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Environmental and risk screening for prioritizing pollution prevention opportunities in the U.S. printed wiring board manufacturing industry

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ABSTRACT

Modern manufacturing of printed wiring boards (PWBs) involves extensive use of various hazardous chemicals in different manufacturing steps such as board preparation, circuit design transfer, etching and plating processes. Two complementary environmental screening methods developed by the U.S. EPA, namely: (i) the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) and (ii) Risk-Screening Environmental Indicators (RSEI), are used to quantify geographic and chemical environmental impacts in the U.S. PWB manufacturing industry based on Toxics Release Inventory (TRI) data. Although the release weight percentages of industrial chemicals such as methanol, glycol ethers and dimethylformamide comprise the larger fraction of reported air and water emissions, results indicate that lead, copper and their compounds' releases correspond to the highest environmental impact from toxicity potentials and risk-screening scores. Combining these results with further knowledge of PWB manufacturing, select alternative chemical processes and materials for pollution prevention are discussed. Examples of effective pollution prevention options in the PWB industry include spent etchant recovery technologies, and process and material substitutions. In addition, geographic assessment of environmental burden highlights states where promotion of pollution prevention strategies and emissions regulations can have the greatest effect to curb the PWB industry's toxic release impacts.

1. Introduction

Integral to the function of many high-tech products in the electronics, communications, defense and automotive industries, the printed wiring board (PWB) (also commonly referred to as the printed circuit board) is used to provide mechanical support and electrical interconnection between components such as semiconductor chips, capacitors, resistors and transistors. Modern manufacturing of PWBs involves extensive use of various hazardous chemicals in different processing steps such as board preparation, circuit design image transfer, etching and plating [1]. Spurred by the chemical intensive nature of PWB manufacturing, the United States Environmental Protection Agency (U.S. EPA) conducted a survey of American PWB manufacturers to create a compilation of materials used by the industry (e.g., glycol ethers, formaldehyde, solder, sulfuric acid, metal plating solutions; and chromium, copper and ammonia-based etchants) [2]. Many of these chemicals are known human toxins, and some are confirmed carcinogens [3,4]. Internationally, occupational safety studies have been conducted in PWB manufacturing facilities to understand health impacts (with some process chemicals showing clear evidence for adverse effects in workers due to extended occupational exposure) [5–8]. Few published studies are available that quantify ecological impacts of PWB industry emissions.

Due to overriding concerns of the environmental and human health toxicity from PWB manufacturing, domestic environmental agencies have made efforts to help reduce the industry's impact. At the federal level, the U.S. EPA's Office of Pollution Prevention and Toxics 'Design for the Environment' (DfE) program has been implemented to identify and evaluate environmentally safer alternatives for chemicals and processes that pose potential hazard to PWB manufacturing employees and their localities [9]. At the state level, Florida's Department of Environmental Planning (DEP) has published a checklist approach to decrease waste generation for different PWB manufacturing process steps [10]. More recently, California's Department of Toxic Substances Control (DTSC) has identified the State's PWB industry as a major hazardous waste generator. Mandated by California's Hazardous Waste Source Reduction and Management Review Act [11], DTSC has moved forward with a state-wide program to work with PWB facilities to promote hazardous waste reduction technologies.

Despite these regulatory agencies' efforts, some pertinent questions remain in terms of having an integrated approach for guiding pollution prevention to optimize environmental benefits within

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the scope of particular industries. These include: (1) what appropriate industry-level environmental impact assessment methods can be used to systematically identify priority chemicals and waste streams of concern to optimally address reduction of environmental and human health toxicity, and (2) can precedence be made geographically (e.g., which states require more attention in order to focus pollution prevention or environmental policy targets)? Previous multi-industry sector analyses have shown that simple prioritization based on toxic release quantities will often not identify chemicals of concern that would otherwise be highlighted through environmental impact assessment methods [12–14].

For this reason, we recognize that the complementary use of life-cycle impact assessment (LCIA)-based and risk-based methods as environmental screening approaches can provide a more robust analysis to capture a wider perspective on impact categories and a localized perspective on human population effects, respectively [15,16]. In addition, as opposed to the high complexity of comprehensive site-specific risk assessments required to determine ecological and human health impact for a large array of industrial chemicals, these environmental assessment methods can ultimately provide pollution prevention guidance faster, with less need for data intensive resources. To date, there has not been any published case study analysis to link these prioritization methods to evaluate toxic releases in order to directly motivate changes in manufacturing processes for individual industries.

