 https://doi.org/10.56279/orseaj.C2024.21

Infrastructure Adequacy for Electricity Trading in East Africa

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Abstract

A well designed, managed, reliable and adequate electricity generation and transmission system infrastructure is essential for inter-country electricity market integration. This paper tracks progress in establishing the infrastructure needed to facilitate electricity trading in East Africa common market since its formation in 2010. Using data on electricity infrastructure development targets set in the EAC electricity infrastructure Master Plan 2013- 2023 and the actual infrastructure delivered by 2022, we conducted Earned Value Analysis (EVA) for generation and transmission infrastructure projects. This aimed at establishing whether the completed infrastructure can adequately facilitate electricity exchange across EAC market. Findings show that by 2022 the region had realized 54% of the 12,567MW planned generation capacity, and 211% of transmission network targets. Investment inflows for establishing infrastructure have been faster than anticipated with actual variance of 325%. This triggered 47% earned value in surplus load worth US$357million of trade, despite actual electricity trading not happening at the same pace. We construed a set of merit-order conditions that can guide iterative planning to synchronize generation infrastructure with cross-border infrastructure for trade efficiency.

Keywords: Infrastructure Adequacy, Earned Value Analysis, Merit-order conditions

Introduction

Globally, cross-border electricity trade (measured by gross imports in each country) has grown at an average of 2.7% of total supplied per annum, from 588 TWh in 2010 to 914 TWh in 2020. This was worth US$ 71.54 million in 2022 and projected to grow at about 6.3 % to US$ 99.46 million by 2026 (IEA, 2022). Among the drivers expected to raise global electricity trade include the increasing integration of domestic markets into regional energy markets, cross-border vendor collaborations, and increasing efficiency of competitive market platforms organized on knowledge sharing programs (Technovio Report, 2019). Regional electricity markets are essentially the interconnection of already existing national electricity markets (Kyriakarakos, 2022). Where, regional electricity markets aim at harnessing economies of scale to enhance supply security and reduce costs (Rubanda et al., 2023). For Africa to achieve the sustainable development goal of clean energy for all (SDG7), the continent should increase cross-border electricity trade as a strategy to avert inefficient investment in domestic generation (Blimpo et al., 2019). Rubanda et al. (2023) identified the four key elements of electricity market integration, including: (i) coordinated physical infrastructure development, (ii) harmonized and standardized operation

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procedures, (iii) existence of market competition, and (iv) coordinated institutional governance. Regardless of approach, whether top-down integration (as the case of Europe (Pollitt, 2019)) or incremental approach driven by the various utilities within a region (as the case of Association of Southeast Asian Nations (Youngho et al. 2019)), physical infrastructure is at the center of both the process and sustainability of electricity market integration (Mewenemesse & Yan, 2022, Scott 2019). Massive infrastructure investment is needed for generating, transmitting and coordinating power exchange across various countries in a regional market (Cramer, 1983).

Because establishing a regional electricity market involves multiple jurisdiction re-arrangements, it necessitates regional planning and agreements on sharing investment cost. Ideally, regional planning should consider the overall regional resource adequacy. This requires aggregating local power systems development plans into a regional plan. This in turn requires agreeing over underlying assumptions, time-frames of analysis, and potential future scenarios (IEA, 2019). Blimpo and Davies (2019) argue that effectively implementing regional power pools could lower power investment costs in Africa by US$ 80 billion through 2040. This results from economies of scale and reduced costs from avoided duplicated investment in peak capacity, reliability and security. In 2012, the East Africa Community (EAC) states created the EAC sub-Power pool (EACPP) within Eastern Africa Power Pool (EAPP), with commitments to integrate their power systems to facilitate electricity trading. Subsequently, a strategic plan (2013-2038 Master Plan) to deliver infrastructure outlay for power trading within the region was adopted (Herscowitz & Amadou, 2019). The implementation of the Master Plan has two phases: Phase-I (2013-2023) and Phase-II (2024-2038). Tables 1 and 2 present electricity generation and transmission targets, respectively.

Table 1: EAC National Electricity Generation Expansion Targets (2013-2038)

Country	Base year (2012)	2013-2023				2024-2038				Average Surplus over period 2013-2038		
	Existing Capacity MW	Installed capacity (MW)	Load (MW)	surplus load	Surplus load (%) (tradable)	Installed capacity (MW)	Load (MW)	Surplus load (MW)	Surplus load (%) (tradable)	Load (GWh)	Surplus Load (GWh)	Surplus load (%) (tradable)
Kenya	1,916	5,604	4,537	1,067	23	15,610	13,852	1,758	12	39,975	6,003	15
Rwanda	103	305	276	29	10	1,094	806	288	35			
DRC	74	306	121	185	152	517	276	241	87	3,369	840	25
Burundi	49	269	204	64	31	489	667	238	35			
Uganda	822	1,629	1,310	319	24	3,147	2,650	497	18	28,386	2,636	34
Tanzania	1,205	4,454	3,352	1,094	44	7,411	6,344	1,067	16	18,455	5,059	27
South Sudan												

Data source. SNC. Lavalin report, 2011

Table 2. EAC Cross- Border Electricity Transmission Infrastructure Targets (2013-2038)

Transmission Capacity	2013-2023		2024-2038		2013- 2038	
	EAPP Total (km)	EACPP Portion (km)	EAPP Total (km)	EACPP Portion (km)	EAPP Total (km)	EACPP Portion (km)
Double -Circuit70/110/132 KV	105	105	120	120	767	767
Single-circuit 220 KV	455	455	500	500	410	410
Double -Circuit 220 KV	1,039	959	1,254	1,174	1,032	952
Double-Circuit 400 KV	1,269	1,269	1,628	1,628	1,618	1,618
Double -Circuit 500 KV	3,110	-	5,109	-	6,813	-
Bipolar 500 KV HVDC	-	-	-	-	3,019	3,019
Bipolar 600 KV HVDC	2,558	-	4,698	-	7,131	-

Data source. SNC. Lavalin report, 2011

Regional electricity trade predominately depends on price differentials. Power is efficiently traded when; a country with a generation surplus is connected to generation deficit country, and when economic rationale for trade exists. For a power deficit country, importing makes sense when it's cheaper than emergency power (reserve) capacity or power from more costly inefficient domestic sources. By 2022, the EAC electricity market still faced supply-demand disequilibrium with about 1,861MW surplus generated in Uganda, Kenya, Rwanda and Tanzania, and a deficit of about 230MW in South Sudan, and Burundi. With joining of Democratic Republic of Congo to EAC regional market (in 2022) the deficit compounded to about 751 MW in the short run (2020-2025). Given the region's average electricity access rate of 26% (International Trade Administration, 2022), there is potential for electricity trading within EAC region.

In EAC, both the EACPP and Common market agendas strive to increase the region's energy security and lower the cost of power to increase access in all parts of the integrating countries. Despite, partner states signing protocols that establish the common market and power pool in 2012, only 0.4% of the region's generated electricity is traded. The trade enroute include; exchange between Uganda and Kenya, exports from Uganda to Tanzania, South Sudan and Eastern DRC, Rwanda-Uganda exchange, exports from Rwanda to DRC and Burundi, and exports from Kenya to Tanzania (EAC, 2022). Available literature attributes the slow growth of electricity trading in the region to prohibitive prices (Mburamatare et al., 2023), uncoordinated institutions and policies (Kyriakarakos, 2022), and failure to base electricity generation to competitive demand (Murphy & Smeer, 2002). Mburamatare et al. (2023) attributes the higher electricity prices in East Africa energy market to cost of electricity generation and transmission losses. However, this current study looks at electricity at market level as an output of infrastructure, with no attention to the infrastructure itself. Kyriakarakos (2022) interrogated institutional and policy harmonization in Africa Power Pools and found lack of regional collaboration at both political and technical levels to cause the slowed infrastructure investment for cross-border electricity trading.

This paper interests itself with infrastructure adequacy by tracking the progress made on the planned infrastructure for EAC Power Pool using Earned Value Analysis (EVA). We track the process progress value (PPV) to establish infrastructure's adequacy in facilitating regional electricity trade through sub-variable focused objectives, including establishing if there is adequate: generation capacity to satisfy the regional market; transmission capacity to evacuate the generated power across the region; and efficient investment inflows to realize the regions infrastructure needs. The rest of the paper proceeds with the theoretical framework underpinning the study in section 2, data presentation and analysis in section 3, results are presented and discussed in section 4 followed by conclusion and probable action in section 5.

Results

Presentation of results in this section is arranged per sub-variable (PGI, CTI, II) and analyzed at two levels: the regional outlook and individual country outlook. The Cross-border infrastructure is presented as joint projects between countries.

Progress on Power Generation Infrastructure.

In attempt to establish if there is adequate generation capacity to satisfy the regional market, we investigated regional power generation using installed capacity and surplus load that can be traded in the EAC region.

Installed Capacity.

At regional level, findings indicate the stock of generation infrastructure has an increasing linear trend. The aggregate capacity of the diverse plants including hydropower (54%), solar (2%), oil & geothermal (12%), wind (2%), coal peat (10%), Natural gas (14%), Bioenergy (3%) and other energy sources (3%) has increased from 4018.2 MW in 2013 to 7173.6MW in 2022 as illustrated in Figure 1.

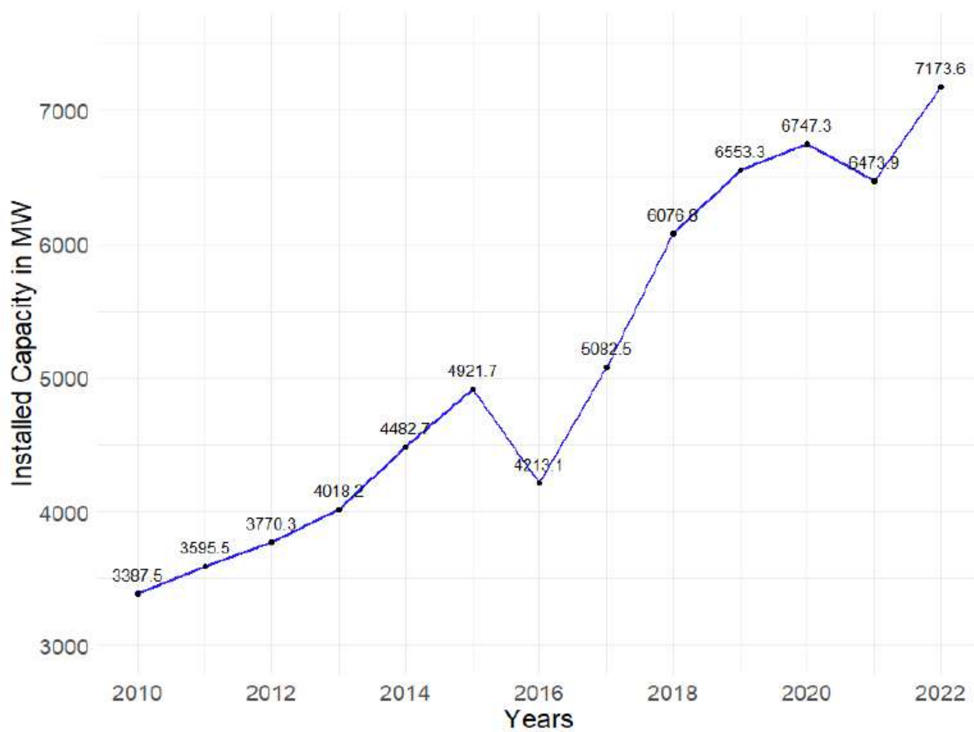

Fig 1: The growth curve for EACPP generation infrastructure.

