as the energy spent per ton of metal recovered.

Payback period was not documented for in-processing technologies because it is assumed that environmental improvement will only be applied to pre- and post-processing technologies to enhance the performance of in-processing technologies.

<sup>a</sup> From Ryshenkov et al. (2006).

<sup>b</sup> From Ziebig and Stanek (2006).

<sup>c</sup> From Akihiko (2004).

<sup>d</sup> From USEPA (1998).

<sup>e</sup> From Zhang et al. (2008).

<sup>f</sup> From Rabah and Barakat (2001).

<sup>g</sup> From Akihiko (2004).

**Table A2**  
Description of evidence for characteristics of improved in-processing smelting technologies.

Type of technology	Type of process	Technology description	Efficiency (process efficiency)	Cost-effectiveness (energy expenditure) (GJ/t of lead)	Effectiveness (purity of metal recovered)
Hydro-metallurgical techniques	LEDCLOR	• Metal content is leached into the solvent (diluted ferric chloride) and extracted by electrowinning <sup>a</sup>	99.4–99.7% <sup>a</sup>	1.8 <sup>b</sup>	97–99% <sup>a</sup>
	Electrowinning acid	• Metal content is leached into the solvent and extracted by electrowinning <sup>b</sup>	98–99.5% <sup>b</sup>	1.8–3.28 <sup>b</sup>	99.98–99.99% <sup>b</sup>
	Electrowinning basic	• Metal content is leached into basic solvent and extracted by electrowinning <sup>b</sup>	85–98% <sup>b</sup>	1.4–1.8 <sup>b</sup>	99.98–99.99% <sup>b</sup>
	PLINT	• Intermediates from the electrowinning process (lead hydroxide) are used as the feed to the kettle (pyro-metallurgy) <sup>c</sup>	99.5% <sup>c</sup>	1.8 – 2.16 <sup>d</sup>	99.99% <sup>c</sup>
Pyro-metallurgical techniques	Ausmelt	• Technology is based on top entry into lance system, delivering combustion gases, fuel and process air below the surface of liquid slag bath <sup>e</sup>	95% <sup>f</sup>	0.36–1.44 <sup>f</sup>	98% <sup>f</sup>
	CX system	• Use of desulphurization and rotary furnace to extract lead from batteries <sup>g</sup>	86.50% <sup>g</sup>	0.61 <sup>h</sup>	99.99% <sup>i</sup>
	ISASMELT	• Technology is based on top entry into lance system, delivering combustion gases, fuel and process air below the surface of liquid slag bath <sup>l</sup>	> 99% <sup>j</sup>	0.47 <sup>k</sup>	Soft lead 99.8%, Hard lead 79.2% <sup>l</sup>
	KIVCET	• Based on combination of charge roasting and smelting technologies in pulverized condition via use of oxygen and electrosmelting <sup>l</sup>	98–98.3% <sup>l</sup>	1.33 <sup>m</sup>	94–96.5 <sup>l</sup>
	Top blown rotary furnace	• Based on rotating tilted furnace with introduction (blowing) of oxygen and fuel gases via a lance <sup>n</sup>	98% <sup>n</sup>	1.93 <sup>o</sup>	94–98% <sup>p</sup>

<sup>a</sup> From Andrews et al. (2000).

<sup>b</sup> From Ferracin et al. (2002).

<sup>c</sup> From Frias et al. (2002).

<sup>d</sup> From Agrawal et al. (2004).

<sup>e</sup> From Baldock and Short (2000).

<sup>f</sup> From Hughes (2000).

<sup>g</sup> From Errington et al. (2005).

<sup>h</sup> From Engitec STE process (2008b).

<sup>i</sup> From Arthur and Edwards (2003).

<sup>j</sup> From Ramus and Hawkins (1993).

<sup>k</sup> From Xstrata (2006).

<sup>l</sup> From Agrawal et al. (2004).

<sup>m</sup> From Akihiko (2004).

<sup>n</sup> From Ryzhenkov et al. (2006).

<sup>o</sup> From Rabah and Barakat (2001).

<sup>p</sup> From Ziebig and Stanek (2006).

- Payback period for improved in-processing technologies varies with the designed production capacity.
- Proprietary technologies, which are acknowledged in the scientific literature, are listed in the table. These technologies are improvement over existing technologies listed in Table A1. LEDCLOR and PLINT technologies are the most widely accepted proprietary hydro-metallurgical technologies in the metal extraction industry. Electrowinning technologies have been implemented with some variations among smelters. Ausmelt, CX System, ISASMELT and KIVCET are improved proprietary pyro-metallurgical technologies which are variations of existing technologies. Top-blown rotary furnace is an improved technology currently in use in the US smelting industry.

**Table A3**  
Description of evidence for characteristics of pre-processing US secondary lead smelting technologies.

Type of technology	Type of process	Technology description	Efficiency	Cost-effectiveness (energy savings/ expenditure)	Payback period (years)	Environmental benefits	Productivity increase
Pre-processing	Battery breaking and hydro-separation	• Scrapped batteries are crushed and metal components and plastic casing parts are density separated in water	95% <sup>a</sup>	Not available	3 <sup>b</sup>	Reduction in furnace slag output <sup>c</sup>	None
	Air separation	• Scrapped lead containing parts are crushed and metal components are separated from other waste using compressed air	Not available	Not available	Not available	Reduction in furnace slag output <sup>c</sup>	None
	Roasting/ drying	• Separated lead metal scrap is dried by passing hot gases produced either from furnace operations or separately	85% <sup>d</sup>	3% savings <sup>e</sup>	1 <sup>e</sup>	None	None
	Desulfurization	• Battery paste separated during hydro-separation is desulfurized by mixing it with sodium carbonate	93% <sup>f</sup>	8–10% savings <sup>g</sup>	3 <sup>b</sup>	75–80% reduction in SO <sub>2</sub> emissions <sup>h</sup>	25–30% increase in smelter throughput <sup>h</sup>
	Hydro-metallurgical processing	• Pure lead is extracted from battery paste or sludge containing lead content by electro-winning process	98–99.5% <sup>i</sup>	10–12% savings <sup>j</sup>	3–4 <sup>j</sup>	> 80% in reduction in SO <sub>2</sub> emissions <sup>e</sup>	25–30% increase in smelter throughput <sup>h</sup>

<sup>a</sup> From Abrams et al. (1999).

<sup>b</sup> From Wolters et al. (2008).

<sup>c</sup> Reduction in furnace slag generated is estimated at  $\geq 10\%$ .

<sup>d</sup> From Warner et al. (2006).

<sup>e</sup> From Chakrabarti and Mitra (2005).

<sup>f</sup> From Lyakov et al. (2007).

<sup>g</sup> From Olympia Resource Limited (2005).

<sup>h</sup> From Missouri Department of Natural Resources Report (2005).

• Hydro-metallurgical processing is considered complementary to improve the performance of existing in-processing technology.

<sup>i</sup> From Ferracin et al. (2002).

<sup>j</sup> From the Environmental Technology Assessment Workshop Report (UNEP, 2000).

**Table A4**

Description of evidence for characteristics of pollution prevention and control technologies.

