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Analysis of the Productivity Dynamics of Electricity Distribution Regions in Ghana

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Abstract: Electrical power distribution is the most important division in the power supply chain. However, its sustainability in terms of efficiency is very important for the growth of every country. This main objective of the paper is to assess the productivity dynamics of this process using the data envelopment analysis (DEA) methodology to analyse the effectiveness of the electricity distribution regions (EDRs) over a period of 7 years. The paper adapts the biennial Malmquist productivity index by infusing it with the slacks-based measure (SBM) to assess the productivity dynamics of EDRs in Ghana. Productivity dynamics were assessed by decomposing the SBM-BMPI productivity scores into the efficiency, technology, and scale change. It was discovered that the productivity of EDRs in Ghana progressed by 16.23% per annum over the sample period. Productivity was driven mainly by technological change and not the efficiency changes and scale changes.

Keywords: productivity; data envelopment analysis; biennial Malmquist; slacks-based measure

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1. Introduction

The electrical power sector is one of the most intricate technological systems, and one that needs efficient administration. The primary tasks in this sector are producing, transmitting, and distributing power in a way that is convenient for the user. This suggests that a certain amount of expense is necessary to make sure that quality electric power reaches the end user.

The Electricity Company of Ghana (ECG) is the main and the most significant power distribution company, distributing power in southern Ghana, and its operational performance has been of significant concern [1–3]. An efficiency assessment of the ECG is imperative to address institutional and market constraints such as the lack of electricity access for the poor, inability to satisfy the growing energy demand, increased power system losses, inadequate power quality, and decreasing operating voltages leading to fluctuations and surges. For these reasons, past and present governments have been very much concerned about its sustenance and hence pay attention to the day-to-day operational activities of the company.

Capital investment projects (CIPs) have been rolled out by the ECG in 2010 and beyond to date, and other projects have been earmarked to bring about improvement in the operational performance and quality of service [4–7]. Several network infrastructural upgrades and interventions have been accomplished in both rural and urban communities. This improved the quality of electricity supply by 17.4% and minimised outages by 78% in addition to meeting the growing demands for energy [4,5]. Interventions in the distribution system through the Loss Reduction Project (LRP) and rolling out of prepayment metering to replace the credit system led to a decrease in system loss from 25.01% in 2011 to 23.37% in 2013 [8,9]. Considering the CIPs carried out by the ECG in order to meet growing demands for energy, decrease system losses, and improve the quality of electricity supply and delivered voltages, system losses remains above the 21% target set by the PURC [1,2,10]. The majority of African nations continue to suffer from an unstable electrical supply. The Afro Barometer cites North African nations as having the most reliable energy supply in all of Africa [11]. This study investigates the progress or the contribution that these improvements in the electricity network, how they have benefited the service provider and contributed to their productive performance over the period of seven years.

The concept of productivity is defined as the ratio or indices of output to input consumed. Ref. [12] extended the concept of [13], which proposed productivity indices as ratios of distance functions. Ref. [14] revised the work of [12] in a nonparametric context. After their seminal presentation, numerous notable studies have extended the calculation and disintegration of the Malmquist index. Productivity change involves the assessment of efficiency dynamics over time. There are several significant efficiency and productivity analysis works, beginning with [13,15,16].

The work by [17], assessing the performance of electricity distribution sector using DEA, has been the pioneering study on assessing relative or dynamic efficiency and productivity of electricity distribution utilities. Since then, other studies on assessing efficiency and productivity in the electricity distribution industry by other researchers have been documented in the DEA efficiency literature. These include [18,19] amongst others. A brief overview of critical works in this research space is briefly detailed in subsequent paragraphs.

Productivity estimates using the Data Envelopment Analysis (DEA) Malmquist index have also provided useful insight in the assessment of dynamic performance over time. Studies focused in this direction have investigated the sources or drivers of productivity through various decompositions of the Malmquist index. Studies reviewed show that productivity growth of electricity distribution utilities is mostly driven by technological innovations of the industry or technical change [18,20–29]. However, Ref. [30] on the contrary found that technical or managerial efficiency change and scale efficiency change were the main drivers of productivity in Colombian utilities rather than technological innovation of the industry. These studies estimated productivity using the adjacent Malmquist index under the constant return to scale (CRS) assumption which may result in LP infeasibilities. These studies employed the radial CCR and Banker Charnes and Cooper (BCC) DEA models. While non-radial models such as the slack-based measure (SBM) are robust and have greater discriminating power [23,31,32], they have not been extensively applied in the electricity distribution literature.

