Effectiveness and efficiency in access to reliable electricity: the case of East African countries*

René Nsabimana[†], Sergio Perelman[‡],
Barnabé Walheer*[§], and Mbangala Mapapa[¶]

April 5, 2024

Abstract

Improving access to reliable electricity has been recognized as a necessary condition to foster economic development and reduce poverty. This is therefore not a surprise to find such a goal in the 2030 Agenda on Sustainable Development of the United Nations. Taking this objective as our starting point, we present, in this paper, a non-parametric performance evaluation exercise of the East African electricity systems over a 10-year period. We focus our attention on two intertwined dimensions: effectiveness, i.e. reaching optimal outcomes, and efficiency, i.e. getting to optimal resource-outcome mixes. We show how these two dimensions can be measured over time, and how they can be compared and combined to construct useful indexes. In particular, we make a distinction between changes and shifts in the performances. The results show dramatic differences in terms of effectiveness and small differences in terms of efficiency. This reveals that to reach universal access to reliable electricity, as defined in the 2030 Agenda on Sustainable Development, resource constraint is the key factor and not resource utilization.

---

*We thank the Editor-in-Chief Rajan Batta, the referees, the participants of the First Virtual African Productivity Conference, and Axel Gautier for their valuable comments.

[†]HEC Liège, Université de Liège, Belgium, Institut Supérieur des Cadres Militaires, ISCAM, Burundi. email: nsabirn@yahoo.fr.

[‡]HEC Liège, Université de Liège, Belgium. email: sergio.perelman@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. Corresponding author.

[¶]Institut Supérieur de Commerce de Kinshasa. email: contact@isckinshasa.cd.

Keywords: : Effectiveness; efficiency; electricity; non-parametric; East Africa.

1 Introduction

Access for all to reliable, sustainable, and modern energy services at an affordable cost, especially by promoting the use of renewable energy technologies, is one of the goals contributing to the United Nations 2030 Agenda on Sustainable Development Goals (SDG).[1] Low access to reliable electricity negatively impacts well-being, hinders income-generating opportunities, makes electricity connection and consumption unaffordable, and increases electricity theft (Dertinger & Hirth, 2020). High access to reliable electricity, mainly in developing countries, combats poverty reduction, enables economic growth, and enhances the quality of life (Bensch, 2019; Walheer, 2018a).

Achieving the electricity access and reliability goals of SDG would contribute to economic development given its economic multiplier effects. Indeed, electricity infrastructure is a long-term investment and an input for the production and service systems (Bacon, 2018; Nepal & Jamasb, 2015). Electricity access and electricity system reliability affect economic growth through different channels, such as physical capital accumulation (Lechthaler, 2017), reduction of household pollution, and adverse health impacts from solid fuel use, as well as providing benefits from improving lighting in the night (Best & Burke, 2018). Access to electricity and system reliability are important for productive engagement and community facilities, such as health, education, government buildings, and public buildings (Bhatia & Angelou, 2015).

Independently of the institutional setting adopted – public or private, vertically integrated or unbundled, ... – national authorities are expected to pursue the SDG's electricity goals or, at least, to put it higher in their agenda. Nevertheless, dramatic differences are observed across developing countries, with some of them doing much better than others, which therefore lag far behind the SDG's electricity objectives. Many studies have tried to identify the potential impact of institutional choices on electricity systems, in Africa and elsewhere around the world, paying particular attention to the efficiency of firms, either vertically integrated or unbundled (production, transmission, or distribution). Such studies include, for example, Barabutu & Lee (2018), Blimpo & Cosgrove-Davies (2019), Eberhard et al. (2016), Estache et al.

[1] To be precise the 2030 Agenda on Sustainable Development consists of 17 goals (Transforming our World: The 2030 Agenda for Sustainable Development, United Nations, 2015). SDG 7 is stated as follows: *Ensure access to affordable, reliable, sustainable, and modern energy for all.* While universal electricity access is named in SDG 7.1, SDG 7.2 advocates for a substantial increase in the share of renewable energy, and SDG 7.3 for improvements in energy efficiency.

(2008), Gore et al.(2019), Imam et al.(2019), Njeru et al. (2020), Nsabimana (2022), Plane (1999), Sergi et al. (2018), and Walheer (2018b, 2019, 2020).

In this paper, we adopt a different point of view and an alternative methodological approach. First, we consider as entities the whole electricity system at the country level. More precisely, the entities are modelled as integrated electricity distribution companies whose central activity is to deliver electricity to the whole country and its population.[2] This modelling is more coherent when studying the ability of countries to reach the SDG's electricity targets as it is defined at the country level. We assume that each country has a bureaucracy, "referred to collectively as a helmsman" (Lovell et al., 1995), who is in charge of providing electricity to the whole population and the economy following SDG's targets. We focus our attention on six electricity systems in East African countries: Burundi, Ethiopia, Kenya, Rwanda, Tanzania, and Uganda. For each country, we obtained rich data on the whole electricity systems for a 10–year period from 2008 to 2017. Even if the limited size of our sample is a disadvantage, it is compensated by its panel structure and its homogeneity. Other than their common geographical localization, the six countries belong to the group of low-income countries, have similar industrial structures (10% to 25% of GDP) and face similar challenges, among them fast fast-growing population (nearly 3% year) and extreme poverty (60% or more of total population with less than $3.65 per day) (World Bank, 2022).

Second, the methodological approach relies on the distinction between two main objectives pursued by the country's decision-makers: effectiveness and efficiency. These two objectives are in direct relation to SDG goals. Effectiveness measures outcome maximization, e.g. to which extent the electricity access and reliability goal is fulfilled (SDG 7.1), and efficiency measures how far the whole electricity system is from the best practice (SDG 7.3). In other words, effectiveness is the degree to which an objective is achieved or over-reached (Winkler et al., 2018), while efficiency balances the resource-outcome mixes. Put differently, the difference between effectiveness and efficiency can be stated as "doing the right things" vs. "doing things right" (Førsund, 2017; Mbuvi et al., 2012; Roghanian et al., 2012).[3]

[2]Note that, in the context of this study, rural electrification grids are considered, even if not interconnected to the central connected network.

[3]Very often in the economic literature on energy provision, the trade-off between efficiency and effectiveness is at the centre of the debate. However, in the context of this study, we assume that East African electricity systems aim to reach higher effectiveness (which implies equity in access)

Effectiveness and efficiency are intertwined (Aparicio et al., 2022; Cherchye et al. 2019; Perelman and Walheer, 2020). The only difference among them, once the outcomes (outputs) and the resources (inputs) are defined in the appropriate form, relies on the fact that resource constraints are not taken into consideration when measuring effectiveness, as is the case for efficiency. As a consequence, the simple ratio between effectiveness and efficiency has a straightforward interpretation of how resources impact performance. The so-called 'resource ratio', defined as the ratio between effectiveness and efficiency indicates to which extent low effectiveness is due to a resource underutilization or a resource constraint. In other words, in the context of this study, when a country's electricity helmsmen are compared with their peers, he is expected to ensure efficiency and effectiveness in electricity transmission and distribution. This means he is indebted to ensure resources – enough supply of electricity, produced in the country or coming from abroad – at his best.

Up to now, the resource ratio has only been used on a cross-sectional basis. In light of our application involving panel data, we suggest new indexes, inspired by the indexes developed by Caves et al. (1982) and Färe et al. (1993), capturing efficiency and effectiveness changes and shifts over time. Shifts capture the performance variations for the East African electricity system, while changes measure the variations for the countries in the East African electricity system. Also, by combining change and shift indexes of efficiency and effectiveness, we obtain new indexes for the resource ratio. The resulting resource ratio shift and change indexes provide additional valuable information about the performance variation for both the East African electricity system and the countries. Finally, we use a non-parametric estimation method, based on Charnes et al. (1978), as it is difficult to find strong arguments supporting a particular parametric functional form given our application to the electricity sector, our aggregated data, and the two dimensions we consider.

All in all, our paper presents three main distinguished features. First, we are the first to study the SDG 7 for the East African countries. Second, we construct a detailed database for six African countries over a long period. Third, while the resource ratio has been used in previous works, we are, however, the first to come up with the notions of shifts and changes in that context. Moreover, we connect our

while, at the same time, increasing efficiency (when there is room for that and resources). As in the United Nations 2030 Agenda, SDG 7.1 and 7.3 are here considered complementary and not competing goals.

concepts to the SDG 7 goals.

The results show that, among the six Eastern African countries' electricity systems studied, dramatic differences in terms of effectiveness persist, despite high positive rates of change, while efficiency differences are small. As a consequence, the resource ratio indicates that, for most of these countries, the key problem resides in a resource constraint and not in resource utilization. This is the case for those countries in our sample which maintained the national integrated electrical system unbounded, Burundi and Tanzania, but also for those, except for Kenya, for which separated vertical integration, that is Ethiopia, Rwanda, and Uganda. In fact, Kenya, whose reforms date back to 1997, appears in our analysis as the benchmark both in terms of effectiveness and efficiency, in the last case aside from Rwanda.

The remaining sections are organized as follows. In Section 2, we define our concepts of efficiency and effectiveness on a cross-sectional basis. In Section 3, we show how using adapted versions of the efficiency and effectiveness measurements, we obtain indexes capturing changes and shifts. Section 4 presents the data, Section 5 the results, and Section 6 concludes.