Type of control	Point of emission	Type of technology	Technology description	Efficiency	Cost-effectiveness (energy expenditure per volume of gas flow) (kWh/Nm <sup>3</sup> )	Payback period (years)	Effectiveness (contaminant concentration per volume of treated gas) (mg/Nm <sup>3</sup> )
Dust abatement	a,b,c,f,o,p	Hot electrostatic precipitator	• Particles are charged and subsequently separated mechanically from gas stream by vibrating the collection electrodes	> 99% <sup>a</sup>	1.27	3.5–4 <sup>b</sup>	< 5–15 <sup>a</sup>
		Wet electrostatic precipitator	• Particles are charged and separated from the gas stream. Settled dust is flushed out of the collection electrodes by spraying suitable solution	< 99% <sup>a</sup>	1.27	3.5–4 <sup>b</sup>	< 1–5 <sup>a</sup>
		Fabric or bag filters	• Particles are separated by passing gas through a series of fabric screens (bags)	> 99.5% <sup>a</sup>	1.5 * 10 <sup>-3</sup> – 4 * 10 <sup>-3</sup>	2 <sup>c</sup>	1–5 <sup>a</sup>
		Wet scrubbers	• Scrubbing liquid is sprayed on the gas passage path to wet the particles and collect them in wetting liquid	> 80–99% <sup>a</sup>	8.6 * 10 <sup>-3</sup>	< 1 <sup>d</sup>	4–50 <sup>a</sup>
		Cyclones	• Particles are separated by changing the direction of gas flow, thus, separating heavier particles	40% <sup>a</sup>	NA	1–3 <sup>e</sup>	100–300 <sup>a</sup>
		Ceramic filters	• Particles are separated by forcing the gas through a series of ceramic filter candles	99.50% <sup>a</sup>	1.5 * 10 <sup>-3</sup> – 4 * 10 <sup>-3</sup>	2–2.5 <sup>a</sup>	0.1–1 <sup>a</sup>
Gas burning	n	After burners	• The gas is heated to suitable temperature to oxidize or decompose excess/low concentration of hazardous gases	98% <sup>d</sup>	2.7 * 10 <sup>-4</sup> – 6 * 10 <sup>-4</sup>	1–2.2 <sup>d</sup>	< 5–15 <sup>a</sup>
Gas scrubbing systems	g,h,l,m	Wet scrubbing	• Scrubbing liquid is sprayed on the gas passage path. The gas is held in the scrubbing chamber till acceptable level of precipitation occurs. The gas molecules react with the media and precipitate or combine to form useful by-products	> 80–99% <sup>a</sup>	4.2 * 10 <sup>-4</sup>	< 1 <sup>d</sup>	< 50–200 <sup>1</sup>
		Dry and semidry scrubbing	• Gas is passed through scrubbing medium (solid or slurry) to capture the molecules in the medium	> 80–99% <sup>1</sup>	1.6 * 10 <sup>-4</sup>	< 1 <sup>4</sup>	< 50 – 200 <sup>a</sup>
Effluent (water) Treatment	E	<i>Process integrated measures</i>					
		Recycling	• Recirculation of effluent water in the process where it is generated	NA	NA	NA	NA
		Reuse	• Redirecting effluent water generated in one process for use in other processes	NA	NA	NA	NA
	J	<i>End-of-pipe measures</i>					
		Chemical precipitation	• Soluble metal ions are separated by adding reagents to form insoluble compounds and forcing them to precipitate in holding tanks	> 99.5% <sup>a</sup>	6.25	1.5–2 <sup>a</sup>	< 0.1 <sup>a</sup>
		Sedimentation	• Solid (heavier) particles are separated from effluent water by holding waste water in tanks and allowing solids to precipitate	Up to 99% <sup>a</sup>	6.25	1–2 <sup>a</sup>	< 0.1 <sup>a</sup>
		Filtration	• Effluent water is passed through filter media (media bed) to separate toxic substances before releasing into holding tanks or water streams	Up to 99% <sup>a</sup>	6.25	1–2 <sup>a</sup>	< 0.1 <sup>a</sup>
		Flotation	• Light density effluent particles are separated from effluent water by holding waste water in tanks and injecting (bubbling) air in water forcing material to float	Up to 99% <sup>a</sup>	6.25	1–1.5 <sup>a</sup>	< 0.1 <sup>a</sup>
Electrolysis		• Effluent water is stored in electrolytic cell and metals are separated by applying a potential between electrodes	> 99.5% <sup>a</sup>	6.25	2–3 <sup>a</sup>	< 0.1 <sup>a</sup>	
	Ion exchange	• Effluent water is passed through a column matrix of ion exchange resins to absorb selective metal ions	> 99.5% <sup>a</sup>	6.25	2–2.5 <sup>a</sup>	< 0.1 <sup>a</sup>	

<sup>a</sup> From the European Commission Report (2007).<sup>b</sup> From PT Seman Pandang (2006).<sup>c</sup> From Chakrabarti and Mitra (2005).<sup>d</sup> From Kenson (2005).<sup>e</sup> From Saman and Nutter (1994).

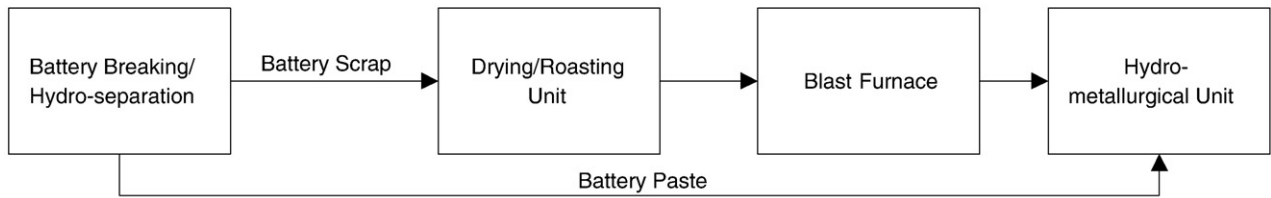
• NA – not applicable.

• Please consult Fig. 4a for points of emission in pyro-metallurgical-based smelting process.

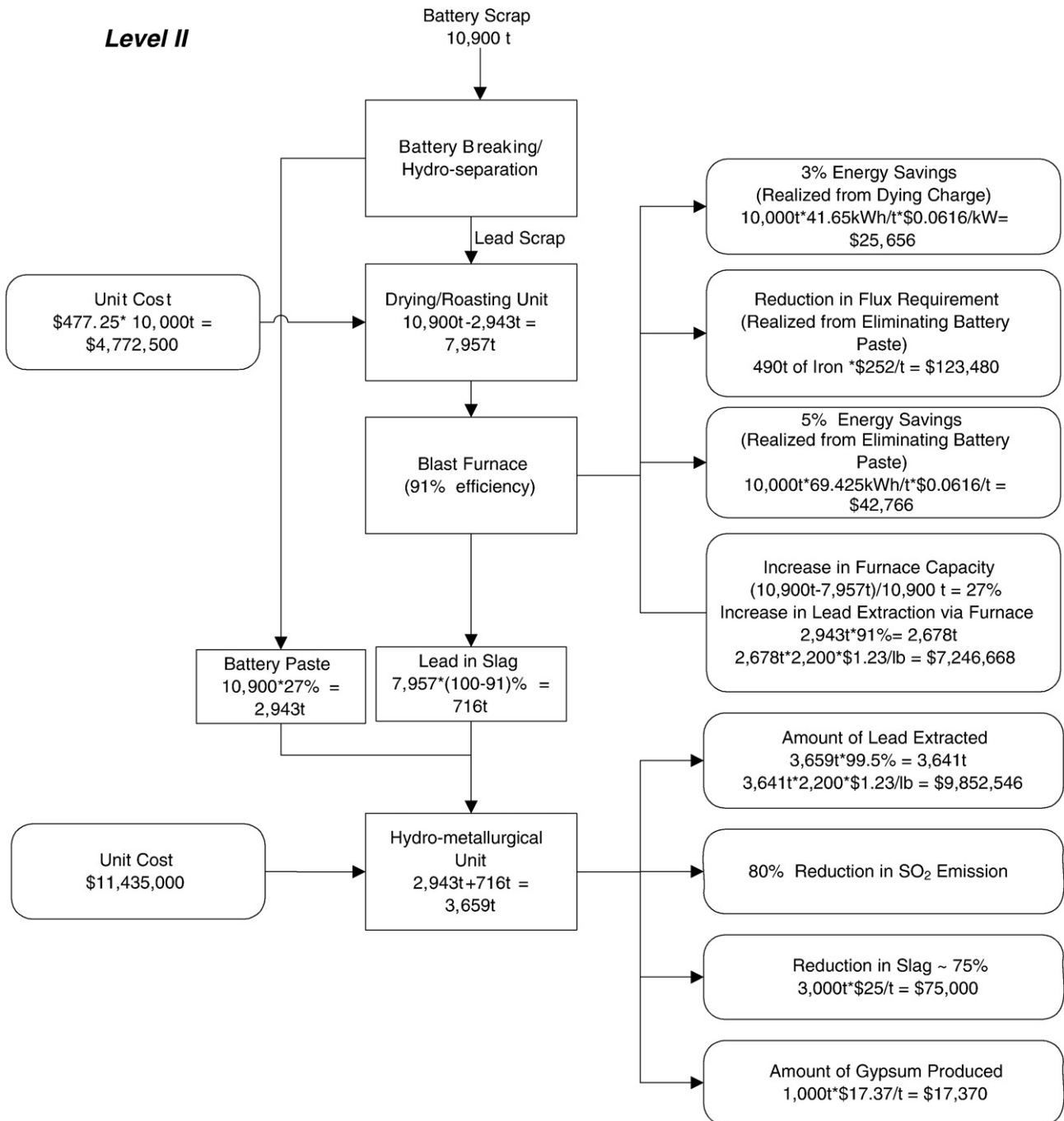
• The values obtained for cost-effectiveness were extracted from the European Commission Report (2007).