Therefore, in the context of PWB manufacturing, the aim of this study is to quantify and benchmark the environmental and health impacts of the industry's waste streams (by chemical and by state) in order to support pollution prevention efforts in achieving overall toxicity reduction. Analyses deriving from the PWB industry's U.S. EPA's Toxics Release Inventory (TRI) datasets [17] are conducted by using appropriate environmental assessment tools. Namely, two U.S. EPA supported environmental screening methodologies are employed: the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) as an LCIA-based approach [18] and Risk-Screening Environmental Indicators (RSEI) as a risk-based approach [19]. With further knowledge of high priority waste streams and PWB manufacturing processes, alternative chemical processes and materials for pollution prevention are discussed. Results from this industrial assessment can provide information for corporate and regulatory bodies on which pollution prevention strategies to emphasize and where geographically to promote them in order to have the greatest effect in mitigating human and ecological toxicity originating from broad-scale exposure of chemicals due to industrial emissions.

1.1. PWB manufacturing process

PWBs can be manufactured as single-sided, double-sided, and multi-layered boards. Production of multi-layered boards comprises over two-thirds of the U.S. PWB market [20]. With no standard circuit design, each manufactured board has a unique function for the intended electronic product system. Given a desired circuit pattern, a negative image, or mask, is printed out with the precise dimensions onto a plastic sheet known as a dry film. Major processes that are commonplace to all PWB manufacturing, regardless of design, include board drilling and preparation, image transfer of the dry film, copper etching and electroplating [1].

The basic construction of a PWB includes a fiberglass reinforced substrate composed of epoxy resin laminate with copper foil material. These are known as blank boards, which are layered onto each other to create multilayered boards. Component holes are drilled through the substrate to provide interconnections between layers according to the intended circuit design. The holes are mechanically and chemically scrubbed to remove any excess remaining debris left on the edges. For multilayered boards, hole surfaces are then plated with electroless deposition of copper to electrically connect between layers [21].

The circuit pattern design is transferred onto the substrate through lamination of the photosensitive dry film. The laminated boards are then exposed to high intensity ultraviolet light to imprint the circuit design. Successive chemical processing steps expose the copper tracings through the removal of the dry film material by aqueous developing solution and rinse. In the more standard subtractive process, excess or unwanted copper is removed with etchant solution to expose the desired copper tracing. This tracing, representing the circuitry of the board, is electroplated (commonly with tin or tin–lead solder as an etch resist) for protection. The remaining dry-film is then further removed through an alkaline resist stripper and unsoldered copper material is etched away. The etch resist solder is then stripped and subsequently cleaned for final solder mask application [22]. Final processing includes silk-screen application for a legend or other nomenclature, routing, electrical testing, inspection and packaging [1,22].

2. Methods and data

2.1. Chemical release data

Established in 1986, the Federal Emergency Planning and Community Right-to-Know Act requires facilities that meet certain toxic emissions criteria to annually report on their use of manufacturing chemicals to the U.S. TRI database [23]. The requirements include public disclosure of toxic releases from facilities producing over 25,000 pounds per year or handling over 10,000 pounds per year for any of the 580-plus listed toxic chemicals. Despite limitations to the use of the TRI database in environmental assessments because it relies on industry self-reporting for a specified list of toxic chemicals [24], the TRI currently represents the most complete quantitative resource describing regulated toxic chemicals that are being used, manufactured, transported or released into the environment by U.S. manufacturing industries.

The TRI database [17] is used in this study to obtain annual emissions information on the U.S. PWB industry (Standard Industrial Classification (SIC) code 3672 or North American Industry Classification System (NAICS) code 334412). Total industry releases reported by U.S. PWB facilities are compiled for years 2002 through 2006.

The two U.S. EPA environmental assessment methodologies, TRACI and RSEI, are utilized to evaluate the environmental impacts of these TRI reported chemical waste streams attributed to air and water media releases, i.e., fugitive and point source air emissions, and surface water discharges. Waste management methods such as landfills and underground injection wells are not included in this assessment as we assume these outlets are being managed properly and thus create little potential for risk especially when compared to substances directly released into air and water media [13].

2.2. Environmental impact evaluation with TRACI

TRACI is originally designed for use in LCIA, but has recently seen wider application as a general pollution prevention and sustainability indicator toolset to understand environmental impact potential of chemicals [12,25,26]. Within the current study, TRACI is used to evaluate the human health toxicity and ecotoxicity potentials for air and water emissions from the PWB industry on the basis of the TRI datasets.

