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Energy Efficiency in the Ceramic and Clay Building Materials Industry in Indonesia

Khusnul Ainia Aprilinda[1], Deni Kusumawardani[2]
[1,2]Department of Economics, Faculty of Economics and Business, Universitas Airlangga, Surabaya, Indonesia

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ABSTRACT

The Indonesian clay and ceramic building materials industry is highly energy-intensive, yet firm-level evidence on energy efficiency during the 2010–2015 period remains limited. This study aims to measure energy efficiency and identify its key determinants within the sector. Energy efficiency is estimated using the Slack-Based Measure Data Envelopment Analysis (SBM-DEA), and a Tobit regression model is applied to examine firm-level determinants using data from the BPS Large and Medium Industry Survey (IBS). The results show an average efficiency score of 0.60, indicating a potential 40% improvement. Subsector disparities are evident, with sanitary ware and porcelain industries outperforming brick and tile industries. Tobit results show that business scale, firm status, and production composition have positive and significant effects on efficiency, while export orientation has a negative effect. These findings indicate that inefficiency is primarily driven by structural and firm-specific factors rather than technological constraints, implying that improving energy efficiency requires structural transformation alongside technological upgrading.

Corresponding Author:

Khusnul Ainia Aprilinda
Department of Economics, Faculty of Economics and Business, Universitas Airlangga, Surabaya, Indonesia
Email: khusnul.ainia.aprilinda-2024@feb.unair.ac.id

1. INTRODUCTION

Improving energy efficiency in the industrial sector is a major challenge in achieving sustainable economic development, particularly in energy-intensive industries. The industrial sector contributes approximately 37% of global final energy consumption and nearly a quarter of energy-related CO_2 emissions, according to the International Energy Agency [1]. In Indonesia, the industrial sector is the largest energy consumer, contributing more than 30% of total national energy consumption and showing an increasing trend in recent years, according to the Ministry of Energy and Mineral Resources [2]. This situation reflects a structural problem: high energy dependence increases production costs, reduces industrial competitiveness, and increases pressure on emission-reduction targets.

One industrial subsector considered highly energy-intensive is the clay- and ceramics-based building materials industry. The production process in this industry relies heavily on high-temperature thermal energy, particularly during the kiln-firing stage, which accounts for more than 50% of total energy consumption [3]. Furthermore, this industry plays a strategic role in supporting the construction sector and infrastructure development in Indonesia. However, increased production that is not accompanied by improvements in energy efficiency can lead to energy waste and higher production costs, indicating inefficiency at the company level.

Theoretically, efficiency measurement is based on the concept of a production frontier, in which company performance is evaluated relative to the best unit (the efficient frontier). The nonparametric Data Envelopment Analysis (DEA) method introduced by Charnes, Cooper, and Rhodes [4] is widely used because it can handle multiple inputs and outputs without requiring a production function specification. However, conventional DEA models have limitations because they cannot capture excess input and insufficient output (slack), which are the core of energy inefficiency. To address this, the Slack-Based Measure (SBM) model developed by Tone explicitly incorporates slack into efficiency measurements, resulting in more accurate estimates [5].

Several empirical studies have applied DEA and SBM in energy efficiency analysis, demonstrating that DEA is a flexible approach in energy and environmental analysis 6]. Sueyoshi Toshiyuki and Goto demonstrated that SBM has better discrimination capabilities than conventional DEA [7]. More recent studies, such as those, have emphasised the importance of considering slack and firm heterogeneity in energy efficiency analysis, particularly in energy-intensive industrial sectors 3], [8], [9].

In addition to measuring efficiency, identifying the factors that influence it is crucial. A two-stage DEA approach is commonly used, in which efficiency scores are analysed using a regression model. Because DEA efficiency scores are bounded between zero and one, the Tobit model introduced by James Tobin is more appropriate than conventional linear regression [7]. This approach is reinforced by Simar Leopold and Wilson, who emphasise the validity of the second-stage analysis [10]. Empirical studies by Lin Boqiang and Du and Zhao Xiliang show that firm characteristics, such as size, ownership, export orientation, and technology, significantly influence energy efficiency [11], [12].