**Appendix B. Environmental improvement in lead smelting practices and technologies**

**Level I**



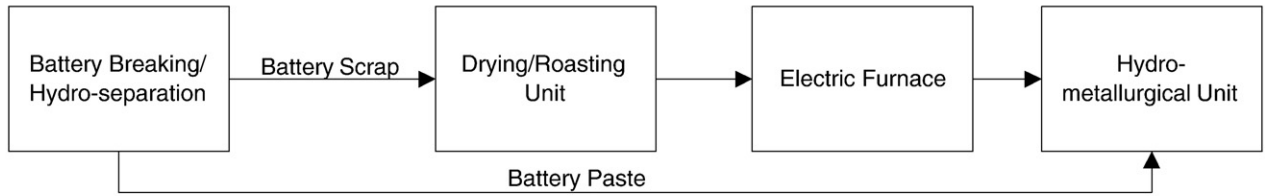
**Level II**



**Fig. B1.** Improvement for blast furnace – small smelter (10,000 t/year).



**Level I**



**Level II**

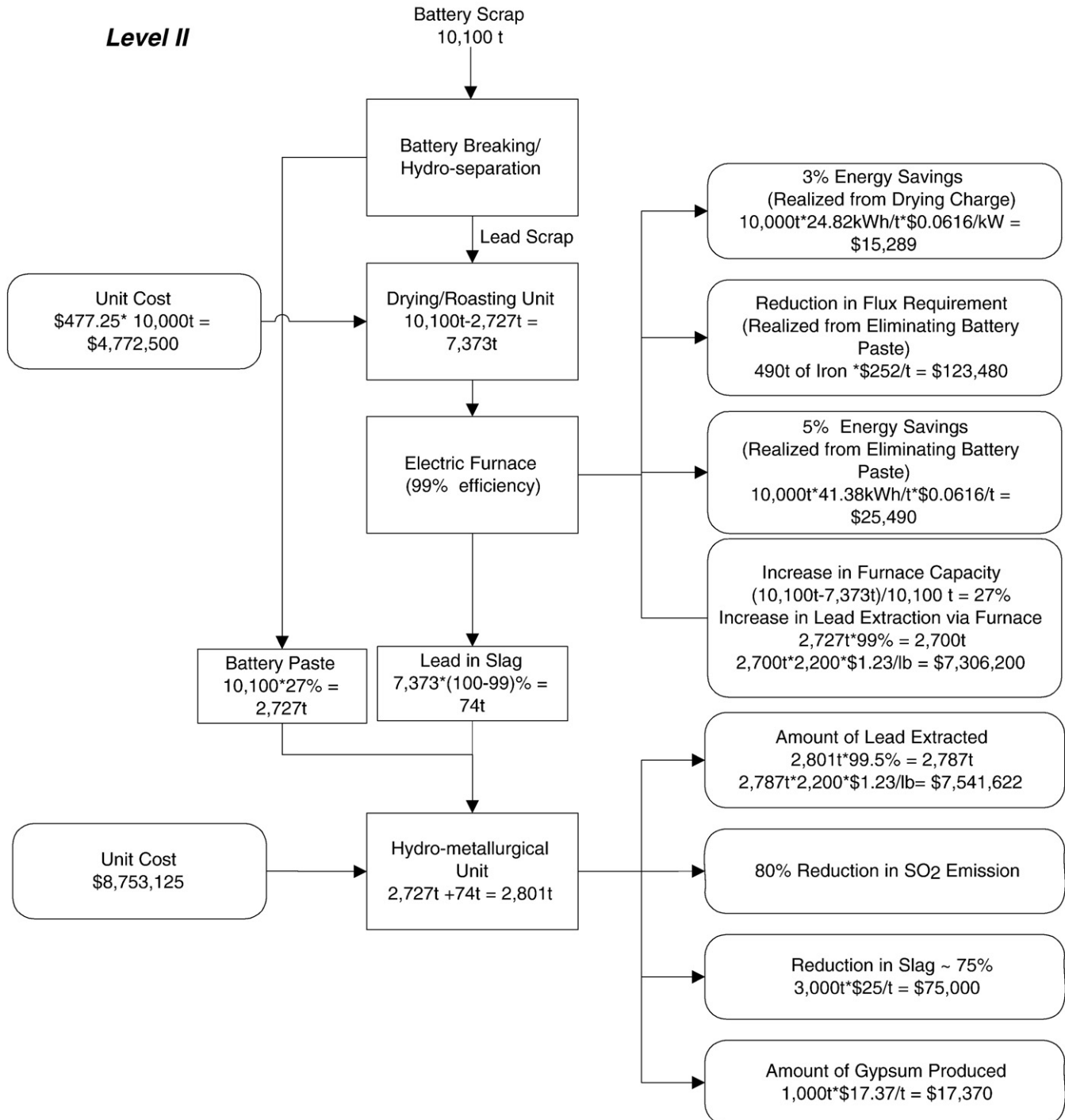
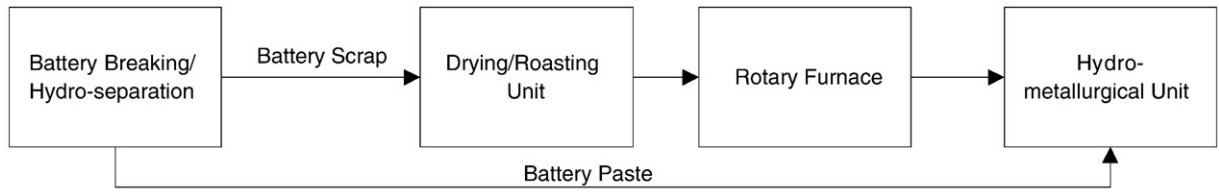


Fig. B2. Improvement for electric furnace – small smelter (10,000 t/year).

**Level I**



**Level II**

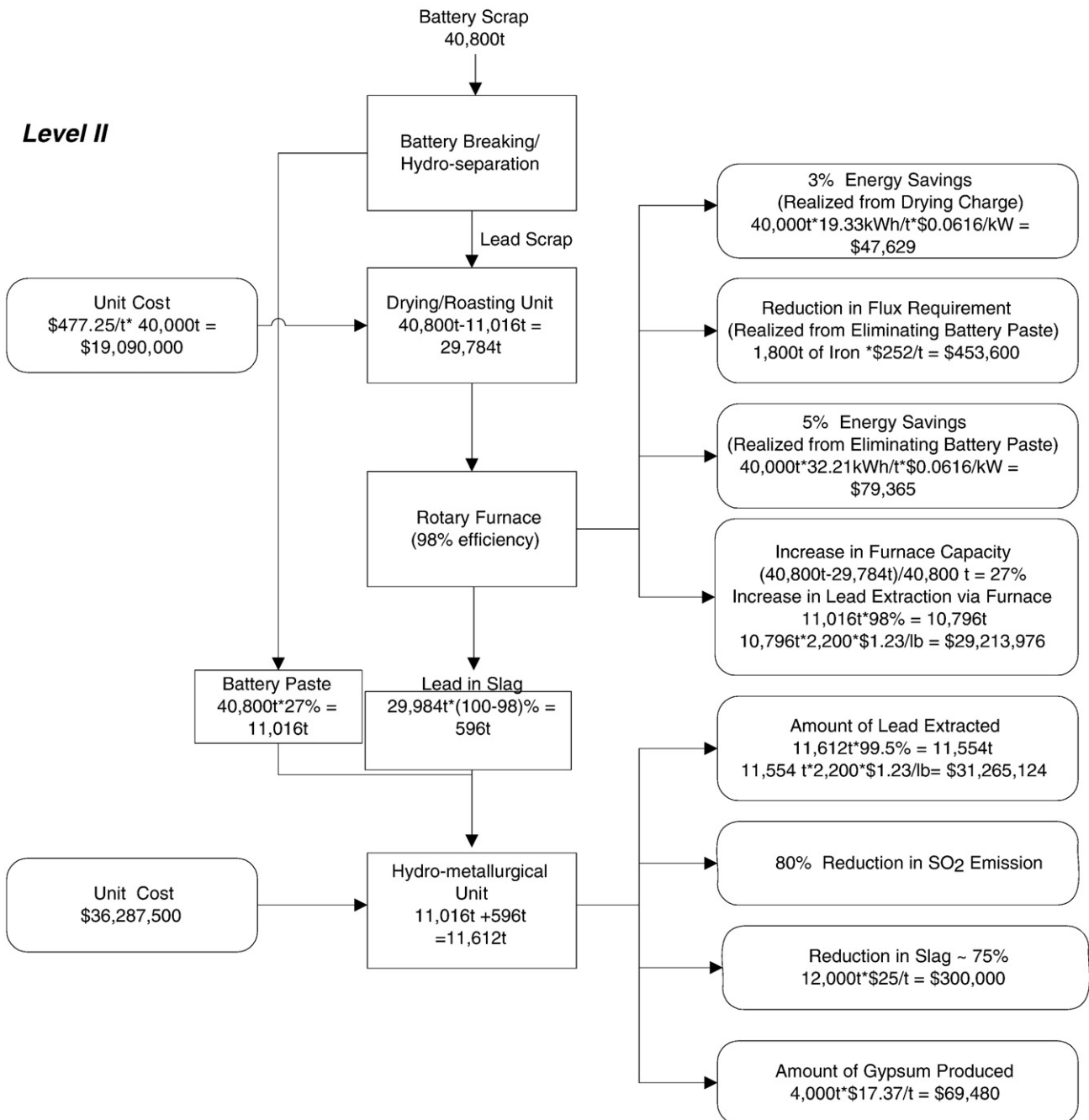
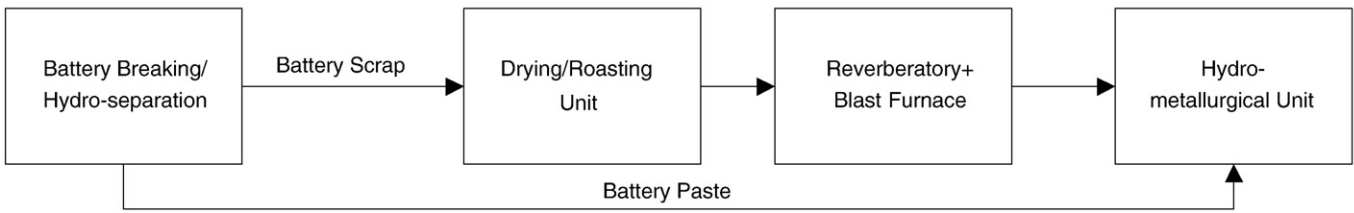


