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Health benefits of adapting cleaner brick manufacturing technologies in Dhaka, Bangladesh

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Abstract A total of 1,000 kilns producing 3.5 billion bricks and consuming 0.85 million tons of coal per year resulted in an estimated 2,200 to 4,000 premature deaths and 0.2 to 0.5 million asthma attacks per year in the Greater Dhaka region. In this paper, the emission reductions and health cost savings are presented for moving to cleaner brick manufacturing technologies for the districts of Gazipur, Savar, Dhamrai, Rupganj, Manikganj, Kaliganj, and Narayanganj. A summary of various technologies and feasibility of these technologies based on lessons learnt from the pilots is discussed. We explored three "what-if" scenarios through 2020 for better energy efficiency, lower coal consumption, and lower emission rates, under which the total health cost savings are estimated to range between USD12 million annually for short-term implementation and up to 55 million annually for long-term implementation. Between 2015 and 2020, the cumulative health cost savings could range between USD126 and 234 million, which clearly outweigh any cost of capital investment necessary for the technology change. An improvement in energy efficiency will result in USD1.8 to 3.0 million per year in coal savings, which will accrue to the kiln owners collectively, and these savings will pay back the capital investment within 3–4 years, in addition to the health cost savings for the city inhabitants. Hence, the entrepreneurs have all the social, environmental, and economic incentives to adopt cleaner technologies. A major gap at the regulatory level is in building awareness for the entrepreneurs and setting up an incentive structure to implement this transition, which is being addressed by an advisory committee by the Government of Bangladesh responsible for the revision of the Brick Burning Act of 1989 and related legislations.

Keywords Particulate pollution · Dispersion modeling · Health impacts · Air quality management · ATMoS

Introduction

In Dhaka, vehicle exhaust emissions (from motorcycles, aged buses, passenger three-wheelers, passenger cars, commercial vans, and freight trucks), resuspended dust (due to the continuous vehicular movement on the roads), and the growing fossil and biomass fuel combustion in the industries and in the domestic sector remain a major concern for the deteriorating air quality (Hasan and Mulamoottil, 1994; Azad and Kitada, 1998; World-Bank 2006a, b; World-Bank, 2007; Begum et al., 2008; Begum et al., 2011; Begum et al., 2013; Guttikunda et al., 2013). The World Health Organization (WHO) studied publicly available air quality data from 1, 100 cities and put Dhaka among the top 20 cities with the worst air pollution in the world (WHO, 2011). The annual average concentration of $PM_{2.5}$ due to all sources is 100 μg/m^3 at a monitoring station near the Sangsad Bhaban (Parliament house—urban site) and 30 μg/m^3 at a monitoring station in the Atomic Energy Center (Dhaka) (campus site); both above the WHO guidelines of 10 μg/m^3 and Bangladesh national ambient air quality standard of 15 μg/m^3. $PM_{2.5}$ refers to the particulate matter (PM) with aerodynamic diameter less than 2.5 μm.

The findings, interpretations, and conclusions expressed in this paper do not reflect the views of the World Bank

Highlights 1. Review of cleaner technology in brick manufacturing industry
2. Atmospheric dispersion modeling of particulate pollution from brick kilns in Dhaka
3. Methodology and estimation of mortality and morbidity due to air pollution in Dhaka

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Among the industries in the Greater Dhaka region, brick kilns form a major source of pollution because they use crude technology and low-quality coal with high ash and sulfur content. The impact of the pollution from brick kilns is accentuated by the fact that the brick burning season coincides with the dry season between October and May, when ambient particulate concentrations are at their peak. The receptor modeling studies estimated an average contribution of 30–40 % originating from brick kilns to the total measured $PM_{2.5}$ pollution in the Dhaka Metropolitan Area (DMA) (Begum et al., 2008; Begum et al., 2011; Begum et al., 2013). Simulations using CMAQ chemical transport dispersion modeling system over Dhaka and Bangladesh estimated that at least 35 % of ambient PM_{10} and at least 15 % of the ambient $PM_{2.5}$ in DMA is associated with brick kiln emissions (Billah Ibn Azkar et al. 2012). Based on the analysis of private and social profitability of brick kiln technologies (World-Bank 2006a; Croitoru and Sarraf, 2012), we estimated the social and economic costs associated with poor air quality in DMA at USD500 million per year (BDT 8.2 million per kiln per 12.5 μg/m^3 of $PM_{2.5}$; 550 kilns; excess pollution of 85 μg/m^3, and per capita gross national income adjusted from USD819 in 2011 to USD1,024 in 2013).

