



## Machinery import, R&D spillover, and energy efficiency


Fengqin Liu, Jae-Yeon Sim, Bless Kofi Edziah, Huaping Sun, Samuel Asumadu Sarkodie & Philip Kofi Adom

**To cite this article:** Fengqin Liu, Jae-Yeon Sim, Bless Kofi Edziah, Huaping Sun, Samuel Asumadu Sarkodie & Philip Kofi Adom (2024) Machinery import, R&D spillover, and energy efficiency, *Journal of Environmental Planning and Management*, 67:6, 1258-1279, DOI: [10.1080/09640568.2023.2166819](https://doi.org/10.1080/09640568.2023.2166819)

**To link to this article:** <https://doi.org/10.1080/09640568.2023.2166819>

 View supplementary material [↗](#)


---

 Published online: 16 Feb 2023.

---

 Submit your article to this journal [↗](#)

---

 Article views: 253

---

 View related articles [↗](#)

---

 View Crossmark data [↗](#)







---

 Citing articles: 5 View citing articles [↗](#)

---



## Machinery import, R&D spillover, and energy efficiency

Fengqin Liu<sup>a,b</sup> , Jae-Yeon Sim<sup>a\*</sup> , Bless Kofi Edziah<sup>c,d</sup> , Huaping Sun<sup>c,e,\*#</sup> ,  
Samuel Asumadu Sarkodie<sup>f</sup>  and Philip Kofi Adom<sup>g</sup> 

<sup>a</sup>Graduate School, Sehan University, Mokpo, Korea; <sup>b</sup>School of Law, Jiangsu University, Zhenjiang, P.R. China; <sup>c</sup>Institute of Industrial Economics, Jiangsu University, Zhenjiang, P.R. China; <sup>d</sup>Faculty of Economics and Business Administration, Vilnius University, Vilnius, Lithuania; <sup>e</sup>School of Economics and Management, China University of Geosciences, Wuhan, P.R. China; <sup>f</sup>Business School, Nord University, Bodø, Norway; <sup>g</sup>Department of Development Policy, School of Public Service and Governance, Ghana Institute of Management and Public Administration (GIMPA), Accra, Ghana

(Received 16 April 2022; revised 20 October 2022; final version received 4 January 2023)

The gap in demand and supply of energy across Sub-Saharan African (SSA) countries has increased energy insecurity in the region. Therefore, power outages have become pervasive, causing unemployment and a decline in production output. Among the several energy-saving factors identified in the literature across developing economies, technological spillover driven by trade openness appears to be a prominent factor in improving energy efficiency. Thus, this study evaluates the impact of machinery imported from OECD and non-OECD countries and its corresponding research and development (R&D) spillover on energy efficiency performance in 18 SSA countries from 1995 to 2017. Using a stochastic energy distance function, we discover that aggregated data from OECD and non-OECD countries have no significant effect on energy efficiency performance across SSA countries. However, results from disaggregated data for OECD and non-OECD machinery imports show that OECD machinery imports improve energy efficiency contrary to non-OECD imports. Thus, technology spillover from OECD countries is advantageous for SSA countries to reduce long-term energy-based emissions. Furthermore, our results show that human capital has no significant effect on SSA energy efficiency. Consequently, the results possess some policy implications; for instance, policymakers responsible for promoting science and technology could increase investment in human capital development by developing technology and engineering expertise and increasing GDP allocation to R&D activities. For energy efficiency scores, we observe substantial differences in efficiency across SSA countries – implying potential improvements in energy efficiency across SSA countries.

**Keywords:** energy efficiency; import; distance function; R&D spillover

### 1. Introduction

Energy is one of the primary and essential needs of any functioning society. The contribution of energy to economic growth is considered very important – as emphasized in several empirical works (Ahmed 2017; Sun *et al.* 2021a). Nevertheless, energy consumption is often linked to carbon emissions and global warming (Edziah *et al.* 2021a;

---

\*Corresponding authors: [simjy@sehan.ac.kr](mailto:simjy@sehan.ac.kr); [shp797@163.com](mailto:shp797@163.com)

#Present Affiliation: School of Business, Shandong University, Weihai, 264209, P.R. China.

Kohler 2013; Ozturk and Acaravci 2013). It is reported that about 67% of these greenhouse gas (GHG) emissions emanate from excessive energy use (IEA 2017).

Energy demand is expected to rise dramatically, with most of this increase in developing countries (IEA 2017). Like many developing countries, several Sub-Saharan African (SSA) countries have witnessed a rise in energy demand, averaging 14.42% between the periods 1995–2017<sup>1</sup> (see Figure 1 in the Appendix [online supplementary material]). Meanwhile, in many developing countries, particularly in the SSA region, energy use per dollar of GDP remains higher than in industrialized countries, suggesting inefficiency in energy use (Blanco *et al.* 2014). Due to the limited energy supply in the region, energy insecurity is also a fundamental problem, causing power outages that affect economic production in the region (Adom, Appiah, and Agradi 2020). According to recent reports, the decline in energy intensity in developed countries over the last few decades has been attributed to energy-saving technologies that improve industrial energy efficiency (Liu *et al.* 2022). In this context, increasing energy-efficient technology in the SSA region is critical to improving energy efficiency.

Energy efficiency is regarded as one of the most cost-effective approaches to mitigating the adverse effects of climate change by reducing the amount of energy required to produce a unit of output (Edziah *et al.* 2022). Increasing energy efficiency has several potential benefits, including energy savings, lower energy costs, and lower carbon emissions. Despite these benefits, SSA countries' commitment to energy efficiency efforts lags far behind that of Europe, Asia, and Latin America, owing primarily to financial constraints (Blanco *et al.* 2014). Given the region's economic situation, research and development (R&D) initiatives are extremely low (Danquah 2018). Consequently, several SSA countries have actively promoted policies encouraging foreign technology transfer and adoption to improve their national energy efficiency performance (Sun *et al.* 2020a; Danquah 2018; Adom and Kwakwa 2014). In most cases, foreign technologies enter SSA countries via trade and investment (Danquah 2018).

Trade is an important means of transferring technology embodied in imported capital goods into SSA countries. As a result, research into the impact of trade (specifically, imported machinery) on productivity efficiency is a hot topic (Jijian *et al.* 2021). For instance, Mazumdar (2001) investigated the effect of imported machinery on productivity growth in 30 least-developed countries and found that importing machinery from

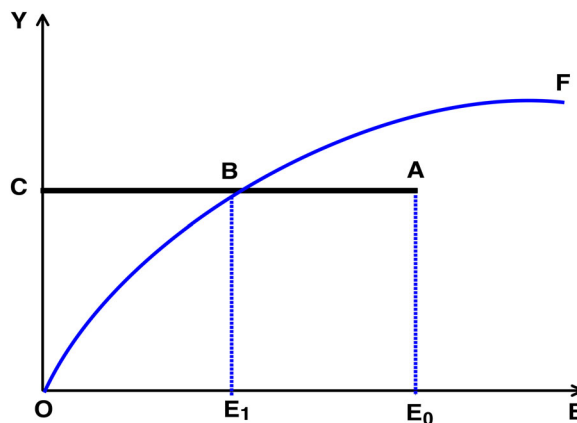


Figure 1. Graphical illustration of the Shepard energy distance function. Adapted from Zhou, Ang, and Zhou (2012).

industrialized countries increases productivity. Henry, Kneller, and Milner (2009) studied productivity efficiency across 57 countries using the Stochastic Frontier Analysis (SFA) model and discovered that importing machinery increases productivity output in developing countries. Danquah (2018) investigated the role of imports on production efficiency using a similar model and found no effect on productivity in SSA countries. However, Danquah and Ouattara (2015) discovered that machinery imports play an important role in illuminating variations in productivity efficiency in SSA.

Other studies look into the effects of machinery imports on energy efficiency. Therefore, with a specific focus on energy, Fisher-Vanden *et al.* (2006) investigated the principal drivers of energy intensity within China's industrial sector from 1997–1999. They observed significant differences in factor biases between domestically produced and internationally imported technology. In other words, imported technology contributes more to energy efficiency improvement. Fisher-Vanden and Jefferson (2008) compared Chinese-developed technology to imported technology and discovered that the former saves more energy than the latter. Teng (2012) examined the effects of domestic R&D spending, imported foreign technology, and human capital on energy intensity in Chinese industries from 1998 to 2006. According to the study, importing foreign technology reduces the intensity of China's industrial energy consumption. Herrerias, Cuadros, and Orts (2013) investigated whether China's improved energy efficiency from 1985 to 2008 was due to the openness of their economy. They confirmed the positive effect of foreign technology imports on China's energy efficiency using a panel-corrected standard error model. Carraro and de Cian (2013) investigated various technological drivers for factor productivity by estimating a factor-specific technical change in trade in thirteen OECD economies. They discovered that imported machinery and equipment reduce the share of energy input in these countries.

While several studies have investigated the impact of imported machinery on regional energy efficiency, none have focused on the SSA region. The SSA region is one of many developing regions that rely heavily on imported technologies (from OECD and non-OECD countries) to produce goods and services – to meet basic economic needs such as lighting, cooking, heating, warming, and entertainment (Doyon-Martin 2015). However, a sizeable portion of these imported technologies are either used products from OECD countries with energy that can be highly inefficient – due to use beyond lifespan and optimal efficiency – or low-grade and energy-inefficient products from non-OECD countries (Fioratta 2019). As a result, there may be reservations about importing these technologies into the region. Given these perspectives, a more in-depth examination of the impact of trade on imported capital goods from OECD and non-OECD countries on energy efficiency in SSA is critical.

Furthermore, internationally traded capital goods (specifically imported machinery) enable countries to import R&D investments. The seminal work of Coe and Helpman (1995) demonstrated that trade boosts domestic productivity through the international R&D spillover effect caused by bilateral trade. According to Coe, Helpman, and Hoffmaister (1997), a percentage increase in R&D capital stock in developed countries increases output by 0.06 percent in developing countries. Without a doubt, R&D benefits developing countries significantly through trade. As a result, studies on R&D spillovers and productivity efficiency are hot topics, with some focusing on (Coe, Helpman, and Hoffmaister 2009; Coe and Helpman 1995; Danquah 2018; Henry, Kneller, and Milner 2009), sectors (Bernstein and Mohnen 1998; Cohen *et al.* 2002), industries (Ben Hassine, Boudier, and Mathieu 2017; Bernstein 1996) and firms (Griffith, Harrison, and Van Reenen 2006).

