Energy Policy 39 (2011) 4939–4946

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Lead emissions from solar photovoltaic energy systems in China and India

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ARTICLE INFO

Article history:
Received 20 January 2011
Accepted 9 June 2011
Available online 7 July 2011

Keywords:
Lead battery
Solar photovoltaic
Solar lantern

ABSTRACT

China and India are embarking on ambitious initiatives over the next decade to expand solar photovoltaic (PV) power in underserved regions. China proposes adding 1.6 GW of solar capacity by 2020, while India plans 12 GW in addition to 20 million solar lanterns by 2022. These technologies rely heavily on lead-acid batteries (LABs) for storage. China and India's lead mining, battery production, and recycling industries are relatively inefficient—33% and 22% environmental loss rates, respectively. Based on the quantity of lead batteries employed in existing PV systems, we estimate environmental lead emissions in China and India for new units installed under their solar energy goals. The average loss rates are 12 kg (China) and 8.5 kg (India) of lead lost per kW-year of installed PV capacity in these countries. The planned systems added in China and India will be responsible for 386 and 2030 kt of environmental lead loss, respectively, over their lifespan—equal to 1/3 of global lead production in 2009. Investments in environmental controls in lead smelting, battery manufacturing, and recycling industries along with improvements in battery take-back policies should complement deployment of solar PV systems to mitigate negative impacts of lead pollution.

1. Introduction

In recognition of the importance of low-carbon renewable energy supplies, many countries are greatly expanding investments in solar and wind power. Climate change, potential disruptions in energy supplies, and threats to global security are encouraging national energy programs to emphasize renewable sources. Much of the emphasis of these efforts is to improve access to electricity in rural areas that remain off-grid. In countries with abundant wind and sunshine, photovoltaic (PV) solar and wind power systems are key growth components of these national plans (NDRC, 2007; Government of India, 2009; Jacobson and Delucchi, 2011; Komatsu et al., 2011).

In particular, China and India have recently established policies that recognize the potential of untapped solar and wind resources. Over two-thirds of China's land mass enjoy more than 2200 h of sunshine annually and there are ample possibilities for expanding wind power (NDRC, 2007). Similarly, India is well endowed with sunshine and most areas receive 4–7 KWh per m^2 per day (Government of India, 2009). In response, long-term plans are being implemented to rapidly accelerate the pace of adopting PV solar and wind power alternatives. Large public investments are being made to expand the use of these technologies.

China has set a goal to obtain 15% of their power needs from renewable sources by 2020 and to focus on rural areas without existing electricity supplies (NDRC, 2007). Similarly, India has established specific goals for renewable energy in areas currently outside the power grid and for distribution of solar lighting systems in rural areas (Government of India, 2009). In fact, rural areas are slated to get the most investment for renewable energy in both the Chinese and Indian national plans. In 2006, only 3% of China's solar capacity was grid-connected, compared to 88% at the global level (Chang et al., 2009).

In India, almost 25% of the 80,000 villages without electricity are not suitable for grid connectivity due to their location and other factors (Shukla, 2007). China has far fewer areas off the electricity grid, but over 700 small village power stations have already been installed. The remaining off-grid areas are considered most suitable for solar and wind applications (Gabler et al., 2006). Renewable energy is particularly well suited to these situations where either household systems or local grids can serve a village or small region.

Solar lanterns are also being promoted in rural communities to address problems ranging from climate change to economic development with promises to provide a range of social benefits. In India the "Lighting a billion lives campaign" seeks to distribute 200 million lanterns and calculates that each unit will displace 40–60 l of kerosene annually (TERI, 2010). This goal has been incorporated into India's national plan, which seeks to distribute 20 million solar lighting systems by 2022.

At the same time, there is a growing recognition of the need for storage systems to realize the full potential of these renewable power sources and to improve reliability from fluctuations in power generation. Power storage is also essential to expand power to rural areas where the lack of access to the electricity grid makes decentralized

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0301-4215/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2011.06.021

grids or home-based systems the only cost-effective alternative. All solar lanterns are also dependent on batteries. Today the lead-acid battery (LAB) is by far the preferred storage technology for both solar and wind power and is likely to remain so for many years (at least the horizon of this study), based on their economic advantage and the existing infrastructure to meet demand. LABs are essential components of home sized units as well as mini power stations and microgrid systems that are envisioned in these plans.

Several recent studies quantify the life-cycle environmental and economic impacts of solar PV energy generation (Kannan et al., 2006; Celik et al., 2008; Stoppato, 2008; Chaurey and Kandpal, 2009a). Unfortunately, these studies focus on energy and greenhouse gas emissions of the system and pay little attention to the industry's reliance on LABs resulting in significant lead emissions during manufacturing and recycling. China's and India's stated goals include deploying solar PV systems throughout rural areas where LAB take-back infrastructure is weak. Moreover, in these countries lead emissions throughout the industrial supply chain are very high relative to global average loss rates.

