Quality performance gaps and minimal electricity losses in East Africa*

Axel Gautier† René Nsabimana‡ Barnabé Walheer§

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Abstract

The electricity sector in East Africa is characterized by high levels of electricity losses. The literature has extensively focused on investments and policy reforms that can potentially reduce losses. In this paper, we follow another approach by nonparametrically estimating the minimal losses given the actual inputs, outputs and electricity generation process. Minimal losses are then compared to actual losses to construct quality performance indicators. Using a tailored database for six East African countries over 10 years, we show that electricity losses could be reduced by 8%, representing savings of approximately $60 million per year.

Keywords: electricity losses; quality performance gap; East Africa.

JEL Codes: C67, Q40

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†HEC Liège, LCII, Université de Liège, Belgium and CESifo (Munich). ORCID: 0000-0001-7700-3814, Email: `agautier@uliege.be`

‡HEC Liège, Université de Liège, Belgium and Institut Supérieur des Cadres Militaires (ISCAM), Burundi. Email: `r.nsabimana@uliege.be`

§HEC Liège, Université de Liège, Belgium. Email: `barnabe.walheer@uliege.be`. This work is supported by the Fonds de la Recherche Scientifique (FNRS) under Grant No. J.0193.23.

1 Introduction

The electricity sector in East Africa is characterized by high levels of electricity losses that negatively impact utilities, customers, and society as a whole. Reducing electricity losses is therefore a major objective for policy-makers and regulators in that part of the world. Solutions such as detection equipment for electricity fraudsters, upgrading the electricity network, expanding inspections, and increasing the use of prepaid meters are available. These solutions generally require modifying the inputs, outputs, or technologies of electricity generation processes. That is, new investments or new staff are needed.

In this paper, we tackle the electricity loss reduction question from another angle. Instead of minimizing inputs for given outputs for a given (unknown) production process (or maximizing outputs for given inputs), we compute potential minimal electricity losses while maintaining the electricity generation process, i.e., the inputs, the outputs, and the technologies, unchanged. Putting it differently, we look for potential electricity loss reduction without requesting new investments. While electricity losses have been previously studied (Arocena, 2008; Fourie and Calmeyer, 2004; Salkuti, 2021; Sanhueza et al., 2004; Susanty et al., 2022), we are the first to consider this setting.

For that, we use a nonparametric method to reconstruct the generation process that is typically unknown. We impose some standard regularity conditions on this process and use a tailored database for six East African countries over a 10-year period to estimate the minimal losses associated with the electricity generation process. By comparing these estimated minimal losses with actual losses, we find that a potential reduction of 8% for the electricity losses is possible while maintaining the inputs, the outputs, and the technologies constant, i.e., These savings could be achieved at no cost by adopting best practices. Using actual electricity prices, this represents a net savings of $60 million per year. Further reductions are still possible, but this would require investing in additional assets and staff.

The rest of the paper is organized as follows. Section 2 presents important facts and figures on electricity losses in East Africa to contextualize our empirical investigation. There, we also give a brief literature review. Section 3 gives our empirical strategy. In Section 4, we explain and describe our data, and we give our results in Section 5. We conclude and provide policy recommendations in Section 6.

2 Context and literature review

To put our contribution in perspective, we provide a discussion of the empirical context and a brief literature review.

2.1 Context

An important aspect of the quality of service (QoS) for an electricity distribution system is the continuity of supply. A lack of continuity results in power outages that cause inconveniences and costs to consumers and firms. In addition to power outages, the transmission and distribution (T&D) of electricity generates power losses. T&D losses can be attributed to technical and nontechnical factors. Technical losses (TLs) are the losses that occur within the transmission and distribution network due to the cables, overhead lines, transformers and other substation equipment that are used to transfer electricity. Nontechnical losses (NTLs) correspond to the electricity consumed but not paid by the consumers. This absence of payment by consumers can be attributed to the inability of the electricity distribution company to collect its debts, illegal connections to the network, electricity theft and fraud (de Souza Savian et al., 2021, Jamil & Ahmad, 2019). Electricity theft decreases the efficiency of the electricity network due to power outages and damage to transformers and meters. More generally, NTLs impact the quality of supply and total system revenue (Costa-Campi et al., 2018, de Souza Savian et al., 2021, and Messinis & Hatziargyriou, 2018). While QoS is typically measured in terms of interruption frequency or duration, losses of electricity are instead measured either as the proportion of purchased energy that did not reach the end user or as the difference between delivered and purchased energy.

T&D losses represent a high cost for utility and society, and the problem is particularly severe in Africa. According to Adams et al. (2020), $5 billion is lost annually in Sub-Saharan Africa (SSA) due to T&D losses, with South Africa alone losing $1.5 billion. Yakubu et al. (2018) state that power losses impact the financial health of utilities and impede new investments in power generation, transmission, and distribution. As a result, electricity losses lead to higher costs for utilities and higher tariffs for users. Eventually, higher electricity tariffs encourage electricity fraudsters, contributing to poorer QoS (de Souza Savian et al., 2021, Jamil & Ahmad, 2019, and Leite et al., 2020). The REN21 2016 report on renewable energy and energy efficiency in East African countries (REN21, 2016) estimates that electricity losses represent

22% of the power supply. This number is relatively high compared to an average of 12% for Sub-Saharan Africa and a world average of 8%.

East African countries are seeking to mitigate electricity losses, with a minimum loss rate of at least 15% as a target. Based on SE4ALL[1] country analysis and other reference documents such as the master plans for electricity generation, transmission and distribution, the national energy policies and/or strategies[2], we detail the situation of each country in the East African Community.