2 Efficiency and effectiveness

The starting point of our analysis is the observation of a panel dataset consisting of n entities during T time periods. In each time period t, entity i is defined by a pair of resources-outcomes (inputs-outputs) labelled $(\mathbf{x}_{it}, \mathbf{y}_{it})$. We adopt a non-parametric spirit by defining efficiency (Debreu, 1951; Farrell, 1957) and effectiveness (Cherchye et al., 2007) from two empirical sets constructed from the observed data. As there is no guideline about the best parametric functional form describing the electricity generation process to select, it is probably the safest way to proceed. Moreover, as the entities are countries in our application, we face aggregated data making the parametric choice even harder to defend. In the Appendix, we explain how efficiency and effectiveness can be computed using linear programming. Finally, we point out that our focus is not only related to the electricity generation process but also to quality and outcomes.

The first empirical set, used to define efficiency, contains all possible resource-outcome combinations. The second one, used to define effectiveness, contains the outcome combinations only. That is, the latter set ignores the resource constraint.

In a sense, these sets form our non-parametric estimator of the unobserved electricity generation processes (see also Section 4). We define the resource-outcome possibility set T_t at time t as follows:

$$T_t = \left\{ (\mathbf{x}_t, \mathbf{y}_t) \Big| \mathbf{y}_t \leq \sum_{i=1}^{n} \lambda_i \mathbf{y}_{it}, \mathbf{x}_t \geq \sum_{i=1}^{n} \lambda_i \mathbf{x}_{it}, \lambda_i \geq 0 \right\}, \tag{1}$$

In words, T_t is the monotone and convex hull enveloping the observed resource-outcome data at time t. It is the most conservative approximation to the data consistent with a monotone and convex technology (Charnes et al., 1978). Note that constant returns-to-scale is implicitly assumed in (1). Based on these sets, we can measure how entities combine their resources to achieve their outcomes at each period t. If done optimally, we declare the entities as efficient. Inefficiency behaviour, therefore, reflects that outcomes may, in principle, be increased without requesting additional resources. In particular, (in)efficiency for an entity, defined by its resource-outcome pair $(\mathbf{x}_t, \mathbf{y}_t)$ is measured as (Debreu, 1951; Farrell, 1957) :

$$e_t(\mathbf{y}_t, \mathbf{x}_t) = \min \left\{ e \mid \left(\frac{\mathbf{y}_t}{e}, \mathbf{x}_t \right) \in T_t \right\}. \tag{2}$$

$e_t(\mathbf{y}_t, \mathbf{x}_t)$ is the inverse of the maximal amount that outcomes $\mathbf{y}_t$ can be expanded while keeping the resources $(\mathbf{x}_t)$ constant. $e_t(\mathbf{y}_t, \mathbf{x}_t) \leq 1$ and $e_t(\mathbf{y}_t, \mathbf{x}_t) = 1$ means that the maximal amount of the outcomes is produced at time t. A smaller value of $e_t(\mathbf{y}_t, \mathbf{x}_t)$ implies more inefficient behaviour at time t. Geometrically, it is the (vertical) distance to the frontier of the resource-outcome possibility set T_t.

Next, we define a second collection of empirical sets containing all possible outcome combinations for each time period. These outcome possibility sets, labelled $\mathcal{T}_t$ for each time period t, ignore the resource constraints. In practice, these sets can be obtained by adapting the definition in (1) with resource values equal to unity for all entities. Intuitively, replacing all resource values with one indicates that the resources are ignored. $\mathcal{T}_t$ is defined at time t as follows:

$$\mathcal{T}_t = \left\{ (\mathbf{x}_t, \mathbf{y}_t) \Big| \mathbf{y}_t \leq \sum_{i=1}^{n} \lambda_i \mathbf{y}_{it}, 1 \geq \sum_{i=1}^{n} \lambda_i, \lambda_i \geq 0 \right\}, \tag{3}$$

Again, $\mathcal{T}_t$ is a monotone and convex hull but, this time envelops the observed outcomes at time t only. This set allows us to verify whether entities have achieved their optimal outcome values. When this is the case, we declare such entities effective. Ineffectiveness means that it is, in principle, possible to increase the outcomes. Note that, this time, resources are ignored. Effectiveness for an entity evaluated at $(\mathbf{y}_t)$ is given by (Cherchye et al., 2007):

$$p_t(\mathbf{y}_t, 1) = \min \left\{ p \mid \left(\frac{\mathbf{y}_t}{p}, 1 \right) \in \mathcal{T}_t \right\}. \tag{4}$$

$p_t(\mathbf{y}_t)$ is the inverse of the maximal possible expansion of the outcomes.[4] When it is one, it shows that the maximal value has been reached at time t. Smaller value reflects greater potential outcome improvement. Geometrically, it is the (vertical) distance to the frontier of the reconstructed outcome set $\mathcal{T}_t$. Intuitively, it is a measure of pure performance as the resources are ignored.

Interestingly, our measurements of efficiency and effectiveness can be related to defining a ratio capturing potential resource constraints on the performances. This measure, introduced by Cherchye et al. (2019) and Perelman and Walheer (2020), is simply defined as the ratio of effectiveness to efficiency. It is given for an entity with the resources-outcomes $(\mathbf{y}_t, \mathbf{x}_t)$ at time t as follows:

$$r_t(\mathbf{y}_t, \mathbf{x}_t) = \frac{p_t(\mathbf{y}_t)}{e_t(\mathbf{y}_t, \mathbf{x}_t)}. \tag{5}$$

$r_t(\mathbf{y}_t, \mathbf{x}_t)$ is, by construction, unbounded as there is no specific ranking between the efficiency and effectiveness measurements. When $r_t(\mathbf{y}_t, \mathbf{x}_t)$ is greater than one, it implies that effectiveness is larger than efficiency at time t. In other words, it reflects that the resources are not used optimally. Therefore, outcomes could be increased to some extent, indicated by the ratio, without requesting more inputs. When, $r_t(\mathbf{y}_t, \mathbf{x}_t)$ is smaller than one, it is the opposite situation: more resources are needed if one wants to increase the outcomes keeping the level of efficiency unchanged.

3 Changes and shifts

Given the time dimension of our dataset, empirical sets and entities can move over time. To capture such variations, we define two types of indices: shifts and changes. The former captures the expansion or shrinkage of the empirical sets, and the lat-

[4]In the following, $p_t(\mathbf{y}_t, 1)$ is replaced by $p_t(\mathbf{y}_t)$ for better readability.

ter indicates how the entities move in the empirical sets. In practice, changes and shifts have to be interpreted together to obtain the full picture. In the following, we show how adapted versions of our efficiency and effectiveness measurements can be combined to define change and shift indexes between two time periods b (base) and c (current).

3.1 Changes

Our first dynamic measures capture how entities move in the empirical sets. Intuitively, to define changes we compare the distances of the entities to the sets in the two time periods b and c. Changes for the efficiency and effectiveness of an entity defined by its inputs-outputs pair $(\mathbf{x}_t, \mathbf{y}_t)$ between two time periods b and c is given by:

$$\nabla e_{change}(\mathbf{y}_b, \mathbf{y}_c, \mathbf{x}_b, \mathbf{x}_c) = \frac{e_c(\mathbf{y}_c, \mathbf{x}_c)}{e_b(\mathbf{y}_b, \mathbf{x}_b)}, \tag{6}$$

$$\nabla p_{change}(\mathbf{y}_b, \mathbf{y}_c) = \frac{p_c(\mathbf{y}_c)}{p_b(\mathbf{y}_b)}. \tag{7}$$

The benchmark value for $\nabla e_{change}(\mathbf{y}_b, \mathbf{y}_c, \mathbf{x}_b, \mathbf{x}_c)$ is one. An index greater than unity reveals an efficiency improvement between time b and c. A value less than one reflects the opposite. A similar interpretation holds for the effectiveness change: the benchmark value for $\nabla p_{change}(\mathbf{y}_b, \mathbf{y}_c)$ is unity with a larger (smaller) value than 1 reflecting pure performance progress (regress).

We can apply the same principle to the resource ratio. We obtain the following index for an entity defined by its inputs-outputs pair $(\mathbf{x}_t, \mathbf{y}_t)$ between two time periods b and c:

$$\nabla r_{change}(\mathbf{y}_b, \mathbf{y}_c, \mathbf{x}_b, \mathbf{x}_c) = \frac{r_c(\mathbf{y}_c, \mathbf{x}_c)}{r_b(\mathbf{y}_b, \mathbf{x}_b)} = \frac{\nabla p_{change}(\mathbf{y}_b, \mathbf{y}_c)}{\nabla e_{change}(\mathbf{y}_b, \mathbf{y}_c, \mathbf{x}_b, \mathbf{x}_c)}. \tag{8}$$

When $\nabla r_{change}(\mathbf{y}_b, \mathbf{y}_c, \mathbf{x}_b, \mathbf{x}_c) > (<)1$, it means that there is an improvement (decline) in the resource ratio. It is straightforward to see that the resource ratio change is itself a ratio between the effectiveness and the efficiency changes. It implies that $\nabla r_{change}(\mathbf{y}_b, \mathbf{y}_c, \mathbf{x}_b, \mathbf{x}_c) > 1$ is equivalent to $\nabla p_{change}(\mathbf{y}_b, \mathbf{y}_c) > \nabla e_{change}(\mathbf{y}_b, \mathbf{y}_c, \mathbf{x}_b, \mathbf{x}_c)$, i.e. effectiveness change is larger than efficiency change. Inputs are used in a worst manner or less inputs are needed between b and c. When $\nabla r_{change}(\mathbf{y}_b, \mathbf{y}_c, \mathbf{x}_b, \mathbf{x}_c) < 1$, we have that $\nabla p_{change}(\mathbf{y}_b, \mathbf{y}_c) < \nabla e(\mathbf{y}_b, \mathbf{y}_c, \mathbf{x}_b, \mathbf{x}_c)$, i.e. inputs are used in a better way or more inputs are requested.