Despite the rapid growth of the literature, several significant research gaps remain. First, studies specifically examining the clay and ceramic building materials industry remain very limited, especially in Indonesia, which is characterised by thermal-based energy consumption. Second, there has been no research that explicitly integrates the SBM-DEA approach with the panel Tobit model using longitudinal firm-level data in this industry in Indonesia. Third, most previous studies use aggregate or cross-sectional data, which have not allowed them to capture heterogeneity and efficiency dynamics at the firm level.

Unlike previous research, this study explicitly integrates the SBM-DEA approach with a panel Tobit model, using longitudinal firm-level data on the Indonesian clay and ceramic-based building materials industry. This practice has never been done before, to the authors' knowledge. Furthermore, the use of microdata from the Large and Medium Industries Survey (IBS) enables analysis of efficiency heterogeneity that aggregate-data-based studies cannot capture, thereby providing a stronger empirical contribution to understanding energy efficiency dynamics at the firm level.

This study analyses the energy efficiency of the clay and ceramic-based building materials industry in Indonesia, identifies the main sources of energy inefficiency, and examines the factors influencing variation in energy efficiency across firms. To achieve these objectives, this study uses the SBM-DEA approach and a panel Tobit regression model, utilising firm data from the Large and Medium Industries Survey (IBS) for the 2010–2015 period. This study makes two main contributions. First, a methodological contribution through the integration of SBM-DEA and the Tobit panel within a single comprehensive analytical framework. Second, an empirical contribution using firm-level microdata, enabling a more in-depth analysis of efficiency heterogeneity than studies based on aggregate data. The results of this research are expected to contribute academically to the development of industrial energy efficiency literature and provide policy implications for designing strategies to improve energy efficiency, enhance industrial competitiveness, and support sustainable industrial development in Indonesia.

2. METHOD

Research Data

This study employs a quantitative approach to analyse energy efficiency in the Indonesian ceramic and clay-based building materials industry and identify its determinants. The analysis is conducted in two main stages: (i) efficiency measurement using the Slack-Based Measure Data Envelopment Analysis (SBM-DEA), and (ii) determinant analysis using the Tobit regression model. The data used are secondary data obtained from the Large and Medium Industry Survey (IBS) published by the Central Statistics Agency (BPS) for the period 2010–2015. The unit of analysis is firms in the ceramic and clay building materials industry. Each firm is treated as a Decision-Making Unit (DMU). The data processing stages include variable identification, data extraction, and data cleaning to ensure consistency and completeness.

Energy Efficiency Measurement Using SBM-DEA

This study used a Data Envelopment Analysis (DEA) approach with the Slack-Based Measure (SBM) model developed by Kaoru Tone. The SBM model was chosen because it addresses the limitations of conventional DEA by directly accounting for excess input use and output shortages via slack variables, thereby yielding more accurate efficiency estimates [10], [13]. DEA is a nonparametric method based on linear programming that evaluates the relative efficiency of several decision-making units (DMUs) that use various inputs to produce a specific output [10]. In this study, each ceramic industry company is treated as a DMU that uses various production inputs, including energy, to produce industrial output.

Input Variables

x_1: Capital (fixed assets)
x_2: Labour (number of workers)
x_3: Energy consumption (fuel and electricity usage)
x_4: Raw materials (material input)

Output Variables

Desirable output (good output):
y_1^g: Production value
Undesirable output (bad output):
y_1^b: Emissions (CO_2)

The SBM model is formulated as follows [13]:

For n DMUs, the SBM model with undesirable outputs is formulated as:

$$\rho^* = \min \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1+\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{r0}^g}+\sum_{r=1}^{s_2}\frac{s_r^b}{y_{r0}^b}\right)} \text{ .... (1)}$$

subject to:

$$x_{i0} = \sum_{j=1}^{n} x_{ij}\,\lambda_j + s_i^-(i = 1, \dots, m) \text{ .... (2)}$$
$$y_{r0}^g = \sum_{j=1}^{n} y_{rj}^g\,\lambda_j - s_r^g(r = 1, \dots, s_1) \text{ .... (3)}$$
$$y_{r0}^b = \sum_{j=1}^{n} y_{rj}^b\,\lambda_j + s_r^b(r = 1, \dots, s_2) \text{ .... (4)}$$
$$\lambda_j \geq 0, s_i^- \geq 0, s_r^g \geq 0, s_r^b \geq 0 \text{ .... (5)}$$

where
s_i^-= input excess
s_r^g= desirable output shortfall
s_r^b= undesirable output excess
y^g= desirable output
y^b= undesirable output

Efficiency values range from $0 \leq \rho \leq 1$. An efficiency value of 1 indicates that the DMU is in an efficient condition, while a value less than 1 indicates potential improvements in input use or increases in output. The SBM approach is widely used in energy efficiency research because it can capture inefficiencies in greater detail than the traditional DEA model [4].

Efficiency Determinant Analysis Using the Tobit Model

The efficiency score from the DEA model is limited to the range 0 to 1. This condition makes the use of ordinary linear regression methods inappropriate, as it can lead to biased estimates. Therefore, this study uses the Tobit regression model introduced by James Tobin to analyse dependent variables that are censored or otherwise limited [7].

The Tobit model is used to analyse the influence of company characteristics on energy efficiency in the ceramic industry. The model specifications in this study are formulated as follows.

$$EE_i = \beta_0 + \beta_1 BS_i + \beta_2 SC_i + \beta_3 OE_i + \beta_4 PC_i \varepsilon_{it} \text{ ....(4)}$$

Where,
EE = Energy Efficiency Score
BS = Company Status
SC = Business Scale
EO = Export Orientation
PC = Production Composition

The Tobit model is widely used in two-stage DEA analysis because it can accommodate the limited nature of efficiency scores and yields more consistent parameter estimates [11], [14].

Software

To ensure reproducibility and accuracy, this study uses:

a. MaxDEA 8.0 for SBM-DEA efficiency estimation
b. Stata 17 for Tobit regression analysis

3. RESULTS AND DISCUSSION

3.1. Results

Descriptive statistics of frontier variables in the clay and ceramic-based building materials industry are presented in Table 1. The results show that the average production value during the 2010–2015 period reached 18,394.41 thousand rupiah, with a standard deviation of 139,988.56, indicating variations in production levels between companies in the industry. The average CO_2 emissions were 249,367.20, with a standard deviation of 4,850,460.99, indicating significant differences in emission levels between companies.

Table 1 . Statistical Description of Frontier Variables

Type of Industry		Produksi (Thousands of Rupiah)	CO2 Emissions	Capital (Million Rupiah)	Labor (Person)	Energy (Tj)	Raw Materials (Million Rupiah)
Building Materials Ceramics, Clay	Mean	18.394,41	249.367,20	10.704,57	84,54	3.368,19	2.862,01
	SD	139.988,56	4.850.460,99	93.011,78	281,90	65.463,29	25.883,29

Source: BPS (2010-2015), processed.

The average capital expenditure in the production process was 10,704.57 million rupiah, while the average labour force was 284.54 people, indicating that this industry remains relatively labour-intensive. Average energy consumption was recorded at 3,368.19 TJ, indicating that energy is a crucial input in this industry's production process. Meanwhile, the average raw material expenditure reached 2,862.01 million rupiah, with a standard deviation of 25,883.29, indicating variations in production scale and raw material use among companies. Overall, these descriptive statistics indicate that the clay and ceramic building materials industry in Indonesia exhibits significant heterogeneity in production scale, energy use, and utilisation of production inputs across companies.

Table 2. Empirical Characteristics of Energy Efficiency Explanatory Variables

Industry Type		Business Status	Business Scale	Export Orientation	Production Composition
Building Materials Ceramics Clay	Mean	0,012	0,121	0,007	8,877
	SD	0,111	0,944	0,081	1,824

Source: BPS (2010-2015), processed

Table 2 presents the empirical characteristics of the explanatory variables for energy efficiency in the clay and ceramic building materials industry during the 2010–2015 period. The results show that the average business status was 0.012 with a standard deviation of 0.111, indicating that the proportion of companies with certain characteristics was relatively small in the study sample. The average business scale was 0.121, with a standard deviation of 0.944, indicating variation in company size within the industry.