In Burundi, the 2011 energy sector strategy reported electricity losses of up to 24.4% in 2011, of which approximately 15% were attributed to technical losses. The sociopolitical crisis of 1993-2005 damaged the electricity transmission and distribution network. An audit conducted in 2015 shows that, in addition to technical losses, invoiced and unpaid electricity is one of the main causes of NTL. In his study on the electricity sector in Burundi, Nsabimana (2020) shows that only 42% of energy receivables are recovered each year. The SE4ALL study plans to reduce losses to 15% in 2020 and to 10% in 2030. To achieve this objective, the SE4ALL study provides for an action plan including the construction of new hydroelectric power plants, the rehabilitation of the electricity network, the reduction of unpaid bills and the generalization of prepaid meters.

In Rwanda, loss reduction is planned through the 2018 National Energy Strategic Plan. In 2017, electricity losses accounted for 22%, 17% were attributed to technical losses and 5% to NTLs. The national energy policy aims to reduce electricity losses to 15% by 2024. It also seeks to improve the reliability of the network by reducing power cuts from 91.7 hours to 14.2 hours. To achieve this, it plans to carry out energy efficiency awareness campaigns, acquire fraud detection equipment, extend the use of prepaid meters, and strengthen the transmission and distribution network.

[1]Sustainable Energy for All (SE4ALL) is an independent organization linked to the United Nations that works toward the achievement of Sustainable development goal 7: access to affordable, reliable, sustainable and modern energy for all. Their website (`https://www.se4all-africa.org`) provides useful information on East African countries.

[2]With the exception of Burundi, whose national energy policy and strategy date back to 2011, all other East African countries have renewed their national policies and/or strategies in the last seven years. This is the case for Tanzania in 2015, Kenya and Rwanda in 2018, and Uganda in 2019. Ethiopia has instead developed a national electrification programme that also dates from 2019. These national policies and strategies outline the main challenges in the energy sector, as well as the main strategic directions for increasing access to electricity and the quality of service. The reports of these national policies and strategies can be downloaded from the websites of the respective ministries in charge of energy and other institutions, such as the energy regulator.

In Kenya, the 2018 National Energy Policy and the 2016 SE4ALL diagnostic study show that the country loses approximately $17 million per year due to electricity theft and the undersizing of feeders. Challenges to be addressed include vandalism and aging of electricity infrastructure, power outages, and electricity theft. The energy policy plans to reduce electricity losses to less than 15% in 2020 through increased transmission capacity, distribution system automation and smart grid projects.

The poor performance of the electricity sector in Tanzania is seen through the 2015 National Energy Policy, the 2015 SE4ALL Action Programme, and the 2018 Energy and Water Utilities Regulatory Authority (EWURA) Performance Report. High tariffs and poor recovery of receivables are a barrier to attracting $IPPs$ and thus new investments in the network. Tanzania plans to reduce electricity losses to less than 14% from 2018. To achieve this goal, the national energy policy foresees new investments in the construction, rehabilitation and expansion of T&D infrastructure and interconnection with neighboring countries.

Loss reduction in Uganda is planned through the 2019 National Energy Policy and the 2015 SE4ALL Action Plan. Despite progress in reducing losses, approximately 600 GWh is lost each year. Uganda aims to reduce losses to less than 15% by 2030 by strengthening the transmission and distribution network, curbing vandalism of transmission infrastructure and attracting $IPPs$ into the transmission sector. It also intends to implement incentive-based regulation for QoS.

Finally, Ethiopia is one of the fastest growing countries in East Africa in terms of electricity generation. However, the National Electrification Program (NEP 2.0) for 2019 reported high commercial losses, 18% out of 23% total losses in 2017. In addition, 10–15% of losses are caused by poor billing and collection systems. The 2019 NEP 2.0 aims to reduce electricity losses to 14% by 2037 by ensuring the financial viability of the two utilities, modernizing institutions, and improving the revenue collection system.

All East African countries have ambitious targets to reduce their power losses. However, their strategies involve investments to increase inputs and outputs. In Section 3, we develop a method to estimate the potential reductions in power losses, maintaining inputs, outputs and technologies constant.

2.2 Literature review

The literature has extensively studied the institutional determinants of electricity losses. Sadovskaia et al. (2019) indicate that improved urbanization, privatization, development, and corruption might reduce electricity losses. Mohsin et al. (2021) find that T&D losses are minimized when the governing bodies in the power sector work with independent power producers (IPPs) and private actors. Nagayama (2010) finds that T&D losses decrease with the introduction of IPPs in developing Asian countries, privatization in Latin America, and unbundling in developed countries. Sen & Jamasb (2012) find a positive impact of unbundling and the introduction of independent regulatory authority in India. Balza et al. (2013) show that a one percent increase in cumulative private investment is associated with a reduction of T&D losses by 0.13 percent in Latin America. Smith (2004) finds that T&D losses are highly correlated with each of the governance dimensions defined by Kaufmann et al. (2010). Nepal & Jamasb (2015) show that a combination of strong governance and proper institutions with corruption control can reduce electricity theft. Our approach differs from previous studies, as we consider the institutional determinants as fixed and that no new investments are made. This is captured by constant input and output levels and fixed technologies for the electricity generation processes. Putting this differently, we look for potential electricity loss reductions without modifying the global electricity environment, as such modifications might be complex in East Africa.