The Government of Bangladesh (GoB) introduced regulations for brick industry under the Brick Burning Act in 1989 with limited success. In 2005–2006, a renewed effort to reduce air pollution from the brick kilns was undertaken by the Department of Energy. The study recommended various policy options and incentive structures to improve energy efficiency and introduce cleaner technologies for the brick manufacturing industry (World-Bank, 2010; World-Bank, 2011). Although not formally recognized as an industry, with a current manufacturing capacity of 12 billion bricks per year from 5,200 kilns surrounding all major cities of Dhaka, Khulna, Rajshahi, and Chittagong, this sector has a major economic significance in the national context. It contributes to 1.0 % of the gross domestic product and employs directly and indirectly over 1,000,000 people. The demand for bricks is expected to grow at least 50 % by 2020 (World-Bank, 2007; UNDP, 2011). A summary of the brick manufacturing industry in Bangladesh is presented in Table 1.

In this paper, we present the potential for reducing emissions and improving air quality upon implementation of cleaner brick kiln technologies, associated health benefits without and with cleaner technologies, and a discussion on the choice of policies to achieve these outcomes.

Table 1 Brick industry in Bangladesh at a glance

Parameter	Value (approximate)
All kilns in Bangladesh	5,000
All kilns within 50 km of the Greater Dhaka region	1,000
Natural gas fired kilns in Bangladesh	26
Annual brick production in Bangladesh	15 billion
Market value of bricks [a]	105 billion BDT (1.3 billion USD)
Contribution of brick manufacturing sector to annual GDP	1 %
Annual coal consumption	2.2 million tons
Import value of coal consumed	USD 140 million
Annual firewood consumption	1.9 million tons
Annual clay consumption	45 million tons
Total employment including supply of clay and coal, transport of bricks, and marketing	1 million
Growth rate between 2000–2010	5.6 % (construction industry)
Expected growth rate between 2010–2020	2–4 %

1 USD=80 Bangladesh Taka (*BDT*) in 2012 and market value per brick is considered at 7 BDT

Data resources

Study domain

The Greater Dhaka region, spread over an area of 1,500 km^2, includes the districts of Dhaka, Gazipur, Savar, Dhamrai, Rupganj, Manikganj, Kaliganj, and Narayanganj and includes approximately 1,000 brick kilns. The location of the brick kilns (Fig. 1) is digitized using the visual images from Google Earth and physically verifying the location of some clusters. Most of these kilns are located along the waterways linking the rivers, which also serve as the arteries for transporting raw material to the kilns and delivery of the finished product from the kilns.

The study domain extends from 89.7°E to 90.8°E in longitude and 23.3°N to 24.4°N in latitude, at a grid resolution of 0.02° in longitude and latitude. For modeling purposes, the Greater Dhaka region is further divided into seven subregions—one for DMA and six surrounding districts with brick kiln clusters. The boxes marked around the districts do not represent the official administrative boundaries of the districts. We are using these boxed boundaries for convenience and to extract the representative emissions and dispersion model results for further analysis.

Brick kiln cluster emissions

Most of the kilns in the region are conventional fixed chimney kilns (FCKs), which are relatively more polluting and energy-inefficient when compared to the newer and cleaner technologies, such as tunnel kilns, Hoffmann kilns, high draft kilns (like Zigzag kilns), and vertical shaft brick kilns (CAI-Asia, 2008; World-Bank, 2010). The FCKs are highlighted with a chimney of 120 ft, which improve dispersion of the

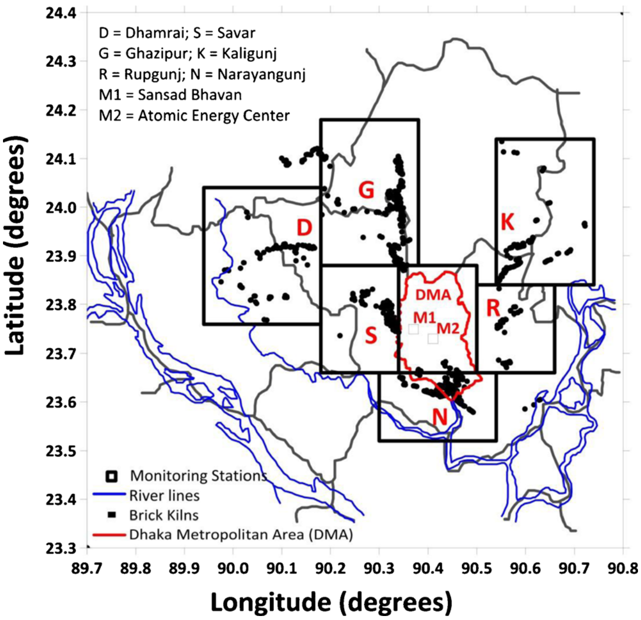

Fig. 1 Modeling domain covering the Greater Dhaka region, along with the location of the brick kiln clusters and monitoring stations (*small boxes* within DMA)

primary emissions and help to reduce the pollution levels in the immediate vicinity of the kilns. However, this means that the impact of long range transport of pollution is felt downwind of the sources. A representative cluster photograph is presented in Fig. 2 showing dispersion of the pollutants from FCK chimneys.