Furthermore, the average export orientation was 0.007, with a standard deviation of 0.081, indicating that most companies in this sector remain oriented towards the domestic market. Meanwhile, the production composition variable had an average of 8.877 and a standard deviation of 1.824, reflecting structural variation and production diversification across companies in the clay and ceramic-based building materials industry.

Table 3 presents the energy efficiency scores of the clay and ceramic-based building materials industry in Indonesia during the 2010–2015 period, calculated using the Slack-Based Measure Data Envelopment Analysis (SBM-DEA) approach. Efficiency scores range from 0 to 1, with values closer to 1 indicating that the production unit is closer to the energy-efficiency frontier.

Table 3. Energy Efficiency Score of the Clay and Ceramic Building Materials Industry

Sub Sector	2010	2011	2012	2013	2014	2015	Average
Clay/Ceramic Brick Industry	0.36	0.48	0.48	0.48	0.50	0.57	0.48
Clay/Ceramic Roof Tile Industry	0.17	0.26	0.31	0.31	0.28	0.34	0.28
Porcelain Sanitary Ware Industry	0.17	1.00	1.00	1.00	1.00	1.00	0.86
Clay/Ceramic Building Materials Industry	0.51	0.50	0.75	0.75	0.72	0.83	0.68
Porcelain Household Goods Industry	0.55	0.68	0.70	0.70	1.00	1.00	0.77
Clay/Other Ceramic Building Materials Industry	0.39	0.51	0.58	0.58	0.58	0.55	0.53
Building Materials/Clay Ceramics Sector	0.36	0.57	0.64	0.64	0.68	0.72	0.60

Source: BPS (2010-2015), processed.

In aggregate, the clay and ceramic building materials industry sector showed an average efficiency score of 0.60 during the study period. This score indicates that, on average, companies in this sector achieved only approximately 60 per cent of optimal energy efficiency, leaving room to increase it by 40 per cent if they could operate their production processes at frontier conditions. This large gap cannot be viewed as marginal inefficiency but rather indicates systemic inefficiencies stemming from limited production technology, suboptimal business scale, and weak energy management practices at the company level. In other words, the efficiency issues in this sector are more structural than merely technical. However, the relatively sharp increase in the initial period, particularly between 2010 and 2011, indicates that this improvement was not entirely due to a uniform increase in efficiency across all firms. Rather, this phenomenon reflects a selection effect: less efficient firms were eliminated or saw their contributions decline, while more efficient firms became dominant. This suggests that the sector's efficiency gains were driven more by the dynamics of the industrial structure than by a gradual, uniform technological learning process.

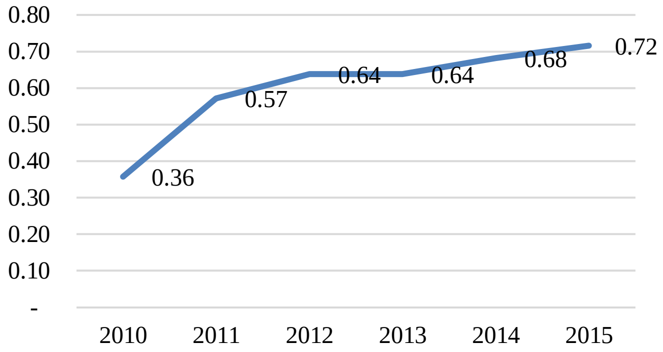

Figure 1. Energy Efficiency Score

In 2010, the sector's energy efficiency score was 0.36, indicating that at the beginning of the study period, the industry was still far from optimal efficiency. In 2011, the efficiency score increased to 0.57, indicating a significant improvement in industrial energy management. In the following period, sector efficiency remained relatively stable but continued to show an increasing trend, namely 0.64 in 2012 and 2013, then increasing to 0.68 in 2014, and reaching 0.72 in 2015. This gradual increase indicates improvements in production practices and energy management in this industrial sector.