This paper examines the potential environmental impacts from LABs used for PV solar applications in China and India. We apply published material flow analyses to estimate lead emissions that will result from the materials going into storage batteries for the planned capacity of solar power in these countries as projected in national plans for India (2022) and China (2020). These country-specific goals are adopted as the future base-case scenario for the purpose of estimating environmental impacts. We exclude projections of LABs needed for wind power and other applications, but have included LABs integral to solar lanterns as stipulated in country-wide projections for India.

2. Methodology

Studies have documented global and regional environmental lead losses during the mining, smelting, manufacture, and recycling process of lead products. These studies have focused on the LAB sector as batteries comprise about 80% of all lead consumption (Lave et al., 1995; Mao et al., 2006, 2007, 2008a, 2008b). Average lead losses over the life-cycle range from less than 5% of the mass of lead in a battery, in countries with advanced infrastructure, to over 30% in some developing regions. In the informal sector, recycling losses alone can exceed 50% of the mass of lead in the battery (Hoffmann and Wilson, 2000).

Mao et al. (2008a, 2008b) developed a material flow analysis framework to estimate aggregate environmental losses of the lead industry, focusing on production, fabrication and manufacturing (F&M), use, and waste management and recycling phases, where each process utilizes inputs from upstream processes, generates product, and deposits lead losses into environmental repositories (e.g. air, water, soil). Their regional analysis distinguishes China and India material flows (including losses).

Emission rate estimates, particularly during the recycling phase, are supported by those published by Mao et al. (2006, 2007), who focus on China's LAB industry. We assume zero losses during the *use* phase.

Recycling rates are difficult to reliably estimate, given the informal nature of collection mechanisms and large number of micro-scale recycling activities. Used lead batteries can also be stored for significant length of time before being processed. In many developing countries used batteries are also used multiple times (until they can no longer hold a charge) following reconditioning at local shops. Reconditioning shops are also involved in recycling spent batteries and/or serve as feeders to recycling facilities. In addition, trash and waste disposal facilities are generally scrutinized by waste scavengers who collect all items of value for use or resale. Because of this and their high inherent value (relative to average income), we assume a 100% recycling rate.

However, smaller lead batteries used in solar lanterns will likely have a lower recycling rate because of their lower unit value and their small size may make them less recognizable by waste scavengers. While their actual recycling rate maybe lower than 100%, there

Table 1
Material flow analysis showing lead (Pb) loss rates and quantities in China and India derived from Mao et al. (2006, 2008a, 2008b).

Step	Material flow (China) (metric tons)		Material flow (India) (metric tons)		Calculation or source
Production					
1	External refined product output [stock inputs (75) and exports (435)]	510	External refined product output [stock inputs (1)]	1	Mao et al. (2008b)
2	Tailing (165) and slag (68) output to environmental repository	233	Tailing (9) and slag (3.7) output to environmental repository	12.7	
3	Refined Pb sent to F&M process	590	Refined Pb sent to F&M process	119	
4	Proportion of refined Pb moved to F&M	0.54	Proportion of refined Pb moved to F&M	0.99	3/(1+3)
5	**Percent (of finished product output) slag and tailing loss**	**21.6%**	**Percent (of finished product output) slag and tailing loss**	**8.7%**	**(10 × 4 × 2)/9**
F&M					
6	Refined input from production process	590	Refined input from production process	119	3
7	External finished product output [export (210), scrap (26.7), discard/recycle (16)]	252.7	External finished product output [scrap (5.2), discard/recycle (3.1)]	8.3	Mao et al. (2008b)
8	F&M environmental loss	10.7	F&M environmental loss	2.1	
9	Finished product output	327	Finished product output	136	
10	Finished product proportion	0.56	Finished product proportion	0.94	9/(7+9)
11	**Percent (of finished product output) F&M environmental loss**	**1.8%**	**Percent (of finished product output) F&M environmental loss**	**1.5%**	**(8 × 10)/9**
Imports					
12	Imports into production and F&M	156	Imports into production and F&M	88.8	Mao et al. (2008b)
13	Global loss rate	12.1%	Global loss rate	12.1%	
14	**Upstream loss rate from imports (as a percentage of China's output)**	**5.8%**	**Upstream loss rate from imports (as a percentage of India's output)**	**7.9%**	**(12 × 13)/9**
15	Battery Pb produced	323	Battery Pb produced	323	Mao et al. (2006)
16	Environmental recycling loss	14.1	Environmental recycling loss	14.1	
17	**Output recycling loss Rate**	**4.5%**	**Output recycling loss rate**	**4.5%**	**16/15**
	Total loss rate China	**34%**	**Total loss rate India**	**22%**	**5+11+14+17**

is no evidence to support a different estimated rate. In assuming a 100% recycling rate, our model presents a lower range estimate of lead emissions per unit of deployed renewable energy capacity.

Estimated loss rates experienced during primary production, F&M, and recycling phases of the industrial supply chain are calculated based on values from existing literature summarizing the available aggregate national and regional data. We also incorporate upstream losses from the portion of refined lead that is imported into these countries by applying global average loss rates (12.1%) as estimated in Mao et al. (2008b).