TRACI characterization factors for particular chemical releases can be used to quantify the major environmental impact effects such as global warming, ozone depletion, acidification, eutrophication, smog formation, ecotoxicity, and human health related effects. For this assessment, only human health and ecotoxicity effects are considered due to a focus on quantifying toxicity impacts from PWB fabrication. Also, only chemical emissions during the manufacturing stage are taken into account; other product life stages such as raw materials production, use and end-of-life disposal are not considered.

TRACI characterizes human health impacts as Human Toxicity Potentials (HTPs) [27]. HTPs represent cancer and non-cancer (all other adverse health effects) toxicity potentials associated with a chemical's release into air or water media relative to the release of a reference chemical. Calculations for HTPs utilize the CalTOX model (Multimedia Total Exposure Model for Hazardous Waste Sites) to determine the pollutant's fate and transport characteristics to estimate the average daily dose from exposure caused by a media release [28]. HTPs are determined by combining the estimated daily dose value with available toxicity data which include reference dose or concentration (RfD/RfC) for non-carcinogens and cancer potency factors for carcinogens.

For ecotoxicity potentials, the characterization factors are determined through combining two components: (1) a concentration-to-source ratio (CSR) from the CalTOX model and (2) an impact-to-concentration ratio (ICR) from the predicted no-effects concentration (PNEC) (based on fraction of species adversely affected), to estimate potential terrestrial and aquatic toxicity impact relative to a reference chemical's media-specific release [18].

The reference chemicals used to represent toxicological equivalency in TRACI include benzene for cancer potential, toluene for non-cancer potential, and 2,4-dichlorophenoxyacetic acid for ecotoxicity potential. The TRACI characterization factor for a metal compound is assumed to be equal to that for the metal. Environmental impact evaluations with TRACI for the PWB industry are performed by chemical and by state.

2.3. Risk screening evaluation with RSEI

Although not a formal risk assessment, the U.S. EPA's RSEI model utilizes a system in which the toxicity of a given chemical is quantified by a dimensionless "risk score" to provide a screening-level perspective for comparing chemical emissions' health impacts on human populations. RSEI incorporates the amount of chemical released, chemical toxicity, fate and transport through the environment, exposure route (including inhalation and ingestion), and population effects during evaluation. The model uses the most potent chronic health endpoint in considering human health impacts due to exposure [19]. "Toxicity weights," derived from RfD/RfC values and cancer potency factors, are developed as a chemical-specific toxicity valuation system within RSEI to calculate risk scores. The toxicity weights for a metal compound, as with TRACI characterization factors, are assumed to be equal to that for the metal. Ecological toxicity is not explicitly addressed in the RSEI model. In this study, risk scores for chemical emissions from the PWB industry are again evaluated by chemical and by state.

3. Results and discussion

3.1. Release weight analysis

In order to show the magnitude of the waste streams generated from PWB facilities in the U.S., the total TRI releases are presented for years 2002 through 2006 in Fig. 1. It is noted that for all five years, the top five high-quantity release chemicals for all media include copper and copper compounds, ammonia, nitrate compounds, lead and lead compounds, and glycol ethers. Significant variations in quantity over time are only observed for copper and copper compounds during this time period, with a decreasing trend.

Ammonia and copper-based compounds originate principally from etching processes that use cupric chloride and ammonia-based etchants [21]. Copper plating processes and a variety of board cleaning steps also contribute to copper and copper compound emissions. Lead and lead compounds originate from solder stripping processes. Nitrate compounds are extensively utilized in dissolving tin-based solder alloy materials. Glycol ethers, although currently being phased out in other electronic manufacturing industries, are still widely used as a general solvent for surface coating, dyes, inks, cleaners, and degreasers in the U.S. PWB industry [20].

The air and water media release values utilized for the environmental impact and risk screening portion of this study correspond to the year 2006 which has the lowest quantity of chemicals released. The associated weight percentages for media releases are shown in Fig. 2. The highest quantity chemicals released in the air are ammonia, glycol ethers, and dimethylformamide; and those for water are methanol, copper and copper compounds, and formaldehyde. Dimethylformamide and methanol are used as organic solvents. Formaldehyde is principally used as a reducing agent in the electroless copper deposition process for through-hole plating [1]. Chemicals of particular interest in the "others" category include the use of brominated flame retardants (BFRs) (commonly tetrabromobisphenol-A (TBBPA)) in PWBs [29]; however they are negligibly reported within the TRI. For example, TBBPA represents less than 0.001% by weight of emissions reported for the entire PWB industry. It is further noted, however, that proprietary formulations are not disclosed publicly in TRI [30], which may contribute to this surprisingly low value.