Based on installed capacity (MW), study findings in Table 3, indicate that in the progress year 2022 the cumulative installed generation capacity is 7173.6MW which is less than the total installed capacity of 12,567MW planned for the period 2013-2023. The trend of investment inflows into generation infrastructure witnessed sharp drops during the 2015-2017 and 2019-2020 periods due to political instability in Burundi and South Sudan, and COVID-19 outbreak respectively (EAC Secretariat, 2021)

Table 3. Earned value on generation infrastructure for EACPP 2022.

Installed Capacity (MW)			
EAC Partner state	**Planned Value (2013-2023)**	**Earned Value (2013-2023)**	**Scheduled Performance Index (SPI)**
Uganda *	1629.00	1764.00	1.08
Kenya**	5604.00	3074.34	0.55
Tanzania***	4454.00	1732.16	0.39
Rwanda****	305.00	276.07	0.91
Burundi*****	269.00	197.00	0.73
South Sudan*+		130.00	
DRC*++	306.00		
Total	12567.00	7173.57	0.57

Data sources: * Electricity Regulatory Authority www.era.go.ug; ** Energy & Petroleum Regulatory Authority www.epra.go.ke; *** Energy &Water utility Regulatory Authority www.ewura.go.tz; **** Rwanda Utility Regulatory Authority https://rura.rw; *****Authority for Regulation of Water & Energy Sector https://areen.bi; *+ Ministry of Petroleum and Mining of South Sudan https://www.mop-rss.org *++ Electricity sector regulatory authority www.are.gouv.cd

The overall Schedule Performance Index for EACPP is 0.57. It indicates that the aggregate earned value on installed capacity for generation infrastructure in the region is currently at 57% of the total planned for the period 2013-2023. This performance index of 0.57, which is below 1, shows the project is behind schedule by 43% in terms of generation capacity. This indicates installed capacity inadequacy relative to the EACPP 2013-2023 Masterplan targets. At country level, there is sharp variation across countries in the rate at which installed power generation capacity has accumulated during the period 2013-2022. Table 3 illustrates that while the Schedule Performance Index for Burundi is 73%, Kenya 55%, Rwanda 73%, Tanzania 39%, and Uganda 108% of the total value planned for the period 2013-2023. The SPIs' for Burundi, Kenya, Rwanda, and Tanzania which are less than 1 show that their domestic effort in terms of installed generation capacity is behind schedule by 27%, 45%, 9% and 61% respectively. On the other hand, Uganda's SPI is greater than 1 implying that domestic performance in terms of installed capacity is above schedule by 8%.

Surplus Load for Trade

The overall trend of surplus (tradeable) load in the EAC has been stochastic. As shown in figure 2, during the period 2010-2015, there was no surplus load for trade. The region had a deficit of up to 0.7 TWh. Much as there was a slight improvement for the period 2015-2017, the tradeable load still remained in negative. During the period 2021-2022, the tradeable load shot to a surplus of 0.7 TWh.

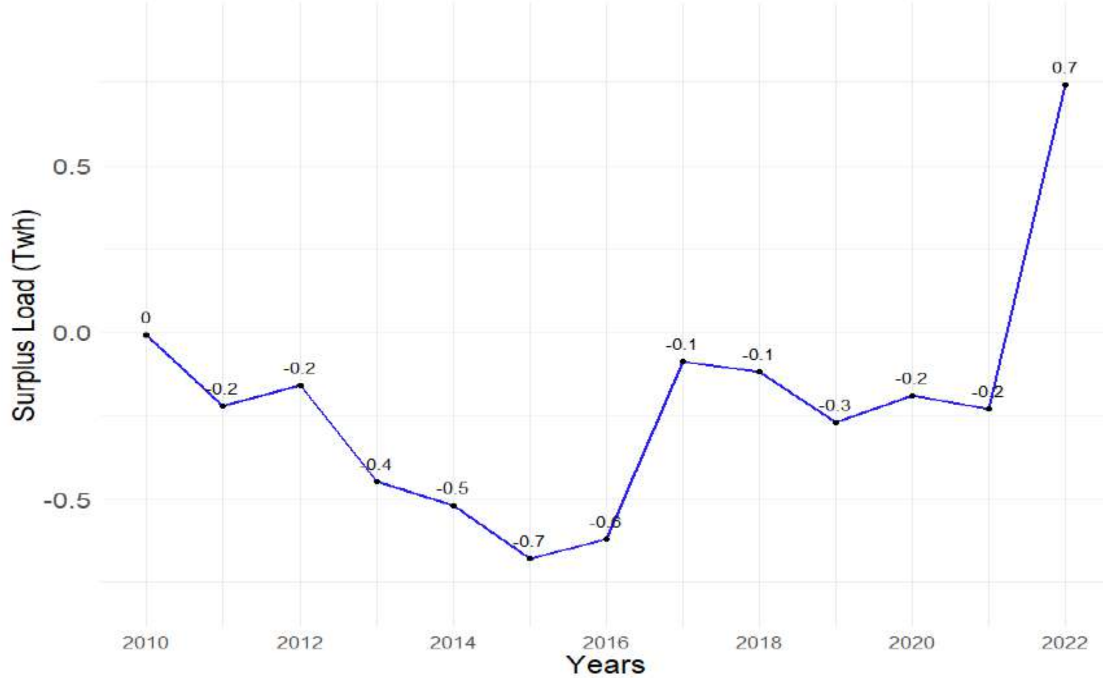

Figure 2. The growth trend in Surplus load 2010-2022.

At regional level, there is significant earned value for surplus load for electricity tading. The EACPP Master Plan 2013-2023 anticipated availability of about 2,758 GWh valued at US$740 million at current prices based on respective country forex rate by 2022. The study findings in Table 4 indicate that by the year 2022, the earned value on surplus load at current prices is about US$167.2 million representing about 47% of the total planned surplus/ tradable load for the period 2013-2023.

Table 4. Earned value on Surplus load for EACPP 2022

EAC Partner state	Planned Surplus load (GWh)	Earned Surplus Load (GWh)	current price/kWh in US$	Planned Value (2013-2023) in US$	Earned Value (2013-2022) in US$
Uganda	319	310	0.164	52,316,000	50,840,000
Kenya	1,067	610	0.168	179,256,000	102,480,000
Tanzania	1,094	-330	0.098	107,212,000	(32,340,000)
Rwanda	29	370	0.24	6,960,000	88,800,000
Burundi	64	-210	0.182	11,648,000	(38,220,000)
South Sudan	0	-10	0.43	0	(4,300,000)
DRC	0			0	0

Total	2,758	740	357,392,000	167,260,000
Surplus load Analysis				
SPI				0.468001522
SV				(190,132,000)
BAC				

The overall schedule performance index (SPI) is 0.47 indicating that about 47% of planned surplus load could be generated by 2022. With one year left to 2023, efforts to rediscover generation of about 53% of planned surplus load ought to be fast-tracked. In terms of earned value, the delayed surplus (scheduled variance) equating to $190.1 million loss of trade. At country level, three EACPP countries have attained positive earned value on surplus load. These are Uganda at $50.8 million, Kenya $102.4 million and Rwanda $88.8 million. Other countries have negative earned value on surplus load worth $32,340,000 for Tanzania, Burundi $38,220,000, and South Sudan $4,300,000. The noticeable inter-country variations in earned value for both installed capacity and surplus load is attributable to difference in domestic implementation rates and investment capacities accruable to each of the individual country. Upon adoption of the EACPP Master plan, each country developed its individual targets to undertake domestically. Policy and legal frameworks were institutionalized to ensure timely delivery on their national electricity generation expansion targets. In 2011, Burundi's grid supply was 30.6MW, majorly generated by two hydro power plants: Rwegura (18 MW) and Mungere (8MW). Basing on Burundi Infrastructure Action Plan for accelerating regional integration that had earlier been developed in 2009, the country formulated Electricity Generation Master Plan 2013-2040. The master plan aimed at diversifying the energy mix, hitherto dominated by the hydroelectric sector. At the begging of year 2022, Burundi was operating 8 hydropower and 2 thermal plants totaling to installed capacity of 45 MW. The construction of Jiji and Lulembwe, hydro power plants with a combined capacity of 48 MW, is in final stages and is expected to be commissioned by end of 2023. In Kenya, the drive to deliver the 2013-2023 infrastructure targets, is undertaken through a business growth strategy anchored on diversification, expansion, rehabilitation and establishment of new plants, and emphasis for renewables. By 2022, the total installed capacity for Kenya was 1,904 MW, comprising of thermal 14% (253MW), Geo thermal 39% (799 MW), hydro 46% (826 MW), and wind 1% (26 MW).

For the period, 2013- 2022, Rwanda established 46 power generation plants of which 42 are connected to grid. This raised the installed generation capacity of the country from 74.8 to 276.07MW. Independent Power Plants is the dominate form of ownership of generation infrastructure having increased from 15% in 2013 to 60% in 2022, while government ownership has reduced to 40%. The main technologies invested in for generation infrastructure in Rwanda include hydro infrastructure 107.3MW (38.8%), thermal 58.8MW (21.3%), solar 12.05 MW (4.4%), peat fired power plant 50 MW (18%). Three major power projects on 2013-2023 master plan for Rwanda are still ongoing; Rusomo hydro power (80mw), Shema-Kivu hydro power (56MW), and Nyaburongo hydro power (43.5MW). By 2022, Tanzania had installed generation capacity of 1,608MW, of which 60% (893 MW) is natural gas infrastructure, 39% (628 MW) is hydro power infrastructure, and 1% (11 MW) is for other renewable energy. In 2020, Tanzania completed its first wind mill farm at Mwenga, in Iringa region. Overall, electricity generation capacity in Tanzania, increased from 6363 Gwh in 2016, when the first project of EACPP master plan was completed in the country, to 7,905 GWh in 2022 as other projects were completed; s

Mwalimu Julius Nyerere hydro power (2115 MW) in 2020, Kinyerezi Gas I (186 MW) and Kinyerezi Gas II (240 MW) in 2017.