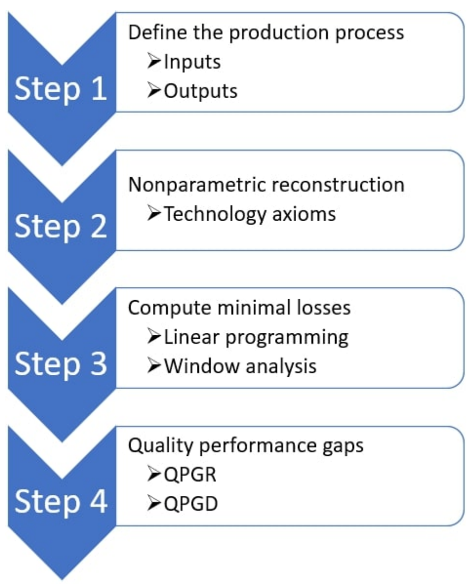
In addition to the important efforts put toward better understanding the institutional determinants of electricity losses, several performance analyses have been conducted for utilities (Abbott and Cohen, 2022, Arcos-Vargas et al., 2017, Bongo et al., 2018, Çelen and Yalçın, 2012, Núñez et al., 2020, Von Hirschhaussen et al., 2006). In those cases, transmission and distribution losses are considered a source of inefficiency, as they represent energy not supplied, which could be billed and generate revenue for the utility. In practice, electricity losses are added to the electricity generation process as an input (Edvardsen & Forsund, 2003, Jamasb & Pollitt, 2003, Ramos-Real et al., 2009, Xie et al., 2017), output (Bongo et al., 2018, Petridis et al., 2019), or byproduct. Table 5 (in Appendix A) lists the main papers using electricity losses in performance measurement. Our approach differs from previous studies, as we do not consider electricity losses as part of the electricity generation processes (Walheer, 2020) but as a measure of the performance gap. Rather, we investigate minimal electricity losses given the inputs, outputs, and technologies of the electricity generation processes.

3 Empirical strategy

We consider N countries during T time periods. The electricity generation process of each country at time t consists of two inputs (captured by $\mathbf{x}_t$): the length of the transmission lines and the purchased electricity, and two outputs (captured by $\mathbf{y}_t$): the number of consumers and the energy delivered. These inputs and outputs are very common in the literature (see Table 5 in Appendix A). Additionally, electricity losses, denoted by l_t, occur at every period t.

Our objective is to evaluate the minimal losses that can be achieved given the inputs and the outputs and the technology used for every time period. The electricity losses represent our proxy for the quality performance gaps. Our empirical strategy can be summarized into four main steps, as highlighted in Figure 1.

Figure 1: Empirical strategy



3.1 Estimating minimal electricity losses

While actual electricity losses are observed, this is not the case for minimal electricity losses. The particularity of our approach is to compute minimal electricity losses given the electricity generation process. In this process, inputs are combined to produce outputs, and losses are a byproduct of this process. As this process is typically unknown, we adopt a nonparametric approach to reconstruct the process using the data, and we impose some regularity conditions. These conditions are very general and avoid trivial and unrealistic reconstruction. We select the following technology axioms:

A1 (free disposable inputs): *It is always possible to produce less outputs for given input quantities.*

A2 (free disposable outputs): *More inputs never reduce the outputs.*

A3 (convex technology set): *If two input quantities can produce a certain output amount, then any convex combination of these two input quantities can produce the same output amount.*

A4 (variable returns-to-scale): *The technology exhibits variable returns-to-scale.*

A5 (no technological degradation): *The technology possibilities do not reduce over time.*

These axioms are standard in production theory. **A1** and **A2** impose a nonnegative relationship between inputs and outputs: a decrease in outputs does not require an increase in inputs, and an increase in inputs does not reduce outputs. Note that these restrictions are weak and are compatible with firms being below the production frontier, i.e., inefficient firms may produce more outputs with their inputs, which, in our case, translates into a lower minimal loss. **A3** implies that the inputs are imperfectly substituted. If the same outputs can be achieved with different combinations of inputs A and B, then a convex combination of A and B can also produce the same outputs. The convexity of the production set is a classical axiom in production theory, and nonconvexities are generally associated with market failure or externalities, which is not the case here. **A4** does not impose a priori the nature of the returns to scale that could be increasing, decreasing or constant and **A5** states that the electricity generation process does not degrade over time, i.e., What was possible in the past is still possible in the present.

A particularity of our sample is that we have few countries per time period. A well-established procedure in that case is window analysis, which is widely utilized as an analytic technique to detect efficiency trends in many fields, such as the banking industry (Asmild et al., 2004, Fadzlan& Muhd-Zulkhibri, 2007), energy and the environment (Wang et al., 2013, Sueyoshi et al., 2017), telecoms (Yang et al. 2009), and power plants (Sueyoshi et al., 2013).

This technique operates on the principle of moving averages and establishes efficiency measures by treating each country in different periods as a separate unit. In practice, we have to select the window's length, and we choose 3 years to have enough entities in each window (18 in our case). Let us define $\mathbf{x}^w \in \mathbb{R}_+^P$ and $\mathbf{y}^w \in \mathbb{R}_+^Q$ as the input?output of the entities in window w.

Given our nonparametric reconstruction of the electricity generation process and the window approach, we end with the following estimator for the minimal losses for a particular country operating at $(\mathbf{x}_t, \mathbf{y}_t)$:

$$l^w(\mathbf{x}_t, \mathbf{y}_t) = min_{\lambda_{j\tau}^w, j \in \{1,\dots,N\}, \tau \in w} \begin{pmatrix} \sum_{\tau \in w} \sum_{j=1}^{J} \lambda_{j\tau}^w l_{j\tau}^w \mid \mathbf{y}_t \leq \sum_{\tau \in w} \sum_{j=1}^{J} \lambda_{j\tau}^w \mathbf{y}_{j\tau}^w, \\ \mathbf{x}_t \geq \sum_{\tau \in w} \sum_{j=1}^{J} \lambda_{j\tau}^w \mathbf{x}_{j\tau}^w, \\ \sum_{\tau \in w} \sum_{j=1}^{J} \lambda_{j\tau}^w = 1, \\ \lambda_{j\tau}^w \geq 0 \; \forall j, \tau. \end{pmatrix}. \tag{1}$$

In other words, $l^w(\mathbf{x}, \mathbf{y})$ gives us the minimal electricity losses that a particular entity operating at $(\mathbf{x}_t, \mathbf{y}_t)$ can reach at time t given the inputs-outputs of the other entities and the technology. We emphasize that the estimator fulfills the imposed axioms. First, **A1** and **A2** are translated by the output and input inequalities. Next, **A3** implies that linear combinations of outputs and inputs are included. This is done, in practice, by including weight variables $\lambda_{j\tau}^w$ for every country j, window w and time τ. These weights are directly useful to consider variable returns-to-scale (**A4**). It suffices to impose that these weights sum to unity. Finally, **A5** is captured by the window-specific sums.