DEA and its variants like SBM and BMPI is a nonparametric outlying methodology, and it is crucial to investigate the sensitivity of productivity scores to sampling variations. Although the bootstrapping procedure shown by [33–35] has been applied to DEA models in EDR studies [18,36], there appears to be no known application of the bootstrap to the SBM-BMPI model. Bootstrapping helps to purge the efficiency estimates of sampling variations and statistical noises, resulting in reliable confidence interval estimates. Consequently, productivity changes can be determined to have been statistically significant or otherwise.

The endogenous growth theory proposed by [37,38] contends that long-run economic progress is dictated mainly by factors intrinsic to the economy. Essentially, the theory posits that economic growth stems from internal (endogenous) activities instead of external actions. These actions include investing in human resources, innovation, and technological know-how, all of which are essential contributors to economic progress. The model by [39] assumes that productivity and economic growth emanate from endogenous technological change. Additionally, it assumes that technology is a non-rival input and that there are positive spill-over effects of technology (knowledge or idea) that other organisations can adopt. Thus, the production of new technology by a firm can be augmented via the use of physical capital, human capital, and prevailing technology. Ref. [40] introduced the concept of industrial innovation into the endogenous growth concept through the 'factor of obsolescence' as a channel of improving the quality of products. They suggested that growth is attained particularly from technological advancement generated from competition among firms that engage in research. Similar evidence was found by [41]. Ref. [42] also found evidence supporting spill-overs emanating from highly technologically endowed to less technologically endowed firms. Technological spill-over has also been found to be a driver of productivity change in manufacturing firms [43].

The objective of this paper is to assess the productivity of electricity distribution regions over a period of seven years. The study adapts the BMPI by incorporating the SBM model (which takes into considerations slacks in estimating efficiency) to create the SBM_BMPI. The strength of this method lies in the fact that the BMPI handles the problem of linear programming infeasibilities which occurs when estimating a cross-period productivity score with the traditional MPI. The novelty of this paper is the use of the SBM-BMPI to assess productivity of the major electricity distribution utility in Ghana. The study contributes to the literature by developing a novel SBM-BMPI model and applying it to EDRs in Ghana. This is the motivation for this study, and it is beneficial for ECG and the various operation managers of EDRs to contextualise the possible areas for improvement. This paper employs the novel SBM-BMPI method to examine the productivity evolution of Ghana's major electricity distribution company (ECG). Analysing the efficiency of EDRs provides substantial insight into these resources and assists policymakers in making better-informed decisions.

2. Methods

The paper employs the DEA models to assess the productivity dynamics of EDRs in Ghana. The Bienniel Malmquist Productivity Index (BMPI) was adapted to include the SBM models which deal with input and output slacks in computing the productivity scores.

2.1. The Basic Malmquist Model

The traditional Malmquist productivity index (MPI) was introduced by [12], building on the foundational work of [13]. Ref. [44] disintegrated the MPI into two factors, efficiency change (EC) and technical change (TC), based on the CRS assumption [45]. Ref. [46] presented the three-factor decomposition of the MPI by disintegrating the EC factor into SEC and PTC. Nevertheless, calculating the scale EC requires estimating efficiency scores under both CRS and variable return to scale (VRS) production technologies. This presents some challenges, as it may result in possible LP infeasibilities when mixed-period efficiencies are calculated using the VRS technology [45]. Malmquist indices have been developed using the variable return to scale (VRS) technology that handles linear programming (LP) infeasibilities. These are the sequential Malmquist index of [47] and the global Malmquist by [48]. The sequential Malmquist method's flaw is that it does not include or identify technological regression or decline. With the global Malmquist method, the main flaw is that all earlier estimates must be recalculated with the addition of another period. This is very likely to change the results [45]. The BMPI proposed by [45] presents a favourable solution to the LP infeasibilities that result from the completion of the computation of productivity with reference to the VRS frontier, allowing for technical retrogression and not requiring re-computation with the addition of another period [45]. The main intuition underlining the BMPI is to generate a distinct biennial frontier under the required production technology which envelopes t and $t+1$ production technologies and all the observations from both periods. This eliminates the issue of LP infeasibility.

