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Emissions and energy performance in South Asian brick kilns

Measurement report 2016

University of Illinois Urbana-Champaign
Civil & Environmental Engineering
&
Greentech Knowledge Solutions Pvt. Ltd.
&
Mountain Air Engineering
&
International Centre for Integrated Mountain Development (ICIMOD)

Cheryl Weyant, Sonal Kumar, Sameer Maithel, Ryan Thompson, Emily Floess, Ananthakrishnan Ravi,
Sagar Adhikari, Santosh Gautam, Sujan Shrestha, Ellen Baum, Tami Bond

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1 Introduction

Process characteristics and emissions from six brick kilns were measured in India and Nepal in March of 2016. These measurements provide climate and pollution relevant metrics from select brick kilns in South Asia. Each brick kiln was chosen to highlight a measurement challenge or to provide evidence of emissions changes due to retrofitting existing kilns. Table 1 shows a summary of the kilns measured. Detailed descriptions of the kiln types and their operations can be found at Lalchandani and Maithel (2013) [3] and Weyant et. al (2014) [9].

Table 1: Kilns measured and key characteristics. The date refers to the measurement dates.

Name	**Type**	**Process**	**Location**	**Dates**	**Scale**
BTK India	Bull's Trench Kiln	Continuous	Hapur, UP, India	Mar 1-3, 2016	35000[a]
NDzig India	Natural Draft zigzag	Continuous	Greater Noida, UP, India	Mar 5-7, 2016	54000[a]
BTK Nepal	Bull's Trench Kiln	Continuous	Kathmandu, Nepal	Mar 17-18, 2016	40000[a]
FDzig Nepal	Forced Draft zigzag	Continuous	Kathmandu, Nepal	Mar 19-21, 2016	64000[a]
Large clamp	Clamp	Batch	Sangli, MH, India	Mar 9-11, 2016	250000[b]
Small clamp	Clamp	Batch	Pune, MH, India	Mar 12-14, 2016	85000[bc]

[a] bricks per day
[b] bricks per batch
[c] double sized bricks

The Bull's Trench Kilns (BTKs) measured in India and Nepal are baseline, unimproved, kilns, while the natural draft and forced draft kilns were converted from BTK technology within the past year. These retrofits were anticipated to improve particulate matter emissions and energy consumption. The clamp kilns measured in Maharashtra, India had not been previously measured and posed challenges due to fugitive exhaust (non-chimney kilns) and non-continuous production. These measurements provide some of the first emission factors from this type of kiln.

1.1 Bull's Trench Kiln, Hapur, India (BTK India)

A fixed chimney BTK was measured in Hapur, UP, India on the 1st - 3rd of March 2016. The kiln produced about 35,000 bricks per day, including both solid and perforated bricks. At this site, bricks were both hand molded and molded by an extruder. Bricks were either sun or shade dried. The primary fuel was bituminous Assam coal and secondary fuels were dried mustard stalk and wood. Each of the fuels were manually fed intermittently. There would be periods were only one fuel type was added. The exhaust was channeled to the stack through a movable shunt system.

The owner was a second-generation brick maker running a 70 year-old family business. The kiln supplied a market with a radius of about 50-70 km, including Delhi. The kiln was operated in the dry season only (Dec to June) and was measured in early March (mid-season). Photographs at the site are shown in Figure 1. This kiln was also monitored in 2012 and the results presented in Weyant et. al (2014) [9].

(a) (b)

(c)

Figure 1: (a) Chimney of BTK measured in India. (b) Scaffolding setup on central stack. (c) Manual coal feeding in BTK.

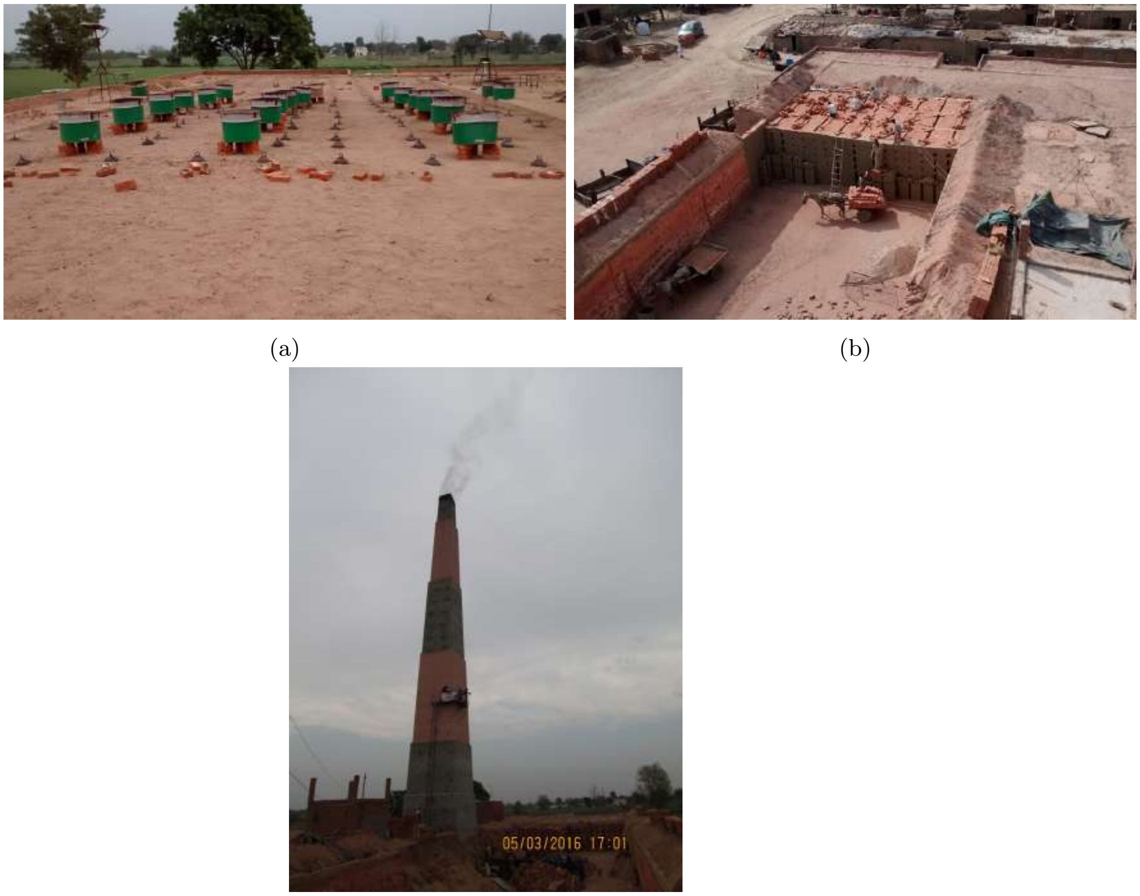
1.2 Natural Draft zigzag, Greater Noida, India (NDzig India)