Finally, all observations in window w are included when evaluating the minimal losses at time t. This implies that our estimator is window dependent. Putting this differently, we may have several estimators for the minimal losses at time t if time t is present in several windows. This is the case for all periods except the beginning and ending periods. As our main interest is the minimal losses for each time period and country, we have to aggregate the window-dependent estimators. A simple way to do that is to take the arithmetic average as follows[3]:

$$l(\mathbf{x}_t, \mathbf{y}_t) = \frac{1}{\#w}.\sum_{t \in w} l^w(\mathbf{x}_t, \mathbf{y}_t). \tag{2}$$

$l(\mathbf{x}_t, \mathbf{y}_t)$, contrary to $l^w(\mathbf{x}_t, \mathbf{y}_t)$, is window-independent and is directly useful to conduct the rest of our analysis.[4]

3.2 Measuring quality performance gaps

It is difficult to interpret the estimated minimal losses without relating them to the actual losses. A simple way to do that is to take the ratio or the difference between both. We define the quality performance gap ratio and difference for a specific entity at time t as follows:

$$QPGR_t(l_t, \mathbf{x}_t, \mathbf{y}_t) = \frac{l_t(\mathbf{x}, \mathbf{y})}{l_t}. \tag{3}$$

$$QPGD_t(l_t, \mathbf{x}_t, \mathbf{y}_t) = l_t - l_t(\mathbf{x}, \mathbf{y}). \tag{4}$$

$QPGR_t(l_t, \mathbf{x}_t, \mathbf{y}_t)$ is smaller than unity by construction, as the minimal losses cannot exceed the actual losses. When this ratio is strictly smaller than one, it indicates that it is, in principle, possible to improve the service quality without modifying the inputs, outputs, and technology. A value of one indicates that the service quality is at its maximum given the inputs, outputs, and technology. Reaching a higher service quality would require a change in inputs, outputs, or technology. $QPGD_t(l_t, \mathbf{x}_t, \mathbf{y}_t)$ gives us the amount of potential electricity losses. A value of zero indicates that the maximal service quality has been reached. Finally, we once more emphasize that these two indicators are nonparametric estimators of the unknown counterparts.

4 Data and descriptive statistics

We first explain how we collect our data, and then we present relevant descriptive statistics.

[3]Taking the average value for the minimal losses potentially reduces variations that can be attributable to the stochastic shocks on inputs or outputs.

[4]It is also possible to take the average in each window. This is not interesting for us. Note also that this aggregation scheme, while simple, is theoretically correct (see e.g., Walheer, 2018).

4.1 Data sources

We collect data from six countries, Burundi, Ethiopia, Kenya, Rwanda, Uganda and Tanzania, for a period of 10 years, from 2008 to 2017. Data were collected either physically by visiting the different electricity utilities and their regulators and online through their websites and specific requests.

Table 1: Organization of the electricity sector

Country	Generation	Transmission	Distribution
Burundi	REGIDESO	REGIDESO	REGIDESO
Ethiopia	EEP	EEP	EEU
Kenya	KenGen + REP + IPPs	KPLC, KETRACO	KPLC
Rwanda	REG + IPPs	REG	REG
Tanzania	TANESCO + IPPs	TANESCO	TANESCO
Uganda	IPPs+UEGCL	UETCL	9 Private firms

East African countries have different organizations for the energy sector (Table 1). Uganda, Kenya and Ethiopia have a vertically separated sector, while the other countries have companies that are still vertically integrated. We use the data provided by vertically integrated operators or newly created companies, completed by secondary sources, including regulators. We collected data from Régie de Production et de Distribution d'Eau et d'Electricité (REGIDESO) for Burundi, Rwanda Energy Group (REG) for Rwanda, Tanzania Electricity Supply Company (TANESCO) for Tanzania, and Ethiopian Energy Power (EEP) and Ethiopian Energy Utility (EEU) for Ethiopia. For Uganda, the data were provided by the regulator, Electricity Regulatory Authority (ERA). For Kenya, we used the annual reports of Kenya Power Lighting Company Limited (KPLC) from 2008 to 2018. KPLC's annual reports include all aggregated data on electricity generation, transmission and distribution. They include data from other entities, such as Kenya Generating Company Limited (KenGen), IPPs, Regional Electrification Program (REP), and its own data.[5] We are well aware that data combined from different sources may suffer from measurement errors, but as there is no standardized data collection in East Africa, our data are the best proxy that we can use for research.

[5]In Kenya, the financial year starts in July and we have considered that it corresponds to a calendar year to make data comparable.

4.2 Descriptive statistics

In this subsection, we present the main summary statistics. To obtain our complete database we use for this study, see Appendix B.

4.2.1 Electricity generation process

In Table 2, we present the descriptive statistics for our two inputs (the transmission length[6] and the purchased electricity) and two outputs (the number of consumers and the energy delivered). For each country, we present the average value over the sample period and the change for the considered period.