While the literature on this scope is extensive but focuses more on how foreign R&D inputs are essential for increasing productivity efficiency (e.g. Coe, Helpman, and Hoffmaister 2009; Cohen *et al.* 2002; Danquah 2018; Henry, Kneller, and Milner 2009; Keller 1998) rather than energy efficiency, which is the focus of this study. Even the few studies that have looked at SSA countries have focused on the impact of R&D spillovers on economic productivity (e.g. Danquah 2018; Danquah and Ouattara 2015; Tiruneh, Wamboye, and Sergi 2017) or agricultural productivity (e.g. Adetutu and Ajayi 2020). Therefore, the effects of R&D activities on energy efficiency performance in SSA countries have received little attention in the existing literature<sup>2</sup>. Since SSA countries rely on foreign R&D investments through trade, the impact of R&D spillovers from imported machinery on energy efficiency is essential for policy consideration. R&D spillover initiatives are critical for developing economies to transfer new technologies and ideas to domestic firms. In light of these concerns, the second objective of this paper is to investigate the impact of R&D spillover from imported machinery on energy efficiency in SSA countries.

In conclusion, the following key points are noted: First, several studies in the field of energy economics have examined the impact of machinery imports in various countries and regions but have failed to consider the SSA region. Second, several studies assess the productivity efficiency of R&D spillovers embodied in technology transfer in developing countries without explicitly addressing their impact on energy efficiency.

To address this gap, the current study examines the effects of machinery imported from OECD and non-OECD countries and the associated R&D spillovers on energy efficiency performance in 18 SSA countries between 1995 and 2017. Thus, we pose the following questions: Do imports of machinery from both OECD and non-OECD countries help the SSA region improve energy efficiency? Second, what role do foreign R&D spillovers play in energy efficiency? Third, does importing solely from OECD countries improve SSA countries' energy efficiency? Fourth, how do imports from only non-OECD countries affect energy efficiency?

In answering these questions, we add to the existing literature in various ways. First, rather than focusing solely on OECD machinery imports, as previous studies have done (Adetutu and Ajayi 2020; Arazmuradov, Martini, and Scotti 2014; Coe and Helpman 1995; Danquah 2018; Danquah and Ouattara 2015; Henry, Kneller, and Milner 2009; Tiruneh, Wamboye, and Sergi 2017), we investigate the energy-saving effects of OECD and non-OECD machinery imports. Second, we extend the initial SFA model used in previous studies (Adetutu and Ajayi 2020; Danquah 2018; Danquah and Ouattara 2015; Henry, Kneller, and Milner 2009; Kneller and Stevens 2006; Mastromarco and Ghosh 2009) by accounting for undesirable outputs (i.e. carbon emissions) within the production framework. According to Mandal (2010), energy efficiency estimates may be skewed if only desirable outputs are considered in the model. Controlling undesirable outputs in a production framework thus provides more reliable and accurate estimates of energy efficiency. Third, we adopt the stochastic energy distance function proposed by Zhou, Ang, and Zhou (2012) and expand it from its cross-sectional nature into a panel form. In this way, we improve the econometric specification of the SFA model by employing Belotti and Ilardi's (2014) pairwise difference estimator (PDE) to account for potential unobserved heterogeneity in the sample countries.

The remainder of the paper consists of methodology elaborated in Section 2, data description and sources presented in Section 3, empirical findings in Section 4 and conclusion and policy implications presented in Section 5.

## 2. Methodology

There are several energy efficiency indicators, most notably the thermodynamic indicator, the physical thermodynamic indicator, and the economic indicator (see Patterson 1996) but for this study, we use the economic indicator. Energy intensity, usually measured as the energy to GDP ratio, is the most commonly used economic indicator in the energy literature. Filippini and Hunt (2015) consider this type of efficiency measurement less accurate. Therefore, we base our energy efficiency measurement on Kopp's (1981) non-radial notion of input-specific technical efficiency. This approach necessitates estimating the frontier using either the stochastic frontier analysis (SFA) or the Data Envelopment Analysis (DEA). Unlike the DEA, the SFA model accounts for measurement error or random noise (see Kumbhakar and Lovell (2000) for more information on the parametric and non-parametric efficiency measurement method). Considering random noise and possible country heterogeneity, we control for these by using the SFA approach. Specifically, we adopt the SFA energy distance function presented by Zhou, Ang, and Zhou (2012).

### 2.1. Shepard energy distance function

For clarity, we begin our analysis by considering a functional relationship between two outputs – desirable and undesirable (GDP-  $\mathcal{Y}$  and CO<sub>2</sub>-  $\mathcal{C}$ ) and three inputs (Capital -  $\mathcal{K}$ , Labor -  $\mathcal{L}$  and Energy -  $\mathcal{E}$ ) which characterize production processes. The multi-output production technology can therefore be represented as:

$$\mathbb{T} = \{(\mathcal{K}, \mathcal{L}, \mathcal{E}, \mathcal{Y}, \mathcal{C}) : (\mathcal{K}, \mathcal{L}, \mathcal{E}) \text{ can produce } (\mathcal{Y}, \mathcal{C})\} \quad (1)$$

Following Färe, Grosskopf, and Margaritis (2006) the set of all potential input-output vectors of  $\mathbb{T}$  is presumed to meet the axioms of the production technology. For example, without inputs, it is impossible to produce anything; therefore, inactivity is often conceivable, and only finite inputs can create finite outputs. Furthermore, it is common to assume that the inputs and desirable output are strongly or freely disposable. Like Zhou, Ang, and Zhou (2012), we adopt the Shepard input distance function to measure energy efficiency. We describe a Shepard sub vector input distance function for energy consumption as:

$$D_{\mathcal{E}}(\mathcal{K}, \mathcal{L}, \mathcal{E}, \mathcal{Y}, \mathcal{C}) = \sup \left\{ \lambda : \left( \mathcal{K}, \mathcal{L}, \frac{\mathcal{E}}{\lambda}, \mathcal{Y}, \mathcal{C} \right) \in \mathbb{T} \right\} \quad (2)$$

where Equation (2) implies that energy is reduced to the frontier, while the input and output vectors are kept constant in the production technology of Equation (1). From Equation (2), it follows that the optimum energy utilization for an efficient country is represented as:  $\mathcal{E}/D_{\mathcal{E}}(\mathcal{K}, \mathcal{L}, \mathcal{E}, \mathcal{Y}, \mathcal{C})$ . To explain this, we adapt the graphical illustration of the Shepard energy distance function from Zhou, Ang, and Zhou (2012).

In Figure 1, the curve line OF is a production isoquant for energy used (E) for production of output (Y) when other inputs (K, L) are held constant. At point C, the required energy to generate output Y is CB; however, as it turns out the actual energy used is CA. If we estimate the energy efficiency (EE) value of point C, we would consider that the actual energy used will reduce from  $E_0$  to  $E_1$  to reach isoquant production. The Shepard energy distance function is therefore equal to  $CA/CB$ , the reciprocal of the Shepherd energy distance function is EE value, and it can be rewritten mathematically as:

$$EE = \frac{\mathcal{E}/D_{\mathcal{E}}(\mathcal{K}, \mathcal{L}, \mathcal{E}, \mathcal{Y}, \mathcal{C})}{\mathcal{E}} = \frac{1}{D_{\mathcal{E}}(\mathcal{K}, \mathcal{L}, \mathcal{E}, \mathcal{Y}, \mathcal{C})} \tag{3}$$

By definition, EE means that if the country to be assessed is situated on the frontier curve OF, the value of EE will be equal to one; hence, considered energy efficient in its production process. However, if the country to be assessed is stationary below the frontier curve OF, the value of EE will be less than one, representing energy inefficiency in production.

**2.2. Stochastic energy distance frontier method**

To employ the energy distance function, we are required to pick a specific functional form. We follow Sun *et al.* (2021b) by using the trans-log function form. According to Christensen, Jorgenson, and Lau (1973), the trans-log is flexible without imposing prior limitations on the production technology. Using this approach, we connect the log of two outputs: GDP ( $\mathcal{Y}$ ) and CO<sub>2</sub> ( $\mathcal{C}$ ), three inputs: capital ( $\mathcal{K}$ ), labour ( $\mathcal{L}$ ), and energy ( $\mathcal{E}$ ) and the energy distance function as:

$$\begin{aligned} \ln D_{\mathcal{E}}(\mathcal{K}_{it}, \mathcal{L}_{it}, \mathcal{E}_{it}, \mathcal{Y}_{it}, \mathcal{C}_{it}) = & \emptyset_0 + \emptyset_K \ln \mathcal{K}_{it} + \emptyset_{\mathcal{L}} \ln \mathcal{L}_{it} + \emptyset_{\mathcal{E}} \ln \mathcal{E}_{it} + \emptyset_{\mathcal{Y}} \ln \mathcal{Y}_{it} + \emptyset_{\mathcal{C}} \ln \mathcal{C}_{it} \\ & + \emptyset_{KK} (\ln \mathcal{K}_{it})^2 + \emptyset_{\mathcal{L}\mathcal{L}} (\ln \mathcal{L}_{it})^2 + \emptyset_{\mathcal{E}\mathcal{E}} (\ln \mathcal{E}_{it})^2 \\ & + \emptyset_{\mathcal{Y}\mathcal{Y}} (\ln \mathcal{Y}_{it})^2 + \emptyset_{\mathcal{C}\mathcal{C}} (\ln \mathcal{C}_{it})^2 + \emptyset_{\mathcal{K}\mathcal{L}} \ln \mathcal{K}_{it} \ln \mathcal{L}_{it} \\ & + \emptyset_{\mathcal{K}\mathcal{E}} \ln \mathcal{K}_{it} \ln \mathcal{E}_{it} + \emptyset_{\mathcal{K}\mathcal{Y}} \ln \mathcal{K}_{it} \ln \mathcal{Y}_{it} + \emptyset_{\mathcal{K}\mathcal{C}} \ln \mathcal{K}_{it} \ln \mathcal{C}_{it} \\ & + \emptyset_{\mathcal{L}\mathcal{E}} \ln \mathcal{L}_{it} \ln \mathcal{E}_{it} + \emptyset_{\mathcal{L}\mathcal{Y}} \ln \mathcal{L}_{it} \ln \mathcal{Y}_{it} + \emptyset_{\mathcal{L}\mathcal{C}} \ln \mathcal{L}_{it} \ln \mathcal{C}_{it} \\ & + \emptyset_{\mathcal{Y}\mathcal{E}} \ln \mathcal{Y}_{it} \ln \mathcal{E}_{it} + \emptyset_{\mathcal{E}\mathcal{C}} \ln \mathcal{E}_{it} \ln \mathcal{C}_{it} + \emptyset_{\mathcal{C}\mathcal{Y}} \ln \mathcal{C}_{it} \ln \mathcal{Y}_{it} + \nu_{it} \end{aligned} \tag{4}$$

where  $\nu_{it}$  is the symmetric error term controlling for statistical noise and it is presumed to follow the standard normal distribution assumption. The input distance function is linearly homogenous to a degree of one (Lovel *et al.* 1994), so is the Shepard energy distance function in energy input Zhou, Ang, and Zhou (2012). Thus, we have:

$$\ln D_{\mathcal{E}}(\mathcal{K}_{it}, \mathcal{L}_{it}, \mathcal{E}_{it}, \mathcal{Y}_{it}, \mathcal{C}_{it}) = \ln \mathcal{E}_{it} + \ln D_E(\mathcal{K}_{it}, \mathcal{L}_{it}, 1, \mathcal{Y}_{it}, \mathcal{C}_{it}) \tag{5}$$