In Uganda, a host of generation capacities has been connected to the grid through investment in large hydro dams and other small renewable energy projects promoted under the Global Energy Transfer Feed in Tariff programme. The programme enabled diversification of generation mix with 14 out of 17 projects for hydro at combined installed capacity of 118MW, two Solar PV projects with combined installed capacity of 20MW and one bagasse cogeneration plant of 20MW. GET FIT provides 8% of total electricity produced in Uganda. Subsequently Uganda's installed electricity generation capacity has increased from 852MW to 1,177MW yet suppressed demand increased by 50MW annually. In 2013, South Sudan expanded its infrastructure action plan drawn earlier in 2010. It aims at promoting electricity interconnection with neighboring countries. The expanded plan earmarked five generation projects envisaged to start operation by latest 2017. These included Fula (1,080 MW), Bedden (720 MW), Lekki (420 MW), Shukoli (250MW), and Juba barrage (120 MW). However, by December 2022, South Sudan had attained installed capacity of 20 MW, primarily of diesel plants. There is high proliferation of Solar PV compared to other technologies notably because of its ease of installation and operation scale for the humanitarian agencies.

Progress on Cross-border Transmission Infrastructure

With intent to establish if there is enough transmission capacity to evacuate the generated power for trade across the region, the findings indicate that as a sub-variable, cross-border transmission infrastructure has generally had a positive trend in the last twelve years depicted by Figure 3.

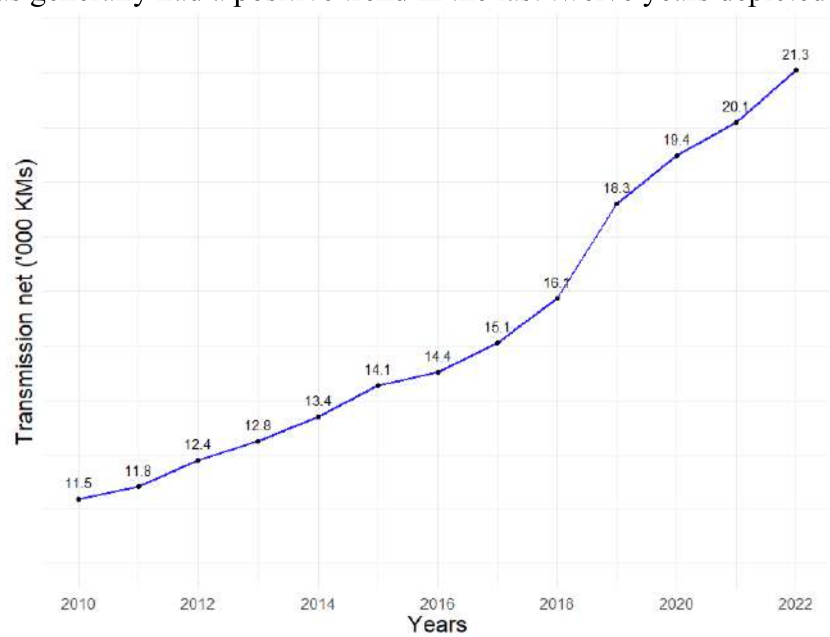

Figure 3. The trend of EACPP cross-border transmission infrastructure 2010-2022.

Analysis of cross-border transmission infrastructure adequacy parameters indicate that for the planned period 2013-2023, there is a positive progress recorded in distance (km), voltage (kV), and load capacity (MW). The earned value on all the three parameters exceeds the respective planned values. As indicated in Table 8, the EAC master plan (2013-2023) had planned an electricity transmission system for a distance of 1,376Km, voltage of 2120 KVA, and load capacity of 5,665 MW.

Table 5. Earned Value on Cross-border Transmission Infrastructure Parameters by 2022.

Metric	Distance (km)	Voltage (kV)	Load (MW)
PV	1,376	2,120	5,665
EV	2,905	2,120	4,200

Figure 4, demonstrates that the EACPP infrastructure agenda had exceeded the targeted distance with a schedule variance of +2.11, achieved targeted voltage at no variance (SPI =1), while there is schedule variance of -0.74 for load capacity.

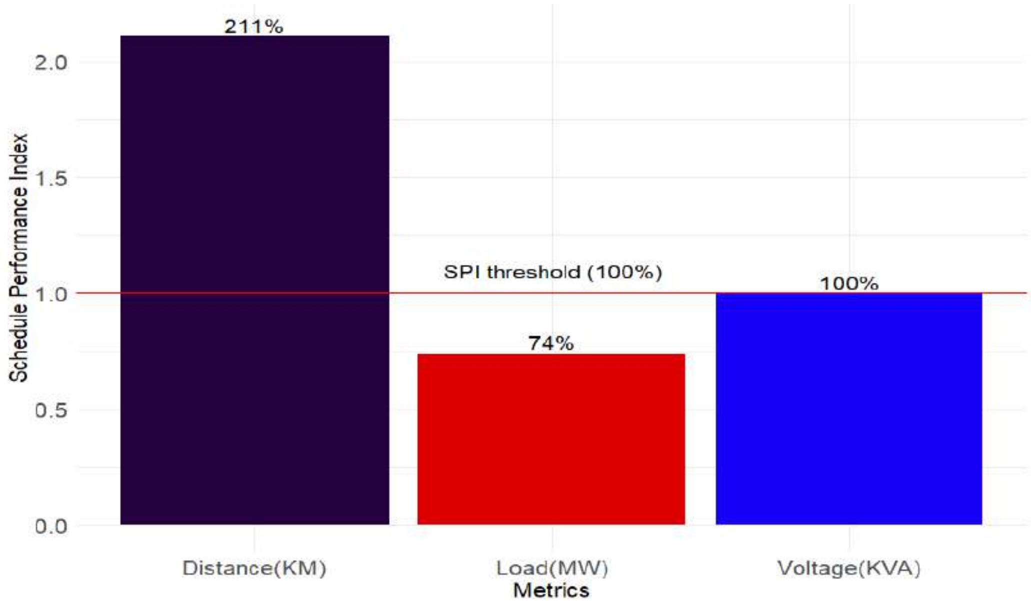

Figure 4. Comparison of SPIs for cross-border infrastructure parameters.

The overshot in transmission line especially for total distance covered is attributed to the EAC cross-border electrification programme adopted in 2015. The programme enables border towns to connect from the neighboring partner state at distribution voltage when it is more economical than connecting with the grid within its own country. It should be noted the infrastructure deliverable for this programme was included/envisaged in the Master Plan 2013-2038. The noticeable lag in load capacity of about 26% could be attributed to majority township connections being extensions other than establishment of new substations. Table 6 highlights the cross-border connections that account for the growth trend depicted in Figure 3 and the earned values for various projects sampled in Figure 5.

Table 6. Disaggregated earned values on EACPP Cross-border Infrastructure 2013-2022

	Planned Value				Earned Value				SPI		
Routes	KV	KM	MW	Est. Cost	KV	KM	MW	Actual Cost	KV	KM	MW

UG - KY	160	203.2	824	71	220	254	440	380	1.36	1.25	0.53
TZ-KY	160	104	608	117	400	959	2400	430	2.5	9.22	3.95
TZ-UG	88	34	280	30.4	220	580	200		2.5	17.05	0.71
TZ-RW	88	46	128	37.4	220	120	400	33	2.5	2.61	3.13
TZ-BR	88	63.2	112	47.9							
UG-RW	88	68.8	208	51.3	220	372	690	58	2.5	5.41	3.32
RW-DRC	88	0	78								
BR-DRC	88	31.2	28		220	78	70	47	2.5	2.5	2.5
UG-DRC	0	0	0		220	352		150			
UG-SS	0	0	0		400	190		47			
Total	848	550.4	2266	355	2120	2905	4200	1145	2.5	5.28	1.85

The study observes that, despite, the overall score of 211% earned value on cross border transmission infrastructure, there is wide variations in performance of individiual interconnect projects. Using a sample of the six inter-country connections illustrated in Figure 5, Tanzania-Uganda (TZ-UG) project with earned value of 1706% is the main contributor to the total km of transmission grid in the region. Tanzania- Rwanda(TZ-RW) at 922% and Uganda – Rwanda (UG-RW) at 541% are the other projects whose earned value on distance is comparatively higher than other parameters (voltage and load capacity). Only Uganda- Kenya (UG-KY) with earned value of 138% has scored higher on voltage compared to other parameters (distance and voltage). While, Tanzania- Kenya (TZ-KY) at 395% and TZ-RW at 312% interconnects have both scored higher earned values on load capacity than other parameters (distance and Voltage). Only Burundi- Democratic Republic of Congo (BR- DRC) project has equal scores of earned values on all the three parameters at 250%.

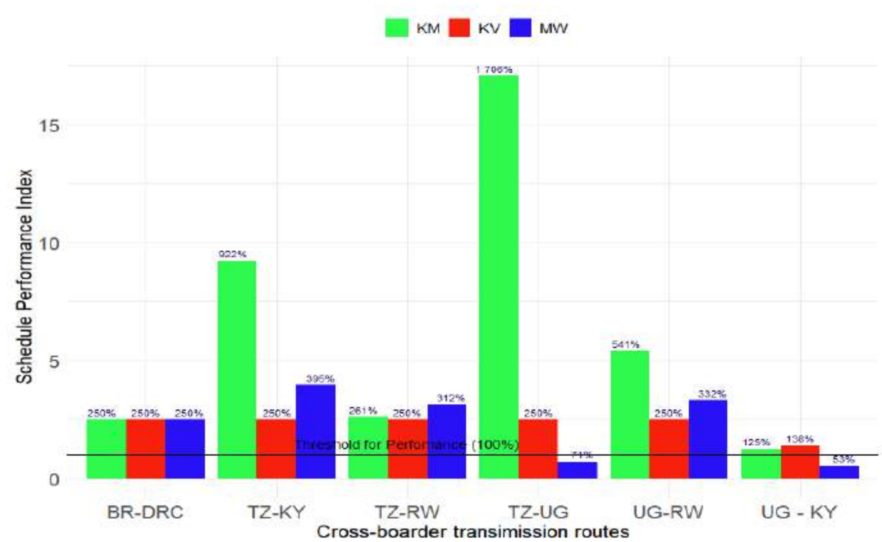

Figure 5. Comparison of SPIs for cross-border infrastructure projects

Progress on Infrastructure Investment.

In attempt to establish whether there is enough investment into regional electricity infrastructure, the study finds that the trend of investment has generally been declining as depicted in Figure 6.

Upon adoption of EACPP Master Plan in 2013, investments increased from US$ 360 million to US$ 809 million by 2015. For the period 2016 to 2018, regional investment averaged about US$270.4 million and dropped slightly during 2019-2021 Covid-19 pandemic period. However, with revival of global economy activities in 2021 and re-stabilization of investment flows, the region received about US$ 394 million for infrastructure development in the year 2022.