3.2 Shifts

The previous indexes give the measurement of the performance changes. Attractively, by modifying and combining the concepts of efficiency and effectiveness, we can also obtain information about the shifts in the resource-outcome and outcome possibility sets. These shifts, related to the frontiers of the corresponding empirical sets, show us potential technological progress and the scope for outcome expansion.

To capture the shift of the resource-outcome possibility set between periods b and c, the basic idea is to fix the time period of a resource-outcome pair and make varying the time period of the set only. Two natural candidates emerge:

$$\nabla e_{shift}(\mathbf{y}_b, \mathbf{x}_b) = \frac{e_c(\mathbf{y}_b, \mathbf{x}_b)}{e_b(\mathbf{y}_b, \mathbf{x}_b)}. \tag{9}$$

$$\nabla e_{shift}(\mathbf{y}_c, \mathbf{x}_c) = \frac{e_c(\mathbf{y}_c, \mathbf{x}_c)}{e_b(\mathbf{y}_c, \mathbf{x}_c)}. \tag{10}$$

Both ratios capture technological change but with respect to a different resource-outcome combination, i.e. a different path. Nevertheless, they are interpreted in the same manner: one is the benchmark value, greater values imply technological improvement, and smaller value technological regress. An issue, at this stage, is that both indexes are, generally, not equal. A natural question is therefore: which index has to be selected? or, say differently, which path has to be followed? An alternative is to construct a path-independent index based on the two path-dependent ones as follows:

$$\nabla e_{shift}(\mathbf{y}_b, \mathbf{y}_c, \mathbf{x}_b, \mathbf{x}_c) = [\nabla e_{shift}(\mathbf{y}_b, \mathbf{x}_b) \times \nabla e_{shift}(\mathbf{y}_c, \mathbf{x}_c)]^{1/2}. \tag{11}$$

The geometric average procedure, introduced by Caves et al. (1982) and Färe et al. (1994) for the Malmquist index and also known as the Fisher ideal decomposition, is a popular technique to overcome the issue of selecting a time period for the resource-outcome pair. $\nabla e_{shift}(\mathbf{y}_b, \mathbf{y}_c, \mathbf{x}_b, \mathbf{x}_c)$ has to be interpreted as $\nabla e_{shift}(\mathbf{y}_b, \mathbf{x}_b)$ and $\nabla e_{shift}(\mathbf{y}_c, \mathbf{x}_c)$, but offers the advantage of avoiding selecting the time period of the entities, i.e. it is path-independent.

Likewise, there are two ways to define the shift of the outcome possibility set change between periods b and c:

$$\nabla p_{shift}(\mathbf{y}_b) = \frac{p_c(\mathbf{y}_b)}{p_b(\mathbf{y}_b)}. \tag{12}$$

$$\nabla p_{shift}(\mathbf{y}_c) = \frac{p_c(\mathbf{y}_c)}{p_b(\mathbf{y}_c)}. \tag{13}$$

When $\nabla p_{shift}(\mathbf{y}_b) > 1$, it implies more potential outcome expansion at time c compared to time b. Indeed, in that case, $p_c(\mathbf{y}_b) > p_b(\mathbf{y}_b)$ meaning that effectiveness is larger when the outcome set is the one at period c. When $\nabla p_{shift}(\mathbf{y}_b) < 1$, there is less scope for effectiveness improvement. A similar interpretation is correct for $\nabla p_{shift}(\mathbf{y}_c)$.

Again, we adopt the Fisher ideal decomposition by taking the geometric average of the two path-dependent indexes to obtain a path-independent counterpart as follows:

$$\nabla p_{shift}(\mathbf{y}_b, \mathbf{y}_c) = [\nabla p_{shift}(\mathbf{y}_b) \times \nabla p_{shift}(\mathbf{y}_c)]^{1/2}. \tag{14}$$

Finally, as done for the change in (8), the ratio of the effectiveness and efficiency shifts give a new interesting shift index:

$$\nabla r_{shift}(\mathbf{y}_b, \mathbf{y}_c, \mathbf{x}_b, \mathbf{x}_c) = \frac{\nabla p_{shift}(\mathbf{y}_b, \mathbf{y}_c)}{\nabla e_{shift}(\mathbf{y}_b, \mathbf{y}_c, \mathbf{x}_b, \mathbf{x}_c)}. \tag{15}$$

This ratio compares the shifts of effectiveness to the one of efficiency. A value larger (smaller) than one indicates that the outcome possibilities have moved faster (slower) than the resource-outcome possibilities. In other words, it captures the dynamics between ”doing better the right things” knowledge and “doing things better” technology. Therefore, relative movements of the ratio indicate either less stringent resource constraints (values greater than one) or improvements in production technology (values lower than one).

It is straightforward to see that this index defines the shift for the resource ratio:

$$\begin{aligned}\nabla r_{shift}(\mathbf{y}_b, \mathbf{y}_c, \mathbf{x}_b, \mathbf{x}_c) &= \frac{[\nabla p_{shift}(\mathbf{y}_b) \times \nabla p_{shift}(\mathbf{y}_c)]^{1/2}}{[\nabla e_{shift}(\mathbf{y}_b, \mathbf{x}_b) \times \nabla e_{shift}(\mathbf{y}_c, \mathbf{x}_c)]^{1/2}}, \\ &= \left[\frac{\nabla p_{shift}(\mathbf{y}_b)}{\nabla e_{shift}(\mathbf{y}_b, \mathbf{x}_b)} \times \frac{p_{shift}(\mathbf{y}_c)}{\nabla e_{shift}(\mathbf{y}_c, \mathbf{x}_c)}\right]^{1/2}, \\ &= [\nabla r_{shift}(\mathbf{y}_b, , \mathbf{x}_b) \times \nabla r_{shift}(\mathbf{y}_c, \mathbf{x}_c)]^{1/2}, \\ &= \left[\frac{r_c(\mathbf{y}_b, \mathbf{x}_b)}{r_b(\mathbf{y}_b, \mathbf{x}_b)} \times \frac{r_c(\mathbf{y}_c, \mathbf{x}_c)}{r_b(\mathbf{y}_c, \mathbf{x}_c)}\right]^{1/2}. \end{aligned} \tag{16}$$

4 Data collection

This study draws on a rich database collected from the power sector in six East African countries – Burundi, Ethiopia, Kenya, Rwanda, Tanzania, and Uganda – over a 10-year period from 2008 to 2017.[5] This represents 60 observations overall. Ethiopia, Kenya, Rwanda, and Uganda have restructured their power sector by separating it vertically and involving the private sector in competitive activities such as generation or distribution. Burundi and Tanzania retain a vertically integrated power sector, in which a single state-owned company performs all activities from upstream to downstream.

At this point, we highlight that while the number of countries might seem small, obtaining complete and truthful data is a challenging task in our empirical context. Also, we focus our analysis on a small sample to obtain a homogeneous group. Studying electricity system performances in (East) Africa over a long time period is an added value to our empirical analysis.

Given that this study aims to compare the effectiveness and the efficiency of national electricity systems, data are aggregated and the variables correspond to the consolidated energy sector.[6] To measure the outcomes of the sector we select two

[5]Kenya, Tanzania, and Uganda publish their data online: data for customers, electricity purchased and delivered are taken from the Electricity Regulatory Authority (www.era.or.ug) in Uganda; the Kenya Power Lighting Company (https://kplc.co.ke) in Kenya and Rwanda Utility Regulatory Authority (https://rura.rw) in Rwanda. For the other countries, data are retrieved directly (by the authors) from the electricity companies such as Régie de Production et de Distribution d'Eau et d'Electricité (REGIDESO) in Burundi, Ethiopian Electric Power and Ethiopian Electric Utility in Ethiopia, and Tanzania Electric Supply Company Limited (TANESCO) in Tanzania. We have ensured the homogeneous definitions and comparability of the variables across countries.

[6]Note that electricity delivered includes, by construction, electricity consumed by the residential,

indicators in line with the SDG's electricity objectives: access and reliability. Access is proxied by the number of electricity customers per 100 households, and reliability by the average quantity of electricity delivered annually per inhabitant. We believe that in the case of reliability, this proxy is the best since low amounts of energy consumption are mainly the result of factors under the control of national electricity systems: interruptions due to outages and losses in the distribution network, on one hand, and energy supply restrictions in production or transmission of energy, on the other hand.[7]

The resources are also represented by a proxy variable, an indicator that corresponds to the electricity supplied, i.e. the electricity entered into the distribution network per inhabitant. In other words, the operation of the electricity system consists of the transmission and distribution of the electricity entered into the system, including the energy generated at the country level plus the net balance between imported and exported energies. All in all, our proxy represents the electricity supplied to national consumers.[8]

We chose not to include other resources, namely installed capacity and transmission lines, in our analysis as we want a fair performance analysis. In fact, including these variables as extra resources somehow penalises some countries. Also, installed capacity is sometimes available to other countries through the exchange of electrical energy. Moreover, high-voltage transmission lines are not uniform for all countries. This is the case, for example, in Burundi where 30 kV lines are used for both transmission and distribution, while in other countries these lines have a capacity of 66 kV or more.