From Equation (5), we derive the Shepard distance function and can write it as follows:

$$\begin{aligned} \ln D_{\mathcal{E}}(\mathcal{K}_{it}, \mathcal{L}_{it}, \mathcal{E}_{it}, \mathcal{Y}_{it}, \mathcal{C}_{it}) = & \ln \mathcal{E}_{it} + \emptyset_0 + \emptyset_K \ln \mathcal{K}_{it} + \emptyset_{\mathcal{L}} \ln \mathcal{L}_{it} + \emptyset_{\mathcal{Y}} \ln \mathcal{Y}_{it} + \emptyset_{\mathcal{C}} \ln \mathcal{C}_{it} \\ & + \emptyset_{KK} (\ln \mathcal{K}_{it})^2 + \emptyset_{\mathcal{L}\mathcal{L}} (\ln \mathcal{L}_{it})^2 + \emptyset_{\mathcal{Y}\mathcal{Y}} (\ln \mathcal{Y}_{it})^2 \\ & + \emptyset_{\mathcal{C}\mathcal{C}} (\ln \mathcal{C}_{it})^2 + \emptyset_{\mathcal{K}\mathcal{L}} \ln \mathcal{K}_{it} \ln \mathcal{L}_{it} + \emptyset_{\mathcal{K}\mathcal{Y}} \ln \mathcal{K}_{it} \ln \mathcal{Y}_{it} \\ & + \emptyset_{\mathcal{K}\mathcal{C}} \ln \mathcal{K}_{it} \ln \mathcal{C}_{it} + \emptyset_{\mathcal{L}\mathcal{Y}} \ln \mathcal{L}_{it} \ln \mathcal{Y}_{it} + \emptyset_{\mathcal{L}\mathcal{C}} \ln \mathcal{L}_{it} \ln \mathcal{C}_{it} \\ & + \emptyset_{\mathcal{C}\mathcal{Y}} \ln \mathcal{C}_{it} \ln \mathcal{Y}_{it} + \nu_{it} \end{aligned} \tag{6}$$

Substituting Equation (6) into Equation (4), we have:

$$\begin{aligned} \ln \mathcal{E}_{it} = & \emptyset_0 \ln \mathcal{E}_{it} + \emptyset_{\mathcal{E}\mathcal{E}} (\ln \mathcal{E}_{it})^2 + \emptyset_{\mathcal{K}\mathcal{E}} \ln \mathcal{K}_{it} \ln \mathcal{E}_{it} + \emptyset_{\mathcal{L}\mathcal{E}} \ln \mathcal{L}_{it} \ln \mathcal{E}_{it} + \emptyset_{\mathcal{Y}\mathcal{E}} \ln \mathcal{Y}_{it} \ln \mathcal{E}_{it} \\ & + \emptyset_{\mathcal{E}\mathcal{C}} \ln \mathcal{E}_{it} \ln \mathcal{C}_{it} + \nu_{it} \end{aligned} \tag{7}$$

Substituting Equation (7) into Equation (4) and making some rearrangements, we get:

$$\begin{aligned}
 -\ln \mathcal{E}_{it} = & \emptyset_0 + \emptyset_K \ln K_{it} + \emptyset_{\mathcal{L}} \ln \mathcal{L}_{it} + \emptyset_Y \ln \mathcal{Y}_{it} + \emptyset_C \ln C_{it} + \emptyset_{KK} (\ln K_{it})^2 + \emptyset_{\mathcal{L}\mathcal{L}} (\ln \mathcal{L}_{it})^2 \\
 & + \emptyset_{YY} (\ln \mathcal{Y}_{it})^2 + \emptyset_{CC} (\ln C_{it})^2 + \emptyset_{K\mathcal{L}} \ln K_{it} \ln \mathcal{L}_{it} + \emptyset_{KY} \ln K_{it} \ln \mathcal{Y}_{it} \\
 & + \emptyset_{KC} \ln K_{it} \ln C_{it} + \emptyset_{LY} \ln \mathcal{L}_{it} \ln \mathcal{Y}_{it} + \emptyset_{\mathcal{L}C} \ln \mathcal{L}_{it} \ln C_{it} + \emptyset_{CY} \ln C_{it} \ln \mathcal{Y}_{it} \\
 & + \nu_{it} - \ln D_{\mathcal{E}} (K_{it}, \mathcal{L}_{it}, \mathcal{E}_{it}, \mathcal{Y}_{it}, C_{it})
 \end{aligned} \tag{8}$$

Following Battese and Coelli (1992), we set  $\ln D_{\mathcal{E}} (K_{it}, \mathcal{L}_{it}, \mathcal{E}_{it}, \mathcal{Y}_{it}, C_{it}) = \bar{\mathcal{U}}_{it}$ . Equation (8) becomes:

$$\begin{aligned}
 -\ln \mathcal{E}_{it} = & \emptyset_0 + \emptyset_K \ln K_{it} + \emptyset_{\mathcal{L}} \ln \mathcal{L}_{it} + \emptyset_Y \ln \mathcal{Y}_{it} + \emptyset_C \ln C_{it} + \emptyset_{KK} (\ln K_{it})^2 \\
 & + \emptyset_{\mathcal{L}\mathcal{L}} (\ln \mathcal{L}_{it})^2 + \emptyset_{YY} (\ln \mathcal{Y}_{it})^2 + \emptyset_{CC} (\ln C_{it})^2 + \emptyset_{K\mathcal{L}} \ln K_{it} \ln \mathcal{L}_{it} \\
 & + \emptyset_{KY} \ln K_{it} \ln \mathcal{Y}_{it} + \emptyset_{KC} \ln K_{it} \ln C_{it} + \emptyset_{LY} \ln \mathcal{L}_{it} \ln \mathcal{Y}_{it} + \emptyset_{\mathcal{L}C} \ln \mathcal{L}_{it} \ln C_{it} \\
 & + \emptyset_{CY} \ln C_{it} \ln \mathcal{Y}_{it} + \nu_{it} - \bar{\mathcal{U}}_{it}
 \end{aligned} \tag{9}$$

where  $\bar{\mathcal{U}}_{it}$  is assumed to be non-negative exogenous variables representing energy inefficiency, which are considered to vary over time in country  $i$  at time  $t$ .  $\bar{\mathcal{U}}_{it}$  and  $\nu_{it}$  are assumed to be distinct from each other and not connected to the independent variables in Equation (9). Accordingly, the energy efficiency in country  $i$  and period  $t$  can be measured by:

$$EE_{it} = E[\exp(-\bar{\mathcal{U}}_{it} \epsilon_{it})] \tag{10}$$

There are two approaches to estimate energy efficiency and its determinants: the single-stage or two-stage approach. However, there are few disagreements over whether a single-stage or two-stage approach is better for assessing the stochastic frontier analysis-based energy efficiency and its determinants. While some researchers have used the two-stage process (Sun *et al.* 2020b), most studies have used a single-stage procedure. Possibly this is because of the parametric nature of the SFA and the observations by Wang and Schmidt (2002) that the two-stage technique provides highly biased results. Furthermore, most SFA models have been designed to incorporate exogenous variables – distinct from the input factors. However, they affect the inefficiency in the single-stage approach by scaling the distribution of  $\bar{\mathcal{U}}_{it}$  and/or  $\nu_{it}$  in Equation (9). Using the approach is also likely to address the problem of conditional heteroscedasticity in energy inefficiency. For these reasons, we employ the single-stage technique to investigate the causal elements of SFA-based energy efficiency estimations. As a result, following Battese and Coelli (1995), we enable  $\bar{\mathcal{U}}_{it}$  to be explained concurrently by a collection of exogenous variables to assess the effect of machinery imports and R&D spillover on energy inefficiency. Thus, we specify the inefficiency function  $\bar{\mathcal{U}}_{it}$  as:

$$\bar{\mathcal{U}}_{it} = \alpha_0 + \beta_1 Imp_{it} + \beta_2 R\&D_{it} + \beta_3 con_{it} + e_{it} \tag{11}$$

where  $Imp_{it}$  denotes the machinery imports,  $R\&D_{it}$  represents R&D spillovers from these imported machineries,  $con_{it}$  denotes the control variables,  $e_{it}$  is the error term and  $\beta$  is the variable parameters. The variables in Equation (11) represent inefficiencies; therefore, a negative covariate indicates a decrease in energy inefficiency. For example, if any of the variables improve energy efficiency, we assume that the sign of the coefficients will be negative – meaning that the distance from frontier decreases due to that variable.

However, if the sign of the coefficients is positive, then it means the variable increases energy inefficiency and, thus, increases the distance from the frontier.