A natural draft zigzag kiln was measured in Greater Noida, India on the 5th - 7th of March 2016. It had been retrofitted to a zigzag kiln from a fixed chimney BTK in 2016. The measurements took place in the first year of transition for this kiln and some of the processes were still being adjusted at the time of measurement. Production capacity was about 54,000 bricks per day. Bricks were hand molded and open dried. The kiln operated in the dry season only. The kiln had four parallel zigzag air flow paths (quadruple zigzag firing). Fuel was fed by one fireman almost continuously by hand. The fuel types included bituminous coal from USA, petcoke, and sawdust. Fuel was fed in six chambers at a time and about three chambers were advanced each day. A different mix of fuels was used in each chamber as shown in Table 2. Chamber six was towards the pre-heating zone or the green bricks and chamber one was towards the cooling zone or the fired bricks; a stationary line of bricks was fed sawdust in chamber six first and US coal & sawdust in chamber one last.

It should be noted that this kiln had not achieved a steady state operation at the time of monitoring. Different brick setting densities were being tried, and the production capacity was around 80% of the rated production capacity for this type of kiln.

Table 2: Fuel added in the six open chambers.

Chamber	1 (fired)	2	3	4	5	6 (green)
Type of fuel	US coal & Sawdust	Petcoke & Sawdust	Petcoke	US coal	US coal & Sawdust	Sawdust



(a) (b)

(c)

Figure 2: (a) Fuel feeding setup in the natural draft zigzag kiln. (b) Green brick setting. (c) Kiln chimney and sampling platform.

1.3 Bull's Trench Kiln, Kathmandu, Nepal (BTK Nepal)

A BTK was measured in Kathmandu, Nepal on the 17th - 18th of March 2016. The BTK kiln measured in Nepal was similar in scale and design to the BTK measured in India, producing about 40,000 standard sized bricks per day. Manually fed external coal was the only fuel used in this kiln.

(a) (b)

(c)

Figure 3: (a) Stack at BTK kiln in Kathmandu, Nepal. (b) Manual coal fuel feeding. (c) Surface of the kiln.

1.4 Forced Draft zigzag, Kathmandu, Nepal (FDzig Nepal)

A forced draft kiln was measured in Kathmandu, Nepal on the 19th - 21st of March 2016. This kiln was part of an effort to reduce climate warming and regional pollution in the Kathmandu valley after the 2015 earthquake by retrofitting damaged BTK kilns into forced draft zigzag kilns. This kiln was in the first season in operation as a zigzag kiln. It was a medium sized kiln, producing 64000 standard sized bricks per day. A mixture of coal and sawdust were used in this kiln, and was added only as external fuel.

(a)

(b)

(c)

Figure 4: (a) Brick unloading at the forced draft zigzag kiln measured in Kathmandu. (b) Manual fuel feeding coal. (c) Kiln stack and platform.

1.5 Clamp kiln, Sangli, India (Large clamp)

A clamp kiln was measured in Sangli, Maharashtra on the the 9th - 11th of March 2016. The season for brick making is from November to May in this region. The bricks from this site were once sold at Pune market (150-200 km away), but now the market is mostly local. In Pune, new alternate materials such as autoclaved aerated concrete (AAC) blocks are preferred while the local market demand for bricks has increased.

The bricks produced were twice the size of standard bricks (230 x 154 x 94 mm). The production capacity at the entire facility was about 1.5 million double bricks per year, all from clamp kilns. Bricks were hand molded and sun dried. The main source of clay is the clay deposits around river Krishna.

The clamp kiln measured was a batch kiln with no permanent structure. It consisted of a stack of green bricks interspersed with combustible material as shown in Figure 5. The clamp was about 5 meters high and had a base of 21.4 x 12.2 meters, consisting of about 250,000 bricks. The green bricks were surrounded with temporary outer walls of burnt bricks on all sides. There was a 2” layer of ash between the outside wall and the green bricks stacked in the clamp. This ash layer prevents heat losses and reduces infiltration of air out of the walls of the clamp. Most of the air entering the clamp should enter from the openings provided at the base of the clamp. The operating period of the clamp was 35 days.

Both internal and external fuels were used at this site. Internal fuel was added to the clay while preparing the green bricks and consisted of ash from a sponge iron plant, bagasse, and coal fines. External fuels included coal lumps from Chandrapur, coal fines (from sieving of Chandrapur coal lumps), and ash from a paper mill. These fuels were added in layers near the bottom of the kiln as shown in Figure 5. The quantity of fuel changed with season; more was used during winters and less during summers.