Table 2: Descriptive statistics − inputs and outputs

Country	Statistics	Transmission length HV (km)	Electricity Purchased (GWh)	Energy delivered (GWh)	Customers (numbers)
Burundi	average	322.00	247.69	191.11	79 783
	change	0.00 %	4.37 %	3.82 %	11.08 %
Ethiopia	average	9587.21	6789.09	5048.20	1 757 104
	change	8.66 %	14.13 %	13.75 %	6.10 %
Kenya	average	4743.08	8076.73	6644.50	2 736 670
	change	4.01 %	5.55 %	5.13 %	21.26 %
Rwanda	average	744.20	484.86	383.42	382 516
	change	4.85 %	12.60 %	12.12 %	24.15 %
Tanzania	average	5059.21	5626.09	4596.52	1 262 224
	change	2.77 %	5.96 %	5.73 %	13.01 %
Uganda	average	1439.97	2694.19	2031.63	632 657
	change	4.58 %	6.50 %	9.31 %	16.16 %

All countries serve an increasing number of customers over time, and the growth is substantial, especially in Rwanda and Kenya, which both have yearly growth rates above 20%. Electricity delivered is also increasing but at a lower rate (except in Ethiopia), implying a lower average consumption per customer. The average annual growth rate for the transmission line is equal to 7.6% with a large disparity between countries, with some countries (Burundi) not investing at all and others, such as Ethiopia, managing to more than double their transmission capacity.

[6]East African countries have different capacities for their transmission lines and they have the target to increase the minimum capacity to 110 kV. For this study, we select transmission lines with a capacity of 60 kV and above.

4.2.2 Actual electricity losses

We compute the electricity losses as the difference between purchased and delivered electricity. Delivered electricity corresponds to the electricity that is effectively billed to consumers. Our definition of losses therefore includes technical and nontechnical losses associated with the electricity generation process. Descriptive statistics are provided in Table 3. On average, over the period, 21% of the purchased electricity was lost. This represents a loss of power of 18 895 GWh per year. Uganda managed to decrease losses from 34% in 2008 to 17% in 2017 by increasing the energy delivered while maintaining the losses in GWh almost constant. All other countries experienced higher losses in 2017 than in 2008. Burundi had the highest percentage losses at the end of the period, with 29% of the purchased electricity being lost. It should also be noted that electricity losses can vary considerably between years.

Table 3: Descriptive statistics − electricity losses

Country	Statistics	Electricity losses (GWh)	Electricity losses (%)
Burundi	Average	56.58	22.68%
	Min-Max	36.43 - 79.13	15%-29%
	Change	12.51%	
Ethiopia	Average	1740.89	24.88%
	Min-Max	673.27 - 2758.33	19%-37%
	Change	27.90%	
Kenya	Average	1432.23	17.56%
	Min-Max	1056.30 - 1933.00	16%-20%
	Change	7.88%	
Rwanda	Average	101.44	20.68%
	Min-Max	53.76 - 149.21	19%-24%
	Change	7.88%	
Tanzania	Average	1029.58	18.62%
	Min-Max	462.09 - 1479.63	7%-23%
	Change	15.05%	
Uganda	Average	662.56	25.56%
	Min-Max	587.95 - 752.09	17%-35%
	Change	-0.81%	

5 Estimated quality performance gaps

In this section, we apply our methodology to East African countries to estimate the minimal losses associated with their production process. Using our estimated minimal electricity losses, we are able to compute our indicators of the quality performance gaps. Given our limited amount of data, our results should be interpreted with caution, and we concentrate mainly on the average value over the period. Table 4 reports the average value per country for $QPGR$ and $QPGD$.

Table 4: Quality performances gaps

Country	$QPGR$ (%)	$QPGD$ (GWh)	Electricity price ($/MWh)	Potential savings ($)	Savings per client ($/client)
Burundi	0.95	2.42	117	283 140	3.54
Ethiopia	0.92	184.48	47	6 956 000	3.97
Kenya	0.98	34.09	231	7 874 790	2.88
Rwanda	0.98	1.85	195	360 750	0.94
Tanzania	0.85	159.65	166	26 501 900	21.03
Uganda	0.86	90.02	193	17 373 860	28.80
Average	0.92	78.82			

The average value of 0.92 for $QPGR$ means that countries can reduce electricity losses by an average of 8% while keeping their inputs, outputs, and technologies constant. This performance gap represents an average savings of 78.82 GWh per year and per country. As illustrated in Table 3, electricity losses are an important problem in East Africa that countries should address seriously. Our results show that some losses can be reduced at no cost by improving the efficiency of the sector. Reducing losses further would require additional resources, generation and grid assets and an improved billing system. The potential reductions are limited in Rwanda and Kenya (approximately 2%), and they are more important in Tanzania and Uganda (approximately 15%). These two countries could substantially improve their performance and reduce their losses by adopting better practices.

Next, we use the electricity price data from the World Bank[7] to transform the performance gap, expressed in GWh, into potential savings in dollars. More precisely, we estimate the average savings per country by multiplying the average value of $QPGD$ by the 2014 electricity price. The estimated annual savings per country are

[7] Retrieved from the GovData360 project available at `https://govdata360.worldbank.org`.

given in Table 4. These savings represent the benefit of reducing the actual losses to the estimated minimal losses. Overall, this represents a potential net savings of $60 million per year in East African countries. We note that Tanzania and Uganda have the largest potential savings, 26 and 17 $ millions, respectively.

Finally, we divide the total savings by the average number of clients (from Table 2). We can identify three groups of countries. Rwanda is the best performing country, with savings of less than $1 per client. In Rwanda, minimal losses are limited. The country has the highest value for QPGR, and the number of clients is relatively large. Consequently, the benefit per client is limited, and there are few potential savings. Next, in Kenya, Ethiopia and Burundi, the benefit per client is approximately $3. Those countries have, compared to Rwanda, lower values for QPGR (except for Kenya), meaning that the potential loss reductions are higher and they have relatively fewer clients. For instance, there are almost 5 times fewer clients in Burundi than in Rwanda for a comparable population. For these reasons, savings per client are greater. Furthermore, Ethiopia and Burundi have the lowest electricity prices, implying that savings in $ are lower. For the last group composed of Tanzania and Uganda, the estimated savings per client are above $20. This reflects the fact that they have a large potential for loss reduction at constant input and relatively high energy prices.