### 2.3. Econometric model

From an econometric perspective, various panel data-based models have been considered for estimating SFA. Previous works have adopted the time-invariant SFA model, which considers individual country effects as part of inefficiency (Battese and Coelli 1992; Pitt and Lee 1981; Kumbhakar 1990). This means the inefficiency may be overestimated, hence, producing biased estimates. Nevertheless, the unobservable individual effects are essential and must be accounted for when estimating SFA panel models. Therefore, the commonly used approach in empirical analysis is the SFA model, with fixed-effects capturing unobserved heterogeneity (Chen, Schmidt, and Wang 2014; Greene 2005). The popular approach is the true fixed-effects model (TFEM), which estimates an inefficiency component that varies over time using the maximum likelihood approach (Greene 2005). However, an incidental parameter problem is identified in Greene's TFE model, which produces inconsistencies in estimating the variance parameter (Belotti and Ilardi 2014; Chen, Schmidt, and Wang 2014). To resolve this "incidental parameter" issue, Belotti and Ilardi (2014) proposed two ways, i.e. by either adopting the maximum simulated likelihood estimator (MMSLE) or the pairwise difference estimator (PDE) model. To avoid the "incidental parameter" issue in our estimation, we use the PDE of the SFA model for fixed effects, where inefficiency follows a first-order autoregressive process.<sup>3</sup>

### 3. Description of data and their sources

This study focuses on 18 SSA countries from 1995–2017. We use an unbalanced panel dataset because of data limitations for other variables. The countries, in our sample, are selected primarily based on data availability for the main explanatory variables. Beginning with the production frontier data, we use real GDP, CO<sub>2</sub> emissions, capital stock, energy consumption, and labour, defined as:

- (1) Real GDP is extracted from the Penn World Table (PWT) and transformed into natural logarithm (in millions of US\$ as of 2011);
- (2) Physical capital stock is sourced from PTW and converted to natural logarithm at current PPPs (millions of US\$ as of 2011);
- (3) Labor data is sourced from PTW and converted into a log of the total number of employed people;
- (4) Energy use is derived from the Energy Information Administration (EIA) and transformed into the log of terajoules;
- (5) Carbon emission data is sourced from World Development Indicators (WDI) and converted to a natural logarithm.

The two main variables used as explanatory variables for inefficiency effects and other control variables considered in this study are explained as follows:

- Import of machinery and transport equipment from OECD and non-OECD countries:

To focus on energy-consuming technologies, we use the same method as Henry, Kneller, and Milner (2009) to extract machinery import data from the United Nations Comtrade Database by narrowing our search to aggregate data on machinery and transport equipment in US\$ (i.e. SITC Rev. 2, Sec. 7). However, imports from non-OECD countries (particularly China) into Africa appear to have surpassed those from OECD countries in recent years (see Figure 2). Thus, in addition to the 14 developed OECD countries, we considered imports from non-OECD countries<sup>4</sup>. As a result, this study considers two major non-OECD exporters to SSA countries (China and Singapore). Only two countries are included based on data availability for R&D in machinery R&D. Imports of machinery and transportation equipment range from capital equipment, such as factory machinery, office machines, and telecommunications equipment, to transportation equipment and household electrical appliances.

- Research and Development (R&D) Spillover

Because most developing countries, particularly SSA, rarely invest in domestic R&D, we assume that SSA countries' knowledge stock is dependent on the stock of foreign R&D. As done in other international spillover studies (Coe, Helpman, and Hoffmaister 1997; Adetutu and Ajayi 2020; Henry, Kneller, and Milner 2009), we calculate the stock of machinery R&D in 16 technologically advanced countries (i.e. 14 OECD and 2 non-OECD countries). The R&D stock of machinery ( $R_{it}$ ) is calculated with a rate of 10% using the continuous inventory approach. The two equations for the calculation of the R&D stock as presented as:

$$R_{it} = (1 - \partial)R_{it-1} + RD_{it-1} \tag{12}$$

$$R_{t0} = \frac{RD_1}{(g^{RD} + \partial)} \tag{13}$$

where  $R_{it}$  indicates the machinery R&D stock<sup>5</sup>,  $\partial$  denotes the rate of depreciation, which is set at 10% following Henry, Kneller and Milner (2009), RD stands for

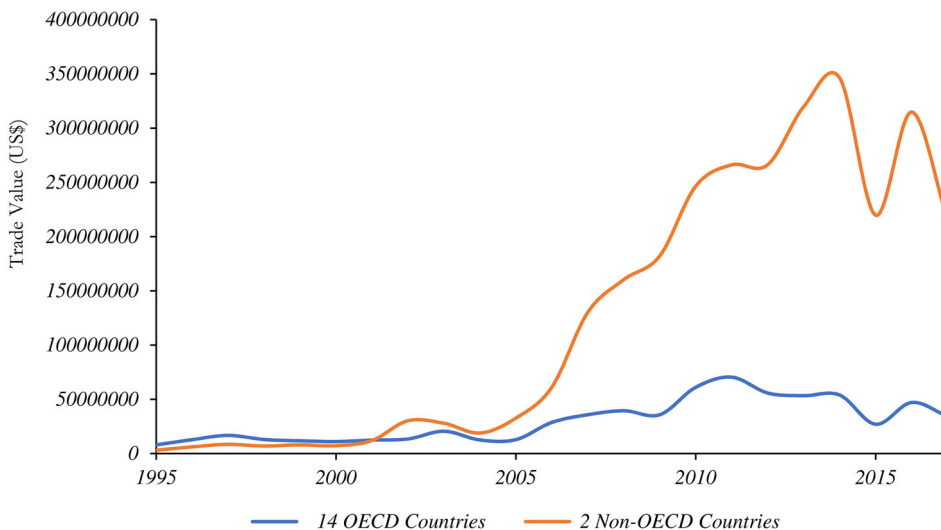


Figure 2. Machinery imports from OECD and non-OECD countries.

machinery R&D investments and  $g^{RD}$  is the average annual rate of growth in R&D over the period. Data for R&D machinery investment in 16 technologically advanced countries are extracted from the OECD ANBERD database. To calculate the R&D stock in each SSA country, the aggregate R&D of the 16 technologically advanced countries are weighed according to the ratio of SSA machinery imports to the GDP of the technologically advanced countries. Therefore, the spillover of foreign machinery R&D stock from the country  $j$  (i.e. technologically advanced OECD and non-OECD countries) through imports by developing SSA country  $i$  is mathematically represented as:

$$RD_i^m = \sum_{j \neq i} \frac{MM_{ij}}{Y_j} RD_j \quad (14)$$

where  $MM_{ij}$  is the import of machinery by developing SSA countries  $i$  from technological advanced country  $j$ , and  $Y_j$  is the technological advanced country's GDP.

- Economic Structure

The economic structure significantly impacts energy consumption (Adom *et al.* 2018). A shift in production structure to less energy-intensive sectors reduces energy demand. One possible explanation for the wide variation in energy efficiency across SSA countries is that different countries have different economic structures. As a result, following other studies, we include the service sector's share of value-added as a percentage of GDP to control the shift in production structure (Filippini and Zhang 2016; Filippini and Hunt 2011)

- Human Capital

Improving energy efficiency depends not only on the efficiency of machinery and the rate of R&D spillover but also on the technical know-how of labour to imitate and operate the technology (Filippini and Hunt 2011; Filippini and Hunt 2012). The ability of a country to innovate or use knowledge spillover from other countries depends on the level of its human capital, and this depends entirely on the education and experience level of the workforce (Edziah *et al.* 2021b; Adom *et al.* 2018; Adom 2019). Thus, education is a widely-used variable in models to control for variation in the quality of human capital across countries. In line with Engelbrecht (1997), we control for human capital in the efficiency model. We assume that human capital will positively affect energy efficiency, but are unsure of the outcome given the quality of human capital in SSA countries. We use the PWT human capital index as a proxy for human capital. Table 1 provides descriptive statistics for the variables adopted in our empirical research.

## 4. Empirical results and discussion

### 4.1. Production function and inefficiency effects results

This section presents the pairwise difference estimator parameters and inefficiency estimates for the trans-log SFA production function. Our empirical strategy is divided into two stages. In the first stage, we look into the energy-saving effects of our two main

Table 1. Descriptive statistics.

Variable	Symbols	Obs	Mean	Std. Dev	Min	Max
Energy use	$\ln E$	390	-11.046	1.232	-14.316	-8.059
GDP	$\ln Y$	414	24.077	1.161	21.609	27.645
CO <sub>2</sub>	$\ln C$	378	8.056	1.271	5.288	11.590
Capital	$\ln K$	414	25.267	1.250	22.393	28.424
Labour	$\ln L$	414	15.667	1.015	12.604	17.992
Total R&D	SSA_R&D	395	12.268	1.775	3.975	16.277
Total machinery	SSA_MI	392	16.599	1.388	13.628	20.669
OECD machinery	OECD_MI	392	16.406	1.286	13.685	20.352
Non-OECD machinery	Non_OECD_MI	392	16.962	1.998	12.311	21.682
Service	SSA_Serv	414	45.429	8.136	25.792	77.020
Human capital	SSA_HC	414	1.609	0.371	1.049	2.648

Note: All variables are in log except service and human capital.

variables, machinery imports and R&D spillover, as well as other factors. In the second stage, we re-examine one of the key variables – machinery imports – to better understand how technologies from the OECD and non-OECD countries affect Sub-Saharan Africa. Therefore, we divide machinery imports into two categories: OECD and non-OECD.

(i) *First stage*

Table 2 presents the results for the first stage, where we examine the impact of our two variables – machine imports and R&D spillover – on energy efficiency. Turning to the first question, this study asks: do imports of machinery from both OECD and non-OECD countries help the SSA region improve energy efficiency? We find that the coefficient of an aggregate of imports of machinery from both OECD and non-OECD countries has a negative sign, denoting an increase in efficiency. However, the sign of the coefficient is statistically insignificant, which means that the sum of machinery imported from both regions has had no effect on energy efficiency. Do foreign R&D spillovers also promote energy efficiency in SSA? According to our estimation results, R&D spillover has a positive and statistically significant effect on energy inefficiency. The positive and significant coefficient of R&D spillover indicates that R&D spillover reduces energy efficiency in SSA. These results mean that neither of the variables improves energy efficiency in SSA.

The same can be said of the controls, as both variables – human capital and economic structure (represented by the service sector) – have a statistically insignificant negative effect on energy efficiency. In models 2 and 3, we drop R&D spillover and import, respectively, from the models. Still, the results remain almost the same regardless of whether the key variables are entered separately in the regressions or combination with other key variables. While our findings are new in the existing literature, they appear to be consistent with Danquah's (2018) finding that machinery, human capital, and R&D spillover have no empirical impact on production efficiency in SSA countries. In model 4, we check for the absorptive ability effect using the interaction term of R&D capital and human capital. The results show that our estimated results, the elasticity of the interaction term of R&D capital and human capital on energy efficiency is  $-0.146$ , while there is no statistically significant relationship in the estimation. This result seems to lend insufficient support to the importance of absorptive ability's effect on the region's energy efficiency, as argued in previous studies.