For the clusters in Gazipur, Savar, Dhamrai, Rupganj, Manikganj, Kaliganj, and Narayanganj, the estimated production rate is 3.5 billion bricks per year, consuming on average 20 t of coal per 100,000 bricks, totaling 0.85 million tons of coal per year. The precursor emissions because of this coal combustion are estimated at 23,300 t of $PM_{2.5}$, 15,500 t of sulfur dioxide (SO_2), 16,100 t of nitrogen oxides (NO_x), 302,000 t of carbon monoxide (CO), 1.8 million tons of carbon dioxide (CO_2), and 6,000 t of black carbon per year. The spatial spread of the emissions follow the density map presented in Fig. 1, with highest densities observed over Gazipur and Narayanganj. Details of production rates, fuel demand, emission factors, and emission estimation methodology are presented in Guttikunda et al. (2013).

Brick kiln combustion technologies

The clay bricks are fired (also known as baked) in a variety of kilns to give strength and permanent hardness for building construction. The technical and operational features of current and cleaner technologies in the brick manufacturing industry are presented in Table 2.

Traditionally, the clay bricks are shaped, sun dried, and readied for firing in "clamps"—a pile of bricks with intermittent layers of sealing mud and fuel. This fuel would vary from agricultural waste to biofuels like cow dung and wood to fossil fuels like coal and heavy fuel oil. The clamp style is a batch process and the most inefficient of the practices. In this type of kilns, all the material is fired at once and cooled to draw the bricks. A significant amount of energy is lost during the cooling process, with no possibility of recycling any heat.

Fig. 2 Cluster of fixed chimney brick kilns in operation in the Greater Dhaka region (photographed by Dr. Khaliquzzaman)

In Bangladesh, since 1990, the clamps have been replaced with FCKs, noted for its low cost of construction, lower energy consumption, and a production capacity of up to 40, 000 per day. In this, the firing is continuous where sun-dried bricks are loaded from one end and finished bricks are drawn from the other end. The fuel saving is achieved by reusing part of the energy that is otherwise lost in clamp kilns. For firing, fuel is stuffed intermittently from the top through the layers of bricks and the kiln is designed such that after combustion, the hot air on its way to the chimney passes through the yet unfired bricks. A major disadvantage of these kilns is associated with weather—an open caste kiln means they can be operated only in the non-monsoonal season. The older FCK designs allowed for a moving chimney; this technology is not available anymore because of higher local pollution from their low stacks.

Zigzag kilns, like the FCKs, are continuous in nature with batch output, with the firing circuit bent into a zigzag form. These kilns are divided into 16 or more chambers. Each chamber is connected to the next by a damper carrying hot gases from the fire. During firing, the hot air is directed into the chamber which passes into the adjacent chamber for preheating the bricks. As the hot air passes from chamber to chamber, it gradually cools, which is essentially a counter-current heat exchange process and a more efficient use of heat and fuel. In principal, they do not differ much from the traditional designs, but with a high rate of fire travel, assisted by a strong fan draught system and better insulation provides for more efficient heating.

The vertical shaft brick kilns (VSBK) is an emerging technology better suited for the small-sized brick kilns with a production capacity of 8,000 to 10,000 per day. This technology further reduces the fuel consumption and toxic emissions compared to FCKs via higher heat efficiency in multiple shaft architecture and better ratio of land used to

Table 2 Comparison of technical and operational benefits and constraints of current and alternative brick manufacturing technologies available in Bangladesh

Technology	Fuel consumed per 100,000 bricks	Investment and operational costs (million USD) [f]	Brick production capacity (million/kiln)	Number of kilns required to produce 3.5 billion bricks	Average tons of CO_2 produced per 100,000 bricks	Average reduction in PM emissions compared to FCK
FCK [a]	20–22 t coal	1.7	4.0	1,000	50	
Zigzag [b]	16–20 t coal	1.6	4.0	1,000	40	40 %
Hoffmann [c]	15,000–17,000 m^3 NG	5.7	15.0	270	30	90 %
Hoffmann [d]	12–14 t coal	5.7	15.0	270	30	60 %
VSBK [e]	10–12 t coal	1.6	5.0	800	25	60 %

[a] *FCK* fixed chimney bull trench kiln, *NG* natural gas, *VSBK* vertical shaft brick kiln