The results show that different operators in the electricity sector might be able to reduce their technical and nontechnical electricity losses if they adopt best practices. Such practices include, for example, a reform of the billing system and the adoption of prepaid meters. Mwaura (2012) shows, for example, that the adoption of prepaid meters in Rwanda reduced technical and nontechnical losses from 26% to 18% from 2004 to 2008, which increased revenues from $8.7 million to 22.9 million. As discussed by Smith (2004) and Tasdoven et al. (2012), electricity theft and unpaid bills constitute the major part of nontechnical losses. The adoption of prepaid meters could reduce not only unpaid electricity bills but also the operating costs associated with additional billing and collection employees.

6 Conclusion and policy recommendations

East African countries have a high level of electricity losses, and they have as a target a reduction of losses to 15% or below. For that, they develop energy policies to improve infrastructures and billing, i.e., they have investment plans to reduce losses.

Reducing electricity losses will have a positive impact not only on the utility, with improved revenue collection and increased profits but also on customers and countries. For customers, minimizing electricity losses helps to increase the QoS and reduce electricity tariffs. For governments, it allows subsidies originally directed to the electricity sector to be allocated to other priority sectors. Given the importance of energy in improving quality of life, poverty reduction and economic growth, minimizing losses will generate new resources to increase installed capacity and access to electricity. In this way, the different countries will be able to achieve the Sustainable Development Goals.

In this study, we analyze the quality performance gap that is estimated through the minimization of electricity losses. We estimate a nonparametric performance analysis model that minimizes electricity losses given inputs, outputs and technologies. That is, we estimate the potential loss reduction that does not require investments but rather adopts the best practice in the electricity generation process. Our methodological approach is similar to classical benchmarking exercises performed in the literature, but instead of estimating an efficiency score for each unit, we estimate a quality performance gap. In other words, we estimate by how much losses could be reduced by adopting best practices.

The model we develop is fairly simple and does not require data on prices but only data on inputs and outputs. For the inputs, we use a transmission input, the network length, and a generation input, the energy purchased. For the outputs, we use the energy delivered and the number of clients. Electricity losses are neither inputs nor outputs but a measure of the quality performance gap. They have to be minimized given inputs and outputs. Simple quality performance estimators can be provided, even with a limited number of observations. Performance gap indicators provide information on what could be saved if a country adopts best practices.

We provide for each country an estimation of the performance gap. Less performing countries have a 15% performance gap, and the best performing countries have a 2% performance gap. This represents the potential for loss reduction if best practices were adopted. Expressed in dollars, the potential savings for East African countries are important and would result in improved financial health of the utilities, better service quality and reduced costs.

Our analysis shows that the potential is high for the least performing countries, indicating that investments and structural reforms are not the only solutions to improve

QoS and that countries can achieve substantial savings by adopting best practices. The adoption of best practices could be effective, particularly through policies aimed at providing access to energy for all. Large-scale electrification, especially in rural areas through renewable energy, would help minimize electricity losses, especially from theft. The interconnected network, which has become obsolete, also needs to be rehabilitated, which is the basis for reducing technical losses. Nontechnical loss reduction solutions depend not only on the economic situation of each country but also on its geographical location. The interconnected network may be unable to reach all parts of the country. In East African countries, a large part of the population lives in rural areas that are sometimes inaccessible to the interconnected network. Even if the grid is available, the poor income status of the population does not allow them to connect to electricity, which can lead to theft (de Oliveira Ventura et al.,2020). To reduce nontechnical losses, it is important to develop a decentralized energy provision through renewable energies by combining solar panels, microwinds, generators, and batteries.

Despite the use of a window analysis, one main limitation of the analysis is our small sample. We use data for six East African countries over 10 years using different sources. Additional data could be used to improve the results and serve as a better proxy for performance, notably by reducing the variations in inputs and outputs that can be attributable to stochastic shocks. This kind of study can also be applied to other sectors facing the same challenges, such as the water sector. The analysis could also be extended to all developing countries, especially in Sub-Saharan Africa.

References

[1] Abbott, M., & Cohen, B. (2022). Economics, ideology, and the creation and performance of state-owned electricity utilities in Australia, 1900 to 1950. *Utilities Policy*, 77, 101380.

[2] Adams, S., Atsu, F., Klobodu, E. M. & Richmond, L. (2020). Electricity transmission, distribution losses and economic growth in South Africa. *Heliyon*, 6(11), e05564.

[3] Arcos-Vargas, A., Núñez-Hernández, F. & Villa-Caro, G. (2017). A DEA analysis of electricity distribution in Spain: An industrial policy recommendation. *Energy Policy*, 102, 583-592.

[4] Arocena, P. (2008). Cost and quality gains from diversification and vertical integration in the electricity industry: A DEA approach. *Energy economics*, 30(1), 39-58.

[5] Asmild, M., Paradi, J. C., Aggarwall, V. & Schaffnit, C. (2004). Combining DEA window analysis with the Malmquist index approach in a study of the Canadian banking industry. *Journal of Productivity Analysis*, 21(1), 67-89.

[6] Bagdadioglu, N., Price, C. M. W. & Weyman-Jones, T. G. (1996). Efficiency and ownership in electricity distribution: a non-parametric model of the Turkish experience. *Energy economics*, 18(1-2), 1-23.

[7] Balza, L., Jimenez, R. & Mercado, J. (2013). Privatization, institutional reform, and performance in the Latin American electricity sector. IDB Technical Note TN-599. *Inter-American Development Bank*, Washington, DC.

[8] Bongo, M. F., Ocampo, L. A., Magallano, Y. A. D., Manaban, G. A. & Ramos, E. K. F. (2018). Input–output performance efficiency measurement of an electricity distribution utility using super-efficiency data envelopment analysis. *Soft Computing*, 22(22), 7339-7353.