3.2. TRACI human health and ecological toxicity potentials

Evaluation of the toxicity potentials for the PWB industry with TRACI shows that the majority of environmental and human health impacts are attributed primarily to lead, copper, and their compounds, as shown in Fig. 3. Cancer potentials for air and water and non-cancer potentials for air are primarily attributed to lead and lead compounds. In contrast to the non-cancer potential for air, non-cancer potential for water is attributed to copper and copper compounds. The ecotoxicity potential for air is primarily from copper and copper compounds, while ecotoxicity potential for water is primarily from both copper and copper compounds and formaldehyde. Despite significant release quantities, other chemicals such as ammonia and methanol, do not exhibit toxicity potentials for human health or for ecosystems.

The TRACI toxicity potentials for different impact categories by state are presented in Fig. 4 to help identify the priority states for controlling air and water emissions from the PWB industry. California has the highest cancer and non-cancer potentials for air; Virginia has the highest cancer potential for water; New York has the highest non-cancer and ecotoxicity potentials for water; and Illinois has the highest ecotoxicity potential for air. These different characteristics may be due to the differences among existing state environmental regulations on chemical releases, as well as to the manufacturing capacities of facilities within these states.

3.3. Risk screening evaluation

As opposed to only utilizing the quantity of toxic releases generated at facility locations within the TRACI evaluation, population effects are also captured within the RSEI risk scores to provide a more regional perspective on human health impacts [19].

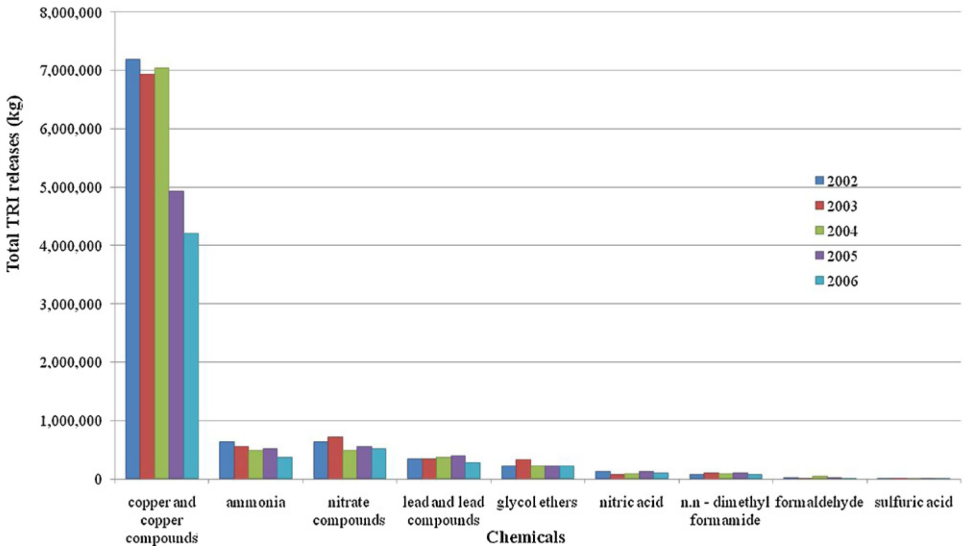

Fig. 1. Total TRI release data for the PWB industry in the United States (2002–2006) [17].

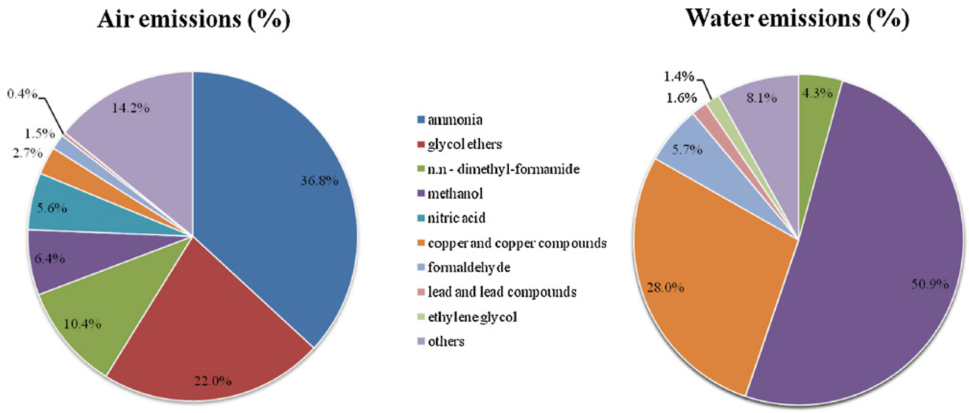

Fig. 2. Air and water emission release weight percents for select chemicals in 2006. The weights are normalized to the total weight of all chemicals released in air or water media from the U.S. PWB industry.