[b] Some zigzag pilot kilns are in operation, listed as poor to medium performance. Any improvement in the efficiency of operations can lead to further reductions in coal consumption

[c] Manufacturing period for Hoffmann kilns is round the year, compared to the current non-monsoonal month operations for the other kilns, thus increasing the land and raw material requirements; link to natural gas grid and continuous fuel supply is a major constraint

[d] Initial investments are higher for Hoffmann kilns

[e] Operational models are available in India and Kathmandu (CAI-Asia, 2008)

[f] Costs include initial investment, land, building, operational, and taxes estimates (World-Bank, 2011)

production output. The sun-dried bricks and combustion fuel are stacked in batches on to the top of the shaft, which progressively move from the pre-heating, firing, and cooling zones before reaching the bottom of the shaft for periodic removal. These kilns can also be designed for all weather conditions with roof-protected arrangement. VSBK design and construction details based on a pilot implementation in Bangladesh are presented as a manual in World-Bank (2011).

Two other technologies currently being introduced in small numbers are hybrid Hoffman kilns (HHK) and tunnel kilns (TKs). These kilns, originally designed and developed in Germany, are most operational in China, with a production capacity ranging between 50,000 and 200,000 bricks per day. Both of these kiln types have better insulation provided by the thick walls to reduce heat loss. Also, due to flue gas scrubbing in the drying tunnels, the particulate emission levels are further reduced. In the HHKs, the fire zone moves similar to the FCKs and in the TKs, the fire zone is fixed, and bricks are moved in trolleys. The tunnel kilns are more automated and operational under all-weather conditions.

Methods and inputs

Health impacts evaluation

The benefits in health impacts of mortality and morbidity are calculated using concentration-response functions established from epidemiological studies. Pope et al. (2002), HEI (2004 and 2010a), and Atkinson et al. (2011) summarize the current scientific literature on the health impacts of outdoor air pollution based on cohort and meta-analysis, and Wong et al. (2008) discuss results from recent epidemiological studies in Asia conducted under the Public Health and Air Pollution in Asia program. The methodology utilized in this study was applied for similar studies as follows: Ostro (2004) for global disease burden; Bell et al. (2006) for Santiago, Mexico city, and Sao Paulo; GAINS (2010) for Asia and Europe regional studies; Cropper et al. (2011) for power plants pollution in India; Guttikunda and Jawahar (2012) for six cities in India; and Croitoru and Sarraf (2012) for private and social profitability of brick kiln technologies in Dhaka. Details on various concentration-response functions and coefficients and their associated confidence intervals are summarized in a case study for Hong Kong and Guangzhou cities (Jahn et al., 2011).

In this study, we analyze the health impacts of $PM_{2.5}$ pollution from brick kiln emissions only, which, therefore, underestimates the actual health burden of the total effects of air pollution from all the other sources combined, such as vehicle exhaust, domestic fuel combustion, other manufacturing industries, garbage burning, and construction activities. The mortality rates are quantified using the relative risk functions defined as follows (WHO, 2004):

$$\delta E = \sum_{i=1}^{\#grids} \delta P^{i}_{\exp} * \delta POP_i * IR \tag{1}$$

$$\delta P^{i}_{\exp} = (RR_i - 1)/(RR_i)$$

$$RR_i = \exp(\beta * \delta C_i)$$

The morbidity rates are quantified using the following equation:

$$\delta E = \sum_{i=1}^{\#grids} \beta * \delta C_i * \delta POP_i \qquad (2)$$

Where

δE = number of estimated health effects (various end points for mortality and morbidity).

IR = incidence rate of the mortality and morbidity endpoints. A total death incidence rate for Bangladesh is set at 6.1 per 1,000 inhabitants.

δPOP = the population exposed to the incremental concentration δC in grid i; defined as the vulnerable population in each grid.

δP_{exp} = prevalence of exposure to the total pollution level in grid i.

RR = relative risk for mortality and morbidity end points at the total pollution level.

β = the concentration-response function, which is defined as the change in number cases per unit change in concentrations per capita. For all-cause mortality in this study, the function is defined as 3.9 % change in the crude mortality rate per 4 $\mu g/m^3$ of change in the $PM_{2.5}$ concentrations (Hart et al. 2011). We also estimate morbidity in terms of asthma cases, chronic bronchitis, hospital admissions, and work days lost. The concentration response functions for morbidity are summarized in Table 3. The following assumptions are applied (a) that the concentration-response to changing air pollution among Dhaka residents is similar to those residents where the epidemiological studies were performed and (b) that the public health status of people in the future years remain the same as in 2010.

δC = the change in concentrations from the ambient standards or between the business as usual and introduction of cleaner technologies scenarios in grid i.

