To Adopt, or Not to Adopt, *Why* is the Question: An Environmental and Economic Case for Zigzag Kilns[Ψ]

Faiza Sharif
Associate Professor
Sustainable Development Center
Government College University, Lahore

Sanval Nasim
Assistant Professor of Economics
Lahore University of Management Sciences

Abstract

In this paper, we compare two brick kiln technologies—the Bull's Trench Kiln (BTK) and the Induced Draft Zigzag Kiln (ZZK)—by focusing on two questions: How clean are ZZKs? What are the economic and social benefits of ZZKs compared to BTKs? To answer the first question, we collected and tested emissions samples from two sites: a newly constructed ZZK in Raiwand, Punjab and a conventional BTK located close to the ZZK. To address the second question, we drew on primary data on input and output quantities and prices from the sample sites to conduct a cost-benefit analysis of the two types of kiln technologies. The environmental results show that the ZZK emitted significantly less amount of harmful pollutants and greenhouse gases compared to the BTK, suggesting that substituting BTKs for ZZKs can substantially reduce the environmental impact of the brick industry. The economic analysis demonstrates that switching from BTKs to ZZKs can improve both private and social welfare—in monetary terms, social benefits are more than tripled over a 20-year time horizon. ZZK owners can recover their initial investment in 1.5 years while it takes BTK owners 2.4 years to recover their initial investment. Our findings provide a strong case for the adoption of ZZKs in Punjab and for the EPD to facilitate the technology transition.

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1. Introduction

Urbanization and infrastructure development in Pakistan have led to a rapid growth of its brick industry. Pakistan is the third largest producer of bricks in South and Southeast Asia after China and India (Skinder et al. 2014). It has an estimated 11,500 brick kilns—with 10,000 located in Punjab—which consume 1.6 million tons of coal to produce 45 billion bricks per year (Mitra and Valette 2017; Techno Green Associates 2012). While other countries in the region have quickly adopted cleaner brick kilns, Pakistan has failed to modernize its conventional kiln technology—the over a century old Bull's Trench Kiln (BTK). The introduction of new kiln technologies such as the Induced Draft Zigzag Kiln (ZZK) presents policymakers an opportunity to improve ambient air quality, mitigate climate change, and in turn reduce social costs.

Evidence indicates that emissions in Punjab are increasing at an alarming rate and that levels of pollutants exceed the thresholds prescribed by the World Health Organization (WHO) (Khan et al. 2011; Lodhi 2006; Colbeck et al. 2009). During a menacing smog episode in November 2017, the average concentration of $PM_{2.5}$ in Lahore was 1077 micrograms per cubic meter ($\mu g/m^3$)—almost 200 times higher than WHO's safe limit of 6 $\mu g/m^3$ (EPD 2017).[1] Exposure to such toxic levels of particulate matter increases the incidence of cancer and can lead to severe cardiovascular and respiratory illnesses such as ischemia, myocardial infarction, asthma, and bronchitis (Kamal et al. 2014; Dominici et al. 2006; Brook et al. 2004). According to WHO estimates, about 135,000 people in Pakistan died in 2015 as a result of exposure to hazardous levels of $PM_{2.5}$ (HEI 2017).

Deteriorated air quality also carries serious non-health implications. Visibly poor air quality increases the risk of traffic accidents and encourages people to spend more time indoors, leading to high absenteeism at work and in schools (Sager 2016; Gilliland et al. 2001). Moreover, the exposure of plants and crops to air pollutants causes foliar damage and stunts growth by affecting their ability to photosynthesize (Adrees et al. 2016). The high indirect costs of emissions, in addition to their direct impacts, make it all the more important for authorities in Punjab to reduce emissions and improve air quality in the province.

Spread widely across Punjab, BTKs are a significant source of greenhouse gas emissions and harmful particulate matter in the province. They use almost 40 percent of locally extracted coal, which has a high sulfur and ash content and releases large amounts of $PM_{2.5}$, sulfur dioxide (SO_2), and black carbons when burned (Techno Green Associates 2012). Other BTK emissions include carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO_x), methane (CH_4), and ozone (O_3). At times, kiln operators burn cheap waste materials such as discarded tires, plastics, and garbage as fuel, resulting in the release of toxic byproducts in the surrounding environmental media. (Sanjel et al. 2016; Tahir et al., 2010).

[1] $PM_{2.5}$ are microscopic air particles with a diameter less than 2.5 micrometers (μm)—3 percent the diameter of a human hair. Their minute size allows them to stay in the air longer compared to larger particles and they can cause severe health problems when inhaled.

Though we don't have exact figures on total kiln emissions in Punjab, some recent inquiries on kilns in South Asia demonstrate the seriousness of the problem: CO_2, CO, and $PM_{2.5}$ emissions from kilns in the region range between 120 – 127 megatons (mt), 2.5 – 3.9 mt, and 0.19 – 0.94 mt, respectively (Stockwell et al. 2016; Jayarathne et al. 2018). Kilns are also a source of carcinogens such as polycyclic aromatic hydrocarbons and volatile organic compounds (Chen et al. 2017; Stockwell et al. 2016; Zavala et al. 2018)—kiln workers have a high risk of exposure to such carcinogens through dermal contact and inhalation. Moreover, the disposal of kiln ash, which contains toxic heavy metals, can contaminate agricultural land and produce (Ismail et al. 2012; Adrees et al. 2016; Mondal et al. 2017).

ZZK is a cleaner alternative to the conventional BTK. Recent experiences from India and Nepal—where a large number of kiln owners have quickly taken up ZZK technology—suggest that ZZKs generate 70 percent less emissions compared to BTKs (Maithel, Kumar, and Lalchandani 2014). The significantly lower emissions of greenhouse gases and particulate matter improve ambient air quality, leading to better social outcomes such as lower healthcare expenditures, higher crop yields, less material damage, and higher attendance rates at schools and workplaces.

ZZKs also have the potential to generate considerable profit margins if properly operated. Owing to the even and consistent distribution of heat through their chambers and the efficient consumption of coal, ZZKs produce 25 percent more high-quality bricks and use 30 percent less fuel (primarily coal) compared to BTKs (Maithel, Kumar, and Lalchandani 2014). The production of more high-quality bricks and lower input costs translate into higher net private benefits for ZZK owners.

Another private financial incentive to substitute ZZKs for BTKs is the low capital investment required to make the technology shift. ZZK technology can be integrated into existing BTK infrastructure through a fairly straightforward process: owners must install an electric fan in the flue, which artificially induces and regulates draft through the kiln, and stack bricks in a zigzag arrangement within the kiln (Rajarathnam et al. 2014; Weyant et al. 2014). If investors can recover their startup costs in a reasonably short period of time, either converting existing BTKs into ZZKs or setting up new ZZKs would be financially prudent ventures.

Encouraging kiln owners to adopt ZZKs provides an avenue for Punjab's Environmental Protection Department (EPD) to bring the provincial ambient air quality levels closer to the mandated Punjab Environmental Quality Standards for Ambient Air (PEQS). Unlike states in India, Punjab does not have exclusive emission and technology standards for kilns. Instead, it uses one set of standards for all industries—the Punjab Environmental Quality Standards for Industrial Gaseous Emissions—to regulate kiln emissions. The EPD has recently placed a moratorium on the construction of new BTKs and will issue permits only to investors who set up ZZKs.