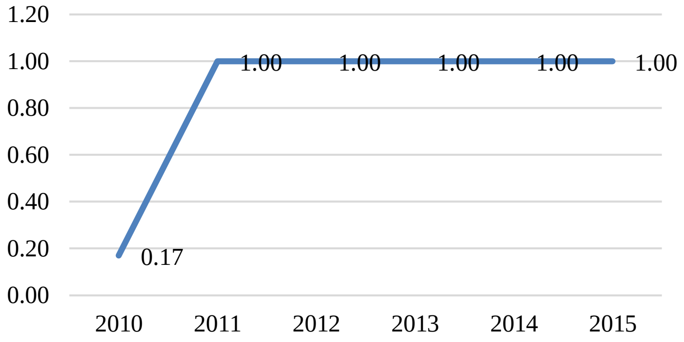

Figure 2. Score Efficiency Porcelain Sanitary Ware Industry

There is considerable variation in energy efficiency levels across subsectors within the clay and ceramic building materials industry. The porcelain sanitary ware industry demonstrated the highest energy efficiency level, with an average score of 0.86. In 2010, this subsector had an efficiency score of 0.17, indicating relatively low energy efficiency at the beginning of the study period. However, in 2011, the efficiency score increased dramatically to 1.00, and this score remained stable until 2015. This indicates that, since 2011, this subsector has reached an energy-efficiency frontier and can maintain optimal efficiency levels in its production processes.

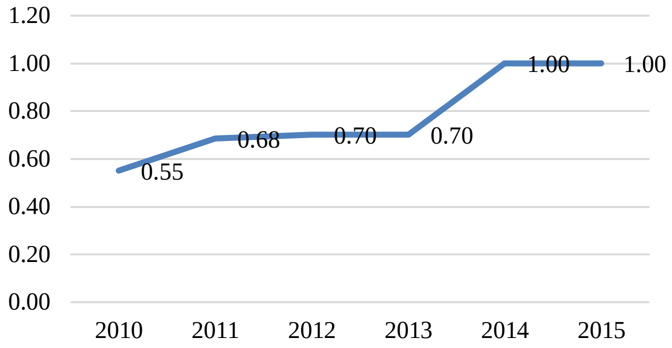

Figure 3. Score Efficiency Porcelain Household Goods Industry

The next subsector with relatively high energy efficiency is the porcelain household goods industry, with an average efficiency score of 0.77. The efficiency value in this subsector increased consistently throughout the study period, from 0.55 in 2010 to 0.68 in 2011, then increasing to 0.70 in 2012 and 2013, and finally reaching 1.00 in 2014 and 2015. This pattern indicates that the subsector experienced significant improvements in energy efficiency during the study period.

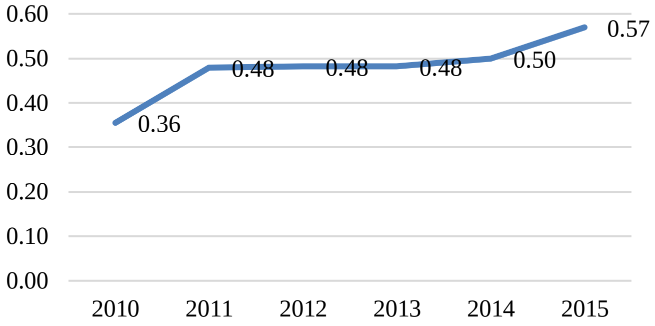

Figure 4. Score Energy Efficiency Clay/Ceramic Brick Industry

The clay and ceramic building materials industry subsector showed an average efficiency value of 0.68. The efficiency value in this subsector showed an increasing trend from 0.51 in 2010, then remained relatively stable at 0.50–0.75 in the 2011–2013 period, before finally increasing to 0.72 in 2014 and reaching 0.83 in 2015. This indicates improvements in energy efficiency in the production process of ceramic-based building materials. The clay and other ceramic building materials industry subsector has an average efficiency score of 0.53. This efficiency score increased from 0.39 in 2010 to 0.51 in 2011, then increased to 0.58 in 2012–2014, before declining slightly to 0.55 in 2015.