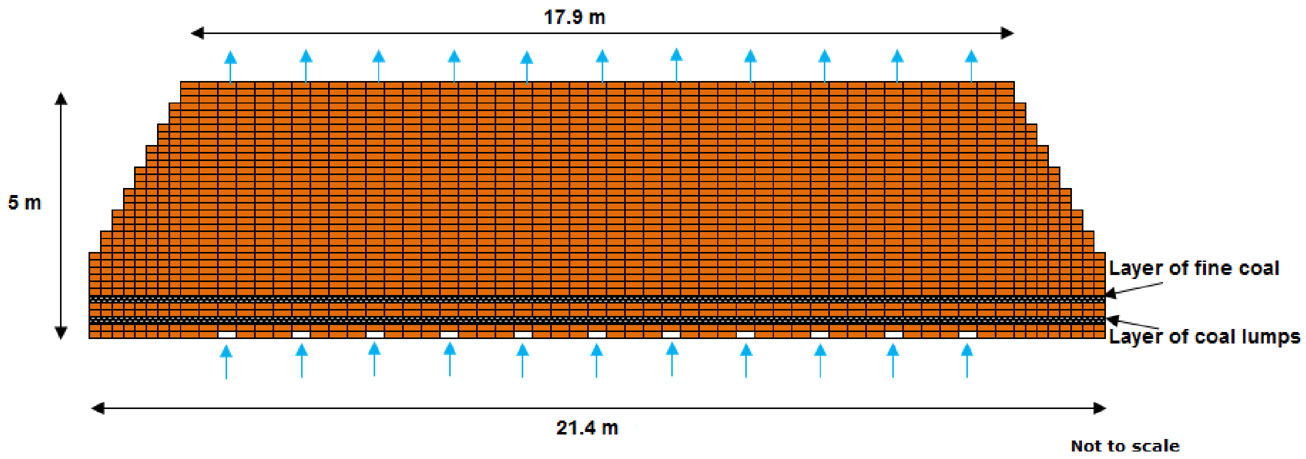
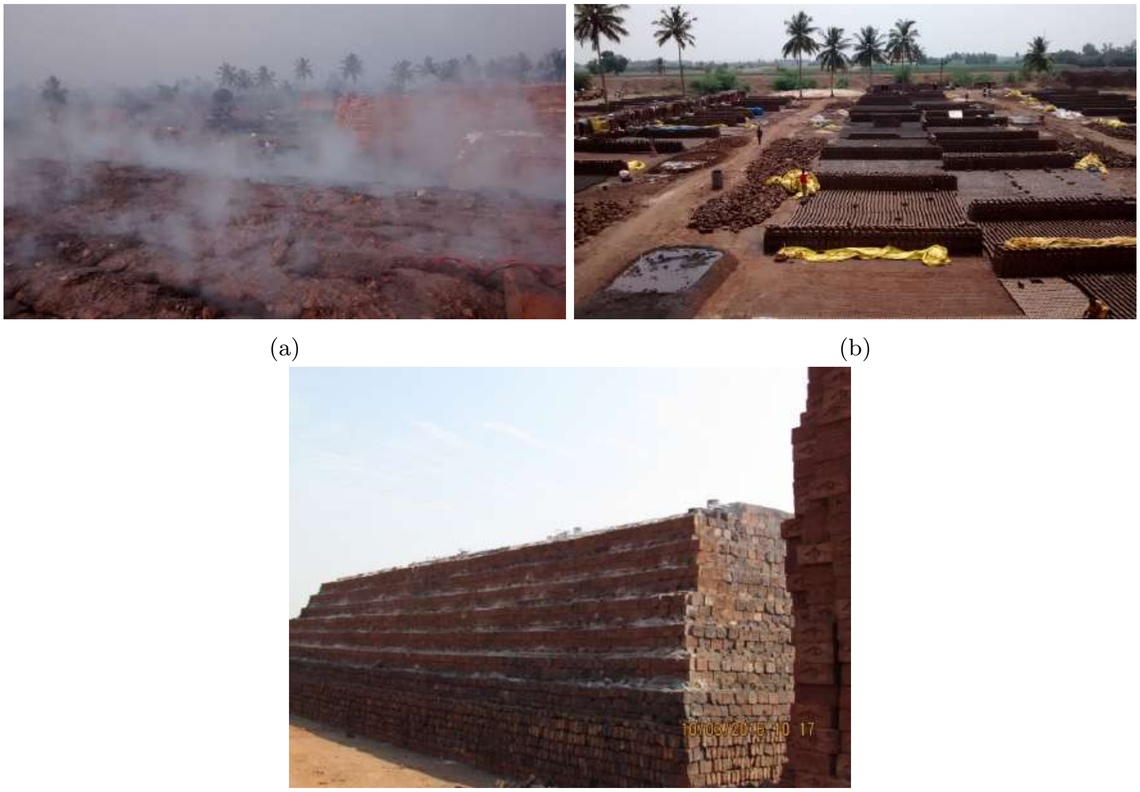


Figure 5: Front view of Sangli clamp. The blue arrows depict the direction of air entrance into the kiln and emission of flue gas from the top of the clamp. Two fuel layers are shown near the bottom of the kiln.



(a)

(b)

(c)

Figure 6: (a) Top view of the clamp measured in Sangli, India. (b) Stacked green bricks for drying. (c) Side view of monitored clamp in Sangli.

1.6 Clamp kiln, Pune, India (Small clamp)

A second, smaller, clamp kiln was measured in Pune, Maharashtra on March 12th-14th, 2016. This facility has a local market and operates seasonally from November to May. The site produced 1- 1.2 million double sized bricks per year. Bricks were hand molded and sun dried.

The clamps were about one third of the size of the clamps measured in Sangli, producing 85,000 double bricks (221 x 146 x 84 mm). The operating period of this clamp was about 15 days. Similarly to the clamps in Sangli, a outer wall of fired bricks was used to contain the green bricks with an additional layer of ash to prevent heat loss and air flow. The brick packing fraction (the ratio of the total volume of a set of green bricks packed into a space to the volume of that space) at this kiln was about 80%.

The green bricks were piled up on three beds of coal that were each about 3” thick. Internal fuels were added to the clay while preparing the green bricks. The quantity of fuel changes with season, more during winters and less during summers. The external fuel was bituminous coal from Chandrapur and the internal fuel was semi-burnt coal from Kohlapur.

(a) (b)

(c)

Figure 7: (a) Top view of the clamp measured in Pune, India. (b) Emissions monitoring at the top of clamp. (c) Front view of the clamp.

2 Methods

The measurements were done according to the protocol: *Brick Kiln Emissions Sampling Protocol: Dilution sampling for climate-relevant particle emissions* [8]. The method is summarized below.

2.1 Energy measurement methods

Specific Energy Consumption (SEC) is defined as the energy consumed per mass of fired brick (MJ per kilogram of brick). SEC is used to compare energy performance of brick kilns. The specific fuel consumption (SFC) is the mass of fuel per mass of fired brick. The SFC is used as an intermediary step in the emissions calculations and also as a brick kiln performance indicator. The SEC and SFC were derived from kiln process monitoring and fuel sample analysis.