Fig. B3. Rotary furnace – medium smelter (40,000 t/year).

**Level I**



**Level II**

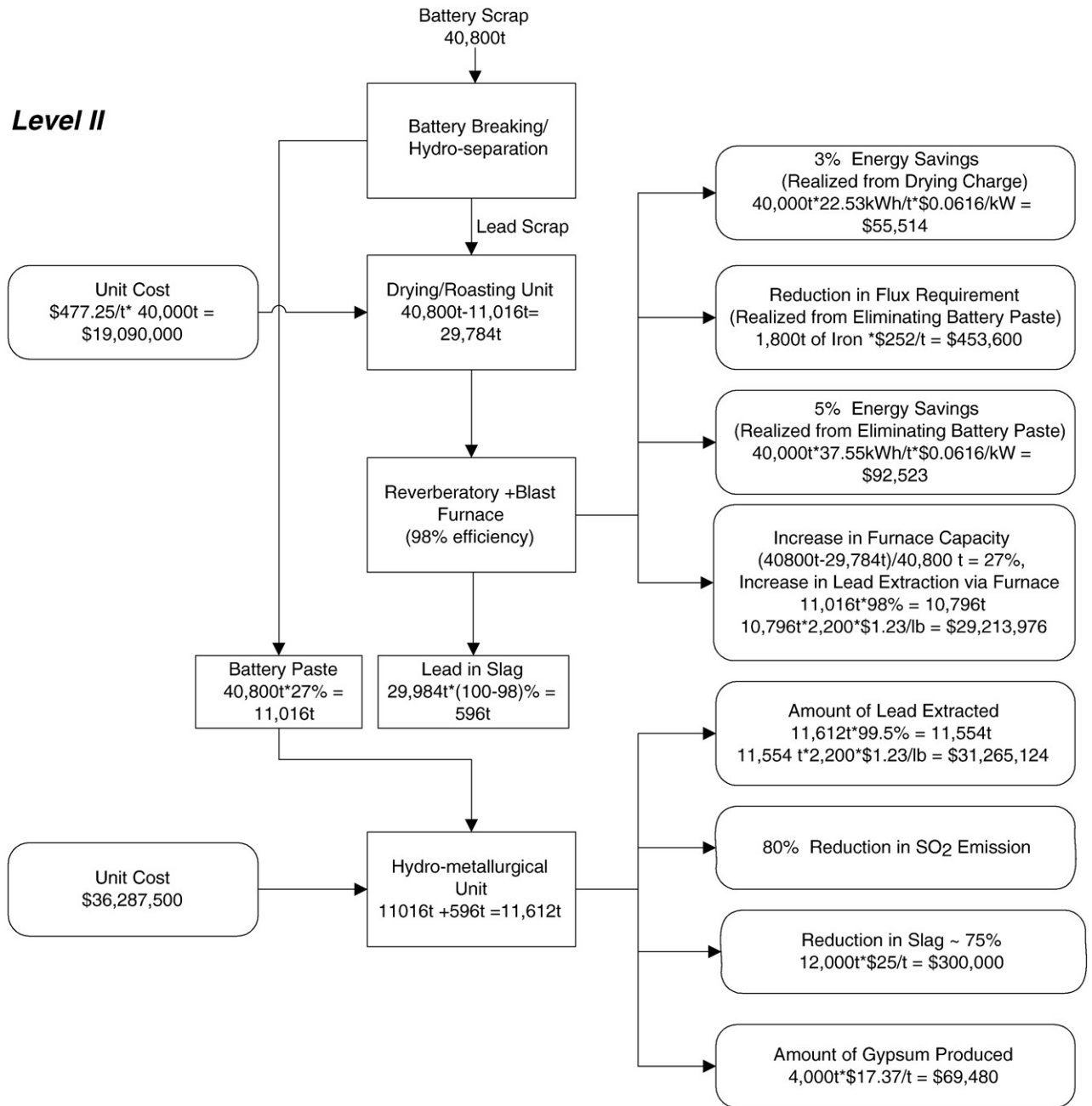
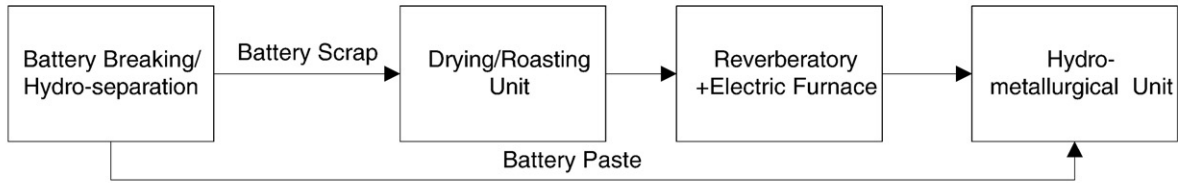
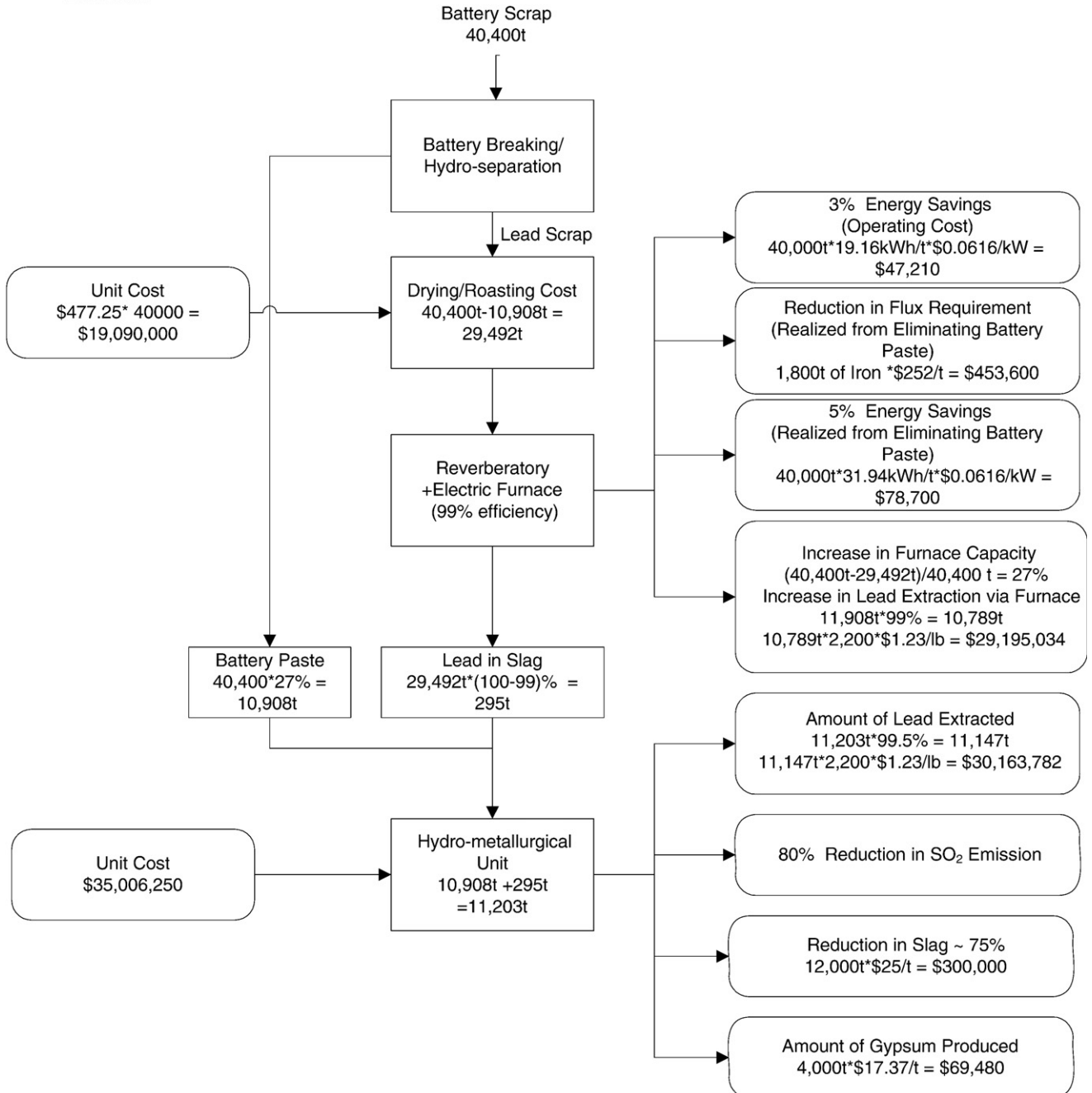