The clay and ceramic brick industry subsector has an average efficiency score of 0.48. This efficiency score increased gradually from 0.36 in 2010 to 0.48 in 2011–2013, then increased to 0.50 in 2014, and reached 0.57 in 2015. The subsector with the lowest energy efficiency score is the clay and ceramic roof tile industry, with an average efficiency score of 0.28. The efficiency value in this subsector increased from 0.17 in 2010 to 0.26 in 2011, then increased to 0.31 in 2012 and 2013, decreased to 0.28 in 2014, and then increased again to 0.34 in 2015. The differences in efficiency values across these subsectors indicate significant heterogeneity in energy efficiency within the Indonesian clay and ceramic-based building materials industry.

The significant variation in efficiency across subsectors further reinforces the industry's dualism. The porcelain sanitary ware subsector, which has the highest average efficiency (0.86) and consistently achieved a score of 1.00 since 2011, demonstrates the characteristics of a more modern, standardised industry dominated by large-scale companies with relatively advanced production technology. However, this perfect efficiency achievement needs to be interpreted with caution, as within the DEA framework, a value of 1.00 is relative to the sample. This condition may reflect the dominance of a few large companies as a benchmark, not necessarily implying that all players in the subsector have achieved absolute optimal efficiency.

Conversely, the clay roof tile subsector demonstrated the lowest efficiency, averaging 0.28 and showing relatively slow improvement throughout the study period. This condition indicates the presence of an efficiency trap (low-efficiency trap), in which businesses struggle to improve their energy performance due to limited access to modern technology, limited investment capacity, and the dominance of small and medium-sized enterprises that still use traditional combustion technology. In this context, low efficiency is not solely due to technical choices but is a consequence of structural limitations that hinder the industrial upgrading process.

Table 4 presents the Tobit regression results for the determinants of energy efficiency in the clay and ceramic-based building materials industry in Indonesia during 2010–2015. The Tobit model was used because the energy efficiency values obtained from the Slack-Based Measure Data Envelopment Analysis (SBM-DEA) approach fall within a limited range of 0 to 1. Under these conditions, ordinary linear regression can produce biased parameter estimates because it does not account for the censored nature of the dependent variable [7].

Table 4. Determinants of Energy Efficiency in the Clay Ceramic Building Materials Industry

Variable	*Regression coefficient*	*Standard error*	*Z value*	*P value*
Constant	0.153703	0.022148	6.94	0.000
Business Scale (SC)	0.0133356	0.0066399	2.01	0.045
Company Status (BS)	0.03326991	0.0822408	4.05	0.000
Export Orientation (EO)	-0.1057167	0.0524181	-2.02	0.044
Production Composition (PC)	0.0192327	0.0021084	9.12	0.000

Source: BPS (2010-2015), processed.

The Tobit model estimation results in Table 4 indicate that all independent variables significantly influence energy efficiency at the 5 percent significance level, as indicated by p-values below 0.05. This indicates that variations in energy efficiency between firms in the clay and ceramic building materials industry can be systematically explained by the firm characteristics used in the model. The significant constant value of 0.1537 also indicates a baseline efficiency level that differs from zero when all independent variables are controlled.

In general, the pattern of results shows differences in the direction and strength of influence between variables. Three variables, business scale (SC), firm status (BS), and production composition (PC), show a positive relationship to energy efficiency, while export orientation (EO) shows a negative relationship. This difference indicates that not all firm characteristics drive efficiency improvements in the same direction. The production composition variable (PC) emerged as the most dominant determinant in the model, as reflected by a coefficient value of 0.0192 and a Z-value of 9.12, the highest among all variables. This high statistical value indicates that variations in energy efficiency across firms are strongly associated with differences in the structure of their outputs. In other words, differences in product types are a key differentiating factor in energy efficiency levels within industries.