Using data from material flow analyses presented in Mao et al. (2008a, 2008b, 2006), we show pollution rates during the life cycle of a LAB based on inputs and outputs from each process, including mining, concentrating, smelting, manufacturing, and recycling. A product output-based model is developed that estimates total lead losses per unit of finished product (mass of lead in batteries) for each process. Table 1 shows the aggregated model with the derived loss rate and quantity for each process. The bold entries in the table summarize loss rates for each process and show the calculations used to derive these rates.

Table 1 indicates the loss rate from F&M is 1.8% in China and 1.5% in India as a proportion of the losses that are attributed to the finished product output (i.e. lead battery), as shown in row 11. Moving back to the refined metal production process, the losses shown in row 5 (slag and tailings) are only attributed to the finished product output while excluding losses from exports or scrap that recirculates into the supply chain. Recycling loss rates for both China and India are 4.5%, as reported in Mao et al. (2006). Loss rates from imported metal used in the Production and F&M processes are 12.1% of imported metal (see row 13). Row 14 expresses the import loss rate as a percentage of the total domestic output. More detailed descriptions of the data and assumptions to generate these figures are available in the source literature. The process losses presented in Table 1 are illustrated in Fig. 1.

Battery life is variable and sensitive to climatic conditions and recharge protocol, but several studies point to a 20-year solar system requiring 2–5 sets of valve regulated lead acid (VRLA) batteries (Sri Lanka Business Development Centre, 2005; Hua et al., 2006; Celik et al., 2008; Chang et al., 2009). Here we assume that each solar PV system will require two sets of VRLA batteries over its lifespan and that each battery is composed of 65% lead, 15% fluid, and 20% plastic and connectors by weight (Linden and Reddy, 2002; Battery Council International, 2009). For solar lanterns we assume that, over a 20-year life, each will use four batteries (Chaurey and Kandpal, 2009b).

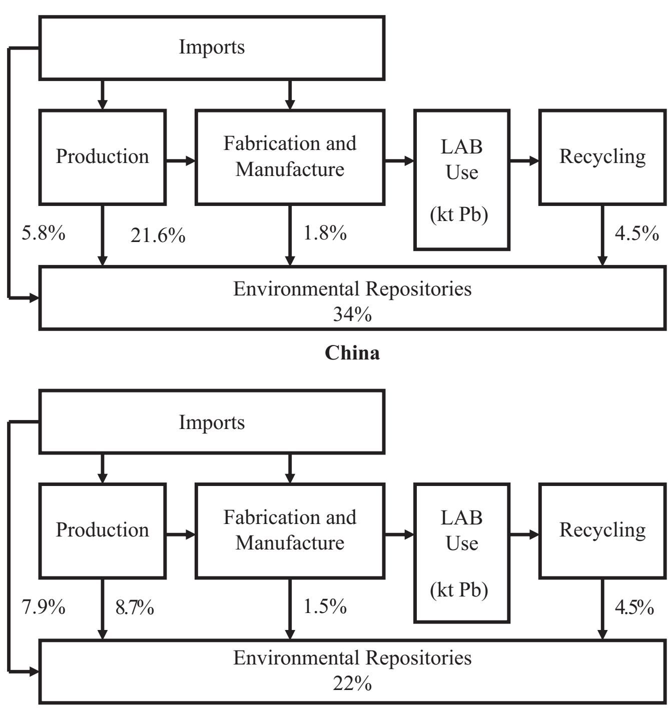

Fig. 1. Environmental lead losses in China and India expressed as a percentage of the mass of lead in LABs used. Derived from Mao et al. (2006, 2008a, 2008b).

LAB technology is evolving along with PV system design and there are a wide range of possible combinations that could be adopted in China and India depending on costs, desired storage capacity, geographical differences in solar arrays, and the speed by which energy grids are expanded and upgraded. However, since this study is illustrative, we do not speculate on the energy density trends and economics associated with stationary energy storage for this application, particularly in the context of rapidly developing countries over a relatively short time horizon. For our primary analysis, we assume current PV and VRLA technologies, grid capacity, battery energy density, and storage capacity will persist over the next decade in these countries. With these assumptions, VRLA batteries will remain the most cost-effective storage solution for stationary applications. For VRLA batteries, we use an energy density of 28 Wh/kg (Hua et al., 2006; Chang et al., 2009). For solar lanterns, we use an energy density of 32 Wh/kg, based on a survey of three commercially marketed solar lantern products (Lambert et al., 2000). In Section 4.1 we discuss alternative battery scenarios.

The optimal size for LAB storage for a particular solar installation or lantern is dependent upon various factors including the solar radiation in a given area, the capacity of the unit, the predicted number of days without sunshine, and the expected electricity demanded from the system. We estimate the number and size of LABs for these solar applications in aggregate from published data on comparable units that are currently in use in the region. We then calculate the mass of the LABs per kilowatt of installed capacity. Because of non-balanced demands, home-based solar systems require significantly higher battery capacity compared to microgrid applications (Chaurey and Kandpal, 2010). For home-based systems, we use data from a large field survey of 300 home solar units installed in Sri Lanka as most of this equipment is imported from Indian manufacturers and the country is representative of conditions in much of Southern India (Sri Lanka Business Development Centre, 2005). Published data on LAB storage employed in existing solar and wind plants serving local communities in China were utilized to estimate battery sizing for decentralized off-grid applications (Hua et al., 2006; Kannan et al., 2006; Celik et al., 2008; Chang et al., 2009). Sizing for solar lantern batteries is estimated from averaging the weights of three commercially available models from different manufacturers (Lambert et al., 2000).