Table 2. Results of the PDE model with an inefficiency component for aggregate imports and R&amp;D from OECD and non-OECD countries.

Distance function	(Model 1)	(Model 2)	(Model 3)	(Model 4)
$\ln \mathcal{L}$	-1.060 (2.158)	-1.005 (2.138)	-0.852 (2.162)	-1.312 (2.266)
$\ln K$	12.27*** (2.893)	12.18*** (2.867)	11.87*** (2.967)	12.59*** (2.754)
$\ln \mathcal{Y}$	-1.562 (2.110)	-0.932 (2.146)	-1.694 (2.096)	-1.379 (2.186)
$\ln C$	-8.427*** (1.585)	-8.601*** (1.612)	-8.366*** (1.588)	-8.354*** (1.504)
$(\ln \mathcal{L})^2$	1.397*** (0.410)	1.417*** (0.428)	1.332*** (0.413)	1.449*** (0.424)
$(\ln K)^2$	-0.821*** (0.234)	-0.735*** (0.224)	-0.821*** (0.237)	-0.794*** (0.221)
$(\ln \mathcal{Y})^2$	-0.0138 (0.283)	0.0686 (0.285)	-0.0503 (0.281)	0.0340 (0.281)
$(\ln C)^2$	-0.159* (0.0941)	-0.154 (0.0949)	-0.166* (0.0941)	-0.154* (0.0922)
$\ln \mathcal{L} * \ln K$	-0.312 (0.276)	-0.320 (0.265)	-0.310 (0.275)	-0.322 (0.284)
$\ln \mathcal{L} * \ln \mathcal{Y}$	-0.545** (0.226)	-0.553** (0.248)	-0.515** (0.222)	-0.560** (0.237)
$\ln \mathcal{L} * \ln C$	-0.0885 (0.126)	-0.0888 (0.126)	-0.0838 (0.126)	-0.0855 (0.130)
$\ln \mathcal{Y} * \ln K$	0.417 (0.270)	0.327 (0.262)	0.435 (0.272)	0.379 (0.272)
$\ln \mathcal{Y} * \ln C$	-0.0228 (0.117)	-0.0418 (0.116)	-0.0162 (0.120)	-0.0383 (0.118)
$\ln C * \ln K$	0.443*** (0.128)	0.466*** (0.129)	0.434*** (0.130)	0.451*** (0.119)
Inefficiency effects				
SSA_MI	-0.110 (0.0923)		-0.0232 (0.0603)	-0.110 (0.0798)
SSA_R&D	0.0897* (0.0543)	0.0147 (0.0509)		0.325** (0.160)
SSA_HC	-0.427 (0.326)	-0.464 (0.323)	-0.415 (0.328)	1.393 (1.583)
SSA_Serv	-0.000288 (0.0123)	-0.000145 (0.0120)	-0.000369 (0.0123)	0.00142 (0.0125)
RD_HC				-0.146 (0.115)
Constant	-0.468 (1.112)	-1.310 (0.819)	-0.826 (0.944)	-3.459 (2.440)
Sigma_v	-3.443*** (0.569)	-3.528*** (0.607)	-3.407*** (0.569)	-3.346*** (0.499)
Criterion function	110.1655	479.9818	485.3895	497.7533
Observation	359	361	359	359
Number of ID	18	18	18	18

Note: SSA\_MI = machinery imports, SSA\_R&D = research and development spillover, SSA\_HC = human capital, SSA\_Serv = share of value-added by the service sector as a percentage of GDP. The Figures (i.e. the standard error) in parentheses symbolizes significance at the 1% (\*\*\*), 5% (\*\*), and 10% (\*) level.

*(ii) Second stage*

To better understand the impact of machinery imports on energy efficiency, we split the import of machinery into two sub-samples, OECD imports and non-OECD imports, in the second stage. Thus, Table 3 presents the results for the second stage, in which we examine the impact of imports from OECD and non-OECD countries on energy efficiency. According to the results of Model 1, OECD imports have a negative sign and are statistically significant at 10%. This finding suggests that OECD imports have a positive and significant impact on energy efficiency. Imports from non-OECD countries, on the other hand, have a positive sign and are significant. This means that imported machinery from non-OECD reduces energy efficiency in SSA countries.

Next, we account for the role of R&D spillover, with estimated results shown in model 2. The results for OECD imports and non-OECD imports remain almost the same as in model 1. Like models 2 and 3 in Table 2, the R&D spillover variable is positive and statistically insignificant, thus denoting that relative R&D exhibits no effect on energy efficiency in SSA countries. In model 3, we add two control variables – human capital and economic structure. Even though these two variables are controlled for in the model, the key variables produce the same results. As in Table 2, the control variables are negative and statistically insignificant. So, both R&D spillover and the control variables exert no effect on energy efficiency. In model 4, we change the production function from its initial trans-log function to a Cobb-Douglass function, but the results remain the same as in model 3. The results show that the coefficient for imports from the OECD has a negative sign and is significant across the models. This result implies that technology transfer through imports from OECD countries may improve energy efficiency in SSA countries. Its coefficients have the largest magnitudes throughout the models, indicating that imports from OECD countries play a dominant role in improving energy efficiency in SSA. Even though our empirical finding is new in the existing literature, they appear consistent with Danquah and Ouattara (2015) and Henry, Kneller, and Milner (2009). They found a positive and statistically significant effect of imports from OECD countries on production efficiency in developing countries.

On the other hand, the coefficient of the imports from non-OECD countries is consistently positive and significant in all models, which indicates that technology spillover through imports from non-OECD countries reduces energy efficiency in the SSA region. The possible reason for such a result might emanate from the large portion of China's exports to other countries (regions) that are mostly low-technology (Mastromarco and Ghosh 2009) – which may be energy inefficient. In 2014, China's total exports of high-and new-tech products rose by 28.2%, with the majority going to developed countries. Besides, the proliferation of affordable, yet shoddy Chinese-made machinery in Africa could contribute to an extent to these results (Huang, Du, and Tao 2017).

Now, turning to the R&D spillover, we observe that the effect of R&D spillover on SSA countries has no significant impact on energy efficiency in all models. The insignificant result of R&D spillover could be attributed to the low absorptive capacity of human capital in SSA, which also turns out to be statistically insignificant in all models. Perkins and Neumayer (2012) argue that countries with higher human capital tend to be more receptive to knowledge from import-weighted international spillovers; thus, there is a greater chance for a significant R&D spillover effect on countries with higher human capital. This means that low human capital reduces the benefits of R&D

Table 3. Results of the PDE model with an inefficiency component for disaggregated data for imports from OECD and non-OECD countries.

Distance function	(Model 1)	(Model 2)	(Model 3)	(Model 4)	(Model 5)
$\ln\mathcal{L}$	-0.792 (2.120)	-0.976 (2.130)	-0.877 (2.145)	6.909*** (2.850)	-0.517*** (0.122)
$\ln K$	11.11*** (3.185)	11.41*** (3.138)	10.62*** (2.732)	22.14*** (4.137)	-0.149 (0.110)
$\ln\mathcal{Y}$	-1.172 (1.822)	-1.113 (1.836)	-0.704 (2.162)	-12.55*** (3.320)	-0.0620 (0.0935)
$\ln C$	-7.776*** (1.985)	-7.804*** (1.978)	-7.259*** (1.490)	-13.93*** (2.398)	-0.335*** (0.0707)
$(\ln\mathcal{L})^2$	1.343*** (0.344)	1.389*** (0.339)	1.374*** (0.431)	3.416*** (0.519)	
$(\ln K)^2$	-0.683*** (0.248)	-0.686*** (0.247)	-0.627*** (0.227)	-1.782*** (0.429)	
$(\ln\mathcal{Y})^2$	0.153 (0.276)	0.177 (0.275)	0.175 (0.288)	-0.195 (0.387)	
$(\ln C)^2$	-0.134 (0.106)	-0.130 (0.106)	-0.101 (0.0842)	-0.389*** (0.120)	
$\ln\mathcal{L} * \ln K$	-0.220 (0.251)	-0.219 (0.253)	-0.224 (0.273)	-1.357*** (0.330)	
$\ln\mathcal{L} * \ln\mathcal{Y}$	-0.606*** (0.196)	-0.628*** (0.196)	-0.628** (0.260)	-1.171*** (0.310)	
$\ln\mathcal{L} * \ln C$	-0.102 (0.112)	-0.106 (0.111)	-0.0830 (0.119)	0.0589 (0.145)	
$\ln\mathcal{Y} * \ln K$	0.273 (0.257)	0.263 (0.256)	0.251 (0.265)	1.531*** (0.387)	
$\ln\mathcal{Y} * \ln C$	-0.00205 (0.101)	-0.00599 (0.0993)	-0.00764 (0.114)	-0.372** (0.153)	
$\ln C * \ln K$	0.399*** (0.151)	0.404*** (0.150)	0.361*** (0.119)	0.976*** (0.217)	
Inefficiency effects					
OECD_MI	-0.210* (0.114)	-0.261** (0.120)	-0.284** (0.121)	-0.212 (0.200)	-0.272* (0.150)
Non_OECD_MI	0.135** (0.0613)	0.121* (0.0696)	0.160** (0.0810)	0.0882 (0.124)	0.227** (0.113)
SSA_R&D		0.0665 (0.0748)	0.0783 (0.0762)	-0.392 (0.382)	0.0161 (0.206)
SSA_HC			-0.546 (0.355)	-4.049 (3.394)	-0.362 (2.358)
SSA_Serv			-0.00271 (0.0131)	0.0117 (0.00906)	-0.0141 (0.0168)
RD_HC				0.296 (0.248)	-0.0275 (0.163)
Constant	-0.693 (1.026)	-0.446 (1.090)	0.0880 (1.357)	4.997 (6.090)	0.359 (4.042)
Vsigma	-3.784*** (0.822)	-3.867*** (0.865)	-3.532*** (0.531)	-2.391*** (0.218)	-3.396*** (0.537)
Criterion function	494.8510	498.2771	538.9399	-97.1831	202.2016
Observation	359	359	359	359	359
Number of ID	18	18	18	18	18

Note: OECD\_MI = machinery imports from OECD countries, Non\_OECD\_MI = machinery imports from Non-OECD countries, SSA\_R&D = research and development spillover, SSA\_HC = human capital, SSA\_Serv = share of value-added by the service sector as a percentage of GDP. The Figures (i.e. the standard error) in parentheses symbolizes significance at the 1% (\*\*\*), 5% (\*\*), and 10% (\*) level.

spillover effect on energy efficiency and reduces the absorptive capacity to take advantage of neighboring R&D spillover. Therefore, this study found that both human capital and R&D stock play no significant and essential role in explaining differences in energy efficiency across SSA countries. With respect to R&D spillover, the results contradict Yang, Cai, and Wang (2014) where higher R&D spillover is observed to improve energy efficiency in China. Teng, Wang, and Chen (2011) also show a decline in industrial energy inefficiency in China due to the imported R&D spillover. Huang, Hao, and Lei (2018) also found that the spillover of import technologies plays a significant role in reducing China's carbon and energy inefficiency.