For continuous kilns, the time, mass, and location of every fuel feeding event was recorded during each day during the monitoring period. The amount of fuel added to each line of stationary bricks and the rate of progression of the fueling lines was determined. The number of bricks in each line was determined by monitoring the brick loading process and confirmed by surveying the kiln operators. A subsample of fired bricks were weighed to determine the average brick weight at each kiln. The SFC is the average mass of fuel per line divided by the average number of bricks per line divided by the average brick weight.

For batch kilns the total mass of fuel and the total number of bricks was determined by surveying the kiln operators and owners. The volume of the kiln was also measured and the number of bricks was estimated to confirm the reported values. The SFC for batch kilns is the total mass of fuel in the kiln divided by the total mass of bricks in the kiln. The rate of fuel use was determined using total fuel consumed per batch divided by the firing duration.

Fuel samples of all fuels were collected for laboratory analysis to determine the higher heating value (HHV) and elemental analysis. The HHV was multiplied by the SFC to determine the SEC (in MJ/kg fired brick).

In the BTK and FDzig measured in Nepal, questionable SEC results were obtained. In general, BTKs and zigzag kilns tend to have a SEC within a fairly narrow range (0.9-1.4 MJ/kg brick), but the SEC observed in Nepal kilns were lower by half. Both laboratory results and processes measurements could contribute to the low SEC. The HHV values obtained for both wood and coal (47 MJ/kg for coal and 32 MJ/kg for wood) were outside of the range expected for these fuels, while the elemental analysis suggested low energy fuels. The process measurements suggested relatively low SFC compared to other kilns. These were the first kiln measurements conducted by the team in Nepal. These measurement difficulties highlight the need for high quality laboratories and quality control procedures.

Given the irreconcilable data, estimated SEC and fuel data were used in the analysis for Nepal kilns. In the BTK, the coal properties were estimated using a coal analysis from a previous monitoring in Kathmandu valley kilns [1, 2]. In the FDzig, the same values were used for coal and approximated values for wood sawdust were used. The SEC measured in the BTK in India was used as an approximation of the SEC for the BTK in Nepal. The SEC for the FDzig was approximated using two previously measured FDzig kilns measured in Kathmandu valley [1, 2].

2.2 Emission measurement methods

Emissions of gases (CO_2, CO, and SO_2) and particles ($PM_{2.5}$, organic carbon (OC), and elemental carbon (EC)) were measured with a portable sampling system (Ratnoze 1, Mountain Air Engineering). The system is described in detail in Thompson (2016) [6] and the method has been described previously in Thompson et. al (2016) [8], and Weyant et. al (2014) [9]).

The sampling system is a dilution sampler, meaning the emission sample is mixed with dry, clean dilution air to condition the sample to near-ambient conditions. The dilution ratio (dilution flow:sample flow) was between 10:1 and 20:1 in stack kilns. No forced dilution was used in clamp kilns. The sampling system has a $PM_{2.5}$ size selective inlet (cyclone) with two parallel filter holders. $PM_{2.5}$ samples were collected on PTFE filters for gravimetric analysis and on quartz filters for OC/EC analysis. The sampling system measures and logs real-time CO, CO_2, and SO_2 concentrations, filter flow rates (for determining PM mass concentrations), dilution ratio, stack (exhaust gas) velocity, temperature, and humidity.

An isokinetic sample probe was used for kilns with stacks (chimneys). The probe assembly included a sampling nozzle and a type S pitot tube to measure exhaust velocity. Emissions were sampled from stack center at a height of 10-15 meters above the kiln, depending on the location of the port hole. For clamp kilns without stacks, a multi-point ARACHNE probe (Roden, 2006 [5]) was placed about 0.5 meters above the top of the kiln, over the firing zone. Individual emission samples lasted for periods ranging from 3 hours to 15 hours to achieve representative samples over several burn cycles.

Emission factors were calculated using the carbon balance method. In this method, the conservation of fuel carbon mass is utilized to determine emission factors. Emission ratios in grams of pollutant per gram of carbon emitted are determined from simultaneously measured concentrations, where the concentration of carbon in CO_2, and CO are used to approximate the total carbon. The emission ratio (ER) in grams pollutant per grams carbon, is shown in Equation 1, where P is the pollutant concentration in grams per m^3, V_m is the molar volume, and CO_2 and CO are the concentrations of these gases in ppm_v.

$$\mathrm{ER} = P * \frac{V_\mathrm{m}}{12(\mathrm{CO_2} + \mathrm{CO})} \tag{1}$$

The fuel carbon fraction (C_{fuel}, in gC/kg fuel), determined in laboratory elemental analysis of the fuel, is then multiplied by the emission ratio to produce the fuel mass based emission factor (grams of pollutant per kilogram fuel), as in Equation 2.

$$\mathrm{EF} = \mathrm{ER} * C_\mathrm{fuel} \tag{2}$$

The fuel energy content (HHV) is used to calculate energy based emission factors (grams pollutant per MJ). The SFC was used to calculate brick based emission factors (grams pollutant per kg fired brick). The fuel consumption rate was then used to calculate emission rates (gram pollutant per hour). The process flow is outlined in Figure 8.

There were 4-5 emission monitoring events per kiln each lasting between 1 - 14 hours. A time weighted (length of test) average was reported for each emission metric.