Fig. B4. Reverberatory and blast furnaces – medium smelter (40,000 t/year).

**Level I**

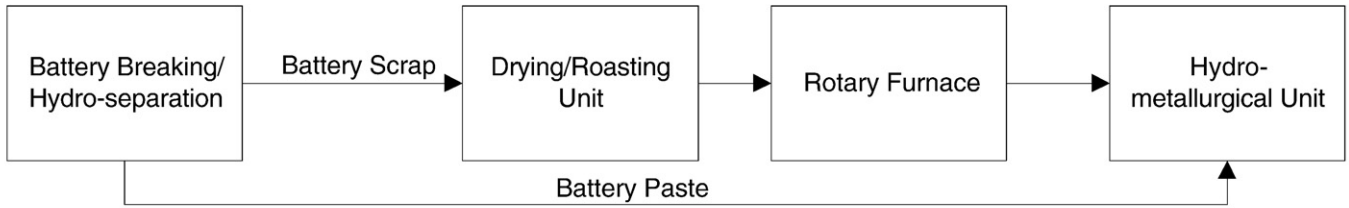


**Level II**



**Fig. B5.** Reverberatory and electric furnaces – medium smelter (40,000 t/year).

**Level I**



**Level II**

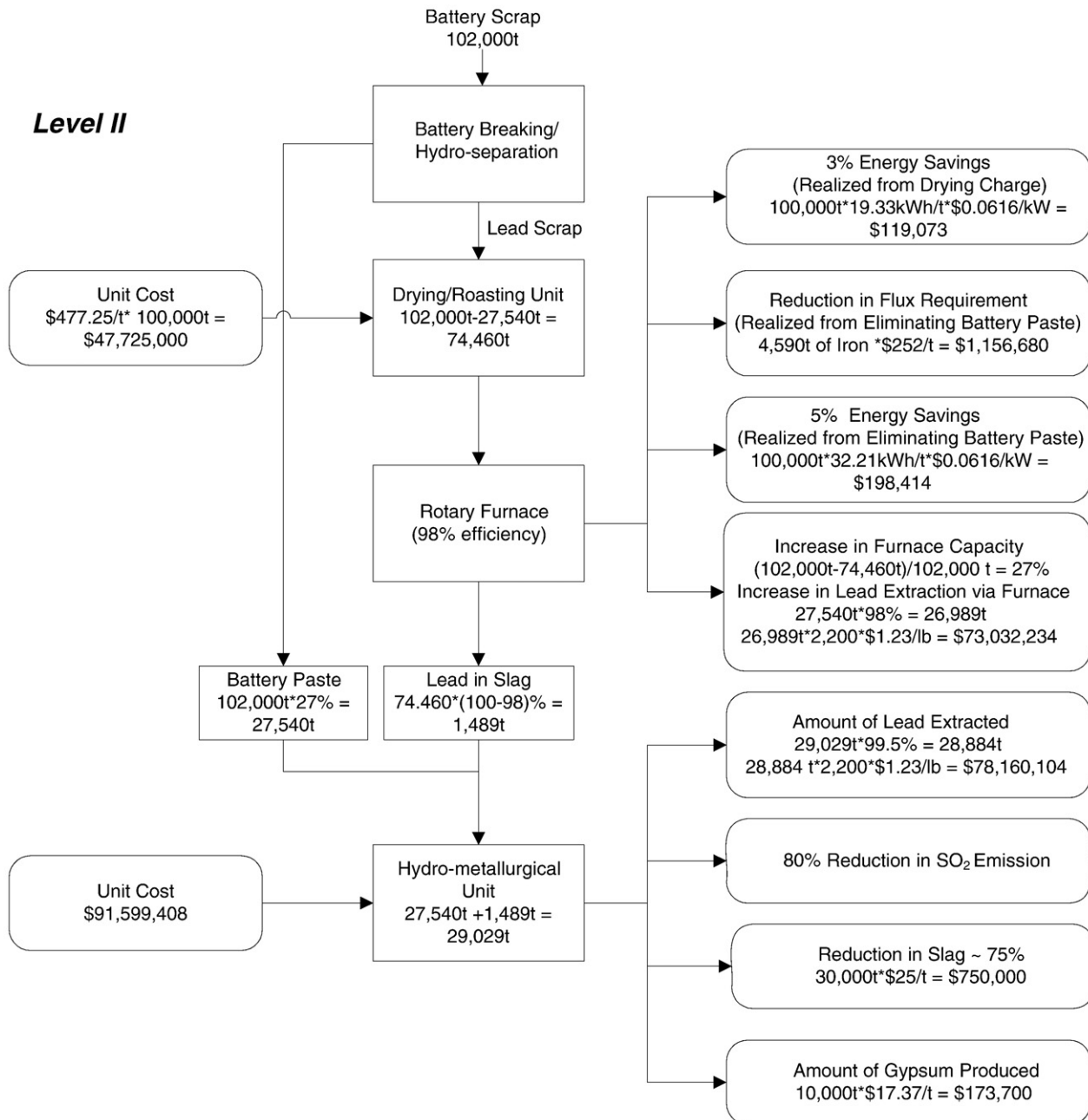
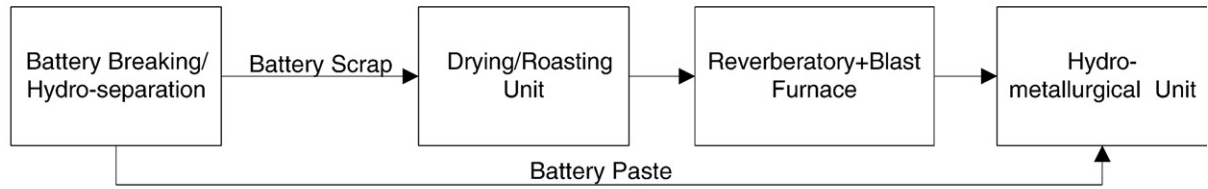
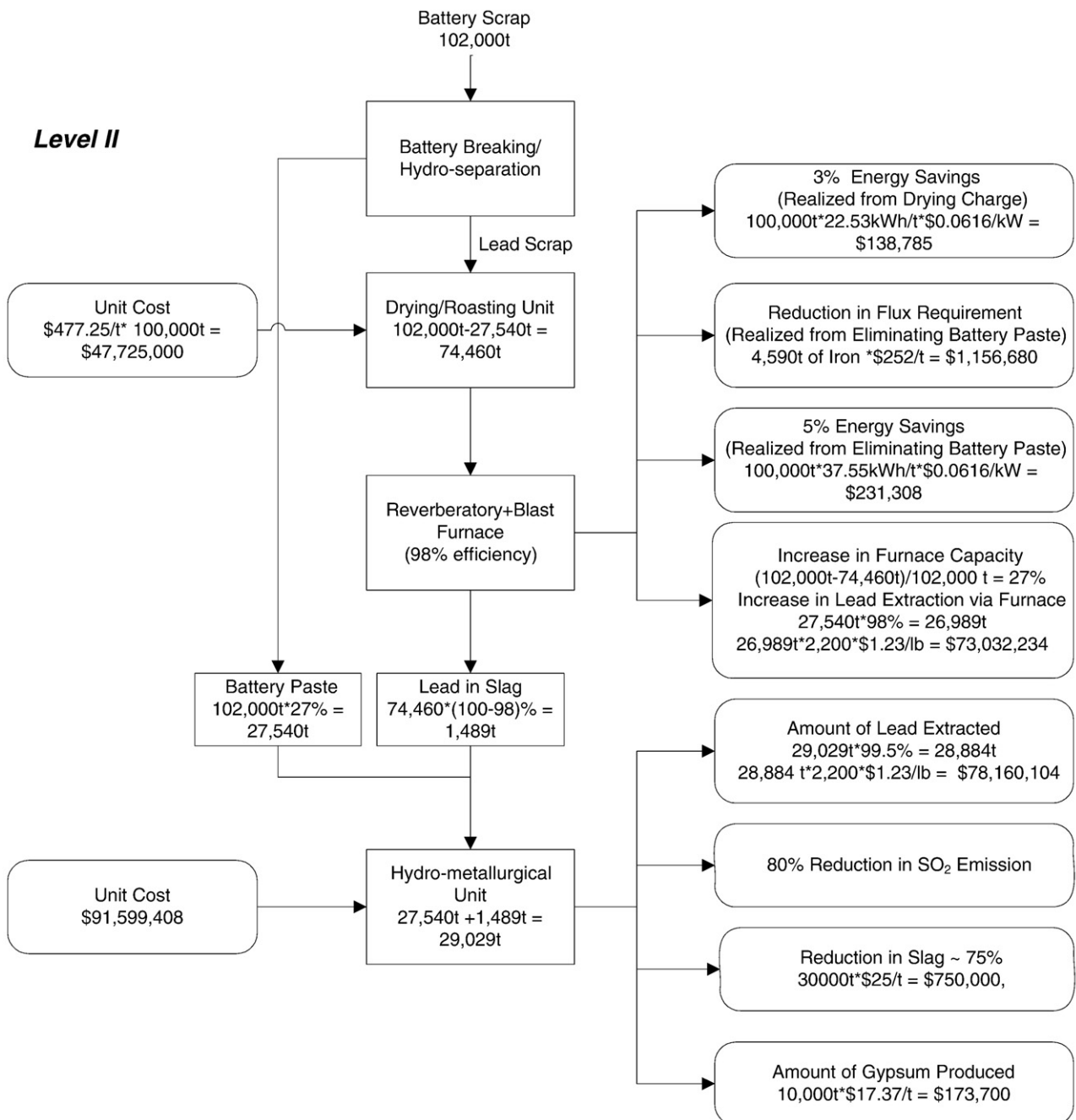