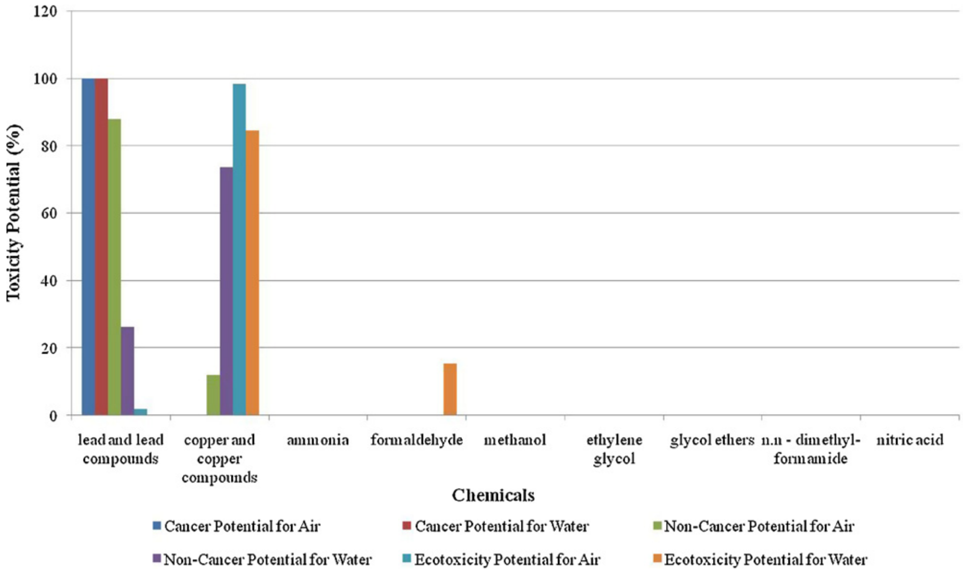

Fig. 3. TRACI toxicity potentials from chemicals released in the U.S. PWB industry for the year 2006. The toxicity potentials are normalized with respect to the total toxicity potential of all chemicals released.

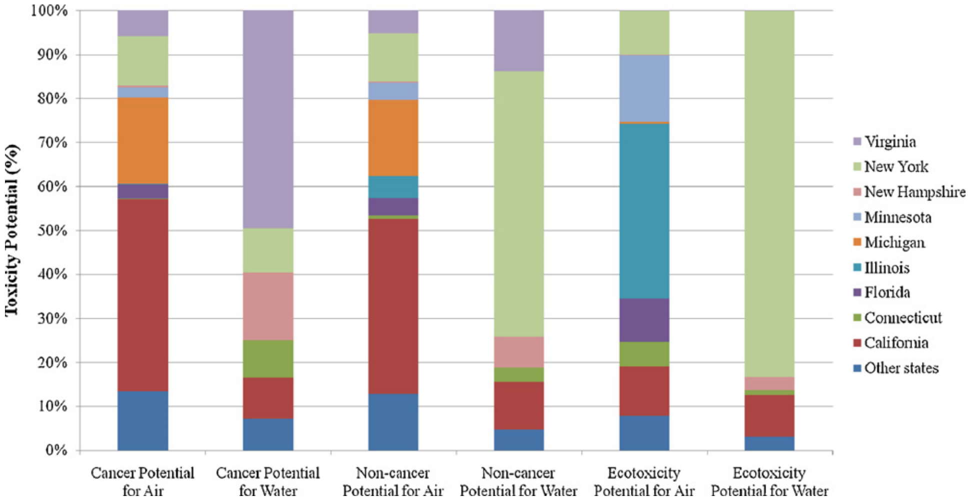

Fig. 4. TRACI toxicity potentials from the U.S. PWB industry in the states with the highest impact values for the year 2006. The toxicity potentials are normalized with respect to the total toxicity potentials for all the states.

Similar to the TRACI evaluation, risk scores for the U.S. PWB industry, displayed for the year 2006 in Fig. 5, depict lead, copper and their compounds as the highest priority chemicals from a human health risk-perspective for both air and water releases. This is principally due to factors of high toxicity weight (e.g., lead and lead compounds) and high toxic release quantity (e.g., copper and copper compounds) across the industry. For these substances, risk scores are driven substantially by both air and water releases. Water emissions contribute minimally to risk scores for other chemicals due to their low release amounts and/or toxicity weight. In addition, although not emphasized in the TRACI evaluation because of unavailable human health characterization factors, glycol ethers and dimethylformamide, which are known reproductive toxins, demonstrate moderate risk scores [31,32]. However, compared to copper and lead compounds, these and other chemicals do not contribute as significantly to the risk scores from the standpoint of the entire industry, as also suggested by TRACI results. Again, for some chemicals such as methanol, despite high release quantities, a negligible RSEI toxicity weight induces only a minimal risk score.