However, the EPD requires assessments on the environmental and economic differences between ZZKs and BTKs before it can push forward a comprehensive plan to support ZZK adoption. We fill this niche by drawing on kiln data and experiences to first provide a portfolio of emissions across the two types of kilns and to then quantify the discounted (present value) cost savings from investing in ZZKs and the payback period for such investments. We further describe a set of recommendations that will help the technology transition from BTKs to ZZKs.

In this paper, we focus on two questions: How clean are ZZKs? What are the economic and social benefits of ZZKs compared to BTKs? To answer the first question, we collected and tested emissions samples from two sites: a newly constructed ZZK in Raiwand, Punjab and a conventional BTK located about three kilometers from the ZZK. An enterprising kiln owner recently setup the ZZK after procuring design plans from the International Center for Integrated Mountain Development (ICIMOD) in Nepal. To the best of our knowledge, this was the only operational ZZK in Punjab till the collection of our data and provides a benchmark for comparison with conventional kilns in the province. To address the second question, we drew on primary data on input and output quantities and prices from the sample sites to conduct a cost-benefit analysis of the two types of kiln technologies.

The environmental results show that the ZZK emitted significantly less amounts of $PM_{2.5}$, SO_2, CO, and CO_2 compared to the BTK, suggesting that substituting BTKs for ZZKs can substantially reduce the environmental impact of the brick industry. The economic analysis demonstrates that switching from BTKs to ZZKs can improve both private and social welfare—in monetary terms, social benefits are more than tripled over a 20-year time horizon. ZZK owners can recover their initial investment in 1.5 years while it takes BTK owners 2.4 years to recover their initial investment. Our findings provide a strong case for the adoption of ZZKs in Punjab and for the EPD to facilitate the technology transition.

The paper is structured as follows: the next section gives an overview of various kiln technologies. Section 3 and Section 4 provide the environmental analysis and the economic analysis, respectively. Section 5 concludes with a set of limitations and recommendations.

2. Brick Kiln Technologies

This section provides a brief description of BTKs and ZZKs followed by an overview of alternative kiln technologies in South Asia.

2.1. Bull's Trench Kiln

Invented in Bengal in 1876 by the British engineer William Bull, the BTK is the most widely used kiln technology across Pakistan (and South Asia). A well-functioning BTK produces 50,000 bricks a day on average. The kiln comprises a large circular structure called the chamber—in which workers place "green bricks" (sun-dried clay molds) for baking—with a fixed chimney, 20 – 30 m high, in its center that allows a natural draft through the structure and discharges flue gases.

The chamber has three zones: firing zone; preheating zone; cooling zone. Combustion occurs in the firing zone, producing flue gases that flow forward to the preheating zone and preheating the next batch of green bricks. The cooling zone, placed behind the firing zone, is where the fresh draft through the kiln cools the fired bricks.

The production process in a BTK begins with workers placing a stack of green bricks in the firing zone where it bakes in a continuously burning fire, which moves in a circular circuit through the chamber by following the flow of the draft provided by the chimney. Workers sustain the fire by adding fuel through feeding holes on top of the chamber every 15 to 20 minutes. Workers cover the stack with ash and brick dust to increase insulation and prevent heat loss. Once the fire sufficiently bakes the stack, it moves forward while cool air from the back of the chamber cools the stack. To guide the flue gases towards the chimney, workers seal the front of the preheating zone. Finally, workers remove the cooled stack of bricks from the front of the cooling zone and replace it with a new stack of bricks and the process repeats.

2.2. Induced Draught Zigzag Kiln

The structure of a ZZK is almost identical to that of a BTK except it has a slightly shorter chimney and an electric fan installed in the vent to control the flow of the draft through the chamber. In a ZZK, workers stack green bricks in a diagonal fashion, which forces the draft to follow a longer zigzag path—hence the name Zigzag Kiln—through the chamber. This longer path taken by the draft increases the airflow in the chamber, leading to more efficient fuel combustion compared to a BTK. It also transfers greater heat from the firing zone to the pre-heating zone, allowing more consistent baking of bricks. The flue gases' zigzag flow causes a significant share of the particulate matter that they carry to deposit at the bottom of the chamber, leading to lower $PM_{2.5}$ emissions.

2.3. Alternatives

Alternatives to BTKs and ZZKs in South Asia include the Hoffman Kiln (HK) and the Vertical Shaft Kiln (VSK). HKs have a sturdy structure with a closed roof and thick walls, allowing them to operate in all seasons, including the monsoons. They use natural gas as fuel, which leads them to have a low emission footprint. HKs were once widely used in Europe for the production of ceramics, lime, and bricks (Maithel, Kumar, and Lalchandani 2014). In South Asia, HKs operate only in India and that too on a small scale in the highlands.

VSKs, once popular in China, are now scattered across parts of India, Nepal, and Vietnam. The main structure of a VSK consists of a vertical shaft in which green bricks move from the top to the bottom on a mechanized lift while a stationary fire in the middle of the shaft bakes the bricks. VSKs have high fuel efficiency, which reduces their environmental impact.

Though HKs and VSKs are environmentally cleaner compared to BTKs and ZZKs, high fixed costs of installation and lack of technical knowhow have discouraged brick manufacturers in Pakistan from adopting these technologies. If brick manufacturers can successfully transition to ZZKs in the next few years, they would be prepped to embark on more complex challenges—such as adoption of HKs and VSKs—and further innovate in the long run.

3. Environmental Analysis

3.1. Methodology

3.1.1. Site Selection

We collected emission samples from a BTK and a ZZK located near Raiwand, Punjab on the outskirts of Lahore, the provincial capital. At the time when we collected our data, our sample ZZK was the only functional kiln of its type in Punjab and constructed six months prior. To reduce spatial heterogeneity and to control for factors such as weather and output and input prices, which might vary over space, we required our sample kilns to be within a reasonable distance of each other. The EPD helped us locate a BTK for emission monitoring in the vicinity (3.2 kilometers) of the ZZK.

Kilns are usually categorized as "intermittent" or "continuous" and our sample BTK and ZZK fall in the latter category. In an intermittent kiln, workers extinguish the fire after baking a particular batch of bricks and relight it to bake a new batch, while in a continuous kiln, workers never extinguish the fire. Our sample BTK relies on natural draft to sustain the fire while our sample ZZK has an electric fan in the vent to artificially induce and regulate a draft through its chambers. Each kiln is also a major source of emissions in their immediate vicinity—other sources include motor vehicles and agricultural activity.

3.1.2. Fuel Sources and Sampling

Coal is the main fuel source of our sample kilns. The BTK uses a mixture of two types of coal: one from Hyderabad and the other from Balochistan, with each comprising 75 percent and 25 percent, respectively, of the mixture. Coal from Balochistan is generally better quality—therefore, more expensive—than coal from Hyderabad. The coal at the ZZK is entirely from Balochistan.

In the ZKK, workers continuously feed coal through 14 rows of fuel holes in the firing zone, with a 35-hour feeding time for each row—it takes 35 hours of firing to bake 5,200 bricks stacked under each row. Every three hours, workers close a row of fuel holes that has completed its 35-hour firing cycle and open a new row at the opposite end of the feeding zone. The ZZK bakes around 72,800 bricks in this 35-hour cycle—equivalent to 50,000 bricks daily.