Fig. B6. Rotary furnace – large smelter (100,000 t/year).

**Level I**



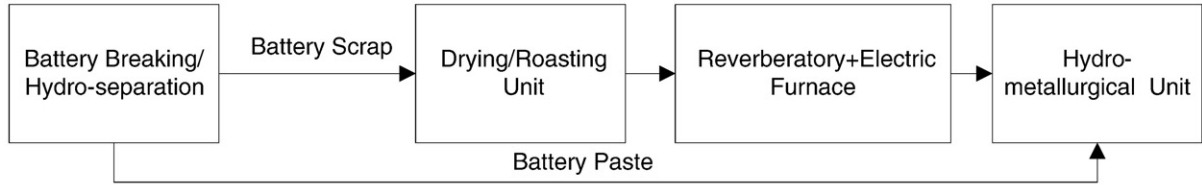
**Level II**



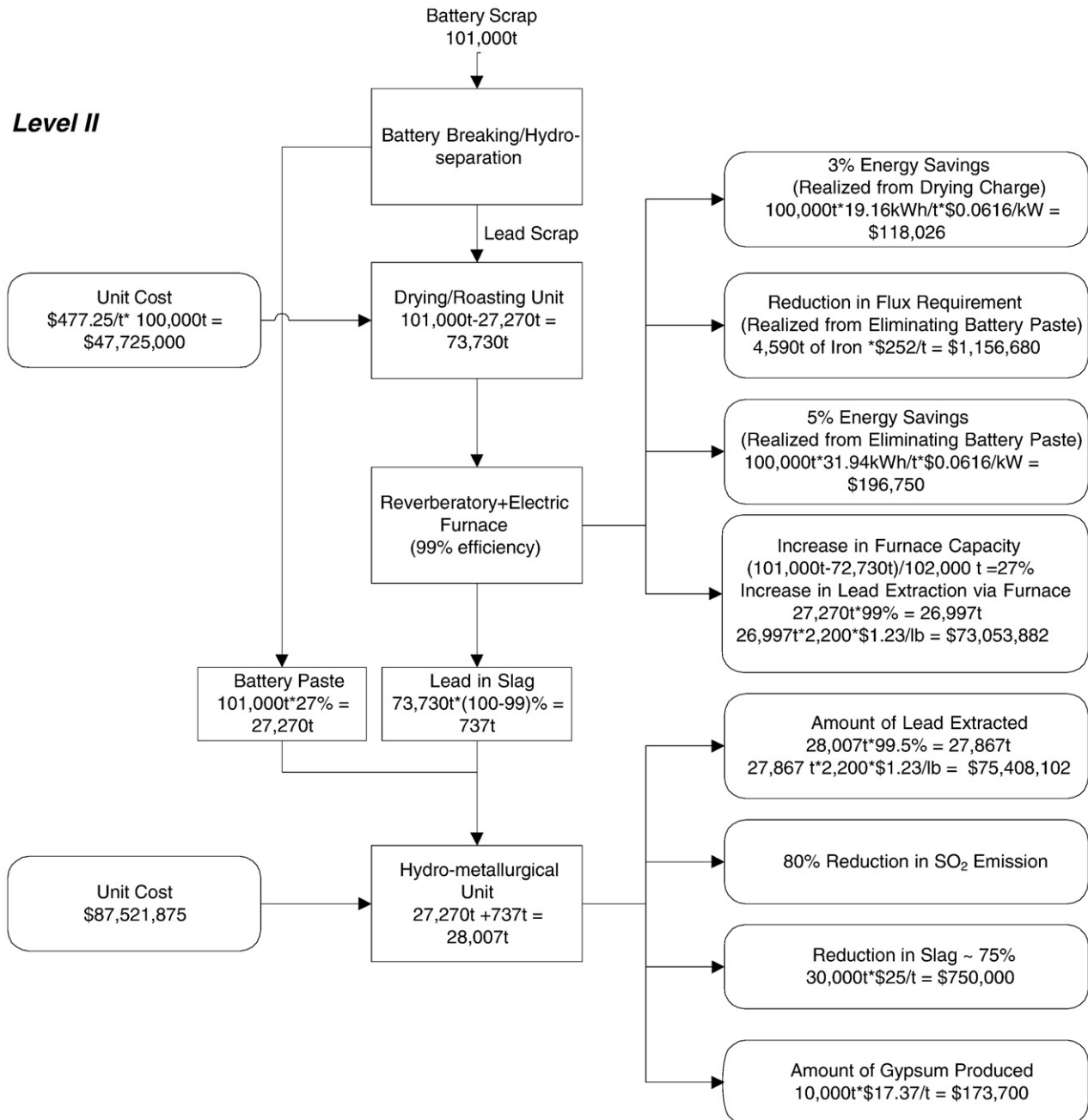
**Fig. B7.** Reverberatory and blast furnaces – large smelter (100,000 t/year).