Geographic analysis of the TRI dataset is used in determining the risk scores for states in year 2006 to compare the relative differences in risk scores and toxic release amounts by location (Fig. 6). Within the top five prioritized states from risk-screening, California ranks with the highest impact and is followed by a steep drop-off of risk scores for Oregon, Illinois, Connecticut and Arizona. Some states show minimal risk scores despite high TRI quantity releases such as New York and Oregon.

A map is shown in Fig. 7 to illustrate the geographic distribution of different capacity PWB manufacturing facilities and is compared to background population density by county for year 2006 in the U.S. This geospatial representation shows that the majority of PWB manufacturing activities are located in more populated regions within the U.S. However, delineation of population density surrounding the fabrication facilities is only partially sufficient in describing a high risk score determined by the RSEI model. Key influences on high risk scores in the current state-level analysis is the pairing of a high density of PWB manufacturing activity with high population areas. For example, while the national average of PWB facilities per county is 2.1, California averages 6.5 facilities per county, suggesting a more concentrated toxic release to the population, which explains the state's elevated risk score. This is in contrast to New York and Oregon (with high release and low risk scores) showing state averages of 1.4 and 1.3 facilities per county, respectively. However, it should be noted that a com-

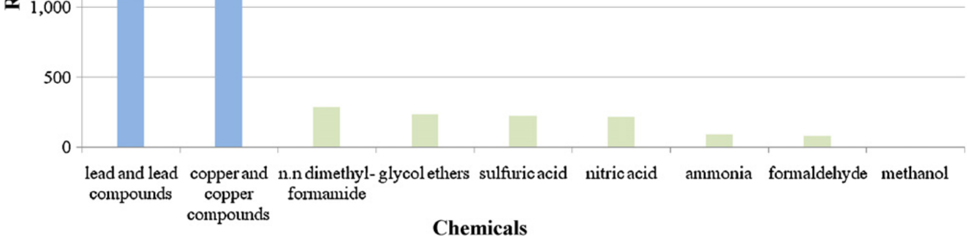

Fig. 5. RSEI risk scores for various chemicals released to air and water by the U.S. PWB manufacturing industry for the year 2006.

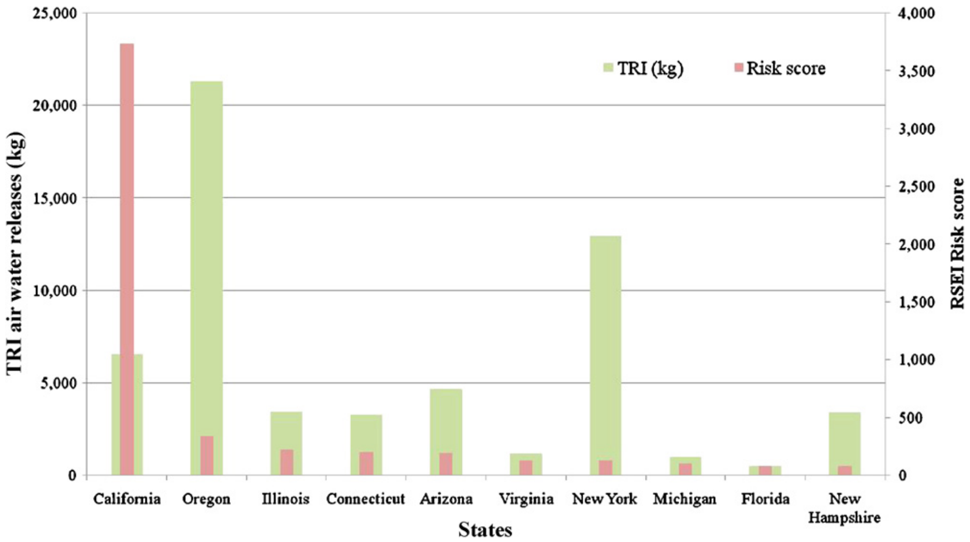

Fig. 6. Comparison of RSEI risk scores and TRI air and water releases (kg) associated with select high waste generating states in the U.S. PWB industry for the year 2006.

plex combination of parameters including facilities location, waste stream identities, and population exposure modeling associated to emissions from each state's facilities would influence the RSEI assessment results for other industry sectors.

