

Assessment of grid electricity systems using the life-cycle carbon-emission model

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Abstract. The previous study developed a life-cycle carbon emissions (LCCE) algorithm in MS Excel. Despite improvements, a comprehensive approach is needed to conduct life-cycle carbon emissions inventory (LCCEI) analysis using current methods. This study diverges from existing research by assessing LCCEI data of power generation and transmission systems on studied grids, considering component lifespans, recycling pollutants, and retirement rates. The life-cycle carbon emissions inventory analysis results improve understanding of power system environmental performance, aligning with stakeholders' objectives. This study aims to enhance the environmental performance of electric power systems in Kenya, Rwanda, and Tanzania by evaluating the LCCE of power generation and transmission within their national grids. The selected grids are the right participants for the study, of non-renewable and renewable grid electricity generation mixes, due to their different environmental features, potential power trade, upcoming grid interconnection, and power transmission practices at various scales. The study applied a life cycle assessment method and simulated the learning patterns using RStudio. The data (emission factors and activity) has been collected from the reports (scientific and technical) and national utility actors. The presented results show that only Kenyan generation and transmission systems have a lifetime decarbonization performance relationship between renewable energy sources dominated power systems and non-renewable energy sources dominated power systems. A major challenge of this study has been the scarcity of primary data, leading to reliance on some secondary and external sources. Therefore, future research should consider the use of more internal and primary data sources, and the use of the most current data, including new technologies adopted from cradle-to-grave of the systems. This study's findings inform better system designs, policies, and plans for improved environmental performance in electrical power systems.

Keywords: Grid electricity systems, Life-cycle carbon-emissions, Renewable and non-renewable power.

1 Introduction

The electrical power system master plans are changing from being dependent on using non-clean and non-renewable energy (fossil-fuel) sources to incorporating clean and renewable electricity [1–3]. The installed renewable capacity in Africa is 49.5 GW out of the total installed capacity of 236.2 GW [4]. Plans are also moving in the direction of the adoption of more efficient power electronic devices for electrical power systems design and operations [5, 6]. Africa accounts for a comparatively small but increasing share of the world's carbon emissions [7]. Specifically, Africa accounts for roughly 4% of the world's energy-related

carbon dioxide emissions regardless of being home to around 17% of the population. The power sector is the leading emitting one (480 MtCO₂), and the next emitting sector is transport (355 Mt CO₂) followed by industry (150 MtCO₂) [7]. However, Africa is among the highest vulnerable regions to the impact of climate change and other environmental phenomena. With growing concerns over environmental governance (EG) for the development of clean power systems, a proper understanding of the significance of the production, transmission, and distribution of renewable power systems [8] and their attributes is required. Therefore, the association of environmentally sustainable power system economies and communities as identified in the United Nations sustainable development goals (SDG) and Goal number seven (7) of the African

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Agenda 2063 [3] should be recognised. The life-cycle inventory analysis (LCIA), in which system output/input data are categorised and combined to better realise their environmental implication, was conducted following the goal and scope in [9]. The process of accounting for energy and emissions is identified as a life cycle assessment (LCA) [10]. The LCA can also be defined as a logical valuation of probable environmental effects and natural resource use related to a product, such as electricity, taking into reflection the whole lifespan of the product itself as well as associated inputs [5]. However, there is inadequate scientific evidence on the life-cycle environmental impact (particularly CO₂ emissions) from electrical power systems in African countries, especially in sub-Saharan Africa. To date, little research has been conducted to check the environmental performance of studied grids.

A previous study showed that areas with indigenous gas resources have the significant advantage of possessing a reliable and relatively clean energy source. However, the policy of saving gas reserves for use as a backup fuel for renewable resources, such as solar [11–13] hydro, and wind power [14], which are intermittent, is still a better option than burning it as quickly as possible [15]. Smart energy systems consider merging electricity with various storage options [16], heating, and transport sectors to create the required tractability to integrate large diffusions of unstable renewable energy [17]. The good thought of the environmental impact of power use in society must contain a comprehensive thoughtful of T&D systems. Such systems have an effect owing to both electricity losses (during operations) and T&D infrastructure (during installations and maintenance). For example, in forested sites, the entire right-of-way (ROW) width is cleared and remains open for the life of the transmission line [18]. However, environmental sustainability assessments of the grid power generation regularly fail to contain the impact of T&D systems, possibly causing improper findings [19, 20]. The previous study estimated the life cycle carbon emissions of new T&D lines on the studied grids, influenced by land cover, topography, and existing land use [21].