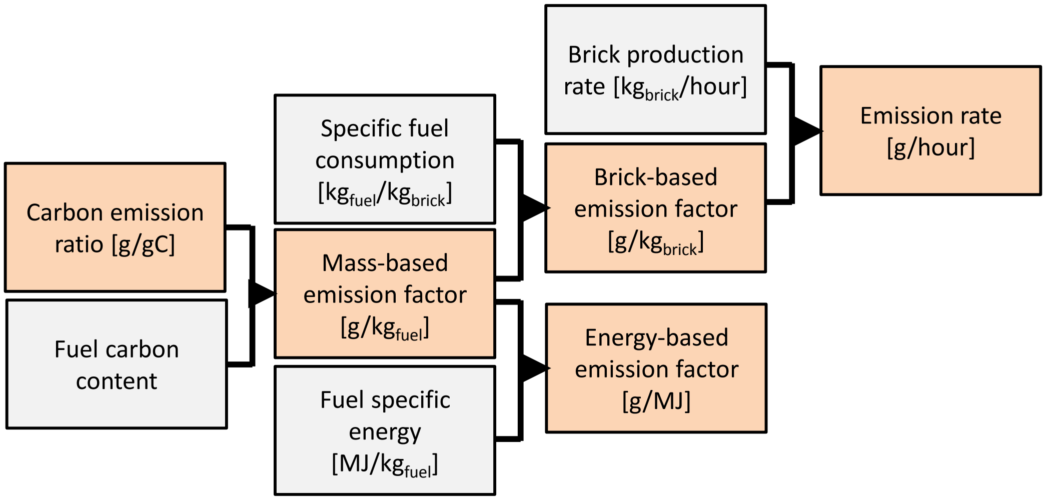


Figure 8: Analysis flow for the carbon balance method. Emission metrics are in orange and energy metrics are in grey boxes.

3 Results

3.1 Fuel

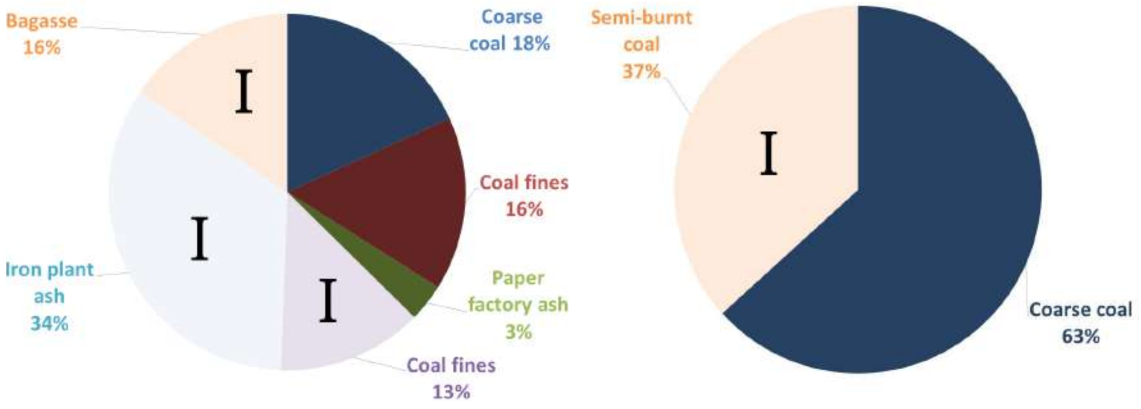
Table 3 shows the elemental content and the fuels used in each of the kilns during the monitoring process. The mass weighted averages for each kiln are the values of carbon content and energy content used in the emission factor calculations. Note that these are averages over many hours and do not necessarily represent longer, seasonal, averages. Values can also fluctuate throughout the process, especially in kilns with external mixtures of different fuels in continuous kilns, where the feeding can change between one fuel and the next. This is particularly notable in the BTK measured in India, where a high energy coal was used for a period followed by a large feeding of mustard stalk. The energy content of the fuel mixture could swing from nearly 7500 kcal/kg to 4000 kcal/kg as the fuel was switched from coal to mustard stalk. For this kiln, the weighted averages of the carbon content and HHV were averages over the duration of each test (range 54 - 61% carbon). In the other kilns, the fuel was added more homogeneously and the weighted averages were used.

Table 3: Elemental content and higher heating value (kcal/kg) of fuels.

Kiln Name	**Fuel**	**Ash**	**H_2O**	**H**	**N**	**O**	**C**	**S**	**HHV**
BTK India	Assam bituminous coal	7.22	8.46	4.34	1.01	15.28	61.65	2.04	7498
	Mustard stalk	4.19	7.58	3.91	1.54	34.40	48.28	0.01	4007
	Weighted average	**5.59**	**7.99**	**4.11**	**1.30**	**25.58**	**54.45**	**0.95**	**5617**
NDzig India	Petcoke	1.05	2.29	4.08	0.63	4.14	82.63	5.18	8419
	USA bituminous coal	12.55	1.81	6.26	0.60	17.69	58.93	2.16	6554
	Sawdust	4.70	7.30	6.10	0.40	42.50	45.50	0.40	3992
	Weighted average	**6.86**	**3.06**	**5.44**	**0.57**	**17.64**	**64.88**	**2.91**	**6728**
BTK Nepal	Coal[a]	3.99	11.54	3.86	0.35	10.75	67.39	2.14	6483
FDzig Nepal	Coal[a]	3.99	11.54	3.86	0.35	10.75	67.39	2.14	6483
	Sawdust[b]	0.85	6.00	5.64	0.94	39.48	47.00	0.09	4000
	Weighted average	**3.61**	**10.88**	**4.07**	**0.42**	**14.17**	**64.96**	**1.90**	**6254**
Large clamp	Chandrapur bituminous coal[c]	17.60	6.48	5.18	0.64	15.91	53.89	0.30	4918
	Paper mill ash	81.38	9.53	1.08	0.29	2.99	4.35	0.38	704
	Iron plant ash[d]	63.51	2.70	2.21	0.51	7.67	22.70	0.70	2789
	Bagasse[d]	2.86	28.81	6.05	0.32	28.19	33.68	0.09	3166
	Weighted average	**43.49**	**8.24**	**3.51**	**0.49**	**11.44**	**32.45**	**0.38**	**3177**
Small clamp	Chandrapur bituminous coal[e]	17.60	6.48	5.18	0.64	15.91	53.89	0.30	4918
	Kolhapur semi-burnt coal[d]	60.98	1.92	2.41	0.40	10.60	23.03	0.68	2906
	Weighted average	**26.15**	**5.58**	**4.63**	**0.59**	**14.86**	**47.81**	**0.37**	**4521**

[a] Estimate coal properties from [1, 2].
[b] Estimated values.
[c] Partial internal fuel.
[d] Internal fuel.
[e] Results of the ultimate analysis of fuel samples collected from large clamp

Of the kilns measured, only the clamps used internal fuels, with an energy distribution as shown in Figure 9. Coarse coal, coal fines, and paper factor ash are external fuel and composed 27% of the fuel energy in the large clamp. In the small clamp the coarse coal was external and was 63% of the fuel energy.