Table 1 presents the averages for our outcomes and resources for the six countries.[9]

---

industrial and commercial consumers. However, the available data does not allow us to identify the corresponding consumption shares.

[7]There is also a potential demand side factor for the low level of energy consumption in East African countries. Poor customers might constrain ex-ante their consumption by choosing small amounts of pre-paid cards as energy bills.

[8]It is important to note that the methodology requires that outcomes are the same for the effectiveness and efficiency measurements. In our case, we choose as outcomes two indicators and, for this reason, also resources are in the form of an indicator. To our knowledge, this is the first paper about the electricity sector applying this approach. For more discussion of the selection of inputs and outputs for efficiency analysis, refer, for example, to Barabutu & Lee (2018), Estache et al.(2008), Real & Tovar (2020), and Walheer (2018b, 2019, 2020).

[9]In Table 1, we present the access variable per household (hh) to make international comparison easier. Indeed, customers per household are used by most international agencies such as the World Bank (2022). The number of households is determined by reference to Rahut et al. (2018) who

The minimums, the medians, the maximums, and the standard deviations are given in Tables 5–8 available in the Appendix. We present extra indicators that we have collected in Table 2.[10] In these tables, we give averages for the overall time period (2008-2017) and three sub-periods (2008-2011, 2012-2014, 2015-2017) for each country and when pooling all countries.

Several lessons emerge from Table 1. First, there exist huge differences across countries in outcomes: in population coverage, e.g. 4.3 customers per 100 households in Burundi vs. 30.1 in Kenya, but particularly in reliability, e.g. 20 kWh/hab by year in Burundi vs. 93.6 kWh/hab and 144.9 kWh/hab in Tanzania and Kenya, respectively. Paying attention to the evolution over the periods, we observe that both outcome indicators clearly increase for most countries. The only exception is Burundi despite a high annual rate of population growth (3.0% on average over the period 2008-2017, see Table 2).

We point out that, in fact, such improvements are relatively low when compared to Sub-Saharan African countries (World Bank, 2022). For instance, from 2015 to 2017 the average access to electricity in Sub-Saharan Africa is 42.2%. Some countries approach 100% of coverage, such as Cabo Verde (88%), Gabon (87%), and Mauritius (99%). Also, reliability in 2014 was 4198 kWh per inhabitant in South Africa, 2182.5 in Mauritius, 1815.5 kWh in Botswana, and 478.9 kWh in Mozambique, bringing the Sub-Saharan African average to 487.32 kWh.

Tables 5 to 8 provide useful additional information. There has been positive growth over the years for the minima of the access variable for all countries. For the reliability and resource variables, the maxima are observed during the 2012-2014 period. Burundi has the lowest minimum values for all variables, while maximum values are observed in Kenya. Greater standard deviations are observed for the reliability and resource variables. This means that inequalities can be observed in the electricity sector, especially in terms of reliability and resources.

Coming back to Table 1, how to explain the extreme range of variation in these indicators? This is what we try to do in this paper. We hypothesise that these differences result either from energy network distribution inefficiencies or from resource

estimated, based on national surveys conducted between 2011-2013, an average family size of 5.12 for the case of Ethiopia, Tanzania, and Uganda. We generalized the household size over all countries and determined the number of households per country and year.

[10] In Table 2, m refers to meter. Note that generation capacity and transmission lines are given per 100 inhabitants for better readability.

Table 1: Outcomes and resource – averages

Country	**Period**	**Outcomes** **Access** (customers /100hh)	**Reliability** (kWh/hab)	**Resource** (kWh/hab)
All	2008-2017	13.9	66.8	84.4
All	2008-2011	8.9	58.3	73.6
	2012-2014	13.6	68.1	87.0
	2015-2017	20.9	76.9	96.2
Burundi	2008-2017	4.3	20.0	25.9
Ethiopia		9.5	51.5	69.2
Kenya		30.1	144.9	175.0
Rwanda		17.7	34.7	43.8
Tanzania		13.2	93.6	114.9
Uganda		8.8	56.0	77.4
Burundi	2008-2011	3.4	20.6	25.8
	2012-2014	4.3	21.2	26.7
	2015-2017	5.3	18.1	25.2
Ethiopia	2008-2011	8.5	36.4	45.6
	2012-2014	9.7	53.6	76.7
	2015-2017	10.5	69.5	93.3
Kenya	2008-2011	17.1	133.5	158.6
	2012-2014	26.7	145.5	176.4
	2015-2017	50.9	159.5	195.3
Rwanda	2008-2011	9.0	27.1	33.6
	2012-2014	19.5	34.3	44.3
	2015-2017	27.5	45	56.9
Tanzania	2008-2011	9.7	85.2	107.8
	2012-2014	12.6	94.9	117.0
	2015-2017	18.3	103.6	122.3
Uganda	2008-2011	5.9	46.7	70.1
	2012-2014	8.7	58.7	80.6
	2015-2017	13.0	65.5	84.0

Table 2: Other indicators

Country	**Period**	**Network losses** (%)	**Population growth** (%)	**Generation capacity** (kW/100hab)	**Transmission lines** (m/100hab)
All	2008-2017	22	2.95	2.36	7.59
All	2008-2011	21.6	2.95	1.98	7.19
	2012-2014	22.8	2.92	2.50	7.57
	2015-2017	21.8	2.97	2.74	8.13
Burundi	2008-2017	22.7	3.24	0.63	3.44
Ethiopia		24.9	2.81	3.88	10.04
Kenya		17.1	2.62	3.93	10.51
Rwanda		20.7	2.58	1.03	6.91
Tanzania		18.6	3.01	2.56	10.56
Uganda		28.1	3.41	2.16	4.05
Burundi	2008-2011	20.2	3.30	0.64	3.78
	2012-2014	20.4	3.19	0.61	3.38
	2015-2017	28.3	3.22	0.63	3.07
Ethiopia	2008-2011	20.1	2.82	3.07	8.09
	2012-2014	30.4	2.86	4.40	10.95
	2015-2017	25.7	2.75	4.44	11.72
Kenya	2008-2011	15.9	2.76	3.33	10.04
	2012-2014	17.5	2.65	3.91	10.44
	2015-2017	18.3	2.45	4.75	11.21
Rwanda	2008-2011	19.3	2.62	0.74	6.62
	2012-2014	22.3	2.50	0.98	6.19
	2015-2017	20.9	2.63	1.46	8.01
Tanzania	2008-2011	20.9	2.95	2.37	10.93
	2012-2014	18.9	3.04	2.69	9.95
	2015-2017	15.3	3.04	2.68	10.68
Uganda	2008-2011	33.4	3.23	1.73	3.69
	2012-2014	27.1	3.31	2.42	4.49
	2015-2017	22.1	3.70	2.48	4.10

constraints. This is what the methodology we adopted allows us to do. Nevertheless, if we pay attention to the last column of Table 1, we have part of the answer. We observe that a comparable range of variation is observed for the resource indicator, e.g. 25.9 kWh by year in Burundi vs. 114.9 kWh and 175 kWh in Tanzania and Kenya, respectively.

The percentage of losses in Table 2 corresponds to the gap between electricity entered into the system and delivered electricity. It appears that, on average, for the whole period and all countries, losses correspond to 22.0% of the total amount of electricity entered into the system. Extreme values are observed for Uganda, 33.4% for the period 2008-2011, and Tanzania, 15.3% for the period 2015-2017. However, we do not observe a decline in the percentage of losses over the period (on average). The level of losses in East Africa is very high when compared to other groups or countries. For example, according to the World Bank (2022), the average losses were established in 2014 at 5.4% for East Asia and Pacific, 14.29% for Latin America and the Caribbean, and 11.4% for Sub-Saharan Africa (e.g. South Sudan, Mauritius and South Africa, with 5.7%, 6.2% and 8.4%, respectively).

Generation capacity and transmission lines per 100 inhabitants, two indicators that, as explained before, are not used in this study give us an approximate idea of the investments done by each country. Ethiopia, Kenya, and Tanzania are, from this point of view, countries that appear in the best situation, especially when compared with Burundi. Both access to and reliability of the electrical system depend on these investments.

We end this part by providing a brief macroeconomic perspective of our six countries. The World Bank (2020) indicates that Burundi's average GDP per capita of US$224 during 2008-2017 is about one-third that of Rwanda, Tanzania, and Uganda, while it is less than one-quarter that of Kenya. Also, Burundi's population density, which averaged 333 persons per square kilometre during 2008-2017, is more than four times that of Kenya, Ethiopia, and Tanzania, with the highest population density observed in Rwanda. High population density is associated with a positive effect on utilities' efficiency (Bobde & Tanaka, 2018) as it reduces per capita electrification costs and increases their financial sustainability (Blimpo & Cosgrove-Davies, 2019). Therefore, access to electricity could increase when population density is high as there are economies of scale for electric utilities (D'Amelio et al., 2016). However, when high population density is associated with low GDP per capita, efforts for new electricity investments are undermined by higher technical and non-technical losses, particularly due to theft and fraud (de Souza Savian et al., 2021; Jamil & Ahmad, 2019).

5 Results

As in the methodology section, we split the presentation of the results into two parts. First, we start off by presenting the results for the efficiency and effectiveness scores. Then, we continue with the results of the change and shift indexes.