The model suggests a biennial benchmark technology that pools the two adjacent periods and estimates the biennial frontier's indices, which envelop the frontiers for both periods. The VRS biennial Malmquist index can, therefore, be calculated regarding a biennial technology frontier, which is defined as:

$$\left\{ \psi_v^t, \psi_v^{t+1} \right\} \in \psi_v^B \tag{1}$$

As ψ_v^t and ψ_v^{t+1} are the VRS production technologies for time t and $t+1$.

BMPI under the CRS and VRS assumptions are defined as:

$$BMPI_c = \frac{\phi_c^B(y^t, x^t)}{\phi_c^B(y^{t+1}, x^{t+1})}$$

$$BMPI_v = \frac{\phi_v^B(y^t, x^t)}{\phi_v^B(y^{t+1}, x^{t+1})} \quad (2)$$

It should be noted that the biennial frontier pools the two time periods' technology frontiers into a single base period frontier and that this does not require the use of geometric means [45].

The superscript, B, represents the biennial benchmark technology, and the subscripts c and v in (2) and (3) represent the CRS and VRS production technologies. The *BMPI* can be decomposed, following Ray and Desli [46], into *EC*, *TC*, and the "biennial scale change" (*BSC*) elements, as shown below.

$$BMPI_c = EC_v \times TC_v \times BSC \quad (3)$$

In line with the adjacent, the biennial *EC* element is defined as:

$$EC_v = \frac{\phi_v^t(y^t, x^t)}{\phi_v^{t+1}(y^{t+1}, x^{t+1})} \quad (4)$$

The *TC* is the ratio of the *BMPI* in (2) to the *EC* in (4), which is expressed as:

$$\begin{aligned} TC_v = \frac{BMPI_V}{EC_v} &= \frac{\phi_v^B(y^t,x^t)/\phi_v^B(y^{t+1},x^{t+1})}{\phi_v^t(y^t,x^t)/\phi_v^{t+1}(y^{t+1},x^{t+1})} \\ &= \left[\frac{\phi_v^B(y^t,x^t)}{\phi_v^t(y^t,x^t)} \times \frac{\phi_v^{t+1}(y^{t+1},x^{t+1})}{\phi_v^B(y^{t+1},x^{t+1})}\right] \end{aligned} \quad (5)$$

The scale change element *BSC* is obtained by estimating the *BMPI* concerning both CRS and VRS frontiers and taking the ratio as expressed below:

$$\begin{aligned} BSC = \frac{BMPI_c}{BMPI_v} &= \left[\frac{\phi_c^B(y^t,x^t)/\phi_c^B(y^{t+1},x^{t+1})}{\phi_v^B(y^t,x^t)/\phi_v^B(y^{t+1},x^{t+1})}\right] \\ &= \left[\frac{\phi_c^B(y^t,x^t)}{\phi_v^B(y^t,x^t)} \times \frac{\phi_v^B(y^{t+1},x^{t+1})}{\phi_c^B(y^{t+1},x^{t+1})}\right] \end{aligned} \quad (6)$$

Note that the explanation for the SBM-BMPI decompositions remains the same as that given earlier.

2.2. The SBM-BMPI

Assessing growth by employing traditional MPI has gained tremendous popularity. Since its formalisation in DEA, the MPI has had several extensions, which include the BMPI adopted in this study. However, extensions like the BMPI are still based on radial efficiency scores. Estimating the efficiency scores used in computing the productivity indices which use radial DEA models (CCR and BCC) could generate misleading results. This is because radial models do not integrate non-radial slacks (surpluses in inputs and deficits in outputs). Hence, to estimate BMPI, the study adopts the SBM by [49] to propose the SBM-BMPI.