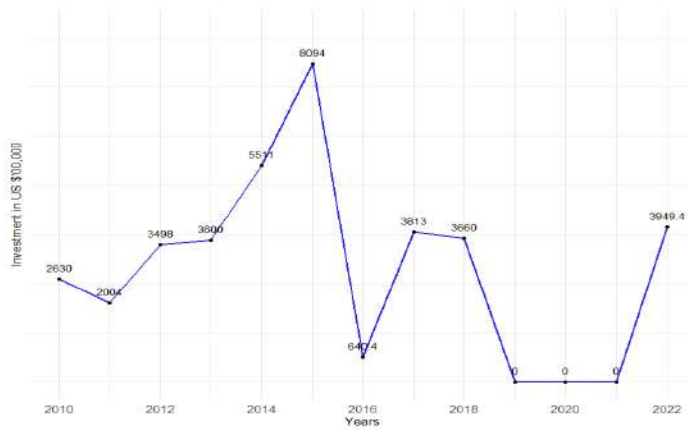

Figure 6. Trend of Investment in EACPP Infrastructure 2010-2022

For the period 2013-2022, a total of US$ 16.1 billion was spent on both generation and cross-border transmission infrastructure. The investment has earned value of about US$ 44.5 billion. The positive Cost Variance (CV) for generation, transmission, and overall infrastructure investment in Table 7, imply that the EACPP 2013-2023 project in both dimensions and overall, by 2022 was still within the slated budget. Relatedly, since the Cost Performance Index (CPI) on generation and transmission is greater than one), the project was still efficient in terms of use of the budgeted resources by the year 2022.

Table 7. Earned value on infrastructure investment for EACPP 2013-2022

Investment	**AC**	**EV**	**CV**	**CPI**
Generation	13,212	38,043	24831.00	2.88
Transmission	2,977	6549.4	3572.40	2.20
Total	16,189	44,592	28403.40	2.75

However, using budget truncates of 2009-2013, 2014-2018, 2019-2023 sampled on generation infrastructure as indicated in Figure 7, there is significant variation in resource efficiency across the implementation period.

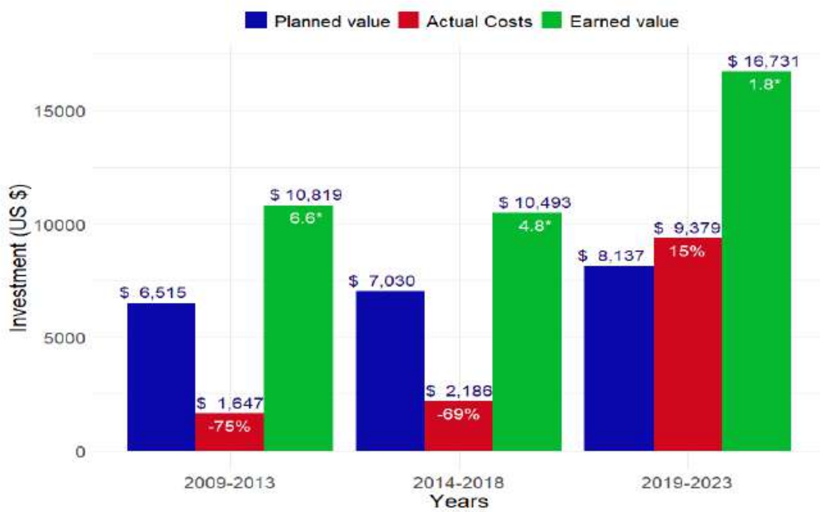

Figure 7. Earned Value on Infrastructure Investment for EACPP 2013-2022.

During the base period, 2009– 2013, the actual investment costs were 75% less than the planned investment cost and induced an earned value on generation infrastructure of US$10,819 million which is 6.6 times the actual cost of investment. The implementation period 2014 – 2018, had the actual investment costs 69% less the planned investment cost, and induced earned value of US$ 10,413 million, which is 4.8 times the Actual cost of investment. For the period 2019 – 2023, the actual investment costs were 15% more than the planned investment cost and induced an earned value of US$ 16, 731 million which is 1.8 times the Actual cost of investment. A sample on four (4) cross-border transmission projects undertaken during the implementation period, indicate efficiency variations in Figure 8, across Tanzania -Kenya (TZ-KY), Tanzania-Rwanda (TZ-RW), Uganda-Kenya (UG-KY), and Uganda-Rwanda projects (UG-RW). The TZ-KY cross border transmission project obtained a 268% change of actual costs compared to planned cost. This means that US$313.56 more than the planned cost was invested. For TZ-RW, the percentage change of actual cost in comparison to planned cost is -12%. This means that the investment was US$4 million less than the planned cost. The UG-KY invested 368% over the planned with a total of US$259.15 million, while UG-RW overshoot by 13%.

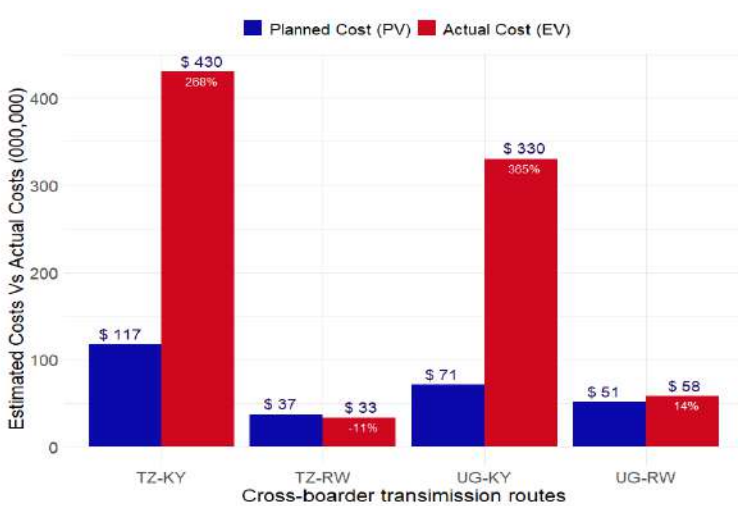

Figure 8. Earned Value on Investment for some of EACPP projects 2013-2022

In terms of scope performance, Figure 9 illustrates that only the TZ-RW project is successfully above the scheduled performance target by 13.3%. The UG-RW is slightly behind schedule by 11.6%. TZ-KY and UG-KY are greatly behind schedule by 72.8% and 78.5% respectively.

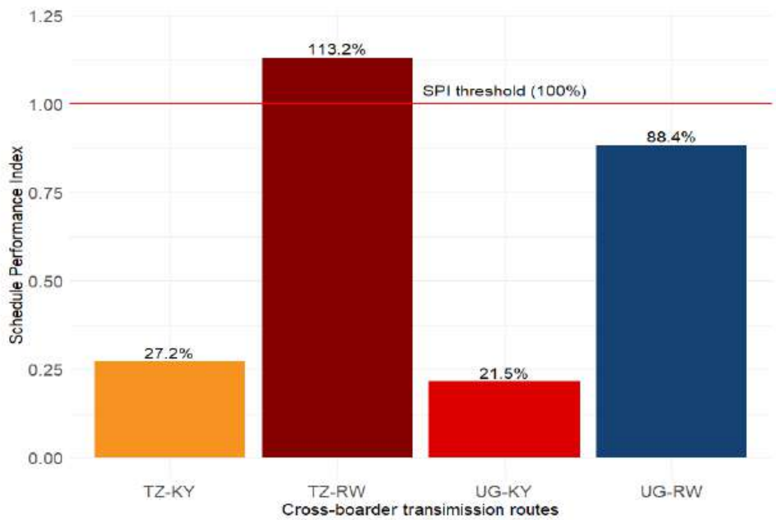

Figure 9. Scope performance of selected EACPP projects

Operationalization of EACPP master plan 2013-2023 interconnection targets, has been majorly delivered under two frameworks; the Eastern Africa Power Pool (EAPP) and the Nile Equatorial Lake Subsidiary Action Programme (NELSAP). The EAPP developed strategic Plan 2016 – 2026 actuated through a set of priority projects and Corporate Plans with a focus on integrating regional investment in power generation and transmission. The Nile Equatorial Lake Subsidiary Action Programme (NELSAP) is regional power grid interconnection programme that brings together Burundi, DRC, Rwanda, Uganda, and Kenya. It aims at facilitating creation of a regional power market through the integration of national grid systems. During the implementation period 2013-2022, ten (10) inter-country electricity transmission projects were launched**.** At the planning time (2011), the regional coordination on harmonized infrastructure master plan was expected to yield a net benefit of US$ 25,194 million by 2023, resulting from reduced operational cost. According to Power Africa Initiative (Annual Report, 2016), Ethiopia was expected to earn over $200 million in power exports to Tanzania by 2023. Tanzania on its part would save up to $500 million per annum by substituting its expensive emergency power with cheap imported electricity. By just wheeling power through its network from Ethiopia to Tanzania, Kenya was to earn about US$ 15 million per annum.

The Uganda-Rwanda line, was estimated to save Rwanda $1.3 million to $2 million per month — money prior spent on diesel powered generation. The savings would represent about 15% of the Rwandan utility's monthly expenditure on energy. Rwanda-Burundi NELSAP interconnect has for instance reduced costs of electricity from US$ 0.20KWh (2016) to an average of US$ 0.08 KWh by 2022. The increase in supply could help to tame peak demand in future. The drive for regional infrastructure has induced policy shifts. For instance, Kenya has revised its electricity sector policy positions in lieu to cross-border trading. In 2019, the Ministry of energy announced cutting down on isolated investment generation capacity target by 2,800 MW despite the growing demand risk for 2030 electrification level. In 2013, the country had set an ambitious target of 6,765 MW by 2018 and thereafter grow it to 10,000MW by 2030. The ambitious plan had targeted to get 1,600 MW from Geothermal, 1,920 MW from coal powered plant, 420MW from hydro, 650 MW from wind, 700MW from liquefied natural gas. The change in policy position is due to low-cost power expected to flow in from Ethiopia (3,019MW) and Uganda (380MW) upon completion of bipolar 500 KV HVDC and Double-Circuit 220 KV respectively. Again, the change has seen a shifting from coal and geothermal to renewable sources that has now added 310 MW from Lake Turkana Wind project and 50MW solar plant in Crarissa that were commissioned in 2018. Such envisaged regional power exchange implies increasing efficient generation's installed capacity by 30,000MW while adding 60 million new households and business connections by 2030. This requires about US$ 3 billion to install 7,500MW capacity transmission lines needed in the 10 cross-border power transmission projects covering a total of 5,000 KMs

Discussion

Implications of the findings in are herein discussed in respect to the broader perspectives of creating an effective integrated energy market.