Fuel feeding in the BTK is intermittent and divided into two cycles: feeding (F) and non-feeding (NF). Workers add coal through a row of feeding holes in intervals of 15 minutes with a break of 30 minutes between each feeding interval. The BTK produces 35,550 bricks daily through this process.

We recorded the total coal consumption over a 24-hour period at the BTK and a 35-hour (firing cycle) period at the ZZK. This allowed us to account for fuel feeding variation over the course of a complete firing cycle at each kiln. We collected coal samples from each kiln and examined them in a laboratory using proximate and ultimate analysis. Proximate analysis shows the chemical content of coal (percentages of moisture, ash, and volatile matter) and gives its calorific value (a measure of energy produced by a unit of coal). Ultimate analysis provides details on the elemental content of coal (percentages of carbon, hydrogen, nitrogen, and sulfur).

3.1.3. Emission Sampling

We measured emissions of oxygen (O_2), CO_2, CO, NO_x, SO_2, and particulate matter (PM). flowing through each kiln's stack (chimney). Given the difference in the heights of the stacks of the kilns—the ZZK's stack stood at 12 meters while the BTK's stack stood at 10 m—we followed the United States Environmental Protection Agency's (US EPA) guidelines on stack concentrations to account for its effect on emission concentrations. We obtained samples of PM using the isokinetic approach recommended by the US EPA (US EPA, Method 17).

We collected PM samples in glass filters and thimbles and gravimetrically measured their concentrations. For the gas samples, we measured their stack velocities (in meters per second (m/s)) and determined their flow rates by taking into account the S-type pitot tube coefficient, absolute stack gas temperature, stack gas velocity pressure head (ΔP), and absolute gas pressure as instructed by the US EPA (US EPA, Method 2).

3.1.4. Emission Factors

We calculated emission factors—a normalization of emissions—for each kiln to allow us to compare the kilns with each other and with kilns of different sizes and with different technologies. Researchers often use data on emission factors from individual kilns in a country to estimate the emissions of its entire brick industry—information which governments can add to their climate inventories. We calculated two types of emission factors for each kiln: fuel mass-based and energy-based. The fuel mass-based emission factor measures the emission of a pollutant per unit of the mass of fuel consumed while the energy-based emission factor shows the emission of a pollutant per unit of energy consumed. We derived these from the emission rate and the fuel consumption rate.

The emission rate ER in grams per hour (g/h) is:

(1)
$$ER = 0.001 \times S \times Q_s,$$

where S is the emission concentration in milligrams per cubic meter (mg/m^3) and Q_s is the flowrate of stack emissions in cubic meter per hour (m^3/h).

The fuel mass-based emission factor EF_m in grams per kilogram (g/kg) is:

(2)
$$EF_m = \frac{ER}{F},$$

where F is the rate of fuel consumption in kilograms per hour (kg/h).

The energy-based emission factor EF_e in grams per megajoules (g/MJ) is:

(3)
$$EF_e = \frac{EF_m}{EC},$$

where EC is the energy content of fuel in megajoules per kilogram (MJ/kg).

3.2. Results

3.2.1. Fuel Analysis

Table 1 and Table 2 present the results of the proximate analysis and the ultimate analysis, respectively, of the coal samples collected from the BTK and the ZZK. The ZZK uses coal from Balochistan while the BTK uses a mixture of coal from Hyderabad and Balochistan in a two to one proportion. The coal in the mixture that we tested came from a different batch—and possibly different mines—than the samples of the pure Balochistan coal and the pure Hyderabad coal that we collected at the ZZK and BTK, respectively. Therefore, the material and elemental content of the sample mixture varies from the proportional sum of the material and elemental content of the pure samples.

The results of the proximate analysis show that the gross calorific value (GCV), measured in megajoules per kilogram (MJ/kg), of Balochistan coal (26.78 MJ/kg) is almost 50 percent higher than the GCV of Hyderabad coal (18.59 MJ/kg). The Hyderabad-Balochistan coal mixture at the BTK has a GCV of 23.13 MJ/kg. The BTK owners use the coal mixture to reduce costs since the coal from Balochistan costs considerably more than the coal from Hyderabad— $Rs.$ 14,000 per ton versus $Rs.$ 9,000 per ton. However, mixing the two varieties of coal also lowers the energy content of the mixture, reducing the number of bricks baked per ton.

Compared to the coal from Hyderabad, the coal from Balochistan has about 2 percent and 8 percent higher ash and volatile material, respectively, and a similar moisture content. The coal mixture has a much higher moisture, ash, and volatile material content compared to the pure samples, reflecting the variation in the batches of coal used to produce the mixture.

The ultimate analysis results show that the sample of the coal from Balochistan contains more nitrogen, carbon, and sulfur, but less hydrogen, compared to the sample of the coal from Hyderabad. The sample of the Hyderabad-Balochistan mixture has lower percentages of nitrogen, carbon, and hydrogen than the pure samples. However, it has the highest sulfur content amongst the three samples. These results do not reflect the average elemental composition of the three samples; they represent the properties of the particular batch of coal from which we collected each sample.

3.2.2. Stack Emissions

Figure 1 and Figure 2 show the mean concentrations of stack emissions from the ZZK and the BTK—during its feeding and non-feeding cycles—compared with the PEQS for each type of emission. Table 3 shows the One-Way ANOVA results of the statistical difference in stack emissions of each kiln while Table 4 shows the One-Sample t-Test results of the statistical difference between each type of emission and its PEQS. Since we only had one reading for the ZZK's PM emissions, we could not calculate its statistical significance.

The results show that the ZZK emits statistically lower amounts of SO_2, CO, and CO_2 and higher amount of O_2 compared to the BTK on its feeding cycle. The emissions of all gases—except NO_x—from the ZZK and the BTK on its non-feeding cycle are statistically similar. The ZZK and the BTK (F) have statistically higher NO_x concentrations compared to the BTK (NF).

The concentration of SO_2 emissions ranges from 134 ± 48 mg/m^3 at the ZZK to 8,550 ± 1,259 mg/m^3 at the BTK (F). The BTK has the highest CO emissions (5,959 ± 685 mg/m^3) during its feeding cycle but also the lowest (440 ± 48 mg/m^3) during its non-feeding cycle. The ZZK emits low concentrations of PM (17 mg/m^3) while the BTK (F) emits relatively higher concentrations (927 ± 537 mg/m^3). The ZZK also has significantly lower concentrations of CO_2 compared to the BTK (F)—47,509 ± 9698 mg/m^3 versus 159,198 ± 12785 mg/m^3. However, the

ZZK has the highest concentrations of NO_x (30 ± 6 mg/m^3) while the BTK (NF) has the highest concentration of O_2 (17 percent).

The comparison of each type of emission with its PEQS shows that the emissions of SO_2 and CO from the BTK (F) are statistically higher than their prescribed standards (1700 mg/m^3 and 800 mg/m^3, respectively). The ZZK's emissions of SO_2 and CO are statistically lower than their respective standards. NO_x emissions are statistically lower than their PEQS at the ZZK and the BTK (both cycles). Given the small sample size of PM, we do not have enough degrees of freedom to find statistical differences between its standard and its concentration at each kiln. The emissions of O_2 and CO_2 cannot be compared since the EPD has not set standards for these gases.