To compute the SBM-BMPI under the VRS assumption, the output orientation requires *SBM* efficiency scores to be estimated concerning the biennial benchmark production technology, B, defined as:

$$SBM - BMPI = \frac{\hat{\rho}_v^B(y^t, x^t)}{\hat{\rho}_v^B(y^{t+1}, x^{t+1})} \quad (7)$$

where $\hat{\rho}_v^B(x^t, y^t)$ and $\hat{\rho}_v^B(x^{t+1}, y^{t+1})$ represent SBM–O–VRS efficiency scores computed relative to the biennial frontier for EDRs in time *t* and *t* + 1 correspondingly. As indicated earlier, the SBM-BMPI is disintegrated into three elements. The *EC* element using *SBM* efficiency scores is defined as:

$$EC = \frac{\hat{\rho}_v^t(y^t, x^t)}{\hat{\rho}_v^{t+1}(y^{t+1}, x^{t+1})} \tag{8}$$

where $\hat{\rho}_v^t(x^t, y^t)$ and $\hat{\rho}_v^{t+1}(x^{t+1}, y^{t+1})$ represents the own-period SBM–O–VRS efficiency scores of EDRs, computed relative to the frontier in their respective periods. The "technical change" element is defined as the ratio of *BMPI* in Equation (7) to the *EC* in (8):

$$\begin{aligned} EC = \frac{BMPI_V}{EC_V} &= \frac{\hat{\rho}_v^B(y^t,x^t)/\hat{\rho}_v^B(y^{t+1},x^{t+1})}{\hat{\rho}_v^t(y^t,x^t)/\hat{\rho}_v^{t+1}(y^{t+1},x^{t+1})} \\ &= \frac{\hat{\rho}_v^B(y^t,x^t)}{\hat{\rho}_v^t(y^t,x^t)} \times \frac{\hat{\rho}_v^{t+1}(y^{t+1},x^{t+1})}{\hat{\rho}_v^B(y^{t+1},x^{t+1})} \end{aligned} \tag{9}$$

The third element, *BSC* requires both SBM-O-CRS and SBM–O–VRS efficiency scores, estimated relative to the biennial benchmark frontier. Thus,

$$\begin{aligned} BSC = \frac{SBM-BMPI_c}{SBM-BMPI_V} &= \frac{\hat{\rho}_c^B(y^t,x^t)/\hat{\rho}_c^B(y^{t+1},x^{t+1})}{\hat{\rho}_v^B(y^t,x^t)/\hat{\rho}_v^B(y^{t+1},x^{t+1})} \\ &= \left[\frac{\hat{\rho}_c^B(y^t,x^t)}{\hat{\rho}_v^B(y^t,x^t)} \times \frac{\hat{\rho}_v^B(y^{t+1},x^{t+1})}{\hat{\rho}_c^B(y^{t+1},x^{t+1})}\right] \end{aligned} \tag{10}$$

Note that the explanation for the SBM-BMPI decompositions remains the same as explained earlier.

2.3. DATA

The data for this study was obtained from the ECG head office located in the Greater Accra Region. It consists of 9 EDRs. The observations cover a period of seven years from 2012 to 2018. as shown in Table 1 below. Three inputs were used, namely the number of employees, transformer capacity measures in megawatts and network length measured in kilometres. The outputs are revenue measured in millions of Ghana Cedis, the number of customers and losses in megawatts.

Table 1. Data used for analysis.

Region	Year	No. of Employees	Transformer Capacity	Network	No. of Customers	Revenue	Losses
ACCRA EAST	2018	212	960,083.00	2,011,568.97	500,815	1,123,164,596.40	882.72
ACCRA WEST	2018	182	868,790.00	1,809,136.52	610,653	940,283,051.80	775.80
TEMA	2018	209	755,041.00	2,639,135.70	416,003	1,092,372,428.88	71.14
ASHANTI WEST	2018	363	847,973.00	4,858,127.61	868,004	754,363,237.78	314.60
WESTERN	2018	174	580,073.50	7,465,034.10	471,586	594,946,973.11	217.87
CENTRAL	2018	185	314,735.00	3,788,527.94	448,522	296,121,583.42	196.01

Source: ECG [50].