**Level I**



**Level II**



**Fig. B8.** Reverberatory and electric furnaces – large smelter (100,000 t/year).

**Footnote:**

- <sup>1</sup>Smelter capacity is assumed 10,000 t for small, 40,000 t for medium and 100,000 t for large smelters. The estimation is based on the industry characterization of smelters.
- <sup>2</sup>The slag generated per smelter is calculated (without hydro-metallurgical unit) from the information provided by [Kreusch et al. \(2007\)](#). It was estimated that the amount of slag generated per ton of recovered pure lead to be 400 kg/t of pure lead. The actual amount of slag generated with the hydro-metallurgical unit was extracted from [Engitec Technologies \(2008a\)](#). With the added features of the above technology bundle, it is assumed that it will closely resemble the CX system.
- <sup>3</sup>The cost of acquiring a drying/roasting unit with installation/modifications is estimated to be \$477.25/t ([European Commission, 2001](#)).
- <sup>4</sup>The cost of a hydro-metallurgical plant is estimated at \$6.25 M with a production capacity of 2000 t/year ([Hanson Westhouse, 2008](#)). The cost is proportionately adjusted for the requirement of each scenario.
- <sup>5</sup>Information on reduction in SO<sub>2</sub> emission is extracted from the [European Commission Report \(2001\)](#). It is estimated that desulfurization of battery paste prior to smelting reduces SO<sub>2</sub> emissions by 80%.
- <sup>6</sup>Information on reduction in energy requirement is extracted from the [European Commission Report \(2001\)](#). It is estimated that drying/heating the furnace feed will result in ~3% in energy savings. The cost of energy is obtained from [Energy Information Administration](#).
- <sup>7</sup>Information on blast furnace efficiency is extracted from [Ryzhenkov et al. \(2006\)](#).
- <sup>8</sup>Information on electric furnace efficiency is extracted from [Ziebig and Stanek \(2006\)](#).
- <sup>9</sup>Information on rotary furnace efficiency is extracted from [Akihiko \(2004\)](#).
- <sup>10</sup>Information on reverberatory furnace efficiency is extracted from [Zhang et al. \(2008\)](#).
- <sup>11</sup>The efficiency of reverberatory + blast furnace is calculated as: 80% reverberatory furnace efficiency + (20%\*91%) for blast furnace efficiency.
- <sup>12</sup>The efficiency of reverberatory + electric furnace is calculated as; 80% reverberatory furnace efficiency + (20%\*99%) for electric furnace efficiency.
- <sup>13</sup>Information on energy expenditure per ton of lead for a blast furnace is extracted from [Ziebig and Stanek \(2006\)](#).
- <sup>14</sup>Information on energy expenditure per ton of lead for an electric furnace is extracted from [Akihiko \(2004\)](#).
- <sup>15</sup>Information on energy expenditure per ton of lead for a rotary furnace is extracted from [Rabah and Barakat \(2001\)](#).
- <sup>16</sup>Information on energy expenditure per ton of lead for a blast furnace is extracted from [Akihiko \(2004\)](#).
- <sup>17</sup>The price per pound of lead was extracted from the [Smith \(2008\)](#). It is reported as \$ 1.23/lb.
- <sup>18</sup>The price per ton of iron was extracted from the [Fenton \(2008\)](#). It is reported as \$ 252/t.
- <sup>19</sup>The price per ton for gypsum was extracted from the [Olson \(2008\)](#). It is reported as \$ 17.37/t.
- <sup>20</sup>The price per ton of slag disposal was extracted from the [State of Idaho \(2004\)](#). It is reported as hazardous waste disposal fees is \$25/t.

**Appendix C. Environmental improvement in lead smelting practices and technologies via changes in pre-processing stage**

Type	Technology/ practice bundles	Benefits	Cost	Benefit	Compatibility	Comments
Blast	U1 + A2 U1 + A2 + U3 + U4 + U5	<ul style="list-style-type: none"> <li>• 91–94% efficiency</li> <li>• 98% efficiency</li> <li>• 8–10% energy savings</li> <li>• 5–6 years payback period</li> <li>• &gt; 80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> <li>• Commercial grade Na<sub>2</sub>SO<sub>4</sub></li> <li>• Reduction in slag generated</li> </ul>	High	Very High	Very High	<ul style="list-style-type: none"> <li>• High in efficiency</li> <li>• Little/no energy savings</li> <li>• Somewhat moderate payback period</li> <li>• Increased environmental benefit</li> <li>• Increased productivity</li> </ul>
	U1 + A2 + U3 + U5	<ul style="list-style-type: none"> <li>• 98% efficiency</li> <li>• 10–12% energy savings</li> <li>• 4–5 years payback period</li> <li>• &gt; 80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> <li>• Reduction in slag generated</li> </ul>	High	Very High	Very High	<ul style="list-style-type: none"> <li>• Little/no energy savings</li> <li>• High in efficiency</li> <li>• Moderate energy savings</li> <li>• Somewhat moderate payback period</li> <li>• Increased environmental benefit</li> <li>• Increased productivity</li> </ul>
	U1 + A2 + U3 + U4	<ul style="list-style-type: none"> <li>• 91–94% efficiency</li> <li>• 3% energy savings</li> <li>• 3.5 years payback period</li> <li>• 75–80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> <li>• Reduction in slag generated</li> <li>• Commercial grade Na<sub>2</sub>SO<sub>4</sub></li> </ul>	Very Low	Somewhat Moderate	Somewhat Moderate	<ul style="list-style-type: none"> <li>• Moderate in efficiency</li> <li>• Little/no energy savings</li> <li>• Somewhat moderate payback period</li> <li>• Increased environmental benefit</li> <li>• Increased productivity</li> </ul>
	U1 + A2 + U3	<ul style="list-style-type: none"> <li>• 91–94% efficiency</li> <li>• 1 year payback period</li> <li>• 3% energy savings</li> </ul>	Very Low	Very Low	Low	<ul style="list-style-type: none"> <li>• Moderate in efficiency</li> <li>• Little/no energy savings</li> <li>• Moderate payback period</li> <li>• No environmental benefit</li> <li>• No increase in productivity</li> </ul>
	Electric	U1 + A3 U1 + A3 + U3 + U4 + U5	<ul style="list-style-type: none"> <li>• 99% efficiency</li> <li>• 99% efficiency</li> <li>• 8–10% energy savings</li> <li>• 5–6 Yrs payback period</li> <li>• &gt; 80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> <li>• Commercial grade Na<sub>2</sub>SO<sub>4</sub></li> <li>• Reduction in slag generated</li> </ul>	Moderate	Somewhat Very High	Somewhat Very High
	U1 + A3 + U3 + U5	<ul style="list-style-type: none"> <li>• &gt; 99% efficiency</li> <li>• 10–12% energy savings</li> <li>• 4–5 years payback period</li> <li>• &gt; 80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> <li>• Reduction in slag generated</li> </ul>	Moderate	High	High	<ul style="list-style-type: none"> <li>• Very high in efficiency</li> <li>• Moderate energy savings</li> <li>• Somewhat moderate payback period</li> <li>• Increased environmental benefit</li> <li>• Increased productivity</li> </ul>
	U1 + A4 + U3 + U4	<ul style="list-style-type: none"> <li>• 99% efficiency</li> <li>• 3% energy savings</li> <li>• 3.5 years payback period</li> <li>• 75–80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> </ul>	Very Low	Somewhat Moderate	Somewhat Moderate	<ul style="list-style-type: none"> <li>• High in efficiency</li> <li>• Little/no energy savings</li> <li>• Somewhat moderate payback period</li> <li>• Increased environmental benefit</li> <li>• Increased productivity</li> </ul>

(continued on next page)