3.2.3. Emission Factors

Table 5 presents the energy-based and the fuel-based emission factors for each type of emission from the ZZK and the BTK. These normalizations provide a more consistent comparison of the emissions of the two kilns. The BTK has significantly higher emission factors for all emissions except NO_x compared to the ZZK. The BTK's emission factors (energy-based) for SO_2, CO, and PM are 43, 9, and 48 times, respectively, those of the ZZK—the ratios of the fuel mass-based emission factors of these emissions are similar.

Table 6 compares the energy-based emission factors from our study with those calculated by Rajarathnam et al. (2018) for a sample of identical types of kilns in India—they did not calculate emission factors for NO_x. The comparison shows that the emission factors for the BTK in our study are considerably higher than the emission factors of the sample Indian BTK. The difference in the emission factors for SO_2 is especially stark—12.93 g/MJ in our study versus 0.39 g/MJ in Rajarathnam et al. (2018).

For the ZZK, the energy-based emission factors of all pollutants, except PM, in our study are comparably close to the emission factors in Rajarathnam et al. (2018). The PM emission factor for the sample Indian ZZK is 6 times the PM emission factor for the ZZK in our sample. The difference in coal quality could explain some of the variation in the emission factors across the two studies. Nonetheless, our results corroborate earlier findings that the ZZK is a significantly cleaner technology than the BTK.

4. Economic Analysis

Below we compare the private and social benefits and costs of our sample ZZK and BTK. The values for the analysis are based on data available up till the time we conducted our fieldwork—approximately two months of data—and on the owners' expectations of the future prices of inputs and output.

4.1. Private Costs

The startup capital costs for both the BTK and the ZZK comprise the down payment for land lease, advanced labor wages, and construction and equipment costs. Most kiln owners in Punjab construct kilns on leased land with contracts that include a down payment in the first year. They also hire the bulk of the labor by paying wages for a fixed number of years in advance—the advance payment is a loan that workers repay by working at the kilns for a predetermined period (Malik 2016). Construction costs include expenditures on material and labor required to erect the kilns.

Figure 3 shows the total startup capital costs in Rupees ($Rs.$) of our two sample kilns. The ZZK's initial investment is $Rs.$ 9 million higher than the initial investment for the BTK. The ZZK has higher land and labor costs compared to the BTK since it requires a larger area to accommodate its wide chimney and it employs more workers. Both kilns require a tubewell for pumping water while the ZZK requires additional equipment, including an electric fan, electricity connection (with a transformer), generator, and coal crusher, which drives up its initial investment.

Figure 4 shows the annual total operating costs (total variable costs plus total fixed costs) in $Rs.$ of the two kilns. The fixed costs consist of yearly land lease payments. The variable costs include expenditures on variable factors of production such as fuel (coal), electricity, and raw material (clay and sand). These also include daily wages for workers hired to meet labor demand—the kilns require more workers than those hired on advanced wages. Both kilns use coal as fuel, which constitutes their largest expense. The ZZK consumes higher quality—and therefore more expensive—coal compared to the BTK. However, the ZZK consumes about 33 percent less coal than the BTK owing to its high fuel-efficiency. The lower consumption of coal mostly offsets the expense on high quality coal.

Both kilns use electricity to power tubewells, which provide water to mold clay and sand into green bricks, while the ZZK consumes further electricity to run its draft fan. During power outages, the ZZK shifts to a diesel-powered generator to operate the fan. The ZZK's expenditure on raw materials is higher than the BTK's since it produces more bricks. The ZZK's maintenance costs are also higher given the range of machinery installed in it. Owing to the ZZK's greater startup costs and expenditures on variable factors of production, its total initial year costs are 18 percent higher than those of the BTK.

4.2. Private Benefits

Kilns produce four grades of bricks, termed, in descending order of quality, Grade A, Hard Brick, Grade B, and Grade C. Brick quality depends on the evenness and consistency of baking, with low-quality bricks being under- or over-burned owing to nonuniform temperatures in the kilns. Figure 5 compares the unit prices (in $Rs.$ per thousand) of the different grades of bricks. The highest quality (Grade A) bricks have the most commercial value and fetch $Rs.$ 7,000 per thousand—the unit price falls by $Rs.$ 1,000 per thousand for each grade reduction.

Figure 6 shows the percentage of each grade of bricks produced by our sample ZZK and BTK. For a fixed amount of bricks baked across the two kilns, the ZZK produces 15 percent more Grade A bricks than the BTK. Since the ZZK and the BTK produce 12 million and 10 million bricks per year, respectively, the ZZK also produces more Grade A bricks in absolute terms—70 percent more than the BTK. This allows the ZZK to generate a larger annual revenue and double the profit as shown in Figure 7, making it more economically attractive than the BTK for private kiln owners.

4.3. Payback Period

Table 7 shows the payback period for the BTK and the ZZK at different real (inflation-adjusted) discount rates. The ZZK's annual profits are more than double (106 percent) the annual profits of the BTK, allowing the owners of the ZZK to recover their initial investment in a shorter period—1.5 years versus 2.4 years under a 10 percent discount rate. The difference between the payback periods of the two kilns becomes larger as the discount rate increases. The profit margins of the two kilns are high enough that owners can recover their initial investments within 2.5 years with a 10 percent discount rate.

4.4. Cost of CO_2 Emissions

The BTK and the ZZK emit considerable amounts of CO_2 as shown by our environmental analysis—each kiln emits more CO_2 than all its other emissions combined. The cost of CO_2 emissions—evaluated using the average price of CO_2 emissions observed in international trading markets—of each kiln provides an approximation of its social cost. In the absence of international prices of the other pollutants, we could not sufficiently approximate their implicit costs. Therefore, the total costs of CO_2 emitted by each kiln gives a lower bound of their total social costs.

The specific energy consumption of coal (SEC^C) for each type of kiln is given by:

(4) $$SEC^C = \frac{GCV^C \times C^C}{W},$$

where GCV^C is the gross calorific value of coal in megajoules per kilogram MJ/kg, C^C is coal consumption per brick in kg, and W is the average weight of each brick produced in kg. Given the variation in the type of coal used at each kiln, we used a standardized value of GCV^C (25.68 MJ/kg) to calculate SEC^C.

Each kiln's annual CO_2 emissions (E^{CO_2}) in t are given by:

(5) $$E^{CO_2} = CF^{C-CO_2} \times EF_e^C \times SEC^C \times Q,$$

where CF^{C-CO_2} is the carbon to carbon dioxide conversion factor in tCO_2/tC, EF_e^C is the energy-based emission factor of carbon in g/MJ, and Q is the total number of bricks produced per year.

Table 8 shows the calculated values of CO_2 emissions and their costs for each kiln. The BTK's CO_2 emissions are 1.5 times those of the ZZK—7274.70 t versus 4849.80 t. This translates into present value (with a 10 percent discount rate and a 20-year time horizon) CO_2 emission costs of $Rs.$ 5.60 per brick for the ZZK and $Rs.$ 10.08 per brick for the BTK—the ZZK's social cost per brick is almost half that of the BTK.