[9] Çelen, A. & Yalçin, N. (2012). Performance assessment of Turkish electricity distribution utilities: An application of combined FAHP/TOPSIS/DEA methodology to incorporate quality of service. *Utilities Policy*, 23, 59-71.

[10] Costa-Campi, M. T., Daví-Arderius, D. & Trujillo-Baute, E. (2018). The economic impact of electricity losses. *Energy economics*, 75, 309-322.

[11] de Oliveira Ventura, L., Melo, J. D., Padilha-Feltrin, A., Pablo Fernandez-Gutiérrez, J., Sanchez Zuleta, C. C., & Piedrahita Escobar, C. C. (2020). A new way for comparing solutions to non-technical electricity losses in South America. *Utilities Policy*, 67, 101113.

[12] de Souza Savian, F., Siluk, J. C. M., Garlet, T. B., do Nascimento, F. M., Pinheiro, J. R. & Vale, Z. (2021). Non-technical losses: A systematic contemporary article review. *Renewable and Sustainable Energy Reviews*, 147, 111205.

[13] Edvardsen, D. F. & Forsund, F. R. (2003). International benchmarking of electricity distribution utilities. *Resource and energy Economics*, 25(4), 353-371.

[14] Fadzlan, S. & Muhd-Zulkhibri, A. M. (2007). Singapore banking efficiency and its relation to stock returns: a DEA window analysis approach. *International Journal of Business Studies: A Publication of the Faculty of Business Administration, Edith Cowan University*, 15(1), 83-106.

[15] Forsund, F. R. & Kittelsen, S. A. (1998). Productivity development of Norwegian electricity distribution utilities. *Resource and energy economics*, 20(3), 207-224.

[16] Fourie, J. W., & Calmeyer, J. E. (2004). A statistical method to minimize electrical energy losses in a local electricity distribution network. In 2004 IEEE Africon. *7th Africon Conference in Africa* (IEEE Cat. No. 04CH37590) (Vol. 2, pp. 667-673). IEEE.

[17] Jain, S. & Thakur, T. (2010). Efficiency assessment of state owned electricity generation companies in India using data envelopment analysis. *International Journal on Emerging Technologies*, 1(2), 32-35.

[18] Jamasb, T. & Pollitt, M. (2003). International benchmarking and regulation: an application to European electricity distribution utilities. *Energy policy*, 31(15), 1609-1622.

[19] Jamil, F. & Ahmad, E. (2019). Policy considerations for limiting electricity theft in the developing countries. *Energy policy*, 129, 452-458.

[20] Leite, D., Pessanha, J., Simões, P., Calili, R. & Souza, R. (2020). A stochastic frontier model for definition of non-technical loss targets. *Energies*, 13(12), 3227.

[21] Meenakumari, R. & Kamaraj, N. (2008). Measurement of relative efficiency of state owned electric utilities in India using data envelopment analysis. *Modern Applied Science*, 2(5), 61-71.

[22] Messinis, G. M.,& Hatziargyriou, N. D. (2018). Review of non-technical loss detection methods. *Electric Power Systems Research*, 158, 250-266.

[23] Mohsin, M., Hanif, I., Taghizadeh-Hesary, F., Abbas, Q. & Iqbal, W. (2021). Nexus between energy efficiency and electricity reforms: A DEA-Based way forward for clean power development. *Energy Policy*, 149, 112052.

[24] Mwaura, F.M. (2012). Adopting electricity prepayment billing system to reduce non-technical energy losses in Uganda: Lesson from Rwanda. *Utilities Policy*, 23, 72-79.

[25] Nagayama, H. (2010). Impacts on investments, and transmission/distribution loss through power sector reforms. *Energy Policy*, 38(7), 3453-3467.

[26] Nepal, R. & Jamasb, T. (2015). Caught between theory and practice: Government, market, and regulatory failure in electricity sector reforms. *Economic Analysis and Policy*, 46, 16-24.

[27] Núñez, F., Arcos-Vargas, A. & Villa, G. (2020). Efficiency benchmarking and remuneration of Spanish electricity distribution companies. *Utilities Policy*, 67, 101127.

[28] Nsabimana, R. (2020). Electricity sector organization and performance in Burundi. In *Multidisciplinary Digital Publishing Institute Proceedings* (Vol. 58, No. 1, p. 26).

[29] Pacudan, R. & Hamdan, M. (2019). Electricity tariff reforms, welfare impacts, and energy poverty implications. *Energy Policy*, 132, 332-343.

[30] Pérez-Reyes, R. & Tovar, B. (2009). Measuring efficiency and productivity change (PTF) in the Peruvian electricity distribution companies after reforms. *Energy Policy*, 37(6), 2249-2261.

[31] Petridis, K., Ünsal, M. G., Dey, P. K. & Örkcü, H. H. (2019). A novel network data envelopment analysis model for performance measurement of Turkish electric distribution companies. *Energy*, 174, 985-998.

[32] Ramos-Real, F. J., Tovar, B., Iootty, M., De Almeida, E. F. & Pinto Jr, H. Q. (2009). The evolution and main determinants of productivity in Brazilian electricity distribution 1998–2005: An empirical analysis. *Energy Economics*, 31(2), 298-305.

[33] REN21 (2016). East African Community (EAC) Renewable Energy and Energy Efficiency Status Report, available at `https://www.ren21.net/wp-content/uploads/2019/05/REN21-EAC-web-EN.pdf.pdf`

[34] Sadovskaia, K., Bogdanov, D., Honkapuro, S. & Breyer, C. (2019). Power transmission and distribution losses–A model based on available empirical data and future trends for all countries globally. *International Journal of Electrical Power& Energy Systems*, 107, 98-109.

[35] Salkuti, S. R. (2021). Minimization of losses in a distribution system with network reconfiguration, distributed generation and D-STATCOM. *International Journal of Advanced Technology and Engineering Exploration*, 8(85), 1557.