(a) Large clamp

(b) Small clamp

Figure 9: (a) Distribution of energy from different fuels for the large clamp in Sangli, India. (b) Distribution of energy from fuels for the small clamp in Pune, India. In both, the dark pies are external fuel and the light pies with 'I's are internal fuels.

3.2 Energy consumption

The SEC and SFC for all kilns are shown in Table 4. The range of SEC observed in these kilns was small. The SEC for all kilns measured was between 1 and 2 MJ/kg brick , whereas SEC up to 5 MJ/kg brick has been observed [7]. Clamp kilns had higher SEC and SFC compared to continuous kilns on average; the SEC was 1.4 times higher and the SFC was 2.4 times higher in clamps.

Table 4: Production and energy properties of measured kilns.

Kiln	**SFC**	**SEC**
	(kg fuel/kg brick)	(MJ/kg brick)
BTK India	0.05	1.17
NDzig India	0.04	1.07
BTK Nepal	– [c]	1.17[a]
FDzig Nepal	– [c]	1.14[b]
Large clamp	0.10	1.33
Small clamp	0.12	1.90

[a] Estimated from SEC of the BTK India.
[b] Estimated from two similar zigzag kilns measured in Kathmandu valley [1, 2].
[c] Values were measured with the protocol at 0.02-0.03 kg fuel/kg brick.

3.2.1 Energy in continuous kilns

The energy required to produce bricks in continuous kilns (BTKs and zigzags) was approximately 1.1 MJ/kg brick with a range of about 0.1 as shown in Table 4. On average, the BTKs were about 0.1 MJ/kg higher than the zigzag kilns.

Intermittent feeding patterns can affect the energy efficiency in kilns. In the BTK in India, large quantities of mustard stalk and coal were fed in short time intervals, which likely results in lower efficiency. The fuel feeding system can be improved by making it more continuous by feeding in smaller quantities. A shift to zigzag firing can result in 20-25% fuel savings.

The energy consumption in the natural draft zigzag kiln in India (NDzig India) may have been influenced by changing brick setting densities during the monitoring period. The specific energy consumption of the kiln is likely to decrease by 5-10% once the kiln reaches a steady state operation.

The reported energy and fuel consumption are instantaneous values based on a short period of monitoring and they should not be confused with a seasonal average energy consumption (based on data for an entire season). The SEC is typically highest at the start of the season which is usually winter (wet ground and wet kiln structure, lower ambient temperatures, higher moisture content in the bricks) and is lower towards the end of the season (drier ground, dry kiln structure, less moisture content in the brick). The energy consumption at the end of the season can be 20-40% lower compared to the energy consumption at the beginning of the season [4]. The kilns reported here were measured in mid-season.

3.2.2 Energy in clamps

The typical energy performance for clamps, reported in the literature for India is 1.5 to 4 MJ/kg of fired brick. There is a distinct difference between the reported energy consumption for slow-firing coal-based clamps, which have lower energy consumption (1.5 to 2.5 MJ/kg of fired brick) and fast-firing wood-based clamps which have higher energy consumption (2.5 to 4 MJ/kg of fired brick).

In this study, both the clamps fall under the category of slow firing coal clamps. In case of the large clamp, the energy consumption was lower (1.33 MJ/kg of fired brick) than reported in earlier studies. For the small clamp, the energy consumption (1.90 MJ/kg of fired brick) was within the range. The reasons for lower specific energy consumption for the large clamp, could provide guidance for developing strategies for improving energy performance. The two key factors that could explain the lower SEC for the large clamp are:

I. Lower surface area-to-volume ratio. Heat loss from the surface of the clamp is an important component of heat balance. The surface area-to-volume ratio for the large clamp is 0.54 while for the small clamp (about 1/3rd the size), the surface area-to-volume ratio is 0.75.

II. Higher internal fuel use. Previous work on continuous brick kilns has shown that a high percentage of internal fuel (fuel mixed in clay body) helps to reduce the energy consumption. For external fuels, the heat released by combustion outside the brick has to be transferred first to the surface of the brick (mainly through process of convection and radiation) and then into the brick body (mainly through conduction). This transfer of heat entails losses. On the other hand, in the case of internal fuels, the heat is released within the body of the brick and the heat transfer is more efficient. The large clamp kiln had more internal fuel compared to the small clamp (63% compared to 27% of the fuel energy was from internal fuel).

3.3 Emission rates

Emission rates for continuous and batch kilns are shown in Table 5. Emission rates can be used to estimate local pollution, but should not be used to compare kiln performance because they also depend on the production scale of the kiln.

Table 5: Emission rates in kilograms per hour for all kilns and total emissions per batch for clamp kilns. The results are expressed as the average ± the standard deviation.

Name	CO	SO_2	$PM_{2.5}$	EC
		g/hr		
BTK India	6.52 ± 2.94	5.61 ± 2.26	0.96 ± 0.19	0.40 ± 0.09
NDzig India	6.12 ± 0.47	7.99 ± 1.14	0.84 ± 0.05	0.13 ± 0.03
BTK Nepal[a]	2 - 5	4 - 11	0.4 - 1.2	0.2 - 0.5
FDzig Nepal[a]	4 - 12	2 - 9	0.5 - 1.3	0.04 - 0.1
Large Clamp	5.85 ± 2.03	1.28 ± 0.53	0.15 ± 0.16	0.0006 ± 0.0004
Small Clamp	10.51 ± 2.24	2.40 ± 0.44	0.38 ± 0.24	0.002 ± 0.001
		g/batch		
Large Clamp	4915 ± 1702	1077 ± 442	130 ± 135	0.53 ± 0.38
Small Clamp	3785 ± 805	863 ± 159	139 ± 85	0.61 ± 0.42

[a] Due to questions about the process measurements, a range of values is presented. The low range is the average using the monitored fuel consumption rate data and the high value is derived from the estimated SEC and the monitored brick production rate.