4.5. Private and Social Benefits

Table 9 shows the discounted costs and benefits of the two types of kilns. We have assumed a 10 percent discount rate and a 20-year time horizon to calculate the present values. The total private costs include the startup capital cost and the annual variable and fixed costs. The total social costs represent the monetary costs of CO_2 emissions. The total private net benefits are equal to the difference between the total benefits (yearly revenue) and the total private costs while the total social net benefits represent the difference between the total private net benefits and the total social costs.

The results show that the ZZK's total private net benefits are more than twice those of the BTK while it generates over three times the total social net benefits over a 20-year period. The ZZK's private net benefits and social net benefits are $Rs.$ 194.65 million and $Rs.$ 171.48 million, respectively, compared to $Rs.$ 85.20 million and $Rs.$ 50.45 million for the BTK. The figures for the social net benefits are lower bounds for the actual values since they exclude costs of the emissions of other harmful pollutants. The perceived social benefits of the ZZK would be even higher given that it emits lower amounts of SO_2, CO, and PM than the BTK.

Table 10 shows the total private benefits and the total social costs for each kiln under different discount rates. The absolute difference between the total social benefits of the two kilns is larger at lower discount rates while the relative (proportional) difference is similar. The results provide evidence that the adoption of ZZK technology would monetarily enhance social welfare.

5. Conclusion, Limitations, and Recommendations

Our environmental and economic comparison of two different kiln technologies—ZZK and BTK—demonstrates that the ZZK is considerably more environmentally friendly and socially cost-effective than the BTK. Our sample ZZK used less coal per brick and emitted far lower amounts of SO_2, CO_2 CO, and PM compared to the BTK. The ZZK produces more high-quality bricks and uses less coal than the BTK, which translates into higher private net benefits for ZZK owners. The higher private net benefits allow ZZK owners to recover their startup capital costs in less than two years—compared to 2.4 years for BTK owners. Since the ZZK also emits lower amounts of pollutants and greenhouse gases, it generates higher social returns than the BTK—almost three times higher. This provides strong evidence for encouraging kiln owners to shift from BTKs to ZZKs.

Our results should be taken with a hint of caution. Though we followed US EPA's recommended procedures to monitor emissions, our sample included one kiln of each type of technology. Since fuel type, fuel quality, and operating conditions vary across kilns, we recommend monitoring of a larger sample of kilns to get more consistent results. Moreover, we monitored emissions at each kiln for 40–45 minutes during daytime, ignoring the variation in emission during nighttime. A 24-hour monitoring regimen would more accurately identify the daily variation in the emissions of each kiln. Lastly, our study—as well as most others in the literature—relied on measurements of flue emissions. As Chen et al. 2017 point out, ignoring fugitive emissions that result through cracks in the furnace roof and the fuel feeding holes will underestimate the actual emissions. Monitoring of both flue and fugitive emissions will provide a better portfolio of emissions from different kiln technologies.

The environmental and economic assessments clearly demonstrate the advantages of substituting ZZKs for BTKs. However, the role of the EPD in helping kiln owners make this transition is not clear-cut. Drawing on insights from interviews with the managerial staff at our sample ZZK site and from literature on India and Nepal's experiences with ZZKs, we list some of the important steps that the EPD must take to facilitate the adoption of ZZKs in Punjab:

- Provide soft loans to prospective investors to help finance the costs of retrofitting BTKs with ZZK technology—approximately Rs 40 million per kiln;
- Ensure consistent electricity supply at ZZK sites to power the electric fans in the chimneys and maintain continuous operations;
- Establish a demonstration site to train ZZK workers and to offer technical assistance on ZZK construction and the brick stacking and baking processes;
- Create a network of ZZK owners in South Asia for knowledge transfer and exchange;
- Organize kiln conventions and support visits of local kiln owners to foreign conventions;
- Engage with ICIMOD, which has had great success with promoting ZZKs in Nepal.

The ZZK presents a promising opportunity for the EPD to improve ambient air quality in the province in a cost-effective manner. Using regional networks, demonstration sights, regular informational sessions, and basic support, the EPD can effectively facilitate kiln owners to transition from BTKs to ZZKs.

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Tables

Table 1: Proximate Analysis of Coal Samples at Kilns

Coal Sample	Moisture (Percent)	Ash (Percent)	VM (Percent)	GCV (MJ/kg)
Balochistan	3.88	13.59	38.80	26.78
Hyderabad	3.69	11.53	30.75	18.59
Balochistan-Hyderabad mixture	10.00	21.00	45.90	23.13

Table 2: Ultimate Analysis of Coal Samples at Kilns

Coal Sample	Nitrogen (Percent)	Carbon (Percent)	Sulphur (Percent)	Hydrogen (Percent)
Balochistan	1.17	68.52	5.60	5.25
Hyderabad	1.07	58.13	2.75	5.74
Balochistan-Hyderabad mixture	0.86	50.63	5.95	4.38

Table 3: One-way ANOVA on Stack Emissions

Emission Type	df	*F*	Sig.
SO_2	2	12.91	0.00
CO	2	16.23	0.00
NO_x	2	6.06	0.01
CO_2	2	20.74	0.00
O_2	2	9.86	0.00

Note: SO_2, CO, NO_x, and CO_2 concentrations are measured in mg/m^3 while O_2 concentrations are in percentages.

Table 4: Comparison of Stack Emissions with the Punjab Environmental Quality Standards (One-Sample *t*-Test)

	ZZK			BTK (Non-Feeding)			BTK (Feeding)		
Emission Type	*t*	*df*	*Sig.*	*t*	*df*	*Sig.*	*t*	*df*	*Sig.*
SO_2	-32.62	3	0.00	-21.65	2	0.00	5.44	10	0.00
CO	-3.18	3	0.05	-7.58	2	0.02	7.54	10	0.00
NO_x	-182.95	3	0.00	-1,900.00	2	0.00	-479.24	10	0.00
PM	-	-	-	-2.04	1	0.29	0.80	1	0.57

Note: The concentrations of all emissions are measured in mg/m^3. We only had one reading for the ZZK's PM emissions, which precluded us from calculating its statistical significance.

Table 5: Emission Factors and Emission Rates

Emission Type	Energy-Based Emission Factor (g/MJ)		Fuel Mass-based Emission Factor (g/kg)		Emission Rate (g/h)	
	ZZK	***BTK***	***ZZK***	***BTK***	***ZZK***	***BTK***
SO_2	0.30	12.93	7.97	299.00	1,833	62,513
CO	1.04	9.81	27.97	227.00	6,432	47,447
NO_x	0.07	0.06	1.80	1.47	414	308
CO_2	106	365	2,836	8,453	652,251	1,766,748
PM	0.04	1.83	1.01	42.22	233	8,823

Table 6: Comparison of Energy-Based Emission Factors

	Energy-Based Emission Factors (g/MJ)			
	Rajarathnam et al. (2014)		Current study	
Emission Type	***BTK***	***ZZK***	***BTK***	***ZZK***
PM	0.66	0.23	1.83	0.04
SO_2	0.39	0.23	12.93	0.30
CO	2.96	1.96	9.81	1.04
CO_2	140	92	365	106
NO_x	-	-	0.06	0.07

Note: The energy-based emission factors are measured in g/MJ.