The firm status (BS) variable shows a positive effect, with a coefficient of 0.0333 and high significance. However, its relatively large standard error value compared to other variables indicates considerable variation in the effect between firms. This indicates that the impact of firm status on efficiency is not uniform but rather depends on each firm’s specific circumstances. The business scale (SC) variable also shows a positive and significant relationship with energy efficiency, with a coefficient of 0.0133. However, compared with other variables, this coefficient is relatively small, suggesting that the effect of business scale on efficiency is more limited. This indicates that although larger firms tend to be more efficient, increasing firm size does not always lead to a proportional increase in efficiency.

Conversely, the export orientation (EO) variable shows a negative and significant coefficient of -0.1057, with a Z-value of -2.02. This coefficient is the largest in absolute value among all variables, indicating a stronger pattern of differences than the other variables. These findings confirm that there are differences in efficiency characteristics between export-oriented and domestic-oriented companies. Overall, the estimation results indicate that energy efficiency in this industry is not influenced by a single dominant factor, but rather by the interaction of various company characteristics with varying directions and strengths of influence. The main pattern observed is the strong role of production composition, followed by company status and business scale. Furthermore, there are differences in the direction of influence on the export orientation variable, distinguishing it from the other variables.

3.2. Discussion

Energy Efficiency

Efficiency findings indicate significant heterogeneity across subsectors within the clay and ceramic building materials industry, primarily driven by differences in production technology, business scale, and equipment modernisation. The porcelain sanitary ware subsector demonstrates the highest level of energy efficiency, closely linked to the use of modern kiln technologies, such as tunnel and roller kilns. This technology enables continuous production processes, more precise temperature control, and minimizes heat loss, significantly reducing energy consumption per unit of output [1], [15]. These findings are consistent with research confirming that technological advancements are a key determinant of energy efficiency in energy-intensive industries [6], [16].

Conversely, the clay roof tile and brick subsectors exhibit relatively low efficiency. This reflects the dominance of small and medium-sized enterprises that still use traditional firing technologies, such as clamp kilns and fixed-chimney kilns, which are low-efficiency [3], [9], [12], [17], [18]. Limited access to capital and slow technology diffusion make it difficult for businesses to adopt more efficient technologies. This pattern aligns with the findings that structural constraints, rather than technological limitations, more strongly influence inefficiency in developing countries 15], [19].

In aggregate, the average efficiency score of around 0.60 indicates that these industries are still far from the efficiency frontier and have significant energy-saving potential. Although efficiency improvements occurred during the study period, these improvements tended to be gradual and did not reflect structural transformation. This is consistent with studies showing that efficiency gains in developing industrial sectors tend to be slow and gradual [0], [21], [22].

Determinant Analysis

The results of the determinant analysis indicate that company characteristics play a significant role in determining energy efficiency levels. Business scale positively affects efficiency, reflecting economies of scale in energy use. Larger companies have greater capacity to adopt modern kiln technology and optimise production processes, thereby reducing energy intensity per unit of output [16], [23], [24], [25]. This finding aligns with research that shows that company size is an important factor in improving energy efficiency [26], [27], [28].

Company status also positively affects energy efficiency. This indicates that ownership structure and access to financial and technological resources play a significant role in improving efficiency. Companies with stronger capital capacity or international connections tend to be more able to adopt modern technology and improve energy management systems [29], [30], [31]. This finding is consistent with Dardati et al. (2018) and Mielnik and Goldemberg (2002), who emphasise the importance of access to and investment in technology for improving energy efficiency.

Production composition also has a positive and significant effect on energy efficiency. Product diversification allows companies to optimise production capacity, improve process integration, and encourage innovation, thereby reducing energy waste.

This aligns with research showing that innovation and process integration contribute to increased technical and energy efficiency [29], [32]. The most critical finding is the negative relationship between export orientation and energy efficiency. This result contradicts conventional literature, which states that exports increase efficiency through learning-by-exporting and technology transfer [33], [34], [35], [36]. In the context of the Indonesian ceramics industry, this relationship actually points in the opposite direction.