3.4 Emission factors

Emission factors on a fuel mass basis, fuel energy basis, and brick mass basis are shown in Table 6 for each of the six kilns. Brick mass based emission factors for all tests are shown in Figure 10.

Table 6: Average and standard deviation of emission factors for CO, SO_2, $PM_{2.5}$, and EC.

Kiln	CO	SO_2	$PM_{2.5}$	EC
		g/kg fuel		
BTK India	39.3 ± 14.5	33.6 ± 10.9	5.0 ± 1.1	2.0 ± 0.5
NDzig India	34.1 ± 2.9	44.7 ± 6.9	4.7 ± 0.3	0.7 ± 0.1
BTK Nepal	28.1 ± 4.8	66.0 ± 9.5	6.8 ± 1.2	3.2 ± 0.7
FDzig Nepal	51.1 ± 4.6	39.3 ± 5.9	5.7 ± 1.5	0.6 ± 0.1
Large Clamp	48.8 ± 16.6	11.2 ± 4.6	1.1 ± 1.1	0.01 ± 0.002
Small Clamp	70.3 ± 17.6	18.3 ± 3.0	2.3 ± 1.5	0.01 ± 0.01
		g/MJ fuel		
BTK India	1.7 ± 0.6	1.4 ± 0.5	0.2 ± 0.05	0.1 ± 0.02
NDzig India	1.2 ± 0.1	1.6 ± 0.2	0.2 ± 0.01	0.02 ± 0.01
BTK Nepal	1.0 ± 0.2	2.4 ± 0.3	0.3 ± 0.05	0.1 ± 0.01
FDzig Nepal	2.0 ± 0.2	1.5 ± 0.2	0.2 ± 0.06	0.02 ± 0.004
Large Clamp	3.7 ± 1.2	0.8 ± 0.3	0.1 ± 0.1	0.0004 ± 0.0002
Small Clamp	4.3 ± 1.1	1.1 ± 0.2	0.1 ± 0.1	0.001 ± 0.001
		g/kg brick		
BTK India	2.0 ± 0.7	1.7 ± 0.5	0.25 ± 0.05	0.1 ± 0.02
NDzig India	1.3 ± 0.1	1.7 ± 0.3	0.18 ± 0.01	0.03 ± 0.01
BTK Nepal	1.2 ± 0.2	2.8 ± 0.4	0.30 ± 0.05	0.1 ± 0.03
FDzig Nepal	2.2 ± 0.2	1.7 ± 0.3	0.24 ± 0.08	0.03 ± 0.01
Large Clamp	4.9 ± 1.7	1.1 ± 0.5	0.10 ± 0.11	0.001 ± 0.0001
Small Clamp	8.1 ± 2.0	1.0 ± 1.2	0.27 ± 0.18	0.001 ± 0.001

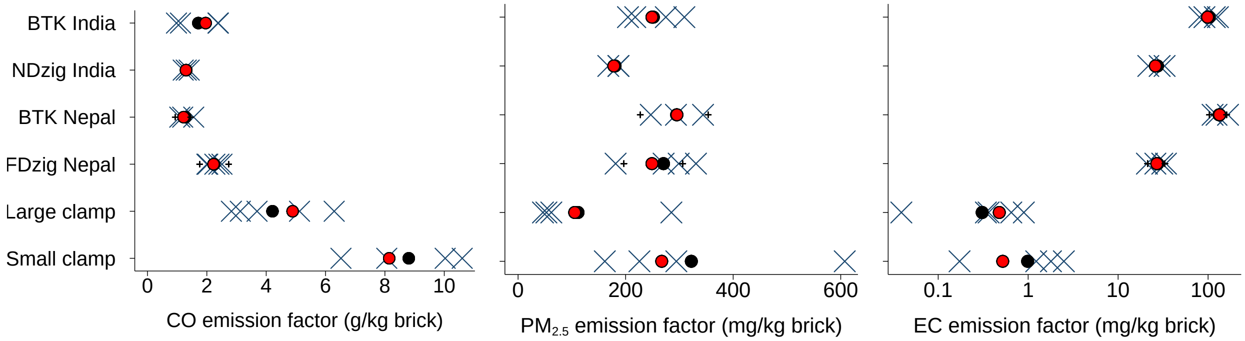


Figure 10: Emission factors of individual tests (X's), mean (black dot), and test length weighted mean (red dot). The black '+'s show the weighted average emission factors for a lower and upper bound SEC in the Nepal kilns (0.9 - 1.4 MJ/kg brick). (a) Carbon monoxide in grams CO per kilogram of fired brick. (b) $PM_{2.5}$ in mg/kg fired brick and (c) Elemental carbon in mg/kg fired brick on a log scale.

3.4.1 Emissions in continuous kilns

The BTK kilns and the zigzag kilns did not have significantly different emission factors of CO, SO_2, or $PM_{2.5}$ ($p > 0.05$) on a fuel, energy or brick mass basis. However, the difference in the EC emission factor on a fuel energy basis was significant ($p < 0.001$) and indicates that the combustion conditions are distinct in these kilns. The emission factor of EC on a brick mass basis was about three times higher in the BTKs compared to the zigzag kilns. The $PM_{2.5}$ emission factor was about 1.3 times higher in the BTKs, but again, the result was not significant (p = 0.2). Based on these measurements, transition to zigzag technology would reduce climate warming due to black carbon, but not significantly reduce CO or particulate pollution.

In 2014, the same BTK in India was measured [9]. At that time, the emissions were higher (2.7 gCO/kg brick, 0.33 gPM/kg brick, and 0.27 gEC/kg brick) compared to this monitoring campaign (2.0 gCO/kg brick, 0.25 gPM/kg brick, and 0.1 g EC/kg brick). However, in that study the emissions were monitored in the first round of firing around the kiln of the season. In this study, the emissions were monitored mid-season and represent the kiln in a more equilibrated state. The emissions here were in the range of those observed in other BTKs in India measured later in the production season. The zigzag kilns and BTK measured here were in the same range as those previously measured [9].