Particulate concentrations

We utilized the Atmospheric Transport Modeling System dispersion model—a regional (and urban) forward trajectory Lagrangian Puff transport model to estimate the ambient PM concentrations (Calori and Carmichael 1999). A detailed review of the data resources, meteorological inputs, model parameters, and validation of the model results for the Dhaka region are presented in Guttikunda et al. (2013). The meteorological data for the city (three-dimensional wind, temperature and pressure, surface heat flux, and precipitation fields) is derived from the National Center for Environmental Prediction global reanalysis (NCEP 2012), interpolated to the model grid.

The dispersion model results are available for 55×55 grids, for the study domain, at a grid resolution of 0.02° in longitude and latitude (approximately 2.0 km). The modeled annual average $PM_{2.5}$ concentrations are presented in Fig. 3. The modeled concentrations from the dispersion model are available as 24-h average and 24-h maximum over the manufacturing period. This information is utilized to estimate the range of exposure rates for health impacts analysis.

For the health impacts, we considered only the $PM_{2.5}$ concentrations, which include the primary and secondary PM contributions via chemical transformation, in the form of sulfate aerosols from SO_2 emissions and in the form of nitrate aerosols from NO_x emissions. The nitrate aerosol transformation is explained in Holloway et al. (2002), and sulfate aerosol transformation is explained in Guttikunda et al. (2003).

The range of concentrations by model grid for the cluster regions is presented in Fig. 4. The bar graph represents the 25th and 75th percentiles, along with the grid-averaged $PM_{2.5}$ concentrations in the cluster region, over one standard deviation. The contribution of the brick kilns in the respective regions is proportional to the number of the kilns located in the vicinity. Except for DMA with no kilns within the administrative boundary that is known to experience dispersed pollution from kilns in the surrounding districts. The modeled $PM_{2.5}$ concentrations over DMA ranged from 4 to 56 $\mu g/m^3$ over the manufacturing period (the range indicates the 5th and 95th percentile concentration per model grid over the grids covered by the designated DMA box in Fig. 2) and an average of 30 $\mu g/m^3$. We also modeled the contribution of particulate pollution from individual clusters to DMA and estimated 27 % originating from Narayanganj (to the south with the highest kiln density), 30 % from Gazipur (to the north with equally large cluster spread along the river and canals), and 23 % from Savar.

Gridded population data

The model grid population is estimated using GRUMP (2010). The total population of DMA, which is a combination of the urban and rural areas, is 15 million in 2010, with a population density of more than 40,000 inhabitants per square kilometer in the main district—one of the highest in the world. The metropolitan region had an estimated 12.5 million inhabitants in 2008. The continuing growth reflects ongoing migration from rural areas, which accounted for more than 50 % of the city's growth in the earlier decades. The modeling domain in Fig. 1, the Greater Dhaka region covering DMA and its satellite districts, accounts for a total population of 22.5 million. For the population exposed (δP) to the incremental concentrations (δC), 55 % of the grid population was considered vulnerable to outdoor air pollution (HEI 2010b).

What if scenarios for cleaner technologies

The technical and operational features of current and cleaner technologies in the brick manufacturing industry are presented in Table 2. Between the available technologies, the newer

Table 3 Concentration-response functions (CRF) per μg/m^3 change in the mean pollution levels and monetized values of health effects (1 USD=80 BDT in 2012)

Health effects	CRF units	CRF for PM	Cost (BDT)
Mortality			3,000,000
Chronic bronchitis	Per 100,000 adults	6.12	350,000
Asthma attack	Per 100,000 asthmatics	3,260	115
Lower respiratory illness	Per 100,000 children	169	80
Chest discomforts	Per 100,000 adults	1,000	100
Respiratory hospital admission	Per 100,000 population	1.2	7,700
Emergency room visits	Per 100,000 population	23.5	230
Restricted day activities	Per 100,000 adults	5,700	100

technologies such as VSBK, zigzag, and HHK could result in at least 40 % reduction in the PM emission rates compared to the currently used FCK technology. World-Bank (2010) and UNDP (2011) are working with the regional bodies and kiln owners in Bangladesh to pilot and promote these technologies in Dhaka. The combination of energy savings and reduction in pollution is a win-win situation, in which the industry benefits because of savings in energy costs and the city benefits because of reduction in health costs.

One documented technology in Bangladesh is VSBK (World-Bank 2010). Currently, there is only one such kiln operational with a production capacity of 8,000 bricks per day. In spite of being a lower cost and low pollution technology, there was no uptake for the VSBKs beyond the one pilot. The major barriers for the uptake of this technology are product quality (bricks are not as red as they are from FCK and HHK—a reason for common rejection among the builders), low production rate (compared to 20,000+ from others), and need for high land above flood level (meaning more capital investment). Similarly, the brick kiln owners regard the HHK technology as more capital intensive, since this technology also needs high land above flood level. Primarily for these reasons, the uptake for HHK is also slow although production rates and brick quality are considered profitable.