3. Results

The results of static productivity for each EDR are presented in Table 2 below. Figure 1 shows the productivity dynamic productivity of all EDRs together with the decomposed productivity changes namely: average EC, TC and BSC of EDRs for adjacent periods. Additionally, the average SBM-BMPI, EC, TC and BSC of each EDR for the study period are presented in Figure 2. The figures and table in this paper are the authors' work. The productivity scores were obtained using the MaxDEA 7 Ultra software.

Table 2. Static Productivity of EDRs.

DMU	2012–2013	2013–2014	2014–2015	2015–2016	2016–2017	2017–2018
Accra East	1.0314	1.2927	1.0919	1.4101	1.0228	0.9842
Accra West	1.0000	1.0000	1.0000	1.1203	1.0162	1.0128
Ashanti East	1.0668	1.1233	1.0210	0.9006	1.2054	1.0001
Ashanti West	1.0144	1.3182	1.0866	1.4993	1.0144	1.2900
Central	1.0770	1.0882	1.1188	1.3204	0.9559	0.9570
Eastern	1.0705	1.1250	1.1099	1.1378	1.0066	1.0134
Tema	1.0073	1.2713	1.6853	0.8843	1.0707	1.4443
Volta	1.0862	1.0000	1.0624	1.0000	1.0229	1.0078
Western	1.1806	1.0722	1.2056	1.1778	1.0661	1.0050

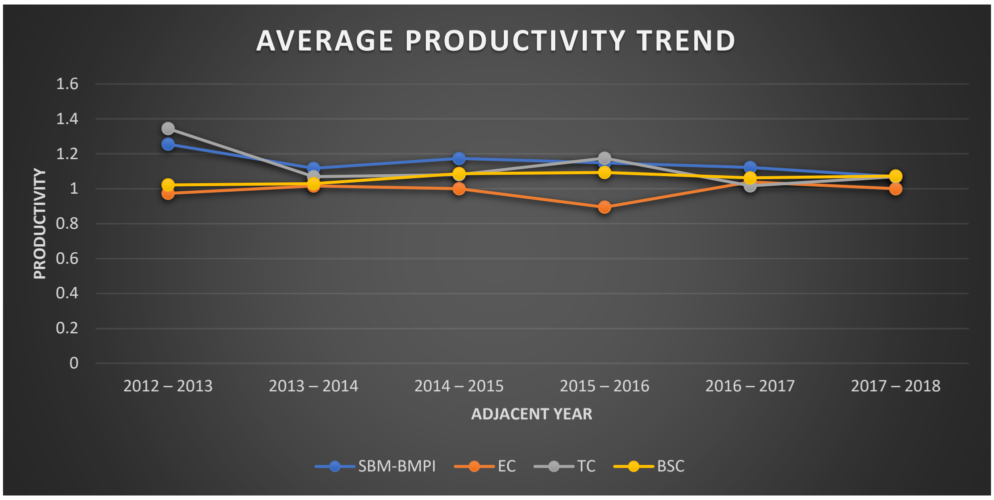

Figure 1. Average productivity trends for the period 2012 to 2018.