We assume that all off-grid PV installations and portable lanterns are reliant on LABs for storage. There are advantages to storing some power on-site even in cases where a PV installation is grid-connected. In China it is estimated that LABs are employed in 75% of all existing PV units (Chang et al., 2009). For our analysis, we therefore assume that 75% of grid-connected units in both urban and rural areas of both China and India will utilize LABs for power storage. In many areas utilities are not purchasing power from small-scale PV solar units and even in urban areas the grid is not suited to energy inputs from this source. Some technical challenges in grid-connected systems include localized voltage regulation and voltage flicker (associated with fluctuations in solar power production) that can be mitigated with battery storage at the point of generation (Walker et al., 2008). Grids in some areas are less robust, operate with fluctuating voltage, and are less able to absorb fluctuating power loads. Therefore even in urban areas served by the grid, storage at the point of generation is advantageous to both the generator and the utility and has been advocated to overcome grid connectivity issues (IT Power Pty Ltd., 2009).

Based on published system descriptions, we estimate average storage capacity for the mix of planned PV systems is 16.7 kWh of battery storage capacity per kW of solar PV generating capacity, or 552 kg of battery per kW of installed solar capacity in China. Due to the reliance on smaller home-based units, we estimate India will require slightly more battery capacity of 581 kg of battery per kW of installed solar capacity (Hua et al., 2006; Kannan et al., 2006; Celik et al., 2008; Chang et al., 2009).

3. Results—LAB demand and emissions

The planned expansion of PV solar power will contribute significantly to the long-term growth in LAB markets and result in significant environmental lead emissions. Given the lack of alternative storage devices that are comparable from a cost or convenience perspective, energy storage for renewable sources in developing countries is expected to continue to be reliant on LAB technology during the life cycle of solar systems installed over the next decade.

3.1. China

Plans for China to install sufficient solar power to help boost its total proportion of renewable energy to 15% by 2020 are projecting 1.6 GW of battery-supported solar power—the majority of which will rely on photovoltaic technology (NDRC, 2007). We estimate the initial battery storage for these on- and off-grid systems will use 884 kt of LABs (containing 574 kt of lead). Using loss rates from those presented in Fig. 1 and based on two battery banks (one initial, one replacement) per solar installation, we estimate lead emissions totaling 386 kt during production, fabrication and manufacture, and recycling processes. This is broken down further, where 243 kt are lost during mining and smelting activities, 21 kt lost during fabrication and manufacture, and 55 kt lost during recycling. Moreover, 66 kt are lost from upstream mining and manufacturing processes for imported lead ore, scrap, and semi-finished products (Fig. 2), borne by the country of origin. The composite loss rate in China is 34% of the total lead output, where 21% is lost during mining processes.

Stated another way, assuming a 10-year LAB lifespan, China's solar installations require 55 kg of battery weight per kW-year of installed solar PV capacity. This is approximately 36 kg of lead per kW-year, representing 12 kg of lead loss per kW-year of installed capacity. A typical solar installation, like the 20 kW system modeled in Chang et al. (2009), would emit an average of 234 kg of lead per year. Two-thirds of those lead emissions will be released during mining and primary smelting, sectors that can presumably be regulated and controlled.

3.2. India

India plans to add 12 GW of PV solar power by 2022 in addition to new solar thermal capacity. India also will distribute 20 million solar lanterns in rural areas, each powered by 2.5 kg LABs. The solar PV systems will be supported by 6975 kt of LABs (Lambert et al., 2000). The solar lanterns will require 50 kt of LABs (assuming one initial plus three replacement batteries based on a 5-year lifespan) (Chaurey and Kandpal, 2009b). For PV solar power, we follow the same assumptions as for China—one initial and one replacement battery bank (10-year lifespan). Solar PV and solar lantern use results in lead emissions totaling 2030 kt. The mining sector loses 727 kt, 133 kt are lost during fabrication and manufacture, 444 kt are lost during recycling processes, and 727 kt are lost from imported lead (Fig. 2). Less than 2% of the losses are from solar lantern batteries. The composite loss rate in India is 22% of lead output, where 13% is lost during mining processes. India's loss rate per unit of installed solar capacity is 8.5 kg of lead loss per kW-year of installed solar PV capacity.

3.3. Implications of lead poisoning

Lead poisoning is among the most serious environmental health threats to children and one of the most significant contributors to occupational disease. Lead exposure causes symptoms ranging from a loss of neurological function to death depending upon the extent and duration of exposure. In children, moderate lead exposure is responsible for a significant decrease in school performance, lower IQ scores, and behavior problems (US Department of Health and Human Services, 2007). Environmental exposures from various sources combine to impact the overall body burden of lead and subsequent health outcomes.