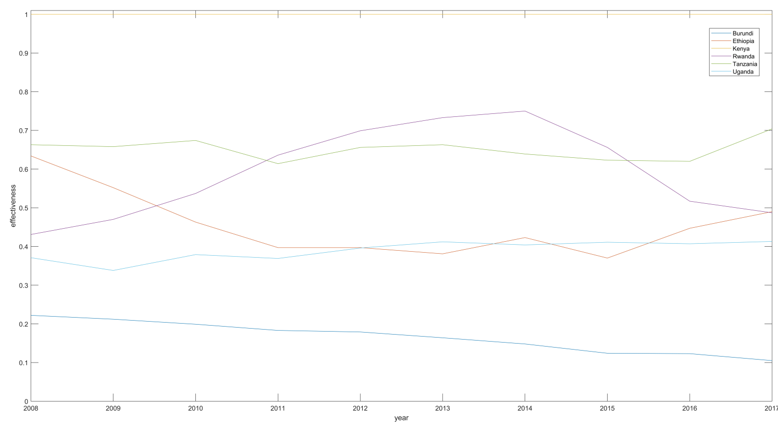
5.1 Efficiency and effectiveness

Figure 1 presents the effectiveness and efficiency scores obtained for the six East African electricity systems over the period 2008-2017. Averages per country and time intervals are reported in Table 3. We compute efficiency and effectiveness using the linear programmings (18) and (19) explained in the Appendix for the six countries and the ten years. In particular, efficiency and effectiveness are computed year by year separately and using, in each case, annual data from the six East African countries. This implies that all countries are used as peers when computing the results. For presentation purposes, average values are computed for the whole period and for sub-periods (2008-2011, 2012-2014, and 2015-2017) in Table 3.

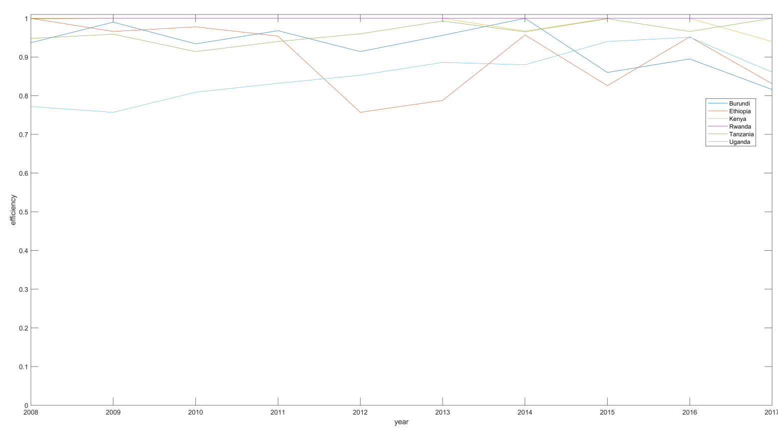
What we remark immediately is that efficiency scores are higher, in most cases close to one (the benchmark value), while effectiveness scores vary dramatically, from 0.166 in the case of Burundi to 1 for Kenya, the benchmark country over the whole period. Overall, the results confirm that access to reliable electricity supply is a major challenge for East African countries. Even if we consider six countries only in this study, the variation among them is huge in terms of effectiveness. Except for the extreme case of Burundi, we observe that Ethiopia and Uganda's scores are close to 0.40, and Rwanda and Tanzania's to 0.60.

Next, the efficiency scores for the six electricity systems indicate that they are close to the best practice. The best performers are Rwanda and Kenya and those lagging behind are Ethiopia and Uganda, but with relatively high efficiency scores: 0.90 and 0.86 on average for the whole period, respectively. In other words, when resource constraints are considered, in this case, the total amount of electricity supplied to

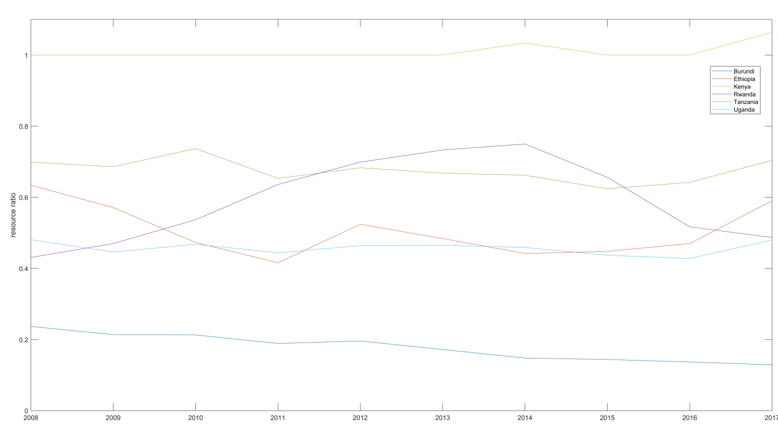
Figure 1: Efficiency and effectiveness by country



(a) effectiveness



(b) efficiency



(c) resource ratio

Table 3: Average efficiency and effectiveness

Country	**Period**	**Effectiveness**	**Efficiency**	**Resource ratio**
All	2008-2017	0.542	0.94	0.57
All by period	2008-2011	0.542	0.944	0.568
	2012-2014	0.558	0.938	0.588
	2015-2017	0.528	0.935	0.553
Burundi	2008-2017	0.166	0.927	0.178
Ethiopia		0.455	0.901	0.505
Kenya		1	0.991	1.01
Rwanda		0.592	1	0.592
Tanzania		0.651	0.964	0.676
Uganda		0.39	0.854	0.457
Burundi	2008-2011	0.204	0.957	0.213
	2012-2014	0.164	0.957	0.172
	2015-2017	0.117	0.857	0.137
Ethiopia	2008-2011	0.512	0.975	0.524
	2012-2014	0.4	0.834	0.483
	2015-2017	0.436	0.87	0.502
Kenya	2008-2011	1	1	1
	2012-2014	1	0.989	1.011
	2015-2017	1	0.98	1.021
Rwanda	2008-2011	0.519	1	0.519
	2012-2014	0.727	1	0.727
	2015-2017	0.553	1	0.553
Tanzania	2008-2011	0.652	0.94	0.694
	2012-2014	0.653	0.973	0.671
	2015-2017	0.649	0.988	0.656
Uganda	2008-2011	0.364	0.793	0.46
	2012-2014	0.404	0.873	0.463
	2015-2017	0.41	0.917	0.448

the network, the electricity systems appear under a more favourable view. By construction, efficiency scores reflect here the share of losses in electricity transmission and distribution. That is, the gap between electricity supplied to the network and electricity delivered, which are the resource and one of the outcomes of the model, respectively

The resource ratio is slightly higher than 1 for Kenya, which means that there is room for efficiency improvement for this country. For all other countries, the resource ratio is lower than 1 indicating that the resource constraint is probably the primary source of low effectiveness.[11] Also, in most cases there is room for efficiency improvement, like in the case of Uganda with an efficiency score of 0.85 on average for the whole period. The exception is Rwanda with an efficiency score of 1.0, which is the benchmark value, in all sub-periods. Thus, state subsidies should be directed to rural electrification, which is expensive for utilities.

Our results are in line with previous studies on Sub-Saharan African countries' electricity systems. For instance, Eras-Almeida & Egido-Aguilera (2020) found that poor access to electricity and system reliability can be attributed to geographic location, low household income, and lack of government effectiveness and leadership. Also, D'Amelio et al. (2016) attribute the general poor performances to the weaknesses of governments in setting sound electrification policies, and, at the same time, to rapid population growth. Finally, let us mention the study by Blimpo & Cosgrove-Davies (2019) who showed that connecting an additional customer results, very often, in lost revenue for utilities.

5.2 Changes and shifts

In Table 4 we report the results corresponding to changes and shifts in effectiveness, efficiency, and resource ratio as well. For the computation aspect, we follow the different steps explained in the Appendix. In particular, the base and the current years are two consecutive periods (for example, when $b = 2008$ then $c = 2009$; when $b = 2015$ then $c = 2016$). Note that, for presentation purposes, all the results are

[11] In this study, the energy supplied to the network is considered, by construction, exogenous. However, it could be argued that supply constraints are, at least partially, explained by a demand factor, the difficulties households have in most developing countries to afford the price of electrical energy.

reported in percentage points.[12]

A clear and net pattern appears when we interpret changes and shifts together. On the one side, we observe negative and relatively low changes and, on the other side, positive and, in many cases, high rates in shifts (higher than 10% per year). In other words, there is an improvement in both the resource-outcome and outcome empirical possibility sets; 9.5% per year in the case of the outcome set (effectiveness) and 1.8% for the resource-outcome set (efficiency). At the same time, we see negative variations for changes inside the possibility sets: -1.3% and -0.4% per year for effectiveness and efficiency, respectively.

As a consequence, the resource ratio, which measures the relative shifts of the effectiveness and efficiency possibility sets, increases rapidly, at a rate of 7.6% per year on average. This means that, over the period 2008-2017, the resource restrictions are partially removed, and at a high rate, particularly if we think that, at the same time, the population grew at a constant rate, near 3%, each year in these countries (see Table 2). A remarkable case is that of Rwanda for which effectiveness, efficiency, and resource ratio shifts have the highest positive scores (18.5%, 5.3%, and 12.5%, respectively). Following Lenz et al. (2017), this evolution may be due to the Electricity Access Rollout Program (EARP), which successfully connected schools, health facilities, and administrative offices to the national grid in its first phase from 2009 to 2013. Moreover, according to Bimenyimana et al. (2018), the EARP enabled an increase in new customers by 364,000 from 2012 to 2017 (representing around 700,000 households, which corresponds to 31% of the total households).