3.4.2 Emissions in clamp kilns

Clamp kilns have significantly different operations compared to continuous kilns, and the emission characteristics reflect the combustion and operations in batch kilns. CO emission factors were higher than those for continuous kilns on a fuel mass basis (p = 0.002), fuel energy basis ($p<0.001$), and especially on a brick mass basis where the emission factor was 3-5 times higher ($p < 0.001$). CO is released when the fuel-to-air ratio is high, such that there is insufficient oxygen available to completely oxidize carbon to CO_2 and CO is formed and released instead. This explains the higher CO emission factor on a fuel mass and MJ basis. The CO emission factors on a brick mass basis are even more disparate and are due to the fact that the energy required to produce one kilogram of brick (SEC) is higher in the batch kilns compared to the continuous kilns (1.33 and 1.9 compared to about 1 kg fuel/kg brick for continuous kilns). The SEC impacts the relative brick based emissions in the clamps for all pollutants.

Elemental carbon was lower in the clamps compared to the continuous kilns on a fuel mass basis ($p < 0.0001$), fuel energy basis (p = 0.002) and on a brick mass basis (p = 0.001). EC is emitted in flaming combustion, suggesting that the $PM_{2.5}$ emissions were almost entirely from smoldering combustion in clamps. Less than 1% of the $PM_{2.5}$ was attributable to EC in the clamp kilns.

The $PM_{2.5}$ emission factors were significantly lower than continuous kilns on a fuel mass basis ($p < 0.001$), but not on a brick mass basis (p = 0.2) due to the poor efficiency observed in clamp kilns. There are three possible reasons for low $PM_{2.5}$ mass based emission factors: First, in the clamps, no new fuel was added during the firing. Start-up emissions from coal tend to be high in $PM_{2.5}$, but after some time, the $PM_{2.5}$ emissions fade and CO emissions dominate. The start-up phase of the clamp kilns were not monitored, and likely has higher $PM_{2.5}$ compared to the mid-operation emissions measured. However, the combustion front moves across the kiln, so some coal was newly lit during the measurement period. So, it is likely that the inclusion of the start-up phase is a partial, but incomplete explanation for the low $PM_{2.5}$. Secondly, the clamps use internal fuels which may reduce the production and emission of particles from inside the brick. Thirdly, the flows in the kiln are likely low and have to flow in long and contorted channels before they exit the kiln. Low and turning flows tend to cause loss of particles due to gravitational settling and deposition on brick surfaces, although small particles (less than 2.5 microns) are more likely to flow out of the kiln.

The clamps have combustion and process characteristics that distinguish them from the continuous kilns, but the two clamps measured were also different from each other. The large clamp had lower CO, $PM_{2.5}$, and EC compared to the small clamp, although the difference was rarely significant (only the CO fuel mass based emission factor was significant, p = 0.01). The lower PM emissions in the large clamp may also be due to the higher percentage of internal fuels.

Sulfur dioxide emissions

Unlike the emission factors of $PM_{2.5}$ and CO which are influenced by the quality of the combustion, SO_2 is largely determined from the amount of sulfur available in the fuel and clay. The emission factors for SO_2 are tabulated in Table 6 and shown in Figure 11 for Indian kilns. The Nepal kilns were not included because the sulfur content of the fuel was not measured. In that figure, a dotted line indicates the theoretical emission factor values (g/kg fuel) if all fuel sulfur became SO_2. When the measured value is above the line, true for the BTK India, and the clamp kilns, it suggests that there are significant levels of sulfur in the clay that also forms SO_2. When the emission factor is below the line, as in FDzig kiln in India, it suggests that some sulfur in released in other forms, such as SO_3, H_2S or other sulfur compounds, or that moisture in the flue gases removes the SO_2.

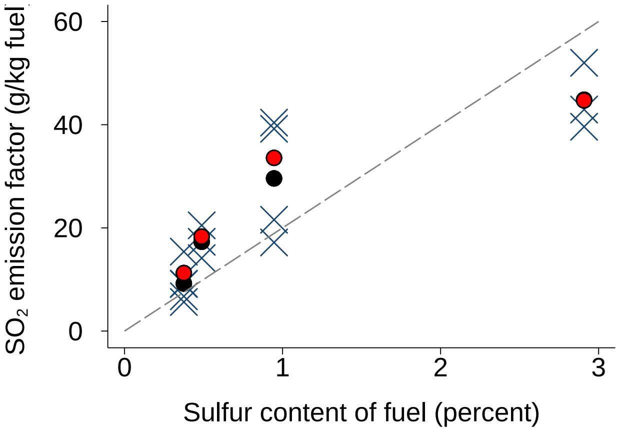


Figure 11: Relationship between the SO_2 emission factor and the sulfur content of the fuel. The X's show the relationship for individual measurements, the black dot is the average, and the red dot is the time weighted average. The dotted line shows the theoretical SO_2 emission factor obtained if all fuel sulfur is oxidized to form SO_2.

3.5 Conclusion

Emissions and energy data were collected from six kilns in South Asia in order to 1) indicate likely effects of retrofitting BTKs to zigzag kilns and 2) quantify clamp kiln emissions, which have few previous measurements and no EC measurements.

Emissions and energy metrics measured at the BTK and zigzag kilns were in the same range as previously measured. The BTK was less efficient than the zigzag kiln in India, with a specific energy consumption (SEC) that was 0.1 MJ/kg brick higher. Both $PM_{2.5}$ and EC were reduced in the zigzag kilns compared to BTKs. $PM_{2.5}$ was 20% lower and the EC was 70% lower on a brick mass basis, while the CO was 10% higher. The difference in EC was significant ($p < 0.001$), but the differences in the $PM_{2.5}$ and CO emission factors were not significant ($p > 0.5$). Transitions from BTK to zigzag technology are expected to reduce climate warming EC, but significant changes in $PM_{2.5}$ were not measured.

Clamp kilns had performance characteristics that were distinct from continuous kilns. On a brick mass basis, the clamps emitted 70% more CO ($p < 0.001$), and 95% less EC ($p = 0.001$), while the $PM_{2.5}$ was 20% less but not significantly different ($p = 0.2$). Very low EC was emitted from clamp kilns; less than 1% of the $PM_{2.5}$ was attributable to EC. The (SEC) in the large clamp was low compared to previously measured clamps. Large volume kilns with a high fraction of internal fuels may be key features for improving the energy efficiency in clamp kilns.

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