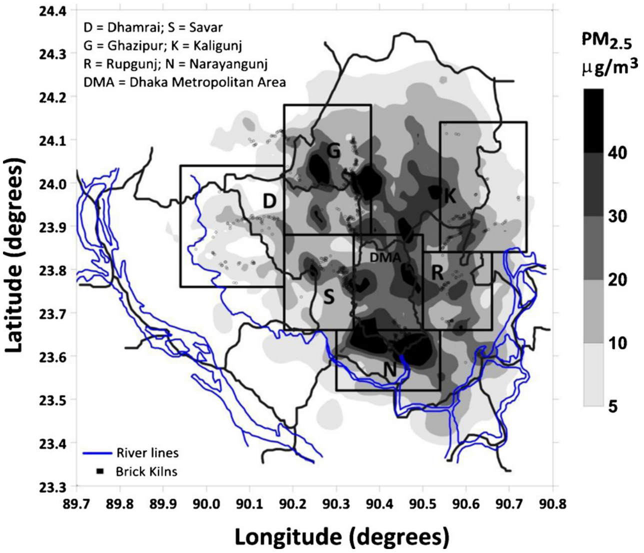

Fig. 3 Modeled PM$_{2.5}$ (μg/m^3) concentrations averaged over the brick manufacturing season for the Greater Dhaka region

On the other hand, FCKs can be converted to Zigzag at low costs in the low lands, at the same site, in less than 3 months of additional physical modifications. The production capacity is the same or higher compared to the FCKs. The brick quality is as good as or better than FCK, with continued additional benefits from energy savings and emission reductions. Of the available cleaner technologies in Bangladesh, the kiln owners find the zigzag technology the most attractive because they neither need to relocate nor they have to look for high land.

For the reasons discussed above, there is now an informed demand from the GoB to push for zigzag technology, since there is limited or no uptake of the VSBK or HHK technologies from the kiln owners. Given the current trend in the brick kiln demand and awareness of the technologies among the kiln owners, we defined the following temporal scenarios:

1. Short-term scenario: conversion of 30 % of the kilns to zigzag or equivalent technologies in the next 3 years (through 2016–2017)
2. Medium-term scenario: conversion of 50 % of the kilns to zigzag and HHKs in the next 5 years (through 2018–2019)

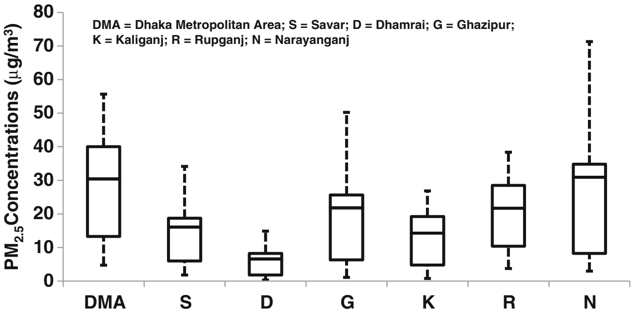

Fig. 4 Range of modeled PM$_{2.5}$ concentrations (25th, 50th, and 75th percentile concentrations over one standard deviation) in the designated cluster regions of the Greater Dhaka region

3. Long-term scenario: conversion of 70 % of the kilns to zigzag and HHKs or equivalent technologies like tunnel kilns in the next 7 years (through 2020–2021)

We calculated the health impacts and benefits associated with the incremental change in particulate pollution, as a result of introducing cleaner technologies under these three scenarios.

For the scenarios, it is assumed that the adoption of these technologies will be proportional to the cluster sizes in the regions presented in Fig. 1. However, it is possible that the adoption rates in these clusters could vary resulting in differential results. For example, the DMA region is estimated to receive 27, 30, and 23 % of its total particulate pollution from brick kilns emissions originating from Narayanganj, Gazipur, and Savar, respectively (Guttikunda et al., 2013). Any prioritized introduction of the cleaner technologies in these clusters will result in higher benefits for the densely populated areas of DMA.