The signs of changes in effectiveness and efficiency are, on average, negative for the whole panel, but mainly for some countries and periods. This is the case of Burundi and Ethiopia, with an average change rate of -8.0% and -2.8% in effectiveness and -1.5% and -2.0% in efficiency, per year, respectively. Also, the change in the resource ratio for these two countries is negative, particularly for Burundi, -6.6% per year, which corresponds to an increasingly stringent situation in terms of available resources over time. One possible explanation is that, as pointed out by Nsabimana (2020), the electricity network depends on investments made in the 1980s in Burundi. As a result, access to electricity and system reliability remain among the lowest in the

[12] For example, for the effectiveness shift, the number we report in Table 4 corresponds to $[\nabla p_{shift}(\mathbf{y}_b, \mathbf{y}_c) - 1] \times 100\%$. Also, note that our indexes are not circular making the comparison difficult over time. Taking the sub-period averages seems therefore a good compromise. See, for example, Walheer (2022) for a related discussion.

Table 4: Changes and shifts

Country	Period	Changes			Shifts		
		Effectiveness	*Efficiency*	*Resource ratio*	*Effectiveness*	*Efficiency*	*Resource ratio*
All	2008-2017	-1.3	-0.4	-0.9	9.5	1.8	7.6
All	2008-2011	-2.0	0.3	-2.3	10.8	1.8	8.9
	2012-2014	0.8	0.5	0.3	8.4	1.2	7.2
	2015-2017	-2.8	-2.0	-0.9	9.3	2.4	6.7
Burundi	2008-2017	-8.0	-1.5	-6.6	12.9	1.0	11.8
Ethiopia		-2.8	-2.0	-0.8	9.0	1.6	7.3
Kenya		0.0	-0.7	0.7	10.1	0.7	9.4
Rwanda		1.4	0.0	1.4	18.5	5.3	12.5
Tanzania		0.7	0.6	0.1	3.2	1.2	2.0
Uganda		1.2	1.2	-0.1	4.2	1.1	3.1
Burundi	2008-2011	-6.2	1.1	-7.2	15.1	0.6	14.4
	2012-2014	-6.8	1.1	-7.8	13.4	0.6	12.8
	2015-2017	-11.0	-6.5	-4.8	10.3	1.9	8.2
Ethiopia	2008-2011	-14.5	-1.6	-13.1	15.1	1.1	13.8
	2012-2014	2.2	0.2	2.1	10.1	0.5	9.6
	2015-2017	5.0	-4.6	10.1	2.0	3.1	-1.0
Kenya	2008-2011	0.0	0.0	0.0	8.3	0.3	8.0
	2012-2014	0.0	-1.1	1.1	8.1	0.5	7.6
	2015-2017	0.0	-0.9	1.0	14.1	1.4	12.5
Rwanda	2008-2011	13.8	0.0	13.8	15.1	8.7	5.9
	2012-2014	5.6	0.0	5.6	13.4	4.9	8.1
	2015-2017	-13.4	0.0	-13.4	27.6	2.6	24.4
Tanzania	2008-2011	-2.5	-0.3	-2.2	4.4	0.2	4.3
	2012-2014	1.3	0.9	0.4	3.0	0.4	2.7
	2015-2017	3.3	1.2	2.1	2.0	3.0	-0.9
Uganda	2008-2011	-0.2	2.6	-2.7	7.6	0.2	7.3
	2012-2014	3.0	1.9	1.1	3.0	0.4	2.7
	2015-2017	0.8	-0.7	1.5	2.0	2.7	-0.6

world.

Two remarkable cases are those of Kenya and Rwanda. As we learned before in Table 3 both countries are among the best performers in terms of effectiveness (Kenya) and efficiency (Rwanda). Interestingly, given this particular situation in those countries, all the variations in effectiveness for Kenya and in efficiency for Rwanda correspond to shifts in the possibility sets, which are 10.1% and 5.3% by year, respectively.

To summarize, the change and shift results show a positive trend toward the fulfilment of SDG's objectives to access reliable electricity, even if some countries lag. This is the case of Tanzania and Uganda where the shifts in the possibility set are at a lower path, 3.2% and 4.2% by year, respectively. Also, the change and shift results confirm that resource constraint is the key factor to reaching the goal of the 2030 Agenda on Sustainable Development and not resource utilization.

6 Conclusion

Population access to reliable and affordable electricity networks is one of the objectives of the Sustainable Development Goals (SDG) adopted by the United Nations as part of the 2030 Agenda. In this paper, we take this objective as our starting point to present a performance evaluation exercise of the whole electricity systems of six East African countries over a 10-year period. In particular, we focus our attention on two dimensions: effectiveness, i.e. to what extent have the electricity systems achieved the optimal outcome values? and efficiency, i.e. to what extent have the electricity systems achieved the optimal resource-outcome values? While intertwined, these two dimensions give two different analyses of the electricity goals of the SDG. As we analyze performances over time, we compute efficiency and effectiveness over time using indexes. We suggest two main categories of indexes: changes and shifts. Finally, our analysis makes use of a non-parametric estimation method based on the construction of empirical possibility sets.

The results show dramatic differences in terms of effectiveness and small differences in terms of efficiency. High rates of changes and shifts, particularly in the effectiveness dimension, are also highlighted by our performance evaluation exercise. Access to reliable electricity supply for the whole population is therefore a faraway goal for most countries, except for Kenya which is the benchmark in both dimensions. We identified resource restriction as the main issue with room for efficiency improvements. This means that new projects and investments in energy production could only have a direct and positive effect on outcomes. These represent a sufficient condition, only valid if, at the same time, the capacity and the quality of the transmission and distribution networks follow; a double challenge for these countries, their economies, and their population, when financial resources are scarce.

However, coming back to the case of Kenya, according to World Bank Indicators (World Bank, 2022), over the last decade rural electrification extended rapidly in this country thanks to investments in new technologies based on renewable sources. Rwanda has also increased its investment in both urban and rural electrification, thanks to the multi-funded EARP program. In Burundi, the higher population growth and the dilapidated state of the electrical infrastructure (especially Bujumbura's underground low-voltage network) have an impact not only on access to electricity but also on the quality of service. As a result, Burundi has been characterized by long periods of electricity load shedding. Ethiopia is the largest country in the region, and much of the electricity generated is consumed by the industrial sector. Uganda has considerably reduced its electricity losses thanks to the implementation of an institutional framework aimed at the vertical unbundling of the electricity sector. Tanzania has increased its investment in generation by exploiting new energy resources such as natural gas. However, as highlighted by our empirical exercise, all these countries still have to put in new efforts to increase their effectiveness if they want to achieve universal access to electricity as defined in SDG 7.

Even without being proof of causality, it appears that a policy consisting of increasing the share of energy from renewable sources, particularly in rural areas, has a direct impact on effectiveness. As for the telecommunications sector in past decades, technological innovations appear also here as an engine of transformation.[13] It is too early to say which will be the future configuration of the electricity sector in East African countries. However, this evolution appears already as a first step in the direction of reaching SDG 7 goals. For this reason, it must be considered by authorities and regulators as a priority in their agenda for policy orientation in the energy sector. Increased expenditure on electrification infrastructure could be achieved by

[13] In Sub-Saharan countries, fixed and mobile phone subscriptions per 100 people were 1.7% and 1.4%, respectively, in the earlier 2000s. Today (2020), they are 0.7% and 82.0%, respectively (World Bank, 2022).

mobilizing domestic and foreign resources. East African countries could develop joint electricity infrastructure projects, enabling easier co-financing.

A limitation of our study is that it concerns grid-connected distribution networks, including local rural electrification agencies, but not energy produced, and consumed, privately. Therefore, the results need to be interpreted from this point of view. Nevertheless, it is important to note here that local rural electrification, as well as private micro-energy production, relies largely on renewable sources, particularly photovoltaic. According to World Development Indicators (World Bank, 2022), the share of electricity from renewable sources, excluding hydroelectric, was 48.3% in Kenya in 2015.[14] Even without being a proof of causality, our hypothesis, as a conclusion, is that increasing the share of energy from renewable sources (SGD 7.2), is not necessarily in competition with effectiveness (SDG 7.1), nor with efficiency (SGD 7.3). On the contrary, the three goals appear to be complementary.

Finally, we point out that the methodology proposed in this paper is also useful for studying other public services performances, like water and sewerage or transportation, as well as for social services like health and education, particularly in the case of developing countries. Furthermore, when panel data is available, we suggest the computation of new indexes capturing efficiency, effectiveness, and resource ratio changes and shifts over time. From a methodological aspect, a direct extension is to define our indexes using alternative definitions of the empirical sets, such as an intertemporal (Cruz-Cazares et al., 2013) or a sequential approach (Walheer, 2024).

Declarations

Conflict of interest: The authors declare that they have no conflict of interests.

Data availability: The data, compiled by the authors from various sources, are made available upon requests.

[14]For the other East African countries covered by this study, this information is only reported for Ethiopia: 7.6%. However, the average estimate for Sub-Saharan countries is 2.8% (World Bank, 2022).

References

[1] Aparicio, J., Perelman, S., & Santín, D. (2020). "Comparing the evolution of productivity and performance gaps in education systems through DEA: an application to Latin American countries.", *Operational Research*, 1-35.