Table 7: Discounted Payback Period

Discount Rate (Percent)	Payback Period (Years)	
	BTK	***ZZK***
0.00	2.03	1.33
2.00	2.10	1.36
5.75	2.24	1.43
10.00	2.40	1.50

Note: We have calculated the payback periods using constant cash flows—they do not include depreciation costs. The real interest rate in Pakistan at the time when we conducted our analysis was 5.75 percent—the third choice of the discount rate in the table.

Table 8: Annual Cost of CO_2 Emissions

	ZZK	BTK
Total Brick Production ($million\ bricks$)	1.20	1.00
Total Weight of Bricks (t)	34,800	29,000
Total Coal Consumption ($t/100{,}000\ bricks$)	16.67	30.00
Coal Consumption per Brick ($kg/brick$)	0.17	0.30
Calorific Value of Coal (MJ/kg)	25.68	25.68
Specific Energy Consumption per Brick ($MJ/brick$)	4.28	7.70
Carbon Emission Factor (C/MJ)	25.80	25.80
Carbon to CO_2 Conversion Factor	3.66	3.66
Annual CO_2 Emissions (t)	4,849.80	7,274.70
Annual CO_2 per Brick ($t/100{,}000\ bricks$)	40.41	72.75
Price of CO_2 Emissions ($\$/t$)	14.69	14.69
Annual Cost of CO_2 Emissions ($)	71,252.36	106,878.54
Annual Cost of CO_2 Emissions per Brick ($\$/brick$)	0.0059	0.0107
Annual Cost of CO_2 Emissions per Brick ($Rs./brick$)	0.66	1.18
Discount Rate (Percent)	10.00	10.00
Present Value Cost of CO_2 Emissions ($\$/brick$)	0.051	0.091
Present Value Cost of CO_2 Emissions ($Rs./brick$)	5.60	10.08

Note: We've used an average brick weight of 0.0029 t (CDM 2014) to calculate the Total Weight of Bricks. We've taken the values of the Carbon Emission Factor and the Carbon to CO_2 Conversion Factor from IPCC 2006 and CDM 2014, respectively. The Price of CO_2 is in 2017 dollars. We've used an exchange rate of 1\$ $=$110.75 $Rs.$ to convert dollar values into rupee values—this was the applicable exchange rate at the time of the analysis.

Table 9: Discounted Costs and Benefits

Costs and Benefits ($Million\ Rs.$)	ZZK	BTK
Startup Capital Costs	35.85	26.75
Operating Costs (Fixed and Variable Costs)	448.88	411.63
CO_2 Emissions Costs	23.17	34.75
Total Benefits (Total Revenue)	679.38	523.58
Private Net Benefits	194.65	85.20
Social Net Benefits	171.48	50.45

Table 10: Private and Social Net Benefits under Various Discount Rates

	Private Net Benefits ($Million\ Rs.$)		Social Net Benefits ($Million\ Rs.$)	
Discount Rate (Percent)	**ZZK**	**BTK**	**ZZK**	**BTK**
2.00	406.86	188.27	362.36	121.53
5.75	281.09	127.19	249.24	79.41
10	194.65	85.20	171.48	50.45

Figures

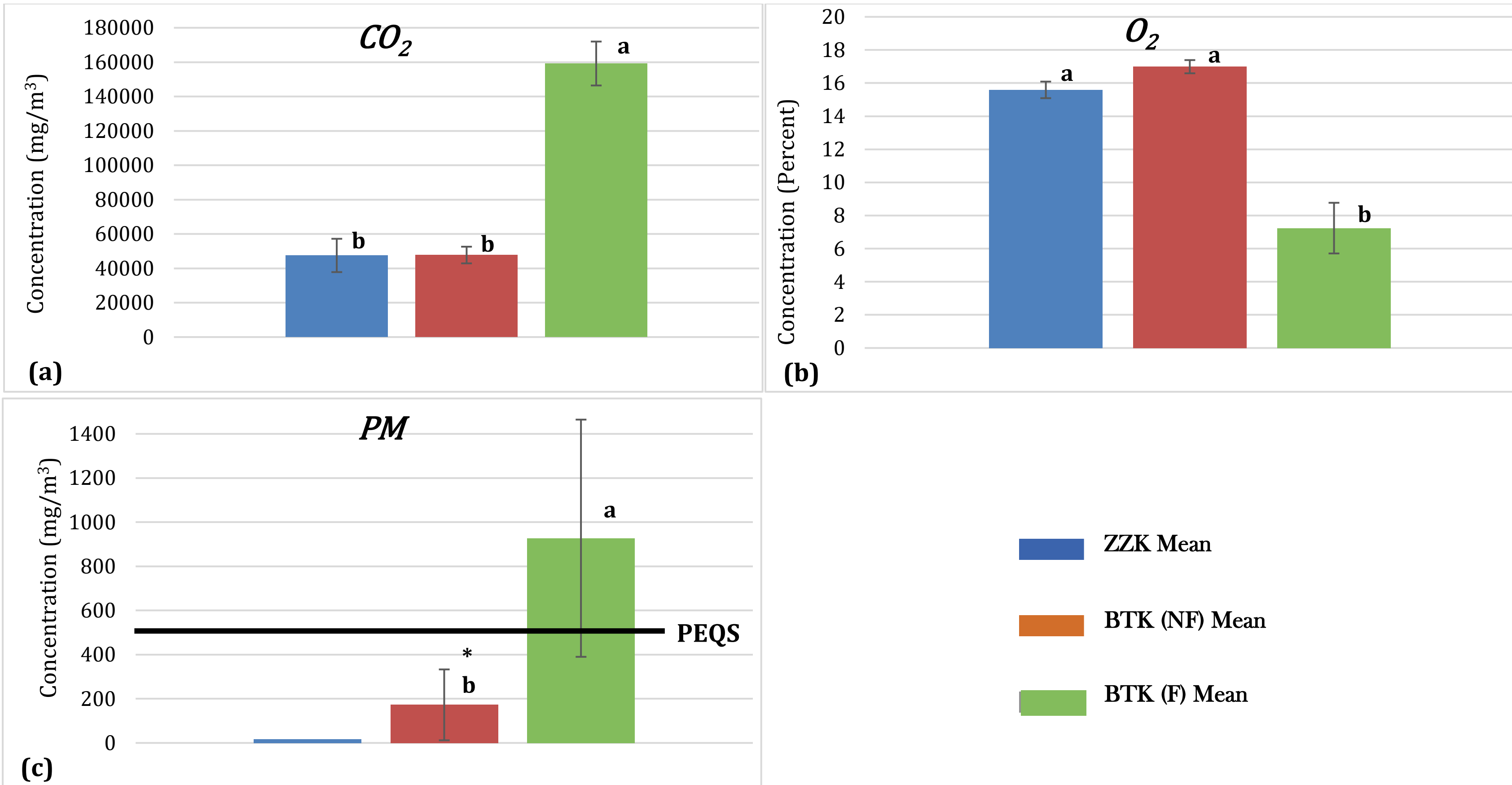

Figure 1: Comparison of mean CO_2, O_2, and PM emissions using One-Way ANOVA

Note: Means followed by the same letter are not statistically different at the 5 percent significance level (Tukey Test); the ends of the whiskers represent ± 1 standard deviation from the mean; * implies that the means are statistically different from the PEQS (One-Sample t-Test); F and NF denote feeding cycle and non-feeding cycle, respectively; CO_2 and O_2 don't have legally mandated PEQS; we only had one reading for the ZZK's PM emissions, which precluded us from calculating its statistical significance.