Even before accounting for the exposures that are likely to result from the environmental emissions that our model predicts will result from future plans to expand PV Solar systems, both China and India are already experiencing negative health impacts as a result of domestic lead battery manufacturing and recycling industries. China has recently witnessed numerous mass poisoning incidents from the manufacturing and recycling of LABs,

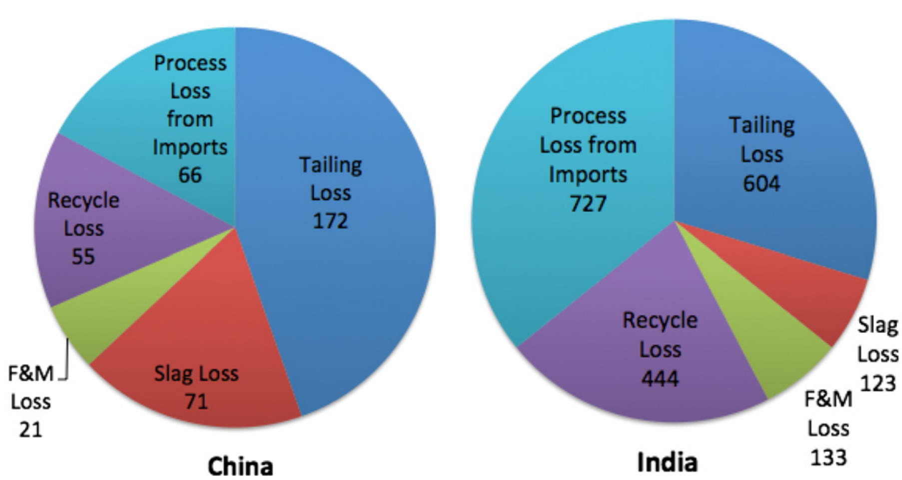

Fig. 2. Life cycle lead losses (kt) in China (installed capacity 2020) and India (installed capacity 2022) from LABs to support projected solar PV capacity.

some of which have sparked riots (Watts, 2009). A Chinese review paper, summarizing 32 published reports, indicates that 24% of children in China have blood lead levels exceeding the World Health Organization level of concern (Wang and Zhang, 2006). Similarly in India, 34% of children tested in a recent study exceeded this level (Ahamed et al., 2010). In April of 2010, the Chinese Minister of Environmental Protection, Zhou Shengxian, stated that, "in order to protect the environment and guarantee public health, avoiding excessive emissions of heavy metals will be on the top of our agenda this year" (Wang, 2010).

4. Discussion

Few studies have examined the life cycle of solar systems dependent upon lead batteries. Alsema (2000) conducted a life-cycle assessment of a small home-based solar system utilizing a "best case technology" scenario based on European and U.S. emission factors. Lead batteries and heavy metal emissions resulting from their production and recycling had the largest contribution to environmental effects but the quantity of lead emissions was not provided. Rydh (1999) examined the environmental impacts of lead-acid batteries for stationary applications with an aggregate weighting approach, but did not separately estimate lead emissions. Chaurey and Kandpal (2009a) calculated carbon emissions associated with PV solar systems (including lead batteries) used in India, but did not estimate the associated lead emissions. To our knowledge this effort is the first to attempt to quantify the lead emissions from the production and recycling of lead batteries over the life cycle of PV Solar systems.

Our analysis finds that large lead emissions will result from plans to develop PV power supplies in India and China over the next decade. As India proposes far more capacity and a greater proportion of solar home systems, it will experience more lead losses than China (2030 vs. 386 kt). These losses total about one-third of the 2009 global lead production (ILZSG, 2010). These emissions will contribute to soil and dust contamination in these countries and result in exposures to children and workers in LAB manufacturing and recycling operations. Although our analysis has focused on environmental emissions, significant occupational exposures are also associated with LAB manufacturing and recycling activities. We make no attempt to estimate incremental occupational exposures that will result from the anticipated increase in production associated with the demand for solar systems.

A small portion of the losses for India (approximately 2%) stems from plans to distribute 20 million solar lanterns. These lanterns will be disbursed in the most rural areas far from reliable transportation networks. Given that these batteries are much smaller and will be more widely dispersed than those associated with solar power installations, the recovery rate of these batteries may be well less than the 100% recycling rate. This application is also the most likely to adopt alternative battery technologies to improve portability, reduce charging time, and extend battery life.

Lead emissions occur at the beginning and end of the LAB life cycle, but the majority of losses are associated with the mining and smelting of lead ore. To the extent that more efficient recycling technologies can be adopted in these countries, actual losses may be lower due to a higher proportion of lead coming from secondary smelting. However, given the rapid growth in all sectors of the LAB industry, mining and primary smelting will continue to provide a substantial portion of lead throughout the time frame covered by our model.

Improvements in mining and smelting and the modernization of LAB manufacturing and recycling industries may significantly reduce emission estimates used in our calculations. However, these industries remain highly fragmented in both China and India and are unlikely to change drastically without major government intervention. Already Chinese regulations impose a minimum size and operating efficiency on lead smelters to force consolidation in this industry (Chinese Ministry of Environmental Protection, 2010). If these measures are fully enforced, we may see improvements in the industry.