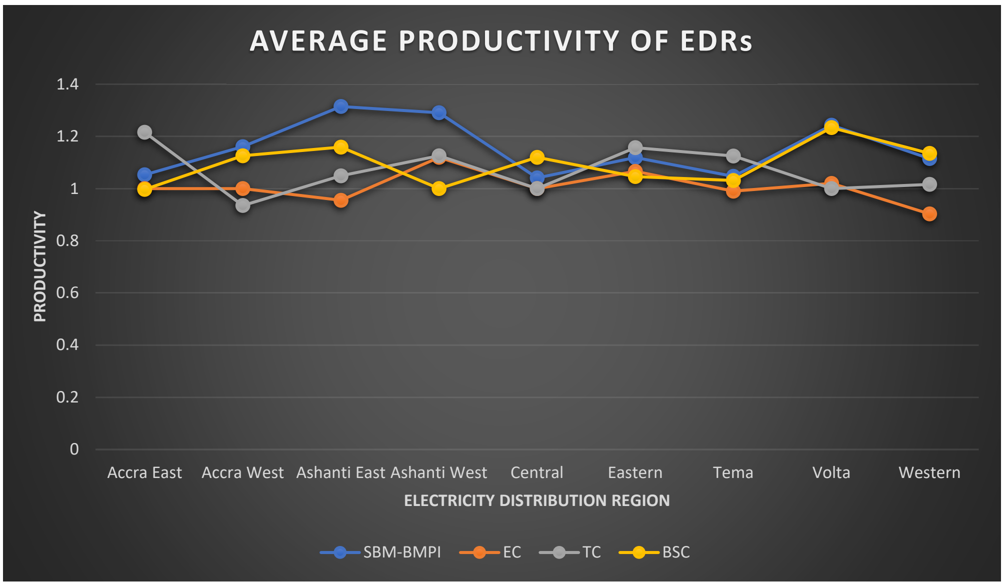

Figure 2. Average productivity of EDRs.

4. Discussion

The results presented in Table 2 show that most EDRs experienced growth in productivity for consecutive years. "**Accra West**" stagnated for three consecutive adjacent periods. Some also regressed for some consecutive periods. The stagnation could be attributed to the problems associated with the prepayment project [51].

The biannual averages on the estimated productivity indices are shown as "SBM-BMPI" together with the EC, TC and BSC in Figure 1.

Note that SBM-BMPI, TC, and EC greater than unity means a productivity improvement; when these values less than unity, a recession is denoted, and values equal to unity denote stagnation in productivity.

The productivity of EDRs has progressed over the sample period. This is evident in growth in productivity for the following adjacent periods; 2012 to 2013 (25.57% (The percentages are computed by subtracting 1 from the average productivity score, if there is a progress or the productivity score is subtracted from 1 when there is a regress (that is SBM-BMPI < 1).) progress), 2014 to 2015 (17.37% progress), 2015 to 2016 (14.86% progress), and 12.19% growth from 2016 to 2017. Nevertheless, statistical inferences through bootstrapping show that the annual average growth is not significant as the confidence intervals include 1 (When the confidence ranges from any number less than 1 to a number greater than1, it is said that the confidence interval includes 1.) [33,52]. The average EC regressed by 1.29% $(1 - 0.9871 = 1.29)$. This was triggered by a regress of 2.65% and 10.59% for the adjacent periods of 2012 to 2013 and 2015 to 2016, respectively. The average EC, which is attributed to managerial expertise, falls below the SBM-BMPI, TC and BSC scores, impling that management of the distribution company needs substantial improvement in their managerial approach. The highest growth in technical change was recorded from 2012 to 2013 (34.50%) and 2015 to 2016 (17.49%). The lowest growth of 1.66% was seen from 2016 to 2017. Statistical inference shows no significant impact of the decline in EC or growth in TC components on the aggregate productivity of EDRs. This could be attributed to an increasing rate of technical and commercial losses (wrong tariff class, power theft) and a high failure rate of both credit and prepaid meters [53]. However, the overall growth in TC, judging from the perspective of the EGT, can be attributed to the technological innovations and spill-over through network improvements or upgrades, as well as the deployment of a prepayment metering system to replace the credit meters in most EDRs [2,6,9]. The general productivity of EDRs is attributed to progress in the technological innovation of the industry rather than managerial innovativeness.

The average productivity indices and decompositions for the various EDRs from 2012 to 2018 are presented in Figure 2. All EDRs recorded some level of growth. "**I**" recorded the highest average productivity growth of 31.53% for the period of 2012–2018. All EDRs recorded growth above 10%, except for "**Accra East**", "**Central**", "**Tema**" and "**Western**" which recorded marginal growth in productivity, with "**Central**" recording the lowest score of 4.12%. Statistical consideration reveals that only the "**Ashanti West**" growth of 29.50% is significant. An inspection of Figure 2 shows that four EDRs experienced growth in productivity attributed to managerial acumen. The highest and lowest growth among EDRs in this aspect is "**Ashanti West**" and "**Volta**" which grew by 12.02% and 1.99%, respectively. Three EDRS stagnated (average EC is equal to unity) from 2012 to 2018 and three EDRs also regressed. "**Western**" regressed by 9.68% being the highest among EDRs. Six EDRs experienced technological growth for the study period. The highest improvement in technical change was 21.64% by "**Accra East**" whiles the lowest growth of 1.61% was achieved by "**Western**". 2 EDRs, "**Centra**l" and "**Volta**", stagnated over the study period. However, 1 (11.11%) EDRs regressed from 2012 to 2018. Deterioration in "**Accra West**" implies that they failed to take advantage of technological spill-over in the industry which could be attributed to the challenges with the prepayment system.