[2] Bacon, R. (2018). "Taking stock of the impact of power utility reform in developing countries: A literature review", *World Bank Policy Research Working Paper*, 8460.

[3] Barabutu, J., & Lee, H. (2018). "An empirical analysis of the efficiency determinants in the Southern African electricity sector: evidence and policy implications.", *Geosystem Engineering*, 21(1), 31-42.

[4] Bensch, G. (2019). "The effects of market-based reforms on access to electricity in developing countries: a systematic review.", *Journal of Development Effectiveness*, 11(2), 165-188.

[5] Best, R., & Burke, P. J. (2018). "Electricity availability: A precondition for faster economic growth?", *Energy Economics*, 74, 321-329.

[6] Bhatia, M.,& Angelou, N. (2015). "Beyond Connections : Energy Access Redefined.", *ESMAP Technical Report*,008/15. World Bank, Washington.

[7] Bimenyimana, S., Asemota, G. N., & Li, L. (2018). "The state of the power sector in Rwanda: a progressive sector with ambitious targets.", *Frontiers in Energy Research*, 68.

[8] Blimpo, M. P., & Cosgrove-Davies, M. (2019). "Electricity access in Sub-Saharan Africa: Uptake, reliability, and complementary factors for economic impact.", *World Bank Publications*.

[9] Bobde, S. M., & Tanaka, M. (2018). "Efficiency evaluation of electricity distribution utilities in India: A two-stage DEA with bootstrap estimation.", *Journal of the Operational Research Society*, 69(9), 1423.

[10] Caves, D. W., Christensen, L. R., & Diewert, W. E. (1982). "The economic theory of index numbers and the measurement of input, output, and productivity.", *Econometrica*, 50(6), 1393-1414.

[11] Charnes, A., Cooper, W. W., & Rhodes, E. (1978). "Measuring the efficiency of decision making units.", *European journal of operational research*, 2(6), 429-444.

[12] Cherchye, L., Moesen, W., Rogge, N., Van Puyenbroeck, T., 2007, "An Introduction to benefit of the doubt composite indicators", *Social Indicators Research* 82, 111-145.

[13] Cherchye, L., De Witte, K., & Perelman, S. (2019). "A unified productivity-performance approach applied to secondary schools.", *Journal of the Operational Research Society*, 70(9), 1522-1537.

[14] Cruz-Cázares, C., Bayona-Sáez, C., & García-Marco, T. (2013). "You can't manage right what you can't measure well: Technological innovation efficiency.", *Research policy*, 2(6-7), 1239-1250.

[15] D'Amelio, M., Garrone, P., & Piscitello, L. (2016). "Can multinational enterprises light up developing countries?: Evidences from the access to electricity in sub-Saharan Africa.", *World Development*, 88, 12-32.

[16] 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.

[17] Debreu G, 1951, "The Coefficient of Resource Utilization", *Econometrica* 19(3), 273-292.

[18] Dertinger, A., & Hirth, L. (2020). "Reforming the electric power industry in developing economies evidence on efficiency and electricity access outcomes.", *Energy Policy*, 139, 111348.

[19] Eberhard, A., Gratwick, K., Morella, E., & Antmann, P. (2016). "Independent power projects in Sub-Saharan Africa: Lessons from five key countries.", *World Bank Publications.*

[20] Eras-Almeida, A. A., & Egido-Aguilera, M. A. (2020). "What is still necessary for supporting the SDG7 in the most vulnerable contexts?", *Sustainability*, 12(17), 7184.

[21] Estache, A., Tovar, B., & Trujillo, L. (2008). "How efficient are African electricity companies? Evidence from the Southern African countries.", *Energy policy*, 36(6), 1969-1979.

[22] Färe, R. , Grosskopf, S. , Norris, M. , & Zhang, Z. (1994). "Productivity growth, technical progress, and efficiency change in industrialized countries.", *American Economic Review*, 84 (1), 66–83.

[23] Farrell M, 1957, "The Measurement of Productive Efficiency", *Journal of the Royal Statistical Society* Series 1, General, 120, Part 3, 253-281.

[24] Førsund, F. R. (2017). "Measuring effectiveness of production in the public sector.", *Omega*, 73, 93-103.

[25] Gore, C. D., Brass, J. N., Baldwin, E., & MacLean, L. M. (2019). "Political autonomy and resistance in electricity sector liberalization in Africa.", *World Development*, 120, 193-209.

[26] Imam, M. I., Jamasb, T., & Llorca, M. (2019). "Sector reforms and institutional corruption: Evidence from electricity industry in Sub-Saharan Africa.", *Energy Policy*, 129, 532-545.

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

[28] Lechthaler, F. (2017). "Economic growth and energy use during different stages of development: an empirical analysis.", *Environment and development economics*, 22(1), 26-50.

[29] Lenz, L., Munyehirwe, A., Peters, J., & Sievert, M. (2017). "Does large-scale infrastructure investment alleviate poverty? Impacts of Rwanda's electricity access roll-out program.", *World Development*, 89, 88-110.

[30] Lovell, C. K., Pastor, J. T., & Turner, J. A. (1995). Measuring macroeconomic performance in the OECD: A comparison of European and non-European countries. *European journal of operational research*, 87(3), 507-518.

[31] Mbuvi, D., De Witte, K., & Perelman, S. (2012). "Urban water sector performance in Africa: A step-wise bias-corrected efficiency and effectiveness analysis.", *Utilities Policy*, 22, 31-40.

[32] 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.

[33] Njeru, G., Gathiaka, J., & Kimuyu, P. (2020). "Technical Efficiency of Thermal Electricity Generators in Kenya.", *International Journal of Energy Economics and Policy*, 10(3), 340-347.

[34] Nsabimana, R. (2020). "Electricity sector organization and performance in Burundi.", *Multidisciplinary Digital Publishing Institute Proceedings*, 58(1), 26.

[35] Nsabimana, R. (2022). "Benchmarking of the Electricity Sector in East Africa: An Assessment of Technical Efficiency.", *East African Journal of Science, Technology and Innovation*, 3.

[36] Perelman, S., & Walheer, B. (2020). "Economic growth and under-investment: A nonparametric approach.", *Economics Letters*, 186, 108824.

[37] Plane, P. (1999). "Privatization, technical efficiency and welfare consequences: the case of the Cote d'Ivoire Electricity Company (CIE).", *World Development*, 27(2), 343-360.

[38] Rahut, D. B., Mottaleb, K. A., Ali, A., & Aryal, J. (2018). "The use and determinants of solar energy by Sub-Saharan African households.", *International Journal of Sustainable Energy*, 37(8), 718-735.

[39] Ramos Real, F. J., & Tovar, B. (2020). "Revisiting electric utilities' efficiency in the Southern African Power Pool, 1998-2009.", *Journal of Energy in Southern Africa*, 31(1), 1-13.

[40] Roghanian, P., Rasli, A., & Gheysari, H. (2012). "Productivity through effectiveness and efficiency in the banking industry.", *Procedia-Social and Behavioral Sciences*, 40, 550-556.

[41] Sergi, B., Babcock, M., Williams, N. J., Thornburg, J., Loew, A., & Ciez, R. E. (2018). "Institutional influence on power sector investments: A case study of on- and off-grid energy in Kenya and Tanzania.", *Energy research & social science*, 41, 59-70.

[42] Walheer B. (2018a). "Labour productivity growth and energy in Europe: a production-frontier approach.", *Energy*,152, 129-143.

[43] Walheer B. (2018b). "Scale efficiency for multi-output cost minimizing producers: the case of the US electricity plants.", *Energy Economics*,70, 26-36.

[44] Walheer B. (2019). "Malmquist productivity index for multi-output producers: an application to electricity generation plants.", *Socio-Economic Planning Sciences*, 65, 76-88.

[45] 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.

[46] Walheer B. (2022). "Global Malmquist and cost Malmquist indexes for group comparison.", *Journal of Productivity Analysis* 58(1), 75-93.

[47] Walheer B. (2024). "A sequential benefit-of-the-doubt composite indicator.", *European Journal of Operational Research* 316, 228-239.

[48] Winkler, J., Magosch, M., & Ragwitz, M. (2018). "Effectiveness and efficiency of auctions for supporting renewable electricity–What can we learn from recent experiences?.", *Renewable Energy*, 119, 473-489.

[49] World Bank (2022). "World Development Indicators.", *Washington D.C.: The World Bank*.