The decline in efficiency in export-oriented companies is driven more by production pressures than by technological improvements. To meet international market demand, companies significantly increase production capacity, resulting in higher kiln operating frequency and increased energy consumption. When technological improvements, energy intensity, and efficiency do not keep pace with increased production, the system's efficiency declines. Furthermore, higher export-quality standards require additional processes, such as finishing and re-firing, which are energy-intensive. Thus, the primary problem lies in the technology gap, not export activity itself. Companies can increase output but lack the technological capacity to maintain energy efficiency amid production pressures. This finding is consistent with those who show that production expansion can increase energy consumption if not accompanied by technological progress [37], [38], [39], [40].

Policy Implication

The findings of this study indicate that improving energy efficiency in the ceramics industry requires a structural approach. Low efficiency in traditional subsectors reflects financial and technological barriers that require appropriate policies to address. The government needs to encourage investment in modern kiln technology through fiscal incentives, subsidies, or low-interest financing schemes, particularly for small and medium-sized enterprises.

Conversely, the negative impact of export orientation suggests that export-promotion policies that focus solely on increasing output may increase energy intensity. Therefore, export policies need to be integrated with energy efficiency policies, for example, through mandatory energy audits, minimum efficiency standards, or incentives for companies adopting energy-efficient technologies. From an energy economics perspective, energy efficiency is a strategic factor influencing industrial competitiveness. Energy is a key input in the ceramics production process, particularly during the firing stage. Highly energy-efficient companies can reduce production costs and increase competitiveness, while inefficient companies face higher operational costs [23], [24], [41], [42]. Therefore, improving energy efficiency needs to be positioned as an integral part of a sustainable industrial development strategy, through the integration of industrial, energy, and trade policies.

4. CONCLUSION

This study finds that energy efficiency in Indonesia's clay and ceramic building materials industry remains suboptimal, as reflected by an average efficiency score of approximately 0.60, indicating that firms operate significantly below the efficiency frontier. The DEA results show that input excesses primarily drive inefficiency and vary across subsectors, with more technologically advanced segments achieving higher efficiency than traditional ones. Furthermore, the Tobit estimation confirms that firm characteristics play a critical role in determining efficiency. Business scale, company status, and production composition positively influence efficiency, while export orientation is negatively associated with efficiency, suggesting that production expansion without technological upgrading increases energy intensity.

This study contributes to the energy economics literature by demonstrating that energy inefficiency in energy-intensive industries is not only a matter of technical inefficiency but also structurally linked to firm heterogeneity. By integrating a non-radial DEA approach with Tobit regression, this research provides a more comprehensive framework that captures both the magnitude of inefficiency and its underlying determinants. This extends prior studies that rely on aggregated approaches and highlights the importance of firm-level analysis in explaining efficiency variation in developing economies.

The findings suggest that energy efficiency policies should not adopt a uniform approach but instead be tailored to subsector characteristics and firm profiles. Policies promoting technological upgrading, modernising production processes, and improving access to energy-efficient capital are essential to reducing the input excesses identified in the DEA results. In addition, the negative relationship between export orientation and efficiency indicates that industrial expansion strategies must be aligned with stricter efficiency standards. Enhancing energy efficiency in this sector can directly reduce production costs, improve industrial competitiveness, and help lower national energy demand.

This study has several limitations. First, the use of an older dataset (2010–2015) limits the generalizability of the findings to current industrial conditions, particularly given recent technological advancements. Second, the analysis is static and does not capture dynamic efficiency changes over time, including technological progress and learning effects. Third, the model may be subject to omitted-variable bias, as relevant factors such as energy prices, environmental regulations, and technological innovation are omitted due to data constraints.

Future research should address these limitations by incorporating more recent datasets, applying dynamic efficiency models, and integrating environmental and technological variables such as emission intensity and innovation indicators. Further studies may also explore subsector-specific energy-saving potential and evaluate the effectiveness of industrial energy efficiency policies. For policymakers and the broader public, this study highlights that improving energy efficiency is essential not only for reducing industrial energy costs but also for strengthening competitiveness and supporting sustainable energy use at the national level.

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