Improvements in battery collection systems will also be necessary to facilitate the development of large-scale, environmentally sound recycling facilities in these countries. Investments in modern and efficient LAB recycling plants can only be justified if a supply of used batteries is readily available at a competitive price and in sufficient quantities in the local market. Competition for scrap batteries from small-scale recyclers and even backyard operators can deter investors from entering what could otherwise be a successful venture.

As low-level lead exposure is known to affect the nervous system, impacting school performance and lowering standardized test scores, this research suggests that increases in emissions (associated with increased demand for LABs) may impact educational outcomes. Since both China and India are increasing reliant on building a strong service sector, over time, these impacts can contribute to country level declines in economic development potential.

Several studies have estimated the costs of childhood lead exposure to society. Gould (2009) conducted a cost–benefit analysis of the social and economic benefits of lead hazard controls in housing accounting for health care costs, social and behavioral costs, special education, and improved lifetime earnings. The analysis showed benefits significantly outweigh costs particularly in early intervention in at risk communities in the U.S. Muennig (2009) calculated costs from improved high school graduation rates and reductions in crime for reducing lead exposures among the cohort of U.S. children up to age 6 that totaled $50,000 per child with a total cost to society of approximately $1.2 trillion. Similarly Landrigan et al. (2002) calculated the annual costs of childhood lead poisoning of $43.4 billion in the U.S.

Lead poisoning also imposes a range of hidden costs on developing countries. One study estimated that a 50% decrease in childhood blood lead levels in Nigeria could save the country $1 billion annually. The health care cost of lead exposure for adults is estimated to total $7 billion dollars (Ogunseitan and Smith, 2007). Without estimating costs associated with loss of lifetime earnings from impaired cognitive function, it is clear that just the healthcare costs associated with lead exposures on the national level can decrease productivity, leading to less investment and contribute to the continuation of the cycle of poverty (Bloom and Canning, 2000).

4.1. Alternative future scenarios

Our estimate of LABs necessary to meet future targets for solar power deployment in China and India is limited to the extent that these goals will be realized in the projected timeframe. A range of technological, policy, and economic constraints may arise over the next decade that can possibly divert resources away from investments in PV solar power. For example, an unexpected decline in global energy prices, or a new breakthrough that would significantly lower the cost of competing energy storage technology, can alter these plans and delay or eliminate such policy goals.

Even if these goals are realized within the anticipated timeline, new storage technologies may emerge to make the use of LABs less attractive. However, with the lack of any feasible, cost-effective alternatives, it is likely that LABs will continue to play a significant role in power storage in these countries over this time frame. For example, lithium ion (li-ion) batteries are technologically feasible alternatives but the cost of producing them is not expected to drop significantly over the next decade despite projections for a large increase in demand for automobiles and other applications (National Research Council, 2010). The costs of li-ion batteries are currently two to four times higher per kWh than LABs (US Department of Energy, 2010). Given the significant upfront capital investment in solar systems and competitive market pressures, it is very unlikely that more expensive storage options will be employed in PV solar systems in China and India.

At the same time new LAB technologies are being developed that have the potential to greatly improve performance without a substantial price increase. Through license agreements with both domestic and international manufacturers, several new technologies may enter developing countries over the next decade although it is not yet clear if they will be well suited to stationary storage applications. Several companies are pioneering new types of lead batteries that have a lower lead content but also claim to have improved battery life. The new technologies are competing to replace the traditional lead plates with either an activated carbon electrode, a carbon-graphite foam grid, or a combination of metallic and ceramic substrate characteristics (Frost and Sullivan, 2007; Axion Power, 2011; Firefly Energy, 2011). Still, it is unclear how successful these technologies will be in the marketplace in the next decade.

We calculated the storage capacity needed based on the national projections for PV solar installations. Both countries are also planning solar thermal power plants that do not require storage or LABs. To the extent that these plans shift over time away from PV systems to solar thermal technology, our analysis may overestimate the use of LABs. However, since much of the emphasis in both countries is on small-scale local power generation, which is more suitable for PV systems, we do not anticipate any major shift to thermal plants in excess of what is already being projected during this time period.

One potential application that could change the results of this analysis, particularly with the future generations of PV batteries, will be the availability of used electric vehicle (EV) batteries. Many countries around the world are embarking on significant EV initiatives. China has stated goals of deploying more than 40,000–60,000 EVs by 2012 (Huo et al., 2010). The li-ion (or derivative) batteries that power these cars are projected to have a useful life of about 8 years, where the battery capacity will have dropped to about 80% of full capacity, making them less useful for cars but potentially suitable for other applications. Considering a 48 kWh EV battery with 80% capacity yields 38 kWh of used battery capacity per vehicle. If 50,000 EV batteries retire in 2020, there could be 1.9 GWh of battery capacity available from second-use EV batteries. This would be enough battery capacity to displace only 16% of the proposed LABs to support China's solar PV goals (1.6 GW) in 2020.