From the context of this chemical-level and state-level assessment of the U.S. PWB industry, using the combination of TRACI and RSEI together allows for a more robust description of wider and local perspectives of ecological and toxicity impacts due to industrial toxic emissions. The LCIA-based approach with TRACI is a strategy to perform a generic environmental impact assessment which is useful in helping account for separate human health cancer and non-cancer toxicity potentials in addition to other impact categories, such as ecological toxicity potential, which are not commonly available in risk screening methods. Utility of RSEI's risk-based evaluation complements this assessment further with the detailed examination of more localized parameters such as population density and facility locations to model potential exposure and implicated human health effects [15].

Ultimately, it is prudent for the PWB industry to consider these environmental assessment results to target possible pollution prevention options for addressing prioritized chemical emissions, particularly for high impact locations.

3.4. Strategies for pollution prevention

As indicated by the TRACI and RSEI chemical evaluations, lead, copper and their compounds contribute most heavily to environmental and health impacts within the U.S. PWB industry (based on the year 2006 TRI data). Although not exhaustive in scope, some overview is provided here to describe possible pollution prevention measures for etching and solder stripping waste streams, which are significant contributors to the releases of these chemicals during PWB manufacturing.

3.4.1. Copper etching

Spent etchant generation is a primary target for pollution prevention. As a key component for the creation of the physical circuit design, etchant solutions are utilized to remove copper from copper foil surfaces. Typically, up to 70% of the original copper surface area is removed. Two types of etchant solutions,

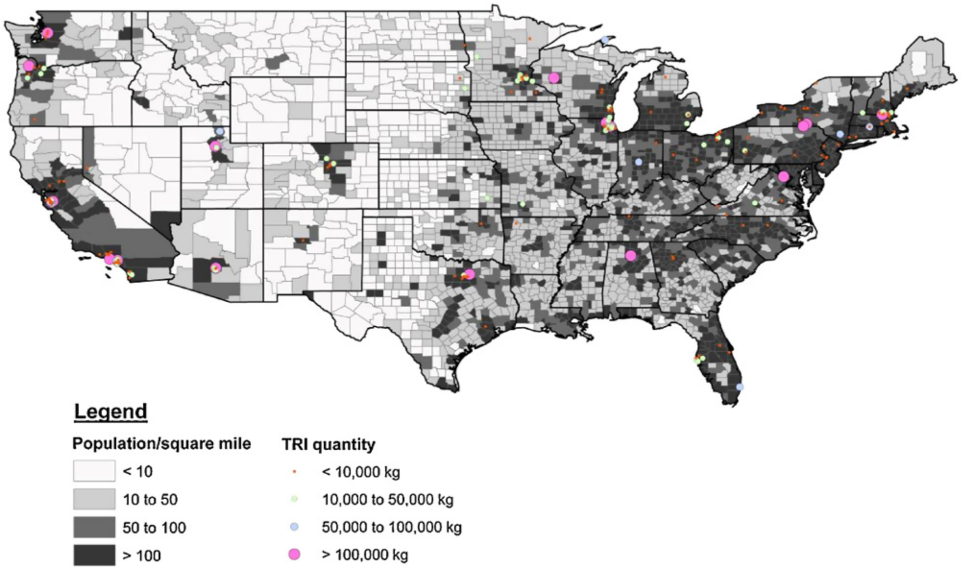

Fig. 7. Geospatial distribution of different capacity PWB facilities versus population by county in year 2006.

ammonia-based and cupric chloride ($CuCl_2$), are well established in the industry. Ammonia-based etchants, commonly ammonium chloride, ammonium hydroxide or ammonium sulfate solutions, have the advantage of being compatible with both organic and metallic resist layers, which selectively protect circuit areas from etching (e.g., dry film for inner layers and solder for outer layers) [33]. Cupric chloride etchants have faster etch rates and are more applicable for fine-line etching, but they react with most solder resists.

From a pollution prevention standpoint, an efficient closed loop regeneration process can be used as a source reduction approach to minimize copper wastes originating from spent etchant streams [34]. In addition, an additive copper plating approach can be used to substantially reduce the waste copper generated due to decreased etching requirements [21].