Decision making or managerial inefficiency are generally not so bad, seeing as most of the EDRs have good scores. However, it appears that tried and tested management strategies and processes have not yielded the desired results and therefore could not have impacted the industry's overall productivity.

The paper also investigated how close EDRs are getting to the ideal size (scale) of operation after some time (scale EC). The result of the BSC component in Figure 1 shows that EDRs made progress in reaching an ideal scale of operation, moving from 2.21% from 2012 to 2013 to 9.33% for the period from 2013 to 2014. However, the growth rate slowed down for the period from 2014 to 2015. This indicates that EDRs are moving away from the ideal size of the operation. In general, EDRs are moving towards an ideal operation scale at an average growth rate of 5.81%. This means that EDRs have good control of their geographical area. The average BSC, for the respective EDRs, is also shown in Figure 2. Most EDRs made progress in moving towards an ideal scale of operation. The minimum average progress was made by "**Ashanti West**" (0.05%) whiles the highest growth towards the ideal size of the operation was made by "**Volta**" (23.38%). One EDR regressed in achieving the ideal scale of operation over the study period, indicating that these EDRs are moving away from the ideal operation scale. This could possibly due to growing customer population through the national electrification initiative by the government of Ghana.

This finding has both empirical and theoretical grounding. From the theoretical perspective, this coincides with the views of advocates of the EGT. Endogenous growth theorists propose that the industry's growth results from technological innovation from purposeful scientific innovation investment choices made by "profit-seeking" firms [39,54]. Empirically, these outcomes follow those of [22], who found similar results that productivity is driven by TC in a study of South African utilities. Additionally, studies by [19,24,28] indicate that the average productivity development hinged on TC and not EC. Contrary to these findings, ref. [30] found that managerial efficiency and scale EC were the drivers of productivity change experienced from 1998 to 2012 in Columbia.

Comparision of Results

Other studies in the electricity distribution literature that assessed productivity of distribution utilities have found both supporting and contrasting outcomes. The results of productivity measurements for the respective EDRs show that most of those regions which experienced growth were marked by scores above 1. This result is similar to the findings of [23] in their assessment of Taiwanese electricity distribution districts. Static productivity reveals that most EDRs experienced growth. Ref. [22] found similar evidence of growth in productivity in other African countries. This shows that counties in Africa are making strides towards improving electricity supply on the continent. The productivity indices were decomposed to investigated the sources or drivers of productivity change. The main driver of productivity change was technological innovation (technical change or frontier shift) and not managerial expertise (efficiency change component). Refs. [24–29] also found similar evidence of technological innovation of the industry being the main driver of productivity change rather than efficiency changes. Similarly, they also sound that managerial performance was rather low, as indicated by the efficiency change components. In this paper it was realised that EDRs are moving towards an optimum scale of operation, as indicated by the scale efficiency change components. Again, Refs. [24–29] found that most utility companies in their study were operating at their optimal size.

5. Conclusions

An evaluation of general productivity shows that EDRs experienced considerable growth in their levels of productivity. However, the average biannual productivity trend shows a gradual decrease in the rate of progress of EDRs. In general, the ECG has improved in their operations, as the productivity score shows some growth. The growth in productivity for the study period was found to be driven by the TC component rather than the managerial EC. Managerial competence is essential to the growth of EDRs as it was found to be more strongly associated with productivity than technological innovations in the industry.

It still stands that managerial innovativeness is not forthcoming among EDRs considered in this study, since the average EC component declined over the study period. The suggestion for the regulator is to enhance the managerial skills of operations managers of EDRs to reap the full benefits of technological innovations in the sector.

Additionally, having established that the growth of the sector is spurred by the adoption of some technological factors, it will be prudent for ECG to invest more heavily in state-of-the-art technologies to improve the operational efficiency of EDRs.

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