Implication of Regional Infrastructure to Electricity Trading

In conjuncture with energy security theory by Shi and Kimura (2010), the region has recorded an improvement of about 3,155.4 MW worth of installed capacity, that can be used to augment emergence needs especially in the areas served by the 2,905 Km transmission network constructed during the study period. The generation infrastructure outlaid during the project period is 61% renewable sources in hydro, wind and solar. This resonates with the conclusions of Pollitt (2019) that a more open and integrating power market offers opportunities for development of renewable sources of energy. The ten inter-country connection networks in table 9, demonstrate a significant milestone for EAC regional power pool, in line with the arguments of Medinilla et al., (2019) and Andrews-Speed, (2011) that regional power pooling implies creation of regional network (grid) and transfer of electrical power between utilities in neighboring countries. Despite the progress in infrastructure layouts, the findings on surplus load implies that EAC region is operating an inefficient power pool system in terms of electricity trading. The recorded progress of about 47% in terms of the earned value for surplus load available for trade seem not to actually being traded. The relationship between surplus load and net electricity traded is insignificant at probability value of 0.26 (> 5%) as indicated in figure 10.

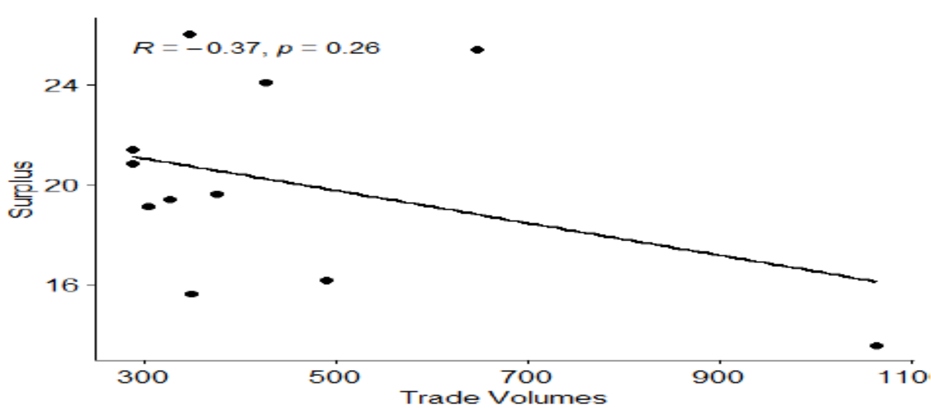

Figure 10. The linear regression curve for surplus load and trade volume

This exacerbates the risks associated with underutilized power generation facilities for countries like Kenya, Rwanda, Uganda and Tanzania where the total installed capacity exceeds domestic peak demand. The situation is less satisfying to the theory of regional growth convergence by Bhattacharya (2008), Kojima (2016), Shi and Kumura (2010) that views energy market integration as a means to reducing energy market volatility and facilitates growth convergence. For instance, electricity prices for EAC (EAC report 2022) continue to be divergent and electricity access indicators expected to arise out of economies of scale (Van heukelom & Bertelsmann-Scott, 2016) are still non-harmonized. However, time-series analysis conducted in this study indicate that even though little electricity has been traded (% of total surplus), it still registers some significant impact on overall GDP growth, industrial growth and electricity access indicators of the region. The statistical output in appendix 2, reveals 95% confident that there is a significant relationship between Net electricity traded (%of total demand) and these three variables. A unit increase in net electricity traded approximately increase the GDP value by US $ 18.7384 million, industrial growth rate by 0.7% and access to electricity (% total population) by 2.7%.

Much as infrastructure development is skewed to the principle of 'ahead of time planning' other than 'real time' or 'reactive demand' (Rubanda et al 2023a), investment analysis ought to signal investment recovery period. The negative relationship between increase in surplus load and exports portrayed in figure 10, signals increasing risk for loss on the investment outlaid in the region's excess capacity. For the period 2013-2022 the region has already lost about $190.1 million ((EAC report 2022) in such inactive trade. We observe and conclude that achieving full cross-border connectivity is not enough in itself to translate into effective electricity trading. This position is in line with proposition of Tandrayen-Ragoobur et al. (2022) that intra-regional trade infrastructure has two components; the hard infrastructure and the soft infrastructure. Both are significant and complement each other for effective trading. Technically, the lack of trade for the surplus load is in-part attributable to market management inefficiencies and weak harmony of policy frameworks among EAC domestic markets (Rubanda et al 2023b). Establishment of infrastructure without corresponding adoption of market governance tools such as compliance codes, coordination frameworks for TSOs and ancillary services (frequency response, voltage control, black start capacity, (Oureilidis, 2020)) and establishment of a regional independent regulatory board (IRB) that operationalizes the market.

The seek for possible solution to such persistent surplus load, draws regional power pool planners to the works of Murphy and Smeers (2005) suggesting that generation capacity expansion models can only be efficient if premised on competitive market generation. They identify three models (perfect competitive equilibrium, Open-loop Cournot game, Closed- loop Cournot game), all of which recognize possible variations in energy mix present in each partner state, and suggests flexibility according to individual market dynamics. This points to hypothetical questions about demand model(s) upon which the EACPP masterplan 2013-2023 targets were derived. Medinalla et al (2019) observes that endeavors in cross-border power exchanges in Africa are largely driven by energy security of individual partners states than regional market convergence goals. This perspective suggests a need for improvement to the resource adequacy assessment framework (Carvallo et al. 2021) used in this paper by disaggregating for clarity cross-border system so that investment is synchronized for both hard and soft infrastructure across the integrating domestic markets. Our conclusion construes five (5) merit-order stylized conditions for effective electricity trading in a regional market.

First, regional peak demand must be greater than domestic peak demand so that surplus generated power is exported.

$$\int_{t=0}^{t=t_1} \left\{ \sum_{\forall x} (H_0 + H_1 + \cdots + H_k) - RD \right\} dt \; > \; \sum_{\forall x} DD_i \; ; \begin{cases} 0 < t_1 < n \\ i = 0,1,2,\ldots,k \\ x = 1,2,\ldots m \end{cases} \quad (1)$$

where:

H_i is the i^{th} power generation technology.

x represents a country within a regional market

t represents any time period between the base period 0 (begin year) and the end period n (any point of time within a given year)

DD_i is the domestic peak demand

RD is regional peak demand

Second, there must be interconnections of utilities in the partner states.

$$i \leftrightarrow j \quad (2)$$

A country i within the region must be interconnected with a country j by transmission lines and other utilities for power trade to exist.

Third, regional market absorption capacity should be greater or equal to regional power supply in order to exploit economies of scale*;*

where:

$$\rightarrow Market\ absorption\ rate = \frac{Total\ power\ sold}{Total\ power\ generated}$$

$$= \frac{\sum_{all\ x} PS_x}{\int_{t=0}^{t=t_1} \{\sum_{allx}(H_0 + H_1 + \cdots + H_k)\}\, dt}$$

$$\rightarrow Regional\ power\ supply = \int_{t=0}^{t=t_1} \left\{ \sum_{allx} (H_0 + H_1 + \cdots + H_k) - DD \right\} dt$$

$$\therefore \frac{\sum_{all\ x} PS_x}{\int_{t=0}^{t=t_1} \{\sum_{allx}(H_0 + H_1 + \cdots + H_k)\}\, dt} \geq \int_{t=0}^{t=t_1} \left\{ \sum_{allx} (H_0 + H_1 + \cdots + H_k) - DD \right\} dt \quad (3)$$

Fourth, the maximum power transfer capacity for the distribution network in a given member country should be greater or equal to the maximum power transfer capacity of transmission lines connecting that country.

$$\sum_{all\ D-nets\ in\ J} TCD_{j_{max}} \; \geq \sum_{all\ T} TCT_{j_{max}} \quad (4)$$

where:

TCD_j is the power transfer capacity of the distribution network for country j .

TCT_j is the power transfer capacity of regional transmission line connecting country j.

T represents an inter-country transmission route within a regional market.

Fifth, the sufficient condition for sustainable trade in regional power pool is that total country benefit of operating in regional energy market must be greater than its accruable benefit of acting alone. Therefore, sustainable regional electricity trade occurs only when it is economically beneficial beyond a means for hedging supply shocks or a mere political endeavor.

$$Benefit\ of\ operating = \sum_{t=0}^{t=t_i} [(R + XR) - (C + XC)]$$

$$Accruable\ benefit\ of\ acting\ alone = \sum_{t=0}^{t=t_i} [(R) - (C)]$$

$$\therefore \sum_{t=0}^{t=t_i} [(R_x + XR_x) - (C_x + XC_x)]$$

$$\geq \sum_{t=0}^{t=t_i} [(R_x) - (C_x)] \quad ; \begin{cases} 0 < t_i < t_k \\ i = 0,1,2,\dots,k \end{cases} \qquad (5)$$

Where:

R_x revenue earned by a country x acting alone in the energy market

C_x cost incurred by a country x acting alone in the energy market

XR_x extra-revenue earned by a country x operating in the regional energy market

XC_x extra-cost incurred by a country x operating in the regional energy market

x represents a country within a regional market

t represents any time period between the base period 0 (begin year) and the end period n (any point of time within a given year)

Implication Earned Infrastructure to Regional Electricity Prices

Pricing mechanisms and market price behaviour is an applied indicator of how a given market operates. Predictable and competitive prices are associated with an effective market (Van heukelom & Bertelsmann-Scott, 2016). Nchofoung et al, (2022) in their study of linear and non-linear effects of infrastructures on inclusive human development in Africa, underscore price reduction as one of key objectives of investing in infrastructure. Despite the increase in stock of infrastructure and the reduction in investment cost by \$ 22,577million, witnessed in the EAC region for the period 2013-2022, that earned value is not reflective in electricity prices of the region. For the period 2013 to 2020, the trend of electricity prices in EAC region in Figure 11, indicates a growing gap between the minimum and maximum location prices of the region.