Health impacts valuation

The "value of statistical life" (VOSL) is established from surveys based on "willingness to pay" (WTP) by individuals for benefits associated with the health impacts. This methodology was applied for assessing the impacts of current air pollution levels and for future "what if" scenarios in a number of countries and cities, in spite of known uncertainties in the associated inputs, such as the relative risk functions for health impacts of air pollution, the emissions inventory for multiple pollutants, spatial resolution of dispersion modeling, and monetizing impacts based on surveys (Bell et al. 2011). For example, this methodology was applied for analyzing the impacts of outdoor air pollution on human health in Alberini et al. (1997) for Taiwan; Kan et al. (2004) for Shanghai; Bell et al. (2006) for Mexico City, Sao Paulo, and Santiago; Wang and Mullahy (2006) for Chongqing; Hedley et al. (2008) for Hong Kong; Desaigues et al. (2011) for nine European countries; Patankar and Trivedi (2011) for Mumbai.

The base values (V) are obtained from the WTP studies conducted in US, which are scaled to Bangladesh using economic indicators like per capita gross national income (World-Bank 2006a, b; Croitoru and Sarraf, 2012). An important question to ask, when performing cost–benefits analysis in developing countries, is whether estimates of WTP computed in US (and other developed countries) can be transferred to developing countries like Bangladesh? There are a variety of approaches to making such a transfer.

$$\log(V_{bd}) = r * \log\left(\frac{GNI_{bd}}{GNI_{us}}\right) + \log(V_{us}) \qquad (3)$$

The value of "r", as elasticity function, is reported to be in the range of 0.4 to 1.2 (Alberini et al. 1997). A value of elasticity less than 1.0 means that WTP is lower in low income country than in a higher income country, but less proportional to the income differential. This is the likely scenario for Bangladesh. However, we utilized a more conservative approach by correcting only for income differentials and assume an elasticity of WTP with respect to income as 1.0 (World-Bank, 2011). The values for the cost of health effects including VOSL and morbidity endpoints are presented in Table 3.

Results

Mortality and morbidity estimates

The health impacts are calculated for the business as usual scenario, with all the kilns operating the lower efficiency FCK technology and for the three temporal scenarios by overlaying the gridding population with the modeled $PM_{2.5}$ concentrations from the brick kiln emissions for each case. Total premature mortality using the average and maximum exposure rates for the business as usual scenario ranged between 2,200 and 4,000 per year. The mortality and morbidity estimates are for pollution due to brick kiln emissions only and do not indicate exposure rates for other sources. For the source apportionment studies, the brick kiln emissions account for 30–40 % of the annual observed $PM_{2.5}$ concentrations in DMA (Begum et al., 2008; Begum et al., 2011; Billah Ibn Azkar et al. 2012; Begum et al., 2013).

For reference and comparison, the city of Delhi, which is similar in size and observed pollution levels as Dhaka, HEI (2010b) estimated an annual mortality of 3,000 due to on-road exposure, based on proximity of inhabitants along the major and arterial roads, and Guttikunda and Goel (2013) estimated the total mortality of 7,350 to 16,200 per year due to air pollution from all sources—up to 10 % of the ambient $PM_{2.5}$ concentrations in Delhi is attributed to emissions from brick kilns, located more than 20 km away from the city.

Since the inventory is based on bottom-up activity data, such as brick production rates per kiln and secondary information on emission factors from studies conducted in India, Asia, and global databases, it is difficult to accurately measure the uncertainty in our estimates. We estimate the overall uncertainty in the emissions inventory development and dispersion modeling as ±20–40 %. The uncertainty in estimating and using the concentration-response functions is explained in Atkinson et al. (2011) and Hart et al. (2011). The spatial variation in the concentrations also led to some uncertainty, which is accounted in the health impacts assessments by using average and maximum exposure rates from the dispersion model results.

Health cost savings of cleaner technologies

The consolidated health savings for moving to cleaner technologies under the three scenarios is presented in Table 4. The health cost savings for the Greater Dhaka region under the three temporal scenarios are estimated to range between USD12 million annually for short-term implementation and up to 55 million annually for long-term implementation, depending on varying degrees of introductions. Between 2015 and 2020, until successful implementation of the cleaner technologies, the cumulative health cost savings for the residents of Dhaka could range between USD126 and 234 million.

The annual fuel savings due to improvement in energy efficiency by shifting from FCK to zigzag technology is estimated between US\$1.8 and 3.0 million. These benefits will accrue to the kiln owners and operators (Table 2).

The transition cost, to shift from FCK to zigzag, is estimated at USD4.0 million (over a 3–4-year period) with benefits outweighing the costs, from fuel savings alone. The investment requirements at plant level are believed to be comparatively small and affordable for most entrepreneurs.