Regarding the proxy used to control for variations in economic structure across countries, we find that the service sector also has an insignificant effect on energy efficiency. This implies that changes in economic structure have no meaningful impact on energy efficiency. Therefore, the focus should be directed towards improving the technology used in producing goods and services in the region.

#### **4.2. Robustness test**

However, one drawback of all the estimated models is their inability to account for endogeneity bias. There is no specified approach in the literature to deal with this issue in SFA models. As a result, most empirical SFA studies do not address this potential issue (e.g. Du, Wang, and Zhang 2018; Sun *et al.* 2019). Dealing with this in a non-linear model like SFA could be difficult. Filippini and Zhang (2016) addressed the endogeneity issue using the two-stage approach. They regressed endogenous variables against some instrumental and exogenous variables in the first stage; the residuals obtained in the first stage are used in the second stage. Danquah (2018) also addressed endogeneity by using lags of explanatory variables to capture the inefficiency effects.

Since no empirical work offers clear guidance on how to deal with this issue, we follow Filippini and Zhang (2016) to check the robustness of the main results. As a result, for the robustness check, we used the residual inclusion method for non-linear models proposed to investigate the GDP endogeneity problem. This is a two-stage method for dealing with endogeneity. In the first stage, the endogenous variable is regressed against instrumental and exogenous variables. In the frontier equation, we use life expectancy at birth to instrument income (or GDP). The Cragg-Donald Wald F test statistics are one of the tests used to identify the appropriate instrumental variables. The Cragg-Donald Wald F test value is 152.490, which is greater than the critical value at a 5% significance level. As a result, we reject the hypothesis that the instrumental variables are weak. The residuals obtained in the first stage are used to estimate the original equation in the second stage. The coefficient values from this method are very close to those from the first estimation. The estimated technical energy efficiency of the baseline model and the modified model (which accounts for endogeneity) is highly correlated. Therefore, we can conclude that our above empirical findings provide an accurate and relatively unbiased estimate.

#### **4.3. Energy efficiency analysis**

Next, we figure out each country's average energy efficiency score over the sample period using the SFA specification of the model (10). With a mean value of 0.72 for energy efficiency across SSA countries and a standard deviation of 0.16, this shows

that estimates of energy efficiency in SSA countries vary a lot. Figure 3 shows the annual average efficiency values for the SSA sample. From Figure 3, the average efficiency scores throughout the years are not stable. The estimates show a decrease in efficiency scores from 0.76 in 1997 to 0.69 in 2000. Afterwards, there was a moderate increase from 0.68 in 2003 to 0.77 in 2012. This was followed again by a sudden drop in 2013 and an increase in 2014. Figure 4 shows the time path of the efficiency estimates for sampled SSA countries. From all indications, there is no sign of convergence in efficiency scores. Table 2 (in the Appendix [online supplementary material]) and Figure 5 give useful information about each country's performance by showing their average energy efficiency score over the sample period. Our results show that about 30% of sampled countries lie below the overall average efficiency score (i.e. Ethiopia, Mozambique, Uganda, Tanzania, Rwanda, and Zambia). At the same time, the rest are significantly higher than the average efficiency score of 0.72.

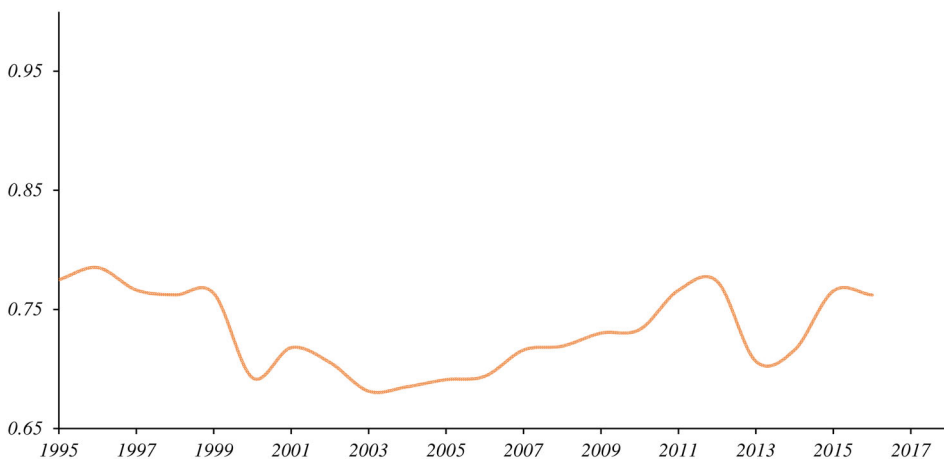


Figure 3. The trend of SSA energy efficiency score for the period 1995–2016.

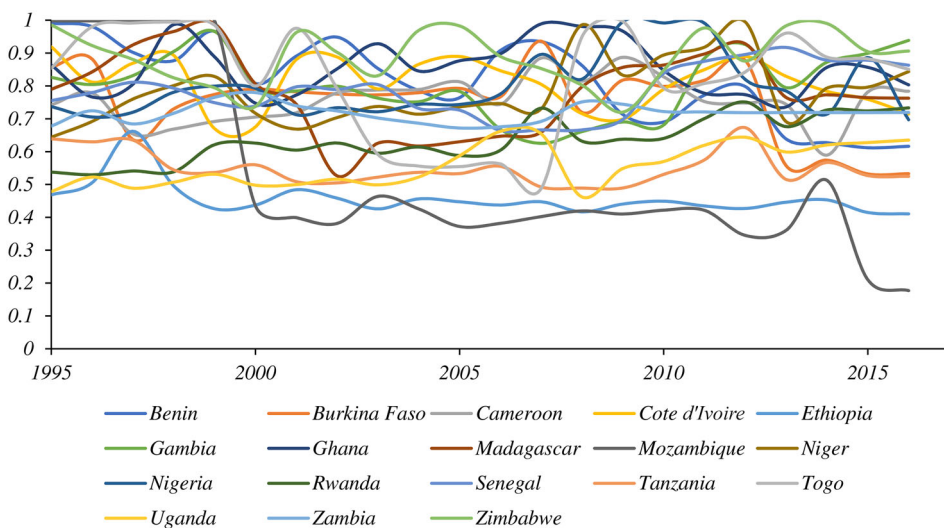


Figure 4. Time series plot of energy efficiency for SSA countries (1995–2016).

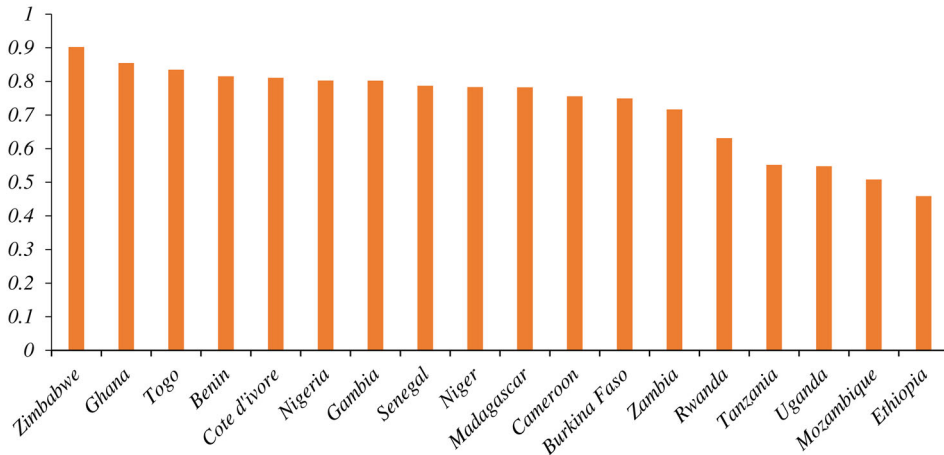


Figure 5. Energy efficiency scores of the SSA countries.

## 5. Conclusions

Even though most Sub-Saharan African countries need more energy than they can provide, they are not very committed to becoming more energy efficient. As a result, their energy consumption far exceeds the required demand. To help close the gap between supply and demand, SSA countries need to adopt and transfer energy-saving technology from other countries. With the help of a stochastic energy distance function, this paper looks at the effects of machinery imports from OECD and non-OECD countries and the R&D spillover on energy efficiency in 18 SSA countries from 1995 to 2017. The results suggest that the import of machinery and R&D spillover has no significant effect on energy efficiency across SSA countries. The two control variables, human capital and economic structure, also prove insignificant in explaining the variation in energy efficiency across the SSA countries.

In the spirit of further examining the import of machinery, we find that machinery imports from OECD countries improve energy efficiency compared to imports from non-OECD countries. These results show that machinery from OECD countries may also contribute to energy efficiency improvements in SSA. Because of this, SSA countries that buy more machinery from OECD countries may use less energy than other SSA countries. To achieve better energy use, the region should import less used or secondhand machinery and equipment from OECD countries. Additionally, the technology imported from technologically advanced non-OECD nations should be thoroughly examined. Stopping the import of cheap, low-quality, and inefficient technology from countries outside the OECD will do more good. However, SSA countries can also help people use energy-efficient technologies in their factories, offices, schools, and homes. In Ghana, for example, where there are a lot of power outages and rolling blackouts, the government has started a labelling system for appliances to show how much energy each product uses and how efficient it is. The initiative paid off, saving approximately 120 megawatts (MW) of energy at peak times, eliminating the need for US\$105 million in power generation while preventing more than 110,000 tons/year of atmospheric carbon (Edziah *et al.* 2022).