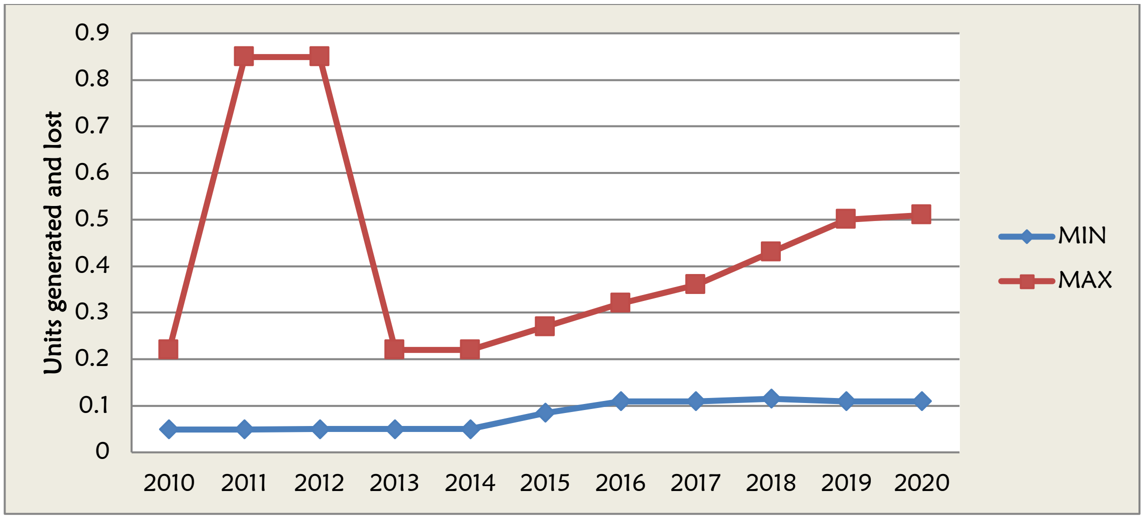

Figure 11. Location price variation for EAC electricity market 2010-2020.

Implication of Earned Value On Infrastructure to Electricity Access

Related to price, slow growth effects of infrastructure are noticeable in electricity access levels as well. Mckay et al. (2023) in the work of rethinking regional integration in Africa for inclusive and sustainable development re-echoes the argument of Blimpo et al. (2019) that for Africa to achieve the sustainable development goal of clean energy for all (SDG7), the continent should increase cross-border electricity trade as a strategy to avert inefficient investment in domestic generation. The trend of electricity supply in the region continues to be influenced by factors exogeneous to the region. For instance, the sharp fall of electricity price for the period 2013-2015, is attributable to global oil shock (IEA 2022). In terms of electricity access, the earned value on EAC infrastructure seem not to translate into harmonized access to electricity. Using selected access indicators in Table 8, there is sharp disparity among the EAC countries and some of them still fall below the average rates for sub- Sahara region.

Table 8. Regional comparisons for selected Electricity Access indicators 2022

Indicator	Burundi	Keny a	Rwanda	South Sudan	Tanzania	Ugand a	Sub-Sahara Average
% of firms experiencing outages	85.1	82.8	39	15.3	85.8	81.5	75.5
Number of electrical outages in a month	16.6	3.8	2.4	1.5	8.9	6.3	8.3
Average duration of outages (hours)	4.8	5.8	1	4.7	6.3	10.1	6.3
Average losses due to outages (% of annual sales)	3.4	5.4	2.4	13.6	15.1	11.2	7.8
% of firms owning or sharing a generator	64.2	65.6	33.8	73.3	43	52.2	50.7

Average proportion of electricity from generator (%)	17.5	17.8	7.8	94.2	24.5	17.6	26.8
Days of obtaining connection upon application	25.3	78.9	30.7	9.7	52.6	18.1	35.5
% of firms identifying electricity as a constraint	46.9	21	7.7	58.6	45.6	26.8	41

Source of data: World Bank; www.enterprise surveys.org

According to IEA report (2023), providing universal access to all Africans requires about USD 22billion annually from 2023 to 2030. This continues to raise the fundamental questions related to where the money will come from, and the methodology of expending it. Mobilizing infrastructure financing will require support from both the public and private sector as well as local and international institutions (IAE, 2023). But this investment has to be properly planned to develop both the supply side and demand side of electricity sector. Regional governments ought to develop electrification plans to stimulate households and businesses while utilities should endeavor to improve quality of services. Given the size and potential of the shadow sector, Ningaye & Ketu (2023), argue that midterm strategy for financing electricity infrastructure in Africa should prioritize commercialization of informal sector with a view of increasing absorption capacity that will in the long run generate revenues for utilities to invest in infrastructure for universal access.

Conclusion

Motivated by the desire to establish if there is adequate infrastructure that can facilitate electricity trading in EAC regional market, in this paper we conducted earned value analysis of the stock of infrastructure that has been constructed since establishment of EAC common market. The progress analysis is based on EACPP master plan targets for 2013-2023 implementation period. We tracked earned value on three sub-variables of infrastructure: - power generation infrastructure, cross-border transmission infrastructure, and infrastructure investment. Objective one, was to establish if there is adequate generation capacity to satisfy EAC regional market. Basing on, EACPP master plan 2013-2023 infrastructure, two indicators were analyzed. The installed capacity targets and surplus load targets. The study finds that progress on installed capacity for generation infrastructure has earned 54% of the planned target but the project is behind schedule by 46%, with one year left of the planned finish time. There is significant earned value for surplus load for electricity tading. The master plan anticipated availability of about 2,758 GWh valued at $740 million at current prices based on respective country forex rate by 2023. By the year 2022, earned value on surplus load at current prices is about $167.2 million representing about 47% of the total planned surplus/ tradable load for the period 2013-2023.

Objective two, was to establish if there is transmission capacity to evacuate the generated power across the region and finds significant progress on three indicators used to analyze cross-border transmission infrastructure. Planned distance (1,376 KM) was surpassed by 111%, planned Voltage (2,120 KV) was attained 100%, whereas planned load capacity was attained only up to 74%. Objective three, aimed at establishing if there are efficient investment inflows to realize the regions infrastructure needs. The study finds that the total cost spent on generation infrastructure is still within the planned budget, while transmission infrastructure has overshot the budgeted cost with cost variance (VAC) of about 323%. Comparatively, there is greater progress in cross-border transmission infrastructure (average SPI 1.2) than generation infrastructure (SPI 0.54). In line with resource adequacy framework, the disparity between generation infrastructure and transmission infrastructure may result into system inefficiencies due to idle resource on the transmission side. We recommend iterative planning guided by merit-order stylized conditions suggested in this study, so that the recorded progress on cross-border transmission infrastructure could incentivize power generation by connecting to a wider market. In the immediate term, supply side energy investment decisions could have significant electricity trade impact if prioritized towards addressing the current imbalance between generation and transmission infrastructure.

Despite the progress in infrastructure layouts, the EAC region is operating an inefficient power pool system in terms of electricity trading. For the period 2011-2022, there is recorded progress of about 47% in terms of the earned value for surplus load available for trade but actual trading is literary insignificant. The relationship between surplus load and net electricity trade in the region is at probability value of 0.2588 (> 5%). This exacerbates the risks associated with underutilized power generation facilities for countries like Kenya, Rwanda, Uganda and Tanzania where the total installed capacity exceeds domestic peak demand. Establishment of capacity-full power generation and cross-border infrastructure is not enough for trading to occur. The power pool system requires synonymous investment in market governance tools such as compliance codes, coordination frameworks for TSOs and ancillary services, and establishment of a regional independent regulatory board (IRB) that operationalizes the market. Policy guided efforts are needed at both bilateral and multi-country level. These include: setting of regional rules, coordinating interests of member countries and keeping political disagreements to a minimum. Establishment of energy trade Centre of excellence for regional power pool to promote exchange of knowledge and experience within the region and between regions could solve market asymmetries impeding trade possibilities. The center can also foster regional and global partnerships for aligned project development.

The erection of infrastructure in the region has majorly been financed through public loans and technical assistance from development agencies such as IEA, World bank, EU, and AfDB. Partner states need to strengthen domestic and regional sources of financing to cushion such an upcoming regional market from negative spills associated with over-externalization. Local financing increases participation, ownership and the desire to use networks efficiently. There is a need for frameworks that create predictable investment climate for independent power investments. Independent power producers provide a viable approach to increasing power generation especially to countries with limitations to accessing large capital for mega infrastructure projects. Investment inflows into regional power pool could make significant impact if channeled more into power generation infrastructure to match the existing cross-border transmission infrastructure especially during the second implementation phase of EAC master plan (2024- 2028). The data obtained on each variable studied was sufficient to draw conclusion for the set objectives. We recommend further studies to examine individual cross-border projects in terms of electricity trading facilitation, and possibilities of synchronizing the various regional power pool projects in terms of funding streams, unit costing and power exchanges. We recommend further studies to examine individual cross-border projects in terms of electricity trading facilitation, and possibilities of synchronizing the various regional power pool projects in terms of funding streams, unit costing and power exchanges.

Star Method Text

This section is organized under three headings; lead contact, material availability and data & code availability. However, to specify the types and analyses used in this paper, two levels of subheadings were adopted for the later headings.

Lead Contact

Further correspondences for information and request for resources used in this work should be directed to lead contact Ezra Muhumuza Rubanda (santarubanda@gmail.com)

Materials Availability

This study did not generate new unique reagents.

Data and Code Availability

Any additional information required to reanalyze this paper is available from the lead contact upon request. No access code is created for information related to this study.

Methods Details

Scope Literature

We conducted theoretical review of studies previously done in the area of electricity infrastructure and markets to align this work to the existing body of knowledge. The literature reviewed specifically focused on scientific knowledge about three study variables: Power Generation Infrastructure, Cross-border Transmission Infrastructure, Infrastructure Investment and how they affect electricity trading. We used four criteria to identify and select relevant scientific studies for inclusion or exclusion from the scope of theoretical review. *Subject relevance*- studies that in part or fully deal with electricity generation infrastructure, cross-border infrastructure, and infrastructure investments; *Level of market*- studies that concern themselves with regional markets with a framework of cooperation for electricity trading. We excluded studies of domestic markets for regional member states because they are majorly a product of inward- looking energy policies other than outward-looking policies relating to trade. *Geographical scope*- studies conducted in USA, Europe, Asia, Latin America, and Africa on topics relating to adequacy of regional electricity infrastructure; *Type of data*- studies of both quantitative and qualitative analysis type.

Theoretical Underpinning

We adopted three theories found relevant to this paper. These are the *energy security theory* by Shi and Kimura (2010) which advances energy security as the rationale for energy market integration. This perspective treats other benefits and incentives of integrated market such as energy efficiency, emergency response systems, reducing carbon emission, and energy trading as strategies to achieve energy security. The *regional growth convergence theory* by Bhattacharya (2008), Kojima (2016), Shi and Kumura (2010) elucidates that energy market integration reduces energy market volatility and facilitates growth convergence. Regional power pooling implies creation of regional network (grid) and market to trade and transfer electrical power between utilities in neighboring countries. For cross-border electricity trading to successfully occur, the generation and transmission are key functions to ensure that domestic customer(s) receive reliable power from distributor(s). Successful power pooling requires surplus power generation in some of the partner states (Andrews-Speed, 2011) plus providing an integrated power transmission grid (Medinilla et al., 2019), reliable and developed domestic transmission and distribution systems (Woolfrey, 2016); and the capacity to exploit economies of scale in the power generation (Van heukelom & Bertelsmann-Scott, 2016).