Appendix A: descriptive statistics

Table 5: Outcomes and resource – minimum

Country	Period	Outcomes: Access (customers /100hh)	Outcomes: Reliability (kWh/hab)	Resource (kWh/hab)
All	2008-2017	3.0	17.2	24.0
All	2008-2011	3.0	19.7	24.1
	2012-2014	4.2	20.2	26.6
	2015-2017	4.8	17.2	24.0
Burundi	2008-2017	3.0	17.2	24.0
Ethiopia		8.2	33.7	42.2
Kenya		13.6	132.8	158.0
Rwanda		5.9	23.7	29.3
Tanzania		9.0	81.6	102.8
Uganda		5.1	42.0	65.1
Burundi	2008-2011	3.0	19.7	24.1
Burundi	2012-2014	4.2	20.2	26.6
Burundi	2015-2017	4.8	17.2	24.0
Ethiopia	2008-2011	8.2	33.7	42.2
Ethiopia	2012-2014	9.3	42.6	67.7
Ethiopia	2015-2017	9.0	59.1	86.5
Kenya	2008-2011	13.6	132.8	158.0
Kenya	2012-2014	23.5	143.7	172.0
Kenya	2015-2017	38.6	159.9	193.2
Rwanda	2008-2011	5.9	23.7	29.3
Rwanda	2012-2014	16.4	28.5	35.6
Rwanda	2015-2017	25.3	41.2	52.5
Tanzania	2008-2011	9.0	81.6	102.8
Tanzania	2012-2014	11.1	94.3	117.6
Tanzania	2015-2017	16.4	99.5	120.3
Uganda	2008-2011	5.1	42.0	65.1
Uganda	2012-2014	7.5	56.9	79.8
Uganda	2015-2017	11.6	65.7	84.4

Table 6: Outcomes and resource – median

Country	Period	Outcomes: Access (customers /100hh)	Outcomes: Reliability (kWh/hab)	Resource (kWh/hab)
All	2008-2017	10.0	56.0	80.2
All	2008-2011	8.5	42.9	60.0
	2012-2014	10.6	58.2	81.4
	2015-2017	15.5	66.9	86.4
Burundi	2008-2017	4.3	20.1	26.8
Ethiopia		9.2	49.4	74.2
Kenya		24.9	144.1	174.5
Rwanda		17.8	34.7	44.5
Tanzania		11.7	95.1	117.9
Uganda		8.2	58.2	81.0
Burundi	2008-2011	3.5	20.9	26.5
Burundi	2012-2014	4.3	21.5	26.9
Burundi	2015-2017	5.4	18.0	25.3
Ethiopia	2008-2011	8.5	35.2	44.1
Ethiopia	2012-2014	9.7	55.0	80.6
Ethiopia	2015-2017	10.8	72.1	93.5
Kenya	2008-2011	16.8	133.8	158.9
Kenya	2012-2014	26.2	144.6	177.0
Kenya	2015-2017	51.0	161.3	199.2
Rwanda	2008-2011	8.5	26.8	33.3
Rwanda	2012-2014	19.2	36.6	48.4
Rwanda	2015-2017	26.4	46.3	58.7
Tanzania	2008-2011	9.7	87.2	109.2
Tanzania	2012-2014	12.3	95.9	118.2
Tanzania	2015-2017	18.8	100.1	124.4
Uganda	2008-2011	5.7	47.8	72.4
Uganda	2012-2014	8.9	59.5	82.2
Uganda	2015-2017	12.7	65.7	85.3

Table 7: Outcomes and resource – maximum

Country	**Period**	**Outcomes** Access (customers /100hh)	Reliability (kWh/hab)	**Resource** (kWh/hab)
All	2008-2017	63.0	164.7	202.7
All	2008-2011	20.8	141.8	168.4
	2012-2014	30.3	155.1	188.5
	2015-2017	63.0	164.7	202.7
Burundi	2008-2017	5.6	22.9	27.8
Ethiopia		11.7	80.7	104.2
Kenya		63.0	164.7	202.7
Rwanda		30.7	49.7	62.2
Tanzania		19.7	115.9	128.0
Uganda		14.6	68.1	86.2
Burundi	2008-2011	3.8	22.2	27.8
Burundi	2012-2014	4.5	22.9	27.7
Burundi	2015-2017	5.6	19.9	27.4
Ethiopia	2008-2011	8.8	43.7	54.8
Ethiopia	2012-2014	10.2	65.7	85.5
Ethiopia	2015-2017	11.7	80.7	104.2
Kenya	2008-2011	20.8	141.8	168.4
Kenya	2012-2014	30.3	155.1	188.5
Kenya	2015-2017	63.0	164.7	202.7
Rwanda	2008-2011	13.2	32.8	40.5
Rwanda	2012-2014	22.8	39.5	51.1
Rwanda	2015-2017	30.7	49.7	62.2
Tanzania	2008-2011	10.4	90.2	116.9
Tanzania	2012-2014	14.4	99.1	120.7
Tanzania	2015-2017	19.7	115.9	128.0
Uganda	2008-2011	7.1	52.4	74.8
Uganda	2012-2014	9.7	62.6	83.6
Uganda	2015-2017	14.6	68.1	86.2

Table 8: Outcomes and resource – standard deviation

Country	Period	Outcomes: Access (customers /100hh)	Outcomes: Reliability (kWh/hab)	Resource (kWh/hab)
All	2008-2017	11.2	43.8	51.9
All	2008-2011	4.6	41.2	48.6
	2012-2014	7.8	43.7	51.6
	2015-2017	16.1	47.4	56.2
Burundi	2008-2017	0.9	1.8	1.5
Ethiopia		1.1	16.8	22.9
Kenya		16.2	12.2	17.2
Rwanda		8.6	8.9	11.6
Tanzania		4.0	9.6	7.6
Uganda		3.3	9.1	7.1
Burundi	2008-2011	0.3	1.3	1.7
Burundi	2012-2014	0.2	1.4	0.6
Burundi	2015-2017	0.4	1.4	1.7
Ethiopia	2008-2011	0.3	4.6	5.8
Ethiopia	2012-2014	0.4	11.6	9.2
Ethiopia	2015-2017	1.4	10.9	8.9
Kenya	2008-2011	3.0	4.2	4.9
Kenya	2012-2014	3.4	6.4	8.4
Kenya	2015-2017	12.2	2.5	4.8
Rwanda	2008-2011	3.2	4.1	4.9
Rwanda	2012-2014	3.2	5.7	8.3
Rwanda	2015-2017	2.8	4.3	4.9
Tanzania	2008-2011	0.6	3.6	5.8
Tanzania	2012-2014	1.7	2.4	1.6
Tanzania	2015-2017	1.7	9.3	3.8
Uganda	2008-2011	1.0	4.9	4.5
Uganda	2012-2014	1.1	2.9	1.9
Uganda	2015-2017	1.6	1.4	0.9

Appendix B: linear programmings

We estimate efficiency and effectiveness using a Data Envelopment Analysis (DEA)-based methodology. DEA, introduced by Charnes et al. (1978), does not assume any functional form for the technology but rather reconstructs the technology by means of a possibility set using the data while imposing some regularity conditions on the technology (here, we assume that the possibility set is compact and satisfies constant returns-to-scale). DEA is easy to deal with as it only requires solving linear programming using all entities as peers. To be fair, DEA presents also some less desirable features. It is sensitive to outliers and measurement errors. As our sample is small and we make use of aggregated data, such two aspects are probably under control.

All our indexes depend on the efficiency and effectiveness measurements evaluated at different time periods: $e_b(\mathbf{y}_b, \mathbf{x}_b)$, $e_c(\mathbf{y}_c, \mathbf{x}_c)$, $e_b(\mathbf{y}_c, \mathbf{x}_c)$, and $e_c(\mathbf{y}_b, \mathbf{x}_b)$; and $p_b(\mathbf{y}_b)$, $p_c(\mathbf{y}_c)$, $p_b(\mathbf{y}_c)$, and $p_c(\mathbf{y}_b)$. Without lost of generality, we show how $e_c(\mathbf{y}_b, \mathbf{x}_b)$ and $p_c(\mathbf{y}_b)$ are computed for an entity evolving at $(\mathbf{y}_b, \mathbf{x}_b)$. Let us start with $e_c(\mathbf{y}_b, \mathbf{x}_b)$ that is obtained solving the following linear programming:

$$
\begin{aligned}
e_c(\mathbf{y}_b, \mathbf{x}_b) = \min_{\lambda_1,\ldots,\lambda_n} e \\
&\text{(C-1) } \mathbf{y}_b/e \leq \sum_{j=1}^{n} \lambda_j \mathbf{y}_{cj} \\
&\text{(C-2) } \mathbf{x}_b \geq \sum_{j=1}^{n} \lambda_j \mathbf{x}_{cj} \\
&\text{(C-3) } \forall j = 1, \ldots, n : \lambda_j \geq 0, \\
&\text{(C-4) } e \geq 0.
\end{aligned}
\tag{17}
$$

To obtain the three other efficiency measurements, it suffices to change the time periods for the evaluated country, i.e. $(\mathbf{y}_b, \mathbf{x}_b)$, and/or the peers, i.e. $(\mathbf{y}_{cj}, \mathbf{x}_{cj})$ for $j = 1, \ldots, n$ in (17).

Next, we explain how $p_c(\mathbf{y}_b)$ can be computed for an entity evolving at $(\mathbf{y}_b)$. Again, a linear programming is used but the resources are not needed. We obtain the following:

$$
\begin{aligned}
p_c(\mathbf{y}_b) = \min_{\lambda_1,\ldots,\lambda_n} & \; p \\
& \text{(C-1) } \mathbf{y}_b/p \leq \sum_{j=1}^{n} \lambda_j \mathbf{y}_{cj} \\
& \text{(C-2) } 1 \geq \sum_{j=1}^{n} \lambda_j \\
& \text{(C-3) } \forall j = 1,\ldots,n : \lambda_j \geq 0, \\
& \text{(C-4) } p \geq 0.
\end{aligned}
\tag{18}
$$

The linear programming in (18) is similar to (17) except that the resources are set to unity. This directly comes from the definition of the effectiveness measurement (see (4)). Again, to obtain the three other effectiveness measurements, it suffices to change the time periods for the evaluated entity, i.e. $(\mathbf{y}_b, \mathbf{x}_b)$, and/or the peers, i.e. $(\mathbf{y}_{cj}, \mathbf{x}_{cj})$ for $j = 1, \ldots, n$ in (18).