The costs and benefits discussions are intended from air pollution and health perspective only. The sectors and issues not included, which can provide more benefits to the kiln owners and the city inhabitants, are the following:

1. The social and labor issues associated with changes in the kiln technologies. Most of the current labor force is seasonal—working in the agricultural sector during the monsoons and at the brick kilns during the non-monsoonal months. We did not study the possible changes in the labor market, if the kilns move their operations from seasonal to annual.
2. The indirect benefits of reduction in occupational health hazards due to the exposure of the labor to high noise, heat, and dust hazards at the brick-manufacturing site (Hai et al. 2001; Gupta 2003; Isabelle et al. 2007; Alam 2012) via any improvement in the energy efficiency and reduction of fuel used.
3. Since most of the kilns are located closer to the agricultural lands, there is also documented evidence of reduced yield from orchards and other crops due to air pollution. A reduction in the ozone precursor emissions such as NOx, CO, and volatile organic compounds will benefit the agricultural sector (Shindell et al. 2012). In this paper, we focused on PM pollution only and no photochemical modeling for ozone was conducted.
4. The topsoil from river beds contains organic matter and rich nutrients necessary for sustainable agriculture. When this topsoil is removed for brick making, the deeper layers with harder surface are exposed and such soils are not so favorable for crop growth for a few more years. Use of topsoil in brick making leads to land degradation and loss of agricultural productivity (Singh and Sarfaraz Asgher 2005). Many countries have banned the use of topsoil for brick making. The negative impacts of topsoil removal include additional use of fertilizers and nutrients to improve soil quality at the cost of additional environmental problems like fertilizers in the water runoff. Raut (2003) and EAERE (2008) quantified productivity losses of up to 20 % due to operational brick kilns. However, no equivalent study was found for Bangladesh.
5. Although the use of fuel wood is banned under the Brick Burning Act of 1989, it is known that considerable amount of fuel wood is still used. Such use has adverse impact on the forestry sector.

Table 4 Reduction in number of annual mortality and morbidity cases and savings in terms of health costs up to the introduction of cleaner technology

Annual reduction in cases of	Short-term	Medium-term	Long-term
Premature mortality	280–500	460–860	660–1,220
Chronic bronchitis	350	600	850
Asthma attack (million)	0.1	0.1	0.1
Lower respiratory illness (million)	0.1	0.1	0.1
Chest discomforts (million)	0.2	0.3	0.4
Respiratory hospital admission	100	160	220
Emergency room visits	1,700	2,800	4,000
Restricted day activities (million)	0.5	1.0	1.0
Annual health cost savings			
In million USD	12–23	21–39	30–55
In million BDT (1 USD=80 BDT)	960–1,800	1,640–3,060	2,360–4,380
Cumulative health cost savings between 2015–2020			
In million USD	126–234		
In million BDT	9,920–18,500		

Conclusions

A change from the current practice of FCKs to any of the emerging technologies will yield significant benefits by improving the energy efficiency of the industry, improving the local air quality and urban environment, reducing the ozone forming precursor emissions, and improving overall well-being of the urban population in Dhaka. The costs and benefits in this analysis are the total equivalent value to the community as follows: kiln owners in fuel savings, general public in health savings, and global community in CO_2 savings. The cumulative benefits from health and fuel savings, between 2015 and 2020, of adapting cleaner technologies at the kilns in Dhaka outweigh any cost of capital investments necessary for the change.

In Bangladesh, for enforcing the technology change, a combination of “command and control” approach is necessary. For example, (a) stricter fuel and emission standards will push the kiln owners towards better operations and energy efficiency, (b) performance-based incentives such as fuel or emission certificates for achieving higher operational energy efficiency, and (c) market-based incentives like emission caps and polluter pay concepts. An important lesson from the pilot projects is the willingness of the kiln owners to adapt, followed by the ease of implementing the changes with minimum hindrances to the status quo. For example, the owners are more willing to convert from FCKs to zigzags (possible 40 % improvement in emissions) more than to convert from FCKs to VSBK and HHK technology (possible 60–90 % improvement in emissions), solely because of higher capital investments in the latter, while the former can be adapted easily in less than 3 months on the same grounds.

The GoB recognizes the need to address the problem of urban air pollution in Dhaka on multiple fronts because of its impact on human health, environmental health, and the economic productivity. The air quality management programs should note that a “combined benefits” approach that helps reduce urban air pollution and mitigate GHG emissions would be ideal, especially in the case of Dhaka, for addressing the energy efficiency and emission reduction programs for the brick manufacturing industry. However, this calls for demonstrating innovative approaches, rather than the regulatory approach, that the GoB has traditionally undertaken. An advisory committee with representatives from the government, industry (owners association), and stakeholder institutions in Bangladesh is planning to develop a long-term policy framework for the industry. The policy and institutional set of the advisory committee will also be responsible for the revision of the Brick Burning Act of 1989 and other related legislations, keeping in mind the financial and technical feasibility of various technologies and lessons learnt from the pilot applications.

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