[36] Sanhueza, R., Rudnick, H., & Lagunas, H. (2004). DEA efficiency for the determination of the electric power distribution added value. *IEEE transactions on power systems*, 19(2), 919-925.

[37] Sen, A. & Jamasb, T. (2012). Diversity in unity: An empirical analysis of electricity deregulation in Indian states. *The Energy Journal*, 33(1), 83-130.

[38] Smith, T. B. (2004). Electricity theft: a comparative analysis. *Energy policy*, 32(18), 2067-2076.

[39] Sueyoshi, T., Goto, M. & Sugiyama, M. (2013). DEA window analysis for environmental assessment in a dynamic time shift: Performance assessment of US coal-fired power plants. *Energy Economics*, 40, 845-857.

[40] Sueyoshi, T., Yuan, Y., Li, A. & Wang, D. (2017). Social sustainability of provinces in China: A data envelopment analysis (DEA) window analysis under the concepts of natural and managerial disposability. *Sustainability*, 9(11), 2078.

[41] Susanty, A., Purwanggono, B., & Al Faruq, C. (2022). Electricity distribution efficiency analysis using data envelopment analysis (DEA) and soft system methodology. *Procedia Computer Science*, 203, 342-349.

[42] Tovar, B., Ramos-Real, F. J. & De Almeida, E. F. (2011). Firm size and productivity. Evidence from the electricity distribution industry in Brazil. *Energy Policy*, 39(2), 826-833.

[43] Vaninsky, A. (2006). Efficiency of electric power generation in the United States: analysis and forecast based on data envelopment analysis. *Energy Economics*, 28(3), 326-338.

[44] Vaninsky, A. Y. (2008). Environmental efficiency of electric power industry of the United States: a data envelopment analysis approach. *International Journal of Industrial and Manufacturing Engineering*, 2(4), 509-515.

[45] Von Hirschhausen, C., Cullmann, A. & Kappeler, A. (2006). Efficiency analysis of German electricity distribution utilities–non-parametric and parametric tests. *Applied Economics*, 38(21), 2553-2566.

[46] Walheer, B. (2018). Aggregation of metafrontier technology gap ratios: The case of European sectors in 1995-2015. *European Journal of Operational Research*, 269(3), 1013-1026.

[47] Walheer, B, (2020). Output, input, and undesirable output interconnections in Data Envelopment Analysis: convexity and returns-to-scale. Annals of Operations Research 284, 447-467. *Annals of Operations Research*, 284, 447-467.

[48] Wang, J. B., Liu, L. & Wang, C. (2013). Single machine SLK/DIF due window assignment problem with learning effect and deteriorating jobs. *Applied Mathematical Modelling*, 37(18-19),

[49] Xie, B. C., Gao, J., Chen, Y. F. & Deng, N. Q. (2018). Measuring the efficiency of grid companies in China: A bootstrapping non-parametric meta-frontier approach. *Journal of Cleaner Production*, 174, 1381-1391.

[50] Yakubu, O., Babu, N. & Adjei, O. (2018). Electricity theft: Analysis of the underlying contributory factors in Ghana. *Energy policy*, 123, 611-618.

[51] Yang, H. H.,& Chang, C. Y. (2009). Using DEA window analysis to measure efficiencies of Taiwan's integrated telecommunication firms. *Telecommunications Policy*, 33(1-2), 98-108.

[52] Yunos, J. M. & Hawdon, D. (1997). The efficiency of the national electricity board in Malaysia: An intercountry comparison using DEA. *Energy economics*, 19(2), 255-269.

A Electricity losses in the performance literature

Table 5: Electricity losses in performance analysis

Authors	**Outputs**	**Inputs**
Bagdadioglu et al. (1996)	Number of customers, electricity supplied, peak demand, service area	Labor, transformer capacity, network size, general expenses, **electricity losses**
Bongo et al. (2018)	Electricity delivered, number of customers, **electricity losses**	Electricity urchased, network length
Edvardsen et al. (2003)	Electricity delivered, number of customers, network length	**Electricity losses**, OPEX, capital
Forsund & Kittelsen(1998)	Customer density, number of customers, electricity supplied	Labor, **electricity losses**, capital and materials
Jain & Thakur (2010)	Electricity supplied	Installed capacity, auxiliary consumption, **electricity losses**
Jamasb & Pollitt(2003)	Electricity delivered, number of customers, network length	TOTEX, OPEX, network length, **electricity losses**
Meenakumari & Kamaraj (2008)	Number of customers, electricity supplied	Installed capacity, network length, **electricity losses**
Pacudan & Hamdan (2019)	Number of customers, service area, electricity sales	labor, network length, **electricity losses**
Pérez-Reyes &Tovar (2009)	Annual sales, number of customers	labor, **elecricity losses**, network length, number of substations, capital
Petridis et al. (2019)	Energy supply, number of customers, number of city served, interruptions, **energy losses**	Labor, elecricity delivered, number of transformers, network length, transformer capacity
Ramos-Real et al.(2009)	Electricity delivered, number of customers	Labor, **electricity losses**, service area
Tovar et al. (2011)	Electricity delivered, number of customers	Number of employees, network length, **electricity losses**

Vaninsky (2006)	Utilization of net capacity	OPEX, share of revenue, **electricity losses**
Vaninsky(2008)	Fuel utilization	OPEX, **electricity losses**
Von Hirschhausen et al.(2006)	Electricity delivered, number of customers, inverse density index	Labor, network length, peak load, **electricity losses**
Xie et al. (2018)	Number of customers, electricity delivered	Network length above 35 kV, transformer capacity above 35 kV, labor, **electricity losses**
Yunos & Hawdon(1997)	Electricity supplied	Installed capacity, labor, **electricity losses**, public generation capacity factor

B Data

The dataset used for this paper can be downloaded at `http://hdl.handle.net/2268/261348`