Second, the fact that stocks of R&D spillover and human capital do not have much effect shows that SSA countries are not very good at using innovations from

technological leaders. It is likely for SSA countries to witness a significant positive effect of R&D spillover on efficiency, provided there is available skilled human capital. So, those in charge of promoting science and technology could make plans and policies to increase investment in human capital development, especially by building expertise in technology and engineering. The skilled science, mathematics, and technology workforce will increase R&D, thereby improving technical development and energy efficiency. This would mean that SSA governments must increase their GDP allocation to R&D activities. Thus, policymakers in SSA need to develop new ways of influencing governments to increase R&D spending significantly.

### Disclosure statement

No potential conflict of interest was reported by the author(s).

### Notes

1. This increase is mainly attributed to the rising middle-class population, the growing level of urbanization and poor energy use practices (Adom, Appiah, and Agradi 2020).
2. Given that SSA countries rarely undertake R&D, the stock of R&D spillover could be used as a proxy for their own knowledge (technology) stock.
3. For this study, the PDE is preferred to the MMSLE due to its restriction-free feature imposed on the inefficiency term (see Belotti and Ilardi 2014).
4. See the Appendix (online [supplementary material](#)) for a complete list of the OECD countries.
5. Individual country R&D stocks are calculated in US\$PPP.

### Supplemental data

Supplemental data for this article can be accessed [here](#).

### Funding

This work was supported by the Key Program of National Social Science Fund of China (21AZD067); the National Natural Science Foundation of China (72243005); and the Sehan University Fund in 2023.

### ORCID

Fengqin Liu  <http://orcid.org/0000-0001-8373-1615>

Jae-Yeon Sim  <http://orcid.org/0000-0002-1316-7067>

Bless Kofi Edziah  <http://orcid.org/0000-0002-9946-1872>

Huaping Sun  <http://orcid.org/0000-0002-9328-7850>

Samuel Asumadu Sarkodie  <http://orcid.org/0000-0001-5035-5983>

Philip Kofi Adom  <http://orcid.org/0000-0001-8135-7260>

### References

- Adetutu, Morakinyo O., and Victor Ajayi. 2020. "The Impact of Domestic and Foreign R&D on Agricultural Productivity in Sub-Saharan Africa." *World Development* 125: 104690. doi:[10.1016/j.worlddev.2019.104690](https://doi.org/10.1016/j.worlddev.2019.104690).

- Adom, Philip Kofi, and Paul Adjei Kwakwa. 2014. "Effects of Changing Trade Structure and Technical Characteristics of the Manufacturing Sector on Energy Intensity in Ghana." *Renewable and Sustainable Energy Reviews* 35: 475–483. doi:10.1016/j.rser.2014.04.014.
- Adom, Philip Kofi. 2019. "An Evaluation of Energy Efficiency Performances in Africa under Heterogeneous Technologies." *Journal of Cleaner Production* 209: 1170–1181. doi:10.1016/j.jclepro.2018.10.320.
- Adom, Philip Kofi, Kwaku Amakye, Kennedy Kwabena Abrokwa, and Christopher Quaidoo. 2018. "Estimate of Transient and Persistent Energy Efficiency in Africa: A Stochastic Frontier Approach." *Energy Conversion and Management* 166 (April): 556–568. doi:10.1016/j.enconman.2018.04.038.
- Adom, Philip Kofi, Michael Owusu Appiah, and Mawunyo Prosper Agradi. 2020. "Does Financial Development Lower Energy Intensity?" *Frontiers in Energy* 14 (3): 620–634. doi:10.1007/s11708-019-0619-x.
- Ahmed, Khalid. 2017. "Revisiting the Role of Financial Development for Energy-Growth-Trade Nexus in BRICS Economies." *Energy* 128: 487–495. doi:10.1016/j.energy.2017.04.055.
- Arazmuradov, Annageldy, Gianmaria Martini, and Davide Scotti. 2014. "Determinants of Total Factor Productivity in Former Soviet Union Economies: A Stochastic Frontier Approach." *Economic Systems* 38 (1): 115–135. doi:10.1016/j.ecosys.2013.07.007.
- Battese, G. E., and T. J. Coelli. 1992. "Frontier Production Functions, Technical Efficiency and Panel Data: With Application to Paddy Farmers in India." *Journal of Productivity Analysis* 3 (1–2): 153–169. doi:10.1007/BF00158774.
- Battese, G. E., and T. J. Coelli. 1995. "A Model for Technical Inefficiency Effects in a Stochastic Frontier Production Function for Panel Data." *Empirical Economics* 20 (2): 325–332. doi:10.1007/BF01205442.
- Belotti, Federico, and Giuseppe Ilardi. 2014. "Sftfe: A Stata Command for Fixed-Effects Stochastic Frontier Models Estimation." Paper presented at the Italian Stata Users' Group Meetings 2014, Milan, Italy, November 13.
- Ben Hassine, H., F. Boudier, and C. Mathieu. 2017. "The Two Ways of FDI R&D Spillovers: Evidence from the French Manufacturing Industry." *Applied Economics* 49 (25): 2395–2408. doi:10.1080/00036846.2016.1240345.
- Bernstein, J. I. 1996. "International R&D Spillovers between Industries in Canada and the United States, Social Rates of Return and Productivity Growth." *The Canadian Journal of Economics* 29 (S463): S463. doi:10.2307/136088.
- Bernstein, J. I., and Pierre Mohnen. 1998. "International R&D Spillovers between US and Japanese R&D Intensive Sectors." *Journal of International Economics* 44 (2): 315–338. doi:10.1016/S0022-1996(97)00026-3.
- Blanco, Gabriel, R. Gerlagh, S. Suh, J. Barrett, H. C. de Coninck, C. F. Diaz Morejon, R. Mathur., et al. 2014. Drivers, Trends and Mitigation. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical Report.* doi:10.1017/cbo9781107415416.011.
- Carraro, Carlo, and Enrica de Cian. 2013. "Factor-Augmenting Technical Change: An Empirical Assessment." *Environmental Modeling & Assessment* 18 (1): 13–26. doi:10.1007/s10666-012-9319-1.
- Chen, Yi-Yi, Peter Schmidt, and Hung Jen Wang. 2014. "Consistent Estimation of the Fixed Effects Stochastic Frontier Model." *Journal of Econometrics* 181 (2): 65–76. doi:10.1016/j.jeconom.2013.05.009.
- Christensen, Laurits R., Dale W. Jorgenson, and Lawrence J. Lau. 1973. "Transcendental Logarithmic Production Frontiers." *The Review of Economics and Statistics* 55 (1): 28–45. doi:10.2307/2235033.
- Coe, David T., and Elhanan Helpman. 1995. "International R&D Spillovers." *European Economic Review* 39 (5): 859–887. doi:10.1016/0014-2921(94)00100-E.
- Coe, David T., Elhanan Helpman, and Alexander W. Hoffmaister. 2009. "International R&D Spillovers and Institutions." *European Economic Review* 53 (7): 723–741. doi:10.1016/j.euroecorev.2009.02.005.
- Coe, David T., Elhanan Helpman, and Alexander W. Hoffmaister. 1997. "North-South R&D Spillovers." *The Economic Journal* 107 (440): 134–149. doi:10.1111/1468-0297.00146.

- Cohen, Wesley M., Akira Goto, Akiya Nagata, Richard R. Nelson, and John P. Walsh. 2002. "R&D Spillovers, Patents and the Incentives to Innovate in Japan and the United States." *Research Policy* 31 (8–9): 1349–1367. doi:10.1016/S0048-7333(02)00068-9.
- Danquah, Michael. 2018. "Technology Transfer, Adoption of Technology and the Efficiency of Nations: Empirical Evidence from Sub Saharan Africa." *Technological Forecasting and Social Change* 131: 175–182. doi:10.1016/j.techfore.2017.12.007.
- Danquah, Michael, and Bazoumana Ouattara. 2015. "What Drives National Efficiency in Sub-Saharan Africa." *Economic Modelling* 44: 171–179. doi:10.1016/j.econmod.2014.10.019.
- Doyon-Martin, Jacquelynn. 2015. "Cybercrime in West Africa as a Result of Transboundary E-Waste." *Journal of Applied Security Research* 10 (2): 207–220. doi:10.1080/19361610.2015.1004511.
- Du, Minzhe, Bing Wang, and Ning Zhang. 2018. "National Research Funding and Energy Efficiency: Evidence from the National Science Foundation of China." *Energy Policy* 120: 335–346. doi:10.1016/j.enpol.2018.05.058.
- Edziah, Bless Kofi, Huaping Sun, Philip Kofi Adom, Feng Wang, and Andrew Osei Agyemang. 2022. "The Role of Exogenous Technological Factors and Renewable Energy in Carbon Dioxide Emission Reduction in Sub-Saharan Africa." *Renewable Energy* 196 (July): 1418–1428. doi:10.1016/j.renene.2022.06.130.
- Edziah, Bless Kofi, Huaping Sun, Emmanuel Anyigbah, and Liang Li. 2021a. "Assessment of Short- And Long-Run Energy Efficiency: Evidence from 141 Countries." *Estudios de Economia Aplicada* 39 (8): 1–16. doi:10.25115/eea.v39i8.4495.
- Edziah, Bless Kofi, Huaping Sun, Emmanuel Anyigbah, and Liang Li. 2021b. "Human Capital and Energy Efficiency: Evidence from Developing Countries." *American Journal of Industrial and Business Management* 11 (06): 599–610. doi:10.4236/ajibm.2021.116038.
- Engelbrecht, Hans Jürgen. 1997. "International R & D Spillovers, Human Capital and Productivity in OECD Economies: An Empirical Investigation." *European Economic Review* 41 (8): 1479–1488. doi:10.1016/S0014-2921(96)00046-3.
- Färe, R., S. Grosskopf, and D. Margaritis. 2006. "Productivity Growth and Convergence in the European Union." *Journal of Productivity Analysis* 25 (1–2): 111–141. doi:10.1007/s11123-006-7134-x.
- Filippini, Massimo, and Lester C. Hunt. 2012. "US Residential Energy Demand and Energy Efficiency: A Stochastic Demand Frontier Approach." *Energy Economics* 34 (5): 1484–1491. doi:10.1016/j.eneco.2012.06.013.
- Filippini, Massimo, and Lester C. Hunt. 2015. "Measurement of Energy Efficiency Based on Economic Foundations." *Energy Economics* 52: S5–S16. doi:10.1016/j.eneco.2015.08.023.
- Filippini, Massimo, and Lester C. Hunt. 2011. "Energy Demand and Energy Efficiency in the OECD Countries: A Stochastic Demand Frontier Approach." *The Energy Journal* 32 (2): 59–80. doi:10.5547/ISSN0195-6574-EJ-Vol32-No2-3.
- Filippini, Massimo, and Lin Zhang. 2016. "Estimation of the Energy Efficiency in Chinese Provinces." *Energy Efficiency* 9 (6): 1315–1328. doi:10.1007/s12053-016-9425-z.
- Fioratta, Susanna. 2019. "A World of Cheapness: Affordability, Shoddiness, and Second-Best Options in Guinea and China." *Economic Anthropology* 6 (1): 86–97. doi:10.1002/sea2.12133.
- Fisher-Vanden, Karen, and Gary H. Jefferson. 2008. "Technology Diversity and Development: Evidence from China's Industrial Enterprises." *Journal of Comparative Economics* 36 (4): 658–672. doi:10.1016/j.jce.2008.07.003.
- Fisher-Vanden, Karen, Gary H. Jefferson, Ma Jingkui, and Xu Jianyi. 2006. "Technology Development and Energy Productivity in China." *Energy Economics* 28 (5–6): 690–705. doi:10.1016/j.eneco.2006.05.006.
- Greene, Willam. 2005. "Fixed and Random Effects in Stochastic Frontier Models." *Journal of Productivity Analysis* 23 (1): 7–32. doi:10.1007/s11123-004-8545-1.
- Griffith, Rachel, Rupert Harrison, and John Van Reenen. 2006. "How Special is the Special Relationship? Using the Impact of US R&D Spillovers on UK Firms as a Test of Technology Sourcing." *American Economic Review* 96 (5): 1859–1875. doi:10.1257/aer.96.5.1859.
- Henry, Michael, Richard Kneller, and Chris Milner. 2009. "Trade, Technology Transfer and National Efficiency in Developing Countries." *European Economic Review* 53 (2): 237–254. doi:10.1016/j.euroecorev.2008.05.001.