Peak Demand Model

We adopted Peak Demand electricity supply model (Kim et'al, 2022) and help the assumption that because of non-storability of electricity, it is efficient if all surplus power to a given domestic market is exported to a country with supply deficit.

Electric Power Grid Structural Model

We conceptualized study variables basing on Electric Power Grid Structural model (Daware, 2016). The model (fig.12) has four stages/components: generation infrastructure, transmission infrastructure; distribution infrastructure and consumption infrastructure. We selected the first two components as scope of this study.

Resource Adequacy Assessment Framework

We adopted Resource Adequacy Assessment framework (RAAF) as a tool for measurement of adequacy of electricity infrastructure (table 10). The framework helps to ensure real-time safe and reliable operations of the grid for sufficiently reliable power supply and to incentivize construction of new resources needed for future grid reliability in a cost effective and flexible manner (Carvallo et al., 2021).

Earned Value Analysis

We adopted Earned Value Analysis commonly used in construction projects (Proano-Narvaez et al., 2022) to analyze actual progress value registered in infrastructure development. The EVA conceptual framework is constructed on three (3) essential aspects of project delivery (scope, cost, and time) analyzed by the metric summarized in table 11.

We adopted EVA curve that illustrates conceptual relationship between the various EVA metrics over time, and at given point of project analysis (fig.13). It helps to establish when deviations from planned values are significant enough to warrant corrective measures, or when good performance, to earmark good practices to leverage for further efficiency improvements (Candido et al., 2014).

Quantification and Statistical Analysis

1) We applied progress monitoring methodology, which allows assessment of the real value attained out of the total intended desires of the entire project work.
2) Infrastructure Adequacy (IA) was identified as an influencing variable, and electricity trading as outcome variable. Infrastructure adequacy is measured by three components (sub-variables), which are generation infrastructure, cross- border transmission infrastructure, and infrastructure investment.
3) Respective formulas were derived and used to estimate the indicators of study sub-variables described in Table 12.
4) To obtain the adequacy of electricity generation infrastructure, we summed up the cumulative installed capacity for all power generation technologies deployed in all EAC countries for the

study period (2013-2022). We compared the spent cost with the estimated budget to install the planned generation capacity by 2023.

$$PGI\ adequacy = \int_{t=0}^{t=t_1} \left\{ \sum_{all x} (H_0 + H_1 + \cdots + H_k) \right\} dt \ ; \begin{cases} 0 < t_1 < n \\ i = 0,1,2,\dots,k \end{cases} \quad (6)$$

Where:
H_i is the i^{th} power generation technology measured in Mega Watts.
X represents a country within the East African Community
t represents any time period between the base period 0 (begin year) and the end period n (any point of time within a given year)

5) To arrive at infrastructure adequacy for surplus load available for regional trading, we obtained the difference between total installed capacity and total domestic demand for all EAC countries for the period 2013 to 2020 (current year).

$$PGI\ adequacy = \int_{t=0}^{t=t_1} \left\{ \sum_{all x} (H_0 + H_1 + \cdots + H_k) - DD \right\} dt \ ; \begin{cases} 0 < t_1 < n \\ i = 0,1,2,\dots,k \end{cases} \quad (7)$$

Where DD is the part of generated power that is consumed domestically.

6) We obtained the earned value from the product of Power Generation Infrastructure Adequacy and Regional average price of electricity expressed in kWh^{-1}

$$Earned\ Vaue = PGIA \times Regional\ Average\ Price\ per\ kwh^{-1}$$

$$EV = \left[\int_{t=0}^{t=t_1} \left\{ \sum_{all x} (H_0 + H_1 + \cdots + H_k) - D \right\} dt \right] * P_A\ per\ kwh^{-1} \quad (8)$$

Where; P_A represents electricity price in the current period

7) Due to difference in the units of measurement, we analyzed the transmission infrastructure adequacy using three parameters: distance, voltage, and load. The values at current period are compared to the projected values for the period 2013-2023.
8) We obtained capacity transmission infrastructure in terms of load by summing the amount of load transmitted by all the cross-border grids for the planned period.

$$CTI_L = \sum_{t=0}^{t=t_i} \sum_{all\ z} L \quad ; i = 0,1,2,\dots,n \quad (9)$$

Where, L represents the load capacity measured in Mega Watts.
Z represents the cross-border transmission grids in the region

9) We obtained the adequacy of transmission grid in terms of distance, by summing the kilometers of all the cross-border grids for the planned period.

$$CTI_d = \sum_{t=0}^{t=t_i} \sum_{all\, z} D \qquad ; i = 0,1,2, \ldots , n \tag{10}$$

Where, d is the distance of cross-border grids measured in Kilometers (KM).

10) We obtained capacity transmission infrastructure in terms of voltage by summing the constructed transmission grid lines' voltage capacity for all the cross-border grids for the planned period.

$$CTI_v = \sum_{t=0}^{t=t_i} \sum_{all\, z} V \qquad ; i = 0,1,2, \ldots , n \tag{11}$$

Where, V is the voltage in terms of transmission capacity measured in kilo-voltage.

11) To obtain the earned value on investment for infrastructure, we assumed the budgeted cost for regional infrastructure to be the initial outlay, and other costs related to operation and maintenance are not included in the analysis.

$$Investment\ (PGI) = \sum_{t=0}^{t=t_i} \sum_{all\, x} (I_0 + I_1 + \cdots + I_m) \qquad ; i = 0,1,2, \ldots , n \tag{12}$$

where, I_i is the investment cost of installed capacity for the i^{th} technology.
X represents a country within the East African Community.

$$Investment\ (CTI) = \sum_{t=0}^{t=t_i} \sum_{all\, z} I_C \qquad ; i = 0,1,2, \ldots , n \tag{13}$$

Where, I_c is the total cost of transmission investment for the c^{th} cross border grid line

z represents cross border grid line

12) We collected data in line with formulas in equations *6-13.*
13) Data on power generation infrastructure, cross- border transmission infrastructure and costs incurred on both the generation and transmission infrastructure projects was collected from EAC. This was done in two levels: first, information was requested on infrastructure planning from the Department of Energy at East Africa community secretariat. The secretariat availed the SNC- Lavalin Report 2011, that presents the infrastructure projects planned in the region for under the EACPP Master Plan 2013-2038. The implementation of the master plan is in two phases, which are Phase-I (2013-2023) and Phase-II (2024- 2038). This study viewed each of these implementation phases as 'a project'.
14) The second level of data collection was on information about of implementation of the 2013-2023 project. The choice to concentrate on Phase-I (2013-2023) project, was based on the fact that its work-break down structure (WBS) was detailed to third level deliverables in terms of costs, time and scope. The 2024-2038 phase is just conceptualized in terms of ambitious targets without funding budgets.
15) Two sections of infrastructure including generation and transmission projects were covered. For each infrastructure section, the collected information included estimated schedule of planned work, work scope progress, expenses incurred, execution time, reference budget, and time extensions. Data on power generation infrastructure covered all the planned and implemented technologies in each EAC member state. However, Democratic Republic of

Congo, which joined the EAC on 8th April 2022, lacks data and was not covered by the analysis. The cross-border transmission data covered planned and implemented infrastructure for inter-connectivity of EAC partner states.

16) Data was collected on three types of overhead transmission lines, including: short transmission lines (line length up to 60 km with voltage below 20 kV); medium transmission line (line length between 60 km and160 km with voltage from 20 kV to 100 kV); and long transmission line (line length beyond 160 km and voltage above 100 kV).
17) Data on investment was based on budget estimates and actual expenditures of a given infrastructure project's approved plans and implementation reports respectively.
14) Additional information on study variables, including energy prices, energy demands, and exchange rates was sourced from progress reports from electricity regulatory bodies and central banks of respective partner states covered in the study.
15) Since the EVA methodology requires working with direct cost values associated with physical progress, data was broken down and grouped according to execution periods (years) of the project. At this stage information was organized according to the deliverables in the work break-down structure. Changes in the overall project budget at this stage due to modifications in the scope of the project were identified too.
16) Data was entered in excel for cleaning, especially identifying and removing duplicates, incorrect or missing values and outliers. Thereafter, *R statistical programming software* was used for data transformation and analysis.
17) The surplus load was obtained by deducting electricity demanded domestically from electricity generated for each country in particular year.
18) To obtain the earned values (in US $), selected variables were multiplied by the Weighted Average Electricity price ($/kwh) with respect to the country and year.
19) Data was analyzed using techniques and metrics defined in tables 10 and 11. With information processed in step 27, analysis tables 3 to 7 were generated on the three study sub-variables; Power Generation Infrastructure (PGI), cross-Border transmission Infrastructure (CTI), and Infrastructure Investment (II) in line with EVA guidelines. Subsequently, basic EVA metrics of PV, AC, EV and BAC (table 11) were determined and used to evaluate the cost and schedule of the project. Further, progress indicators including CV, SV, CPI and SPI, were computed, and used to evaluate the status of the project in terms of cost and scope performance.
20) Results relating to basic metrics, schedules, and performance indicators were then presented in figures 1 to 9 for visualization.
21) We computed Pearson's correlation coefficient between surplus load and the megawatts of electricity traded in EAC, to determine the relationship between infrastructure adequacy and electricity trading. The outcome of the correlation coefficient draws the implication of the earned value on infrastructure adequacy.
22) We conducted a time-series (2010-2022) analysis to ascertain the impact of traded electricity growth of the region. Traded electricity was regressed on GDP value, industrial growth, and electricity access.
23) We analyzed the implication the recorded progress in infrastructure has had to electricity pricing in the EAC region.
24) Analysis was done of the impact of infrastructure progress on electricity access since electricity trading is a means for increasing energy access.