Moreover, the ability of used EV batteries to support distributed energy storage poses significant challenges and might not be cost-effective (US Department of Energy, 2010). One constraint is the physical size of EV battery packs, with weights ranging from 181 to 300 kg, making them difficult to transport and even more difficult to locate in homes (Battery Energy Storage System & Technologies LLC, 2010). Additional considerations include the cost to refurbish used li-ion batteries, voltages, the potential lack of compatibility with charge controllers (used to protect batteries from overcharge), and battery terminal sizes. As a result, significant costs may be incurred for PV solar systems to be reconfigured to accommodate different battery types and sizes.

Based on current usage patterns, we estimate that LABs in home-based solar systems use three times more lead by weight per kW output than the LABs needed in small power stations. A shift away from individual home units to village-sized power plants would reduce the quantity of LABs necessary for storage. Upgrades to the electrical power grid along with the deployment of smart meters to facilitate the sale of electricity back to the grid can potentially reduce the reliance on LABs for storage. To the extent that such systems can be integrated with existing national grids and are deployed in rural areas currently without electricity supply may reduce our LAB consumption and lead emission estimates.

4.2. *Cumulative loss estimate scenarios*

We develop three alternative scenarios (Fig. 3) to account for the possible trends identified in the discussion above. The base case (Constant LAB, Constant Loss) life-cycle inventory shown in Fig. 2 is the cumulative total losses for India and China that account for the full lifespan of LABs to be utilized in these PV applications. The first alternative "Constant LAB, Low Loss" scenario assumes that improvements will be made to reduce lead losses throughout the production, manufacturing, and recycling phases of LABs at a steady rate of 5% (China) and 4% (India) per year until loss rates approach industrialized rates (about 5% loss). The second alternative scenario (Low LAB, Constant Loss) assumes that fewer LABs per kW will be used to meet the projected PV demand (at a rate of 5% reduction per year). This projection accounts for the possible introduction of new storage technologies or a shift to less storage requirements per kW that can come with improvements in electricity grids and metering. Both of these scenarios are arbitrary estimates based on possible, but not inevitable developments in the industry. The third "best case" scenario combines scenarios two and three showing additive reductions in lead losses. These scenarios omit the contribution of solar lantern batteries.

These alternative life-cycle assessments depict a range of estimates that can be expected over the lifespan of batteries to be employed in the PV solar installations (omitting solar lanterns) planned for China and India. The base case (Constant LAB, Constant Loss) results in 386 and 2001 kt of lead emissions in China and India respectively. Compared to the base case, the "Constant LAB, Low Loss" scenario reduces emissions by 33% and 26% in China and India, respectively; the "Low LAB, Constant Loss" scenario reduces emissions by 22% and 27% in China and India, respectively; and the best case "Low LAB, Low Loss" scenario reduces emissions by 47% and 44% in China and India, respectively, over the next 30 years (installation of a PV system at the end of the projected horizon, 2020 or 2022, with a 20-year lifespan).

5. Conclusion

New product diffusion is fraught with uncertainty, particularly in rapidly evolving markets like India and China. Moreover, our study focuses not on reliability of aspirational goals for solar PV application, but secondary systems for energy storage to support these goals. This study is exploratory in nature and limited by a lack of empirical evidence and the unpredictable nature of market adoption based on future energy economics and a range of other factors. We base assumptions about systems that will be installed over the next 10 years on solar PV systems in these countries that have installed to date and extrapolate some potential pathways to provide a likely range of values for lead losses. Some of our assumptions are limited by the lack of data (e.g. battery life span) that affect the strength of this study. However, modifying our assumptions will not substantially impact the outcome—documenting significant lead losses due to battery storage technology.

Despite the inherent limitations in predicting future technology adoption, the overall findings hold—LABs are likely to play a major role in storing power generated from solar applications in developing countries including China and India during the lifespan of systems