- Herrerias, M. J., A. Cuadros, and V. Orts. 2013. "Energy Intensity and Investment Ownership across Chinese Provinces." *Energy Economics* 36: 286–298. doi:10.1016/j.eneco.2012.08.043.
- Huang, Junbing, Dan Du, and Qizhi Tao. 2017. "An Analysis of Technological Factors and Energy Intensity in China." *Energy Policy* 109: 1–9. doi:10.1016/j.enpol.2017.06.048.
- Huang, Junbing, Yu Hao, and Hongyan Lei. 2018. "Indigenous versus Foreign Innovation and Energy Intensity in China." *Renewable and Sustainable Energy Reviews* 81: 1721–1729. doi:10.1016/j.rser.2017.05.266.
- IEA 2017. *CO<sub>2</sub> Emissions from Fuel Combustion 2017 – Highlights*. doi:10.1787/co2\_fuel-2017-en.
- Jijian, Zhang, Angelina Kissiwaa Twum, Andrew Osei Agyemang, Bless Kofi Edziah, and Emmanuel Caesar Ayamba. 2021. "Empirical Study on the Impact of International Trade and Foreign Direct Investment on Carbon Emission for Belt and Road Countries." *Energy Reports* 7: 7591–7600. doi:10.1016/j.egy.2021.09.122.
- Keller, Wolfgang. 1998. "Are International R & D Spillovers Trade-Related? Analyzing Spillovers among Randomly Matched Trade Partners." *European Economic Review* 42 (8): 1469–1481. doi:10.1016/S0014-2921(97)00092-5.
- Kneller, R., and P. A. Stevens. 2006. "Frontier Technology and Absorptive Capacity: Evidence from OECD Manufacturing Industries." *Oxford Bulletin of Economics and Statistics* 68 (1): 1–21. doi:10.1111/j.1468-0084.2006.00150.x.
- Kohler, Marcel. 2013. "CO<sub>2</sub> Emissions, Energy Consumption, Income and Foreign Trade: A South African Perspective." *Energy Policy* 63: 1042–1050. doi:10.1016/j.enpol.2013.09.022.
- Kopp, Raymond J. 1981. "The Measurement of Productive Efficiency: A Reconsideration." *The Quarterly Journal of Economics* 96 (3): 477–503. doi:10.2307/1882683.
- Kumbhakar, S. C. 1990. "Production Frontiers, Panel Data, and Time-Varying Technical Inefficiency." *Journal of Econometrics* 46 (1–2): 201–211. doi:10.1016/0304-4076(90)90055-X.
- Kumbhakar, S. C., and C. K. Lovell. 2000. *Stochastic Frontier Analysis*. New York: Cambridge University Press.
- Liu, Fengqin, Jae-yeon Sim, Huaping Sun, Bless Kofi Edziah, Philip Kofi Adom, and Shunfeng Song. 2022. "Assessing the Role of Economic Globalization on Energy Efficiency: Evidence from a Global Perspective." *China Economic Review* 77: 101897. doi:10.1016/j.chieco.2022.101897.
- Lovel, C.A. Knox, Sue Richardson, Peter Travers, and Lisa Wood. 1994. "Resources and Functionings: A New View of Inequality in Australia." In *Models and Measurement of Welfare and Inequality*, edited by Wolfgang Eichhorn, 787–807. Heidelberg: Springer. doi:10.1007/978-3-642-79037-9.
- Mandal, Sabuj Kumar. 2010. "Do Undesirable Output and Environmental Regulation Matter in Energy Efficiency Analysis? Evidence from Indian Cement Industry." *Energy Policy* 38 (10): 6076–6083. doi:10.1016/j.enpol.2010.05.063.
- Mastromarco, Camilla, and Sucharita Ghosh. 2009. "Foreign Capital, Human Capital, and Efficiency: A Stochastic Frontier Analysis for Developing Countries." *World Development* 37 (2): 489–502. doi:10.1016/j.worlddev.2008.05.009.
- Mazumdar, Joy. 2001. "Imported Machinery and Growth in LDCs." *Journal of Development Economics* 65 (1): 209–224. doi:10.1016/S0304-3878(01)00134-1.
- Ozturk, Ilhan, and Ali Acaravci. 2013. "The Long-Run and Causal Analysis of Energy, Growth, Openness and Financial Development on Carbon Emissions in Turkey." *Energy Economics* 36: 262–267. doi:10.1016/j.eneco.2012.08.025.
- Patterson, Murray G. 1996. "What is Energy Efficiency? Concepts, Indicators and Methodological Issues." *Energy Policy* 24 (5): 377–390. doi:10.1016/0301-4215(96)00017-1.
- Perkins, Richard, and Eric Neumayer. 2012. "Do Recipient Country Characteristics Affect International Spillovers of CO<sub>2</sub>-Efficiency via Trade and Foreign Direct Investment?" *Climatic Change* 112 (2): 469–491. doi:10.1007/s10584-011-0204-8.
- Pitt, Mark M., and Lung-Fei Lee. 1981. "The Measurement and Sources of Technical Inefficiency in the Indonesian Weaving Industry." *Journal of Development Economics* 9 (1): 43–64. doi:10.1016/0304-3878(81)90004-3.
- Sun, Huaping, Bless Kofi Edziah, Chuanwang Sun, and Anthony Kwaku Kporsu. 2019. "Institutional Quality, Green Innovation and Energy Efficiency." *Energy Policy* 135: 111002. doi:10.1016/j.enpol.2019.111002.
- Sun, Huaping, Bless Kofi Edziah, Anthony Kwaku Kporsu, Samuel Asumadu Sarkodie, and Farhad Taghizadeh-Hesary. 2021. "Energy Efficiency: The Role of Technological

- Innovation and Knowledge Spillover.” *Technological Forecasting and Social Change* 167: 120659. doi:10.1016/j.techfore.2021.120659.
- Sun, Huaping, Bless Kofi Edziah, Chuanwang Sun, and Anthony Kwaku Kporsu. 2022. “Institutional Quality and Its Spatial Spillover Effects on Energy Efficiency.” *Socio-Economic Planning Sciences* 83:101023. doi:10.1016/j.seps.2021.101023.
- Sun, Huaping, Bless Kofi Edziah, Xiaoqian Song, Anthony Kwaku Kporsu, and Farhad Taghizadeh-Hesary. 2020a. “Estimating Persistent and Transient Energy Efficiency in Belt and Road Countries: A Stochastic Frontier Analysis.” *Energies* 13 (15): 3837. doi:10.3390/en13153837.
- Sun, Huaping, Anthony Kwaku Kporsu, Farhad Taghizadeh-Hesary, and Bless Kofi Edziah. 2020b. “Estimating Environmental Efficiency and Convergence: 1980 to 2016.” *Energy* 208: 118224. doi:10.1016/j.energy.2020.118224.
- Teng, Yuhua. 2012. “Indigenous R&D, Technology Imports and Energy Consumption Intensity: Evidence from Industrial Sectors in China.” *Energy Procedia*.16: 2019–2026. doi:10.1016/j.egypro.2012.01.307.
- Teng, Yuhua, Huogen Wang, and Yan Chen. 2011. “R&D Spillover Embodied in Imports and Energy Consumption Intensity in China: An Empirical Analysis Based on Panel Data of 32 Industries.” In 2011 *Asia-Pacific Power and Energy Engineering Conference, 2011*, 1–4. doi:10.1109/APPEEC.2011.5748673.
- Tiruneh, Esubalew Alehegn, Evelyn Wamboye, and Bruno S. Sergi. 2017. “Does Productivity in Africa Benefit from Advanced Countries’ R&D?” *Technology Analysis & Strategic Management* 29 (7): 804–816. doi:10.1080/09537325.2016.1242719.
- Wang, Hung-Jen, and Peter Schmidt. 2002. “One-Step and Two-Step Estimation of the Effects of Exogenous Variables on Technical Efficiency Levels.” *Journal of Productivity Analysis* 18 (2): 129–144. doi:10.1023/A:1016565719882.
- Yang, Yuan, Wenjia Cai, and Can Wang. 2014. “Industrial CO<sub>2</sub> intensity, Indigenous Innovation and R&D Spillovers in China’s Provinces.” *Applied Energy* 131: 117–127. doi:10.1016/j.apenergy.2014.06.033.
- Zhou, P., B. W. Ang, and D. Q. Zhou. 2012. “Measuring Economy-Wide Energy Efficiency Performance: A Parametric Frontier Approach.” *Applied Energy* 90 (1): 196–200. doi:10.1016/j.apenergy.2011.02.025.