Star Methods Table

Table 9. Resources used in the study methodology

#	Resource	Source	Identifier
Infrastructure Measurement tools			
1	Electricity Peak demand Model	Kim et'al (2022)	https://doi.org/10.3390/math10234486
2	Hypothetical Electric Power Grid System (PGS)	*Daware, 2016*	https://www.electricaleasy.com/2016/01/electrical-power-grid-structure-working.html
3	Resource Adequacy Assessment Framework (RAAF)	Carvallo et al., (2021)	https://emp.lbl.gov/publications/implications-regional-resource
4	Earned Value Analysis (EVA)	Proano-Narvaez et al., (2022)	https://www.pmi.org/learning/library/earned-value-management-systems-analysis
5	EVA Analysis curve		https://doi.org/10.3390/buildings12030301
6	Pearson's correlation coefficient	Xu et al., (2022),	http://dx.doi.org/10.1098/rsos.200386

Supplemental Information

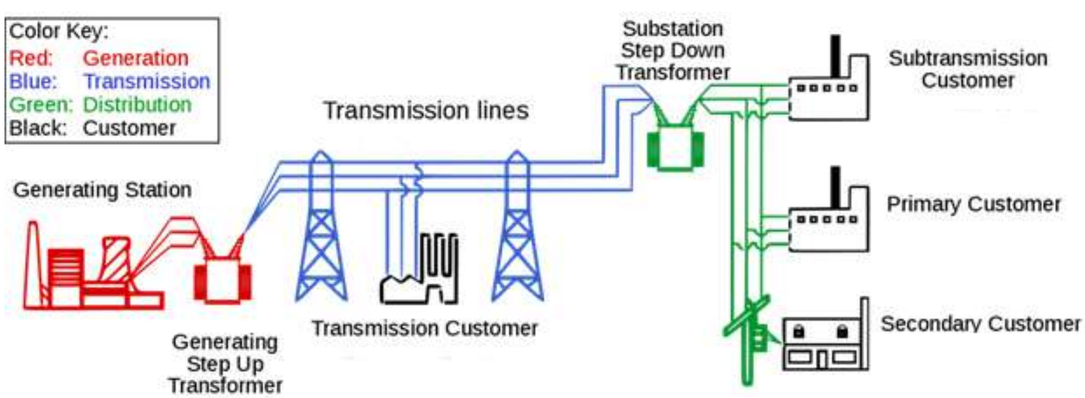

Fig 12. Hypothetical electric power system (*Source: Adopted from Daware, 2016.*)

Table 10. Resource Adequacy Assessment framework metrics for electricity trading system

Resource	Planning drivers	Application
Functional cross-border power system	Infrastructure adequacy	Estimating Load carrying capacity
	Load demand	Jurisdictional load forecasts
	Reliability	System load forecasting
	Cost efficiency	Designing of Maximum Import Capacity (MIC) methodology

Source: Carvallo et al. (2021)

Table 11: EVA parameters for infrastructure development

Metrics	Formula	Interpretation	Application
Planned Value (PV)		Approved budget for work scheduled to be completed by a specified time.	Basic EVM metric computation
Earned Value (EV)		Value of work completed as of specified time.	
Actual Cost (AC)		Costs incurred for work completed at specified time	
Cost Variance (CV)	CV = EV- AC	Variance indicating whether a project is under (+) or over (-) budget	Progress Performance Indicators (PPIs)
Schedule Variance (SV)	SV = EV-PV	Indicates whether a project is ahead (+) or behind (-) schedule.	
Cost Performance Index (CPI)	CPI = EV/AC	Measures the efficiency with which economic resources are used. if less than 1, the project has a higher actual cost than budgeted (cost overrun); if equal to 1, the project has actual price equal to the projected cost; and if greater than 1, the project has lower actual cost than budgeted.	
Schedule Performance Index (SPI)	SPI =EV/PV	Measures efficiency in the use of time. if it is less than 1, the project is behind schedule; if it is equal to 1, the project is on schedule, and if is greater than 1, the project is ahead of schedule.	
Budget at Completion (BAC)	Total of budget	Total sum of all budgets authorized at the beginning of a project.	
Cost Variance (VAC%)	VAC=(BAC-EAC) /BAC	Indicates the variance in the final cost of the project with respect to the original.	
Estimated cost at Project Completion (EAC)	EAC =AC+(BAC-EV) /CPI	Indicates how much the project will cost in the end if the cost performance index (CPI) remains the same.	Forecast Indicators
Estimated cost to complete the project (ETC)	ETC=(BAC-EV) /CPI	Estimated cost required to complete the remainder of the project.	

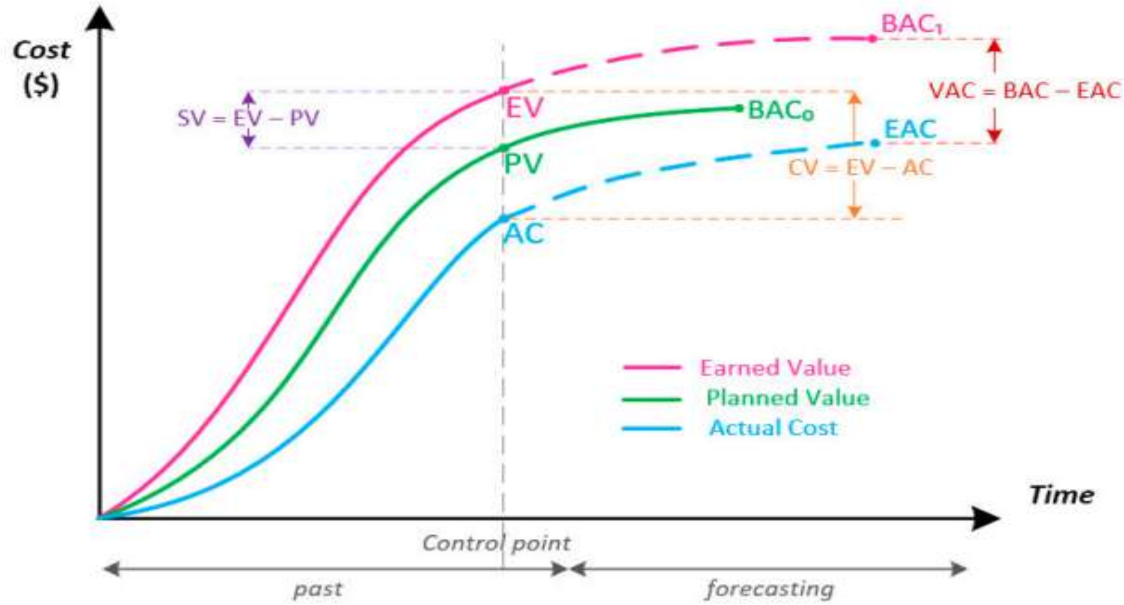

Figure 13: Key parameters of EVA (adopted from Proano-Narvaez et al., 2022)

Table 12. Description and measurement of Infrastructure Adequacy

Sub-Variables	Indicator	Description	Unit of Measurement	Assessment Metrics
Power Generation Infrastructure (PGI)	Installed Capacity	Power generation of a particular plant. It can come from hydropower, thermal, solar, wind or nuclear energy	Megawatts	PV, EV, SPI
	Electric Load	An electric load is the part of circuit in which current is transformed into something useful	Megawatts	PV, EV, SPI
	Tradeable load	Surplus load to domestic market of an electricity generating country that can be exported to a regional market.	Megawatts	PV, EV, SPI, SV
Cross-border Transmission Infrastructure (CTI)	Transmission capacity	The amount of power which can be sent over a transmission line within acceptable line losses limit	Megawatts	PV, EV, SPI
	Transmission Voltage	The technological capacity of the transmission line to efficiently transmit power from the source in a generating country to substation in importing country	Kilo-voltage	PV, EV, SPI
	Length	Total distance covered by all categories of overhead	Kilometers	PV, EV, SPI

Sub-Variables	Indicator	Description	Unit of Measurement	Assessment Metrics
		transmission lines short, medium and long lines for cross-border connectivity.		
Infrastructure Investment (II)	Investment cost	The amount of money spent to establish power infrastructure for power pool	US $	VAC, CPI, CV, AC
	Project time	The time between the Start date and End date of constructing a given power infrastructure	Years	SV, SPI

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Appendices

Appendix 1: Some of EAC cross-border projects (2013-2023)

Countries	Sub-stations	Updated COD	Capacity (MW)	Voltage (KV)	Length (KM)	Cost (USD) Million
Ethiopia - Kenya	Wolayta-Sodo-Suswa	2019	2,000	500	1,010	1,260
Kenya-Tanzania	Isinya-Singida(EKT)	2021	2,000	400	463	310
Kenya - Tanzania	Kisumu-Mwanza (Nile basin)	-	400	220	496	120
Uganda -Kenya	Bujagali- Tororo-Lessos	2019	440	Ug 220 KV KY 400KV	151	380
Uganda-Rwanda	Mbarara- Mirama	2018	440	220	200	58
Uganda-Tanzania	Masaka-Mwanza	2022	200	220	582	-
Uganda-SS	Karuma- Juba	2021	-	400	190	47
Uganda- DRC	Kasese-Bunia	2019	-	220	352	150
Rwanda - Tanzania	Rusumo- Nyakanzi	2019	400	220	120	33
Burundi- DRC	Ruzizi II hydroelectric dam Bujumbura	-	-	-	78	47

Appendix 2. Electricity traded and selected growth Indicators for EAC

```
## Set working directory
setwd("E:\\Projects\\WORKS\\ElecPool\\Call261123")

library(tidyverse)
DataQ <- readxl::read_xlsx("DataQ.xlsx")
```

GDP value in U$

```
model <- lm(V003~V001, data = DataQ)
summary(model)
##
## Call:
## lm(formula = V003 ~ V001, data = DataQ)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -37.592 -10.429   3.007   8.067  42.168
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) 294.1210     7.1370   41.21   <2e-16 ***
## V001         18.7384     0.9794   19.13   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 17.48 on 50 degrees of freedom
## Multiple R-squared:  0.8798, Adjusted R-squared:  0.8774
## F-statistic: 366.1 on 1 and 50 DF,  p-value: < 2.2e-16
```

General Consumer Index

```
model <- lm(V004~V001, data = DataQ)
summary(model)
##
## Call:
## lm(formula = V004 ~ V001, data = DataQ)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -26.043 -18.064  -1.686  10.139  40.916
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  197.141      8.631  22.842  < 2e-16 ***
## V001           7.215      1.184   6.092 1.57e-07 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
```

```
## Residual standard error: 21.13 on 50 degrees of freedom
## Multiple R-squared:  0.4261, Adjusted R-squared:  0.4146
## F-statistic: 37.12 on 1 and 50 DF,  p-value: 1.573e-07
```

Industrial Growth Rate (%)

```
model <- lm(V005~V001, data = DataQ)
summary(model)
##
## Call:
## lm(formula = V005 ~ V001, data = DataQ)
##
## Residuals:
##    Min     1Q Median     3Q    Max
## -9.510 -3.518 -1.138  4.062 17.174
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  10.6867     2.4325   4.393 5.81e-05 ***
## V001          0.7509     0.3338   2.249   0.0289 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 5.956 on 50 degrees of freedom
## Multiple R-squared:  0.0919, Adjusted R-squared:  0.07374
## F-statistic:  5.06 on 1 and 50 DF,  p-value: 0.02892
```

Access to Electricity (% total popn)

```
model <- lm(V006~V001, data = DataQ)
summary(model)
##
## Call:
## lm(formula = V006 ~ V001, data = DataQ)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -5.5115 -1.2438  0.2211  1.1859  5.7678
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  37.5778     0.9059   41.48   <2e-16 ***
## V001          2.7210     0.1243   21.89   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 2.218 on 50 degrees of freedom
## Multiple R-squared:  0.9055, Adjusted R-squared:  0.9036
## F-statistic: 479.1 on 1 and 50 DF,  p-value: < 2.2e-16
```