3.4.1.1. Spent etchant regeneration. For high volume PWB manufacturers, the costs of managing spent etchant and the danger they pose to the environment can be reduced dramatically with regeneration of etchant waste streams. Cupric chloride etchant can be recycled using a variety of processing methods including chlorine regeneration, sodium chlorate regeneration, hydrogen peroxide regeneration, oxygen regeneration, electrolysis and electrodialysis [34]. Specific for ammonia-based etchants, electrolytic recovery, ion exchange, precipitation or solvent extraction can be used to remove copper and recycle the etchant while shipping recovered copper for downstream metal reclamation [35].

It is important, however, for manufacturers to critically evaluate the advantages and disadvantages of regeneration options [34]. For example, chemical regeneration through chlorine gas injection is often economically the cheapest to install; however, the downside is the increased safety hazard of introducing chlorine into the workplace. In addition, chemical regeneration for cupric chloride does not handle the removal of etched materials.

A general technique for simultaneously addressing etchant regeneration and etched copper recovery are electrolytic recovery methods [22]. An electrolytic process utilizes an electrochemical separation technique where the waste etchant is regenerated in a reaction cell consisting of anodes and cathodes wired in parallel while metal ions in solution are plated out. The electrodialysis process is a variation of the electrolytic process where the dilute metal cations are transferred from the spent etchant to a concentrate solution by applying electric current.

3.4.1.2. Additive processing. The copper in a PWB serves as a conductive base material that is either plated or etched away on the surface of the substrate. The conventional subtractive process etches off the copper surface to create the desired circuit pattern. An alternative is an additive process, which prints or screens the circuitry image directly onto the polymer laminate [21]. A semi-additive option can be used where only a thin layer of copper is plated over the laminate. After application of photoresist, additional copper is selectively electroplated onto circuit areas. A fully additive process usually involves forming permanent resist on a substrate with a catalyst such as palladium in order to obtain the desired circuit pattern for electroplating. The fully or semi-additive process negates the need for extensive etching of copper and ultimately reduces the amount of copper waste generated by manufacturing facilities [33].

3.4.2. Solder stripping

The process of solder stripping removes excess solder that is applied to the PWB to protect tracings from being etched away during chemical processing. Nitric and sulfuric acids are standard formulations used to strip off etch resist solder, which is commonly tin or tin–lead. The solder stripper only reacts with the solder material without attacking the copper layer underneath.

3.4.2.1. Lead-free solder. Because lead-based compounds contribute to substantial environment concern in PWB manufacturing, a possible option is the adoption of lead-free solder etch resist processing in replacement for tin–lead options. On boards that are processed with solder-mask-over-bare-copper (SMOBC) (a typical method of surface finishing), it is possible to substitute the conventional tin–lead solder with an etch resist comprised principally of tin (usually including traces of other metals such as copper and nickel) [20]. However, the drawback from a tin-only solder material substitution is the loss of tin–lead solder's oxidation resistance and suitability for work-in-progress boards [33].

In general, execution of actual pollution prevention measures for waste streams such as etchant regeneration or lead-free etch resist in PWB manufacturing will also involve many other considerations outside the scope of environmental and health impact assessments. These may include considerations of product and process profitability, technological and engineering barriers, as well as limitations on material and process alternatives. In some instances, environmental policy and regulations are powerful factors to stimulate process and material changes. For example, due to stringent facility discharge requirements for lead and growing international awareness of end-of-life environmental impacts of lead, leaded solder is being phased out of electronics globally [36]. California has been the first U.S. state to enact lead-free legislation, having adopted Senate Bill 20 (SB 20) which is modeled after the European Union's Restrictive on Hazardous Substances (RoHS). The legislation bans the use of lead (amongst other chemicals such as mercury, cadmium and hexavalent chromium) in commercial electronic products which invariably contain PWBs [37].

4. Conclusions

In U.S. PWB manufacturing, chemical emissions are prioritized with complementary environmental impact and risk screening tools. Using TRI data as the basis, lead, copper and their compounds are identified as having the highest environmental impact potential and risk scores through both the TRACI and RSEI methods which operate under different evaluation bases. By combining these results with further knowledge of manufacturing processes, select pollution prevention strategies for chemical processes and materials substitutions can be emphasized. Consideration of the geographic distribution in environmental impact highlights states where promotion of pollution prevention may be most effective towards ecological and toxicity impact reduction.

In addition, a cornerstone of this paper is to provide an example of a methodology that utilizes available environmental and health assessment approaches to estimate environmental impacts of chemical emissions in hazardous waste generating industries. An acknowledged limitation of the method is the need to depend on the self-reported data in the TRI database. With the adoption of effective pollution prevention strategies paired with the knowledge of priority chemicals and regions, corporate leaders and environmental agencies can make more informed decisions in achieving better environmental performance for manufacturing industries.

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