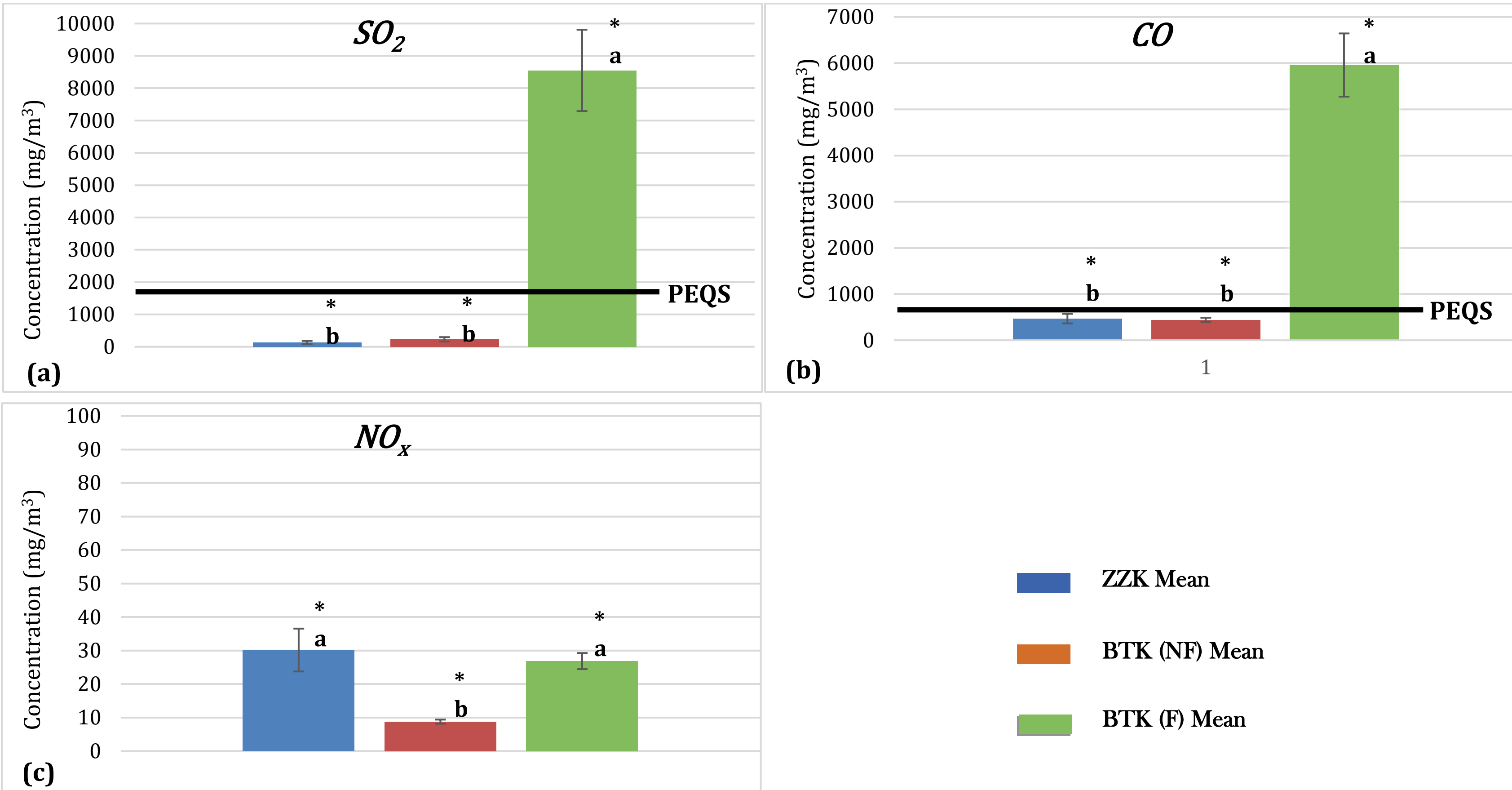

Figure 2: Comparison of mean SO_2, CO, and NO_x emissions using One-Way ANOVA

Note: Means followed by the same letter are not statistically different at the 5 percent significance level (Tukey Test); the ends of the whiskers represent ± 1 standard deviation from the mean; * implies that the means are statistically different from the PEQS (One-Sample t-Test); F and NF denote feeding cycle and non-feeding cycle, respectively; the PEQS for NO_x emissions (1200 mg/m^3) are too high to be shown in the figure.

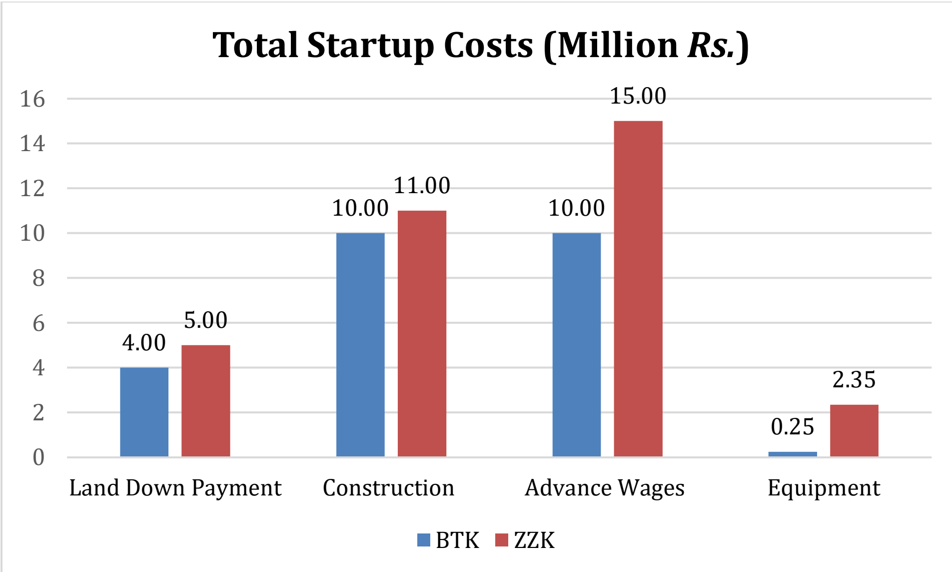

Figure 3: Total startup capital costs

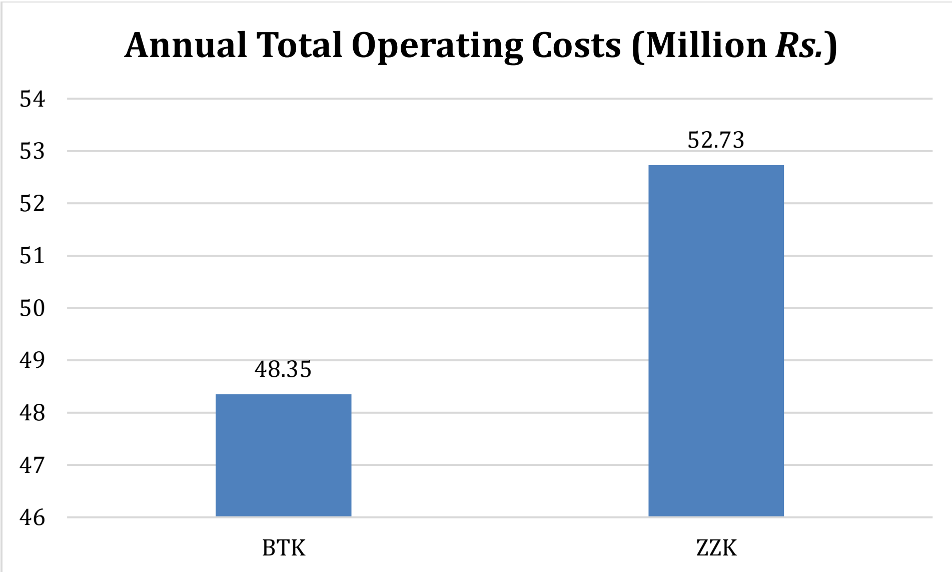

Figure 4: Annual total operating costs

Note: Total operating costs comprise total variable costs and total fixed costs.