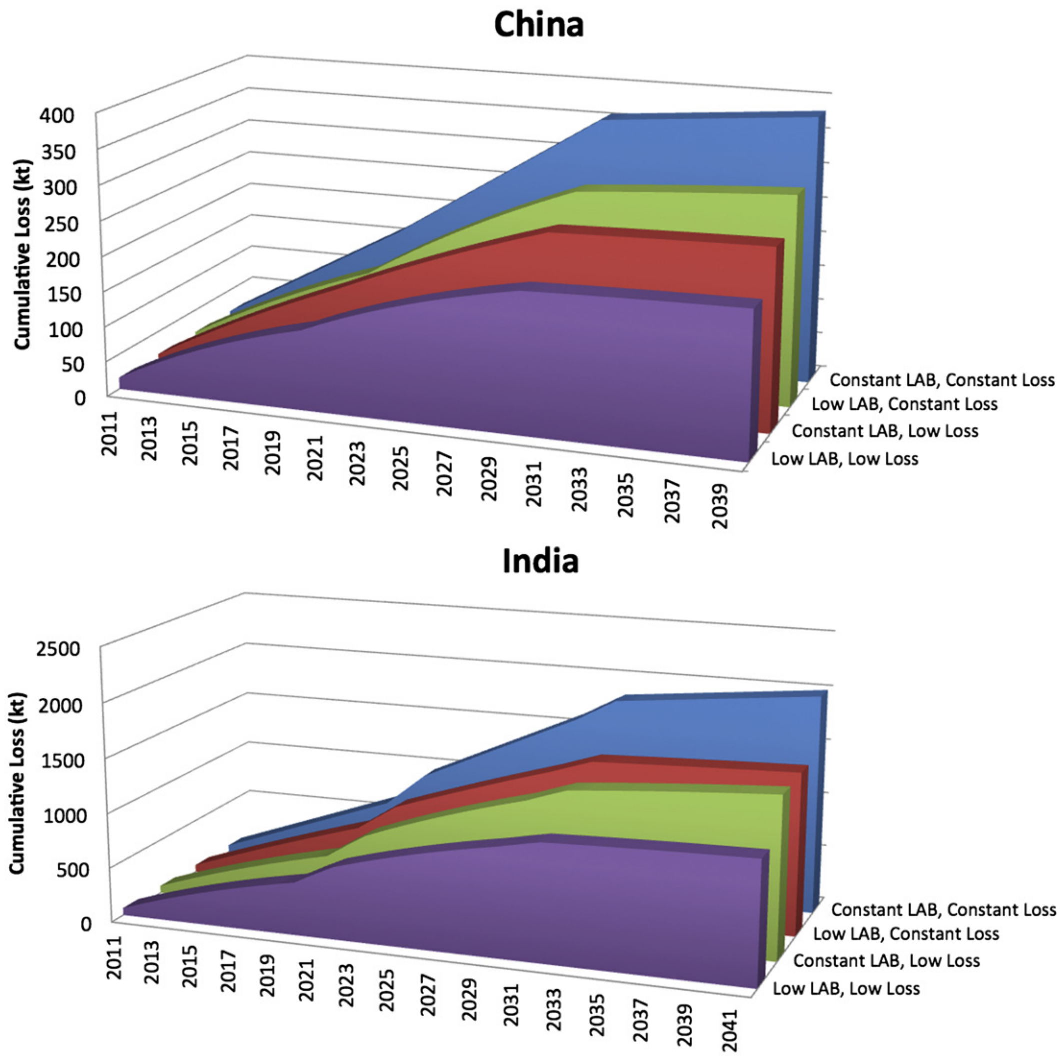

Fig. 3. Base and alternative lead emission scenarios for solar PV systems. Constant LAB: current LAB intensity (kWh LAB per kW PV) throughout system life cycle, Low LAB: LAB intensity decreases by 5% per year throughout timeline, Low Loss: ongoing annual improvement (5% China, 4% India) in mining and smelting, manufacturing, and recycling efficiency.

put into service over the next decade. It is increasingly clear that the use of these batteries will contribute significantly to environmental and occupational lead exposures. Our projections, while based on plans articulated by these two countries, are likely to be repeated throughout much of the developing world. In Africa, where an even larger portion of the population resides in areas off the electricity grid, small-scale solar technology holds even more promise. LABs are also the only energy storage technology used in that region and even fewer options exist to recycle them in an environmentally sound manner.

As advocates struggle to accelerate the adoption of PV solar technology, their reliance on LABs poses a significant threat to their environmental and sustainable development goals. Improving lead mining and primary smelting efficiency, LAB recycling practices, and developing collection systems to facilitate large-scale, environmentally sound LAB recycling, can help mitigate this criticism. However, it is much easier to implement large-scale collection programs if the cost and infrastructure are built into the distribution system from the time of installation. Solar companies must incorporate the collection of used LABs into their business model. Good product stewardship must include tracking the location of all batteries employed in these systems and offering a competitive monetary reward or deposit system for returning the LAB to a central location. One option may be to lease the LABs in these systems so that the solar power equipment distributors control their ownership.

Distributors of solar lanterns should also account for the collection of used batteries as units are sold. Deposits, purchase discounts on replacement LABs, and/or free pre-paid mailers to send back discarded LABs are possible measures to minimize losses from these applications. As there are plans to distribute ten times more of these lanterns (200 million) in India than what is accounted for in our estimates, and calls to distribute two billion of these globally, this technology represents a huge potential source of lead pollution in the future.

Governments can also play a role in controlling the pollution associated with backyard recycling operations by regulating the collection of used LABs. Very few developing countries have any mandatory take-back requirements and therefore the recycling industry is dominated by very small collectors and inefficient smelters. Although China and India both have regulations calling for the collection of used batteries by LAB manufacturers, neither has any specific requirement for how that should happen.

Without specific government regulations that mandate how used batteries will be collected, LAB companies and solar power distributors have little incentive to institute policies to improve product stewardship given the competitive nature of the industry. Mandatory purchase discount or deposit systems can be structured to greatly improve collection networks that can support large-scale smelters. Without large-scale collection, the investment needed to develop environmentally sound recycling will not materialize. Recycling plants must be assured an adequate, long-term supply of used LABs to invest in the appropriate infrastructure for environmentally sound recycling.

Acknowledgment

This research was supported in part by a generous grant from the Energy Foundation. The views expressed reflect those of the authors and not the Energy Foundation.

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