## Appendix C (continued)

Type	Technology/ practice bundles	Benefits	Cost	Benefit	Compatibility	Comments
Electric	U1 + A3 + U3	<ul style="list-style-type: none"> <li>• Reduction in slag generated</li> <li>• Commercial grade Na<sub>2</sub>SO<sub>4</sub></li> <li>• 99% efficiency</li> <li>• 1 year payback period</li> <li>• 3% energy savings</li> </ul>	Very Low	Very Low	Low	<ul style="list-style-type: none"> <li>• High in efficiency</li> <li>• Little/no energy savings</li> <li>• Moderate payback period</li> <li>• No increase in environmental benefit</li> <li>• No increased in productivity</li> </ul>
Rotary	U1 + A4	<ul style="list-style-type: none"> <li>• 98% efficiency</li> </ul>	–	–	–	–
	U1 + A4 + U3 + U4 + U5	<ul style="list-style-type: none"> <li>• 98% efficiency</li> <li>• 8–10% energy savings</li> <li>• 5–6 years payback period</li> <li>• &gt;80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> <li>• Commercial grade Na<sub>2</sub>SO<sub>4</sub></li> <li>• Reduction in slag generated</li> </ul>	Moderate	Somewhat Very High	Somewhat Very High	<ul style="list-style-type: none"> <li>• High in efficiency</li> <li>• Little/no energy savings</li> <li>• Somewhat moderate payback period</li> <li>• Increased environmental benefit</li> <li>• Increased productivity</li> </ul>
	U1 + A4 + U3 + U5	<ul style="list-style-type: none"> <li>• 98% efficiency</li> <li>• 10–12% energy savings</li> <li>• 4–5 years payback period</li> <li>• &gt;80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> <li>• Reduction in slag generated</li> </ul>	Moderate	High	High	<ul style="list-style-type: none"> <li>• High in efficiency</li> <li>• Moderate energy savings</li> <li>• Somewhat moderate payback period</li> <li>• Increased environmental benefit</li> <li>• Increased productivity</li> </ul>
	U1 + A4 + U3 + U4	<ul style="list-style-type: none"> <li>• 98% efficiency</li> <li>• 3% energy savings</li> <li>• 3.5 years payback period</li> <li>• 75–80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> <li>• Reduction in slag generated</li> <li>• Commercial grade Na<sub>2</sub>SO<sub>4</sub></li> </ul>	Very Low	Somewhat Moderate	Somewhat Moderate	<ul style="list-style-type: none"> <li>• High in efficiency</li> <li>• Little/no energy savings</li> <li>• Somewhat moderate payback period</li> <li>• Increased environmental benefit</li> <li>• Increased productivity</li> </ul>
	U1 + A4 + U3	<ul style="list-style-type: none"> <li>• 98% efficiency</li> <li>• 1 year payback period</li> <li>• 3% energy savings</li> </ul>	Very Low	Very Low	Low	<ul style="list-style-type: none"> <li>• High in efficiency</li> <li>• Little/no energy savings</li> <li>• Moderate payback period</li> <li>• No increase in environmental benefit</li> <li>• No increase in productivity</li> </ul>
Reverberatory + Blast	U1 + A1 + A2	<ul style="list-style-type: none"> <li>• 93–98% efficiency</li> </ul>	–	–	–	–
	U1 + A1 + A2 + U3 + U4 + U5	<ul style="list-style-type: none"> <li>• 98% efficiency</li> <li>• 8–10% energy savings</li> <li>• 5–6 years payback period</li> <li>• &gt;80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> <li>• Commercial grade Na<sub>2</sub>SO<sub>4</sub></li> <li>• Reduction in slag generated</li> </ul>	Moderate	Somewhat Very High	Somewhat Very High	<ul style="list-style-type: none"> <li>• High in efficiency<sup>2</sup></li> <li>• Little/no energy savings</li> <li>• Somewhat moderate payback period</li> <li>• Increased environmental benefit</li> <li>• Increased productivity</li> </ul>
	U1 + A1 + A2 + U3 + U5	<ul style="list-style-type: none"> <li>• 98% efficiency</li> <li>• 10–12% energy savings</li> <li>• 4–5 years payback period</li> <li>• &gt;80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> <li>• Reduction in slag generated</li> </ul>	Moderate	High	High	<ul style="list-style-type: none"> <li>• High in efficiency</li> <li>• Moderate energy savings</li> <li>• Somewhat moderate payback period</li> <li>• Increased environmental benefit</li> <li>• Increased productivity</li> </ul>
	U1 + A1 + A2 + U3 + U4	<ul style="list-style-type: none"> <li>• 93–98% efficiency</li> <li>• 3% energy savings</li> <li>• 3.5 years payback period</li> <li>• 75–80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> <li>• Reduction in slag generated</li> <li>• Commercial grade Na<sub>2</sub>SO<sub>4</sub></li> </ul>	Very Low	Somewhat Moderate	Somewhat Moderate	<ul style="list-style-type: none"> <li>• High in efficiency</li> <li>• Little/no energy savings</li> <li>• Somewhat moderate payback period</li> <li>• Increased environmental benefit</li> <li>• Increased productivity</li> </ul>
	U1 + A1 + A2 + U3	<ul style="list-style-type: none"> <li>• 93–98% efficiency</li> <li>• 3% energy savings</li> <li>• 1 year payback period</li> </ul>	Very Low	Very Low	Low	<ul style="list-style-type: none"> <li>• High in efficiency</li> <li>• Little/no energy savings</li> <li>• Moderate payback period</li> <li>• No increase in environmental benefit</li> <li>• No increase in productivity</li> </ul>
Reverberatory + Electric	U1 + A1 + A3	<ul style="list-style-type: none"> <li>• 95–99% efficiency</li> </ul>	–	–	–	–
	U1 + A1 + A3 + U3 + U4 + U5	<ul style="list-style-type: none"> <li>• 99% efficiency</li> <li>• 8–10% energy savings</li> <li>• 5–6 years payback period</li> <li>• &gt;80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> <li>• Commercial grade Na<sub>2</sub>SO<sub>4</sub></li> <li>• Reduction in slag generated</li> </ul>	Moderate	Somewhat Very High	Somewhat Very High	<ul style="list-style-type: none"> <li>• High in efficiency</li> <li>• Little/no energy savings</li> <li>• Somewhat moderate payback period</li> <li>• Increased environmental benefit</li> <li>• Increased productivity</li> </ul>
	U1 + A1 + A3 + U3 + U5	<ul style="list-style-type: none"> <li>• &gt;99% efficiency</li> <li>• 10–12% energy savings</li> <li>• 4–5 years payback period</li> <li>• &gt;80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> <li>• Reduction in slag generated</li> </ul>	Moderate	High	High	<ul style="list-style-type: none"> <li>• Very high in efficiency</li> <li>• Moderate energy savings</li> <li>• Somewhat moderate payback period</li> <li>• Increased environmental benefit</li> <li>• Increased productivity</li> </ul>
	U1 + A1 + A3 + U3 + U4	<ul style="list-style-type: none"> <li>• 95–99% efficiency</li> <li>• 3% energy savings</li> </ul>	Very Low	Somewhat Moderate	Somewhat Moderate	<ul style="list-style-type: none"> <li>• High in efficiency</li> <li>• Little/no energy savings</li> </ul>

## Appendix C (continued)

Type	Technology/ practice bundles	Benefits	Cost	Benefit	Compatibility	Comments
Reverberatory + Electric	U1 + A1 + A3 + U3	<ul style="list-style-type: none"> <li>• 3.5 years payback period</li> <li>• 75–80% reduction in SO<sub>2</sub> emission</li> <li>• 25–30% more throughput</li> <li>• Reduction in slag generated</li> <li>• Commercial grade Na<sub>2</sub>SO<sub>4</sub></li> <li>• 95–99% efficiency</li> <li>• 3% energy savings</li> <li>• 1 year payback period</li> </ul>	Very Low	Very Low	Low	<ul style="list-style-type: none"> <li>• Somewhat moderate payback period</li> <li>• Increased environmental benefit</li> <li>• Increased productivity</li> <li>• High in efficiency</li> <li>• Little/no energy savings</li> <li>• Moderate payback period</li> <li>• No increase in environmental benefit</li> <li>• No increase in productivity</li> </ul>

## Footnote:

- Appendix C is constructed based on input information from Tables A1 and A3 in Appendix A.
- It is assumed that there are no changes in in-processing technologies.
- Only pre-processing technologies and processes are considered for environmental improvement management.
- The most significant benefits are only reported for technology bundles.
- U1 – Battery breaking and hydro-separation.
- U2 – Air separation of metal and non-metallic components.
- U3 – Drying of lead scrap extracted from hydro-separation.
- U4 – Desulfurization of battery paste for lead extraction.
- U5 – Hydro-metallurgical processing of slag, battery paste and sludge.
- A1 – Reverberatory furnace.
- A2 – Blast furnace.
- A3 – Electric furnace.
- A4 – Rotary furnace.

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