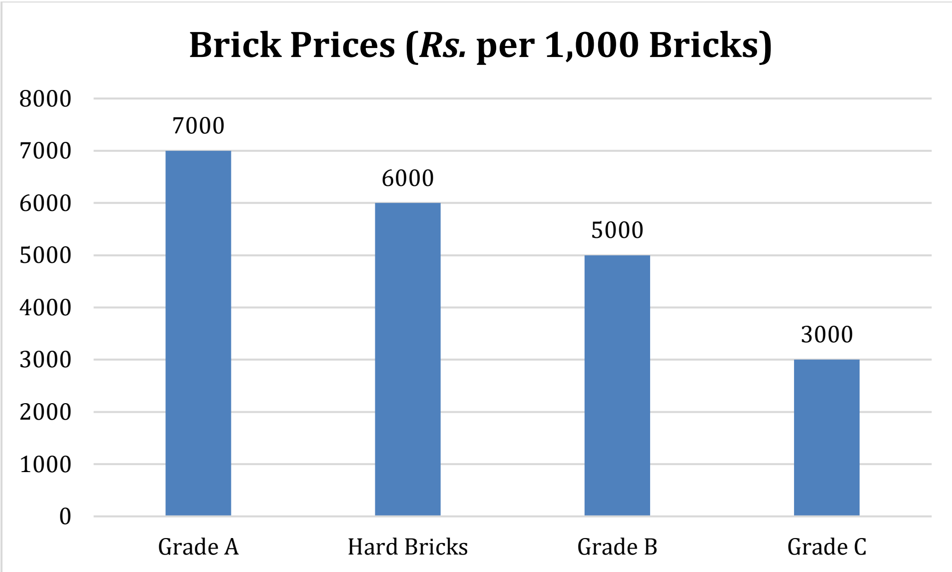

Figure 5: Brick prices by quality

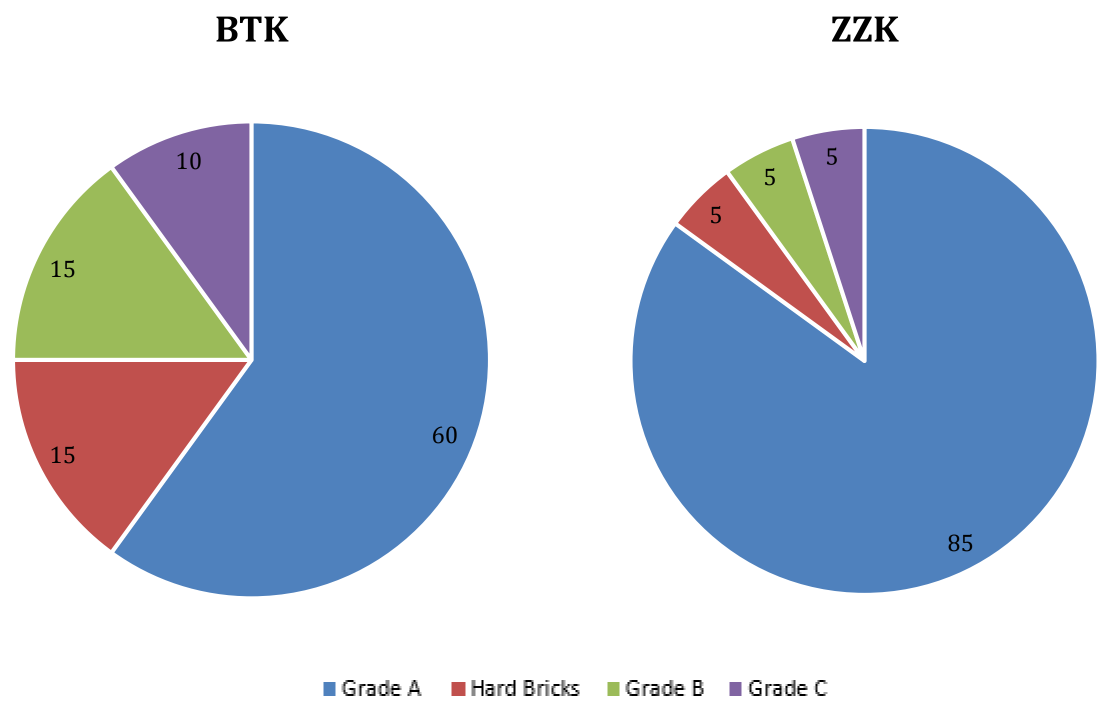

Figure 6: Share of different quality bricks in total production

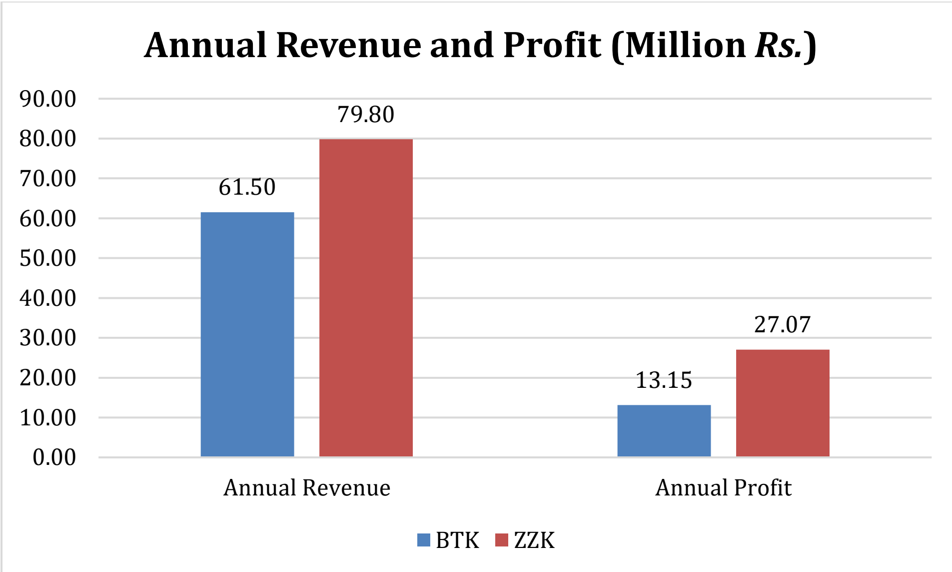

Figure 7: Annual revenue and profit