The previous study also established the life-cycle carbon emissions (LCCE) mathematical algorithm [8] and coded it in the MS Excel worksheets [22]. Earlier results revealed that the LCCE due to vegetation cleared in the operation of electrical power transmission and distribution [21] contribute less impact on climate change than LCCE due to power generation [23]. Although some efforts have been made to improve LCCE methods, and the life-cycle carbon emissions inventory (LCCEI), there's still a need for a comprehensive approach to undertake the life-cycle carbon emissions inventory analysis (LCCEIA) using the prevailing LCCE methods and obtained LCCEI data. Carrying out the LCCEIA of both electric power generation and transmission systems is essential for providing information on the design of technologies related to clean electrical power systems. Nonetheless, most earlier studies engaged data that did not necessarily reveal the power systems and the environment in the country's status at the moment. This study therefore diverges from existing research by evaluating the LCCEI data of both electrical power generation, and transmission systems, including component lifespans,

recycling pollutants, and retirement rates of new and existing installations focused on the studied grids. The obtained LCCEIA results enhance understanding of the environmental performance of various power system designs and operations, aligning with the goals of system operators, researchers, and policymakers. The findings are used to propose improved plans, policies, and designs for electrical power systems with higher environmental performance.

The overall problem talked about in this study is an inadequate understanding of the lifetime decarbonization performance relationship between renewable energy sources dominated power systems and non-renewable energy sources dominated power systems. The goal of this study was to improve the environmental performance of electric power systems in Kenya, Rwanda, and Tanzania by reducing emissions through optimizing energy efficiency and promoting sustainable planning and practices in the power systems. The objective of this study is to assess the LCCE of electric power generation and transmission in studied national electric grids using a mathematical model developed within the LCA system boundary framework. However, the study has answered the research question “Is there a lifetime decarbonization performance relationship between renewable energy sources dominated power systems and non-renewable energy sources dominated power systems?”.

Given their environmental features, potential power trade, upcoming grid mixes and grid interconnection make Kenya, Tanzania and Rwanda the impeccable nominees for the study of both non-renewable and renewable electricity generation sources, and transmission practices at diverse scales located in both Southern Africa and Eastern Africa power pools. The environmental performance of the studied grids was assessed in terms of potential life-cycle carbon-emission (CO₂e) intensities. The LCA is among the most promising methods for sustainability assessment of designed plans and policies for an electrical power system.

Section 2 explores the grid electricity generation capacity from various electricity natural wealth in the study area. It also presents the evaluation of power loss using the developed MS Excel dataset for the studied grids of three sub-Saharan countries, from the base year 2019 to 2049. Section 3 provides results showing the relationship between renewable-dominated power systems and environmental improvement using more advanced graphical tools with improved reproducibility obtained through Monte Carlo simulations with RStudio and discusses its policy, design and practice implications. However, in this study, the primary data sources are limited, with the majority of the results drawn from secondary and external sources. The study concludes with the pre-defined postulation that could be used to develop clean electrical power systems flows within the studied countries and the region as a whole.

2 Methods

2.1 Scope, boundary settings, elementary flows, and data collection

The methodology overview of this study is shown in Figure 1. Each life cycle sub-component process involves

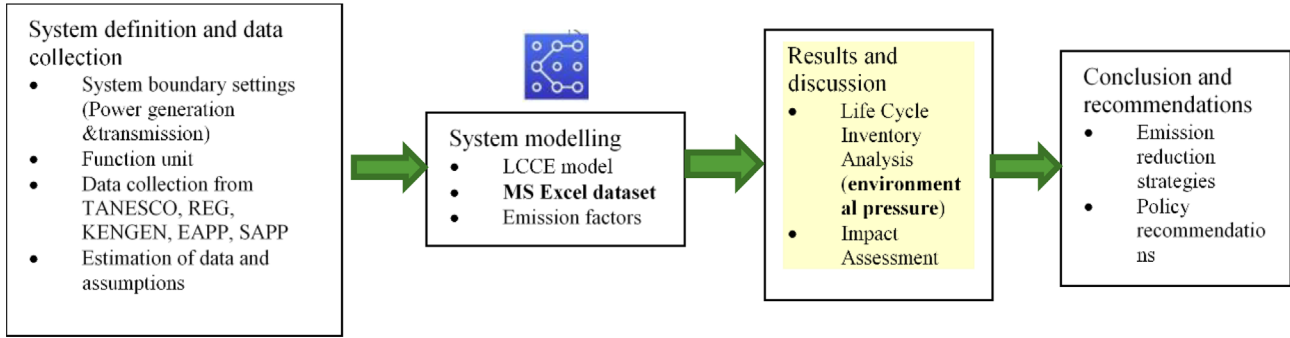


Fig. 1. Methodology overview for assessing the LCCE of the studied, electrical power systems, series of activities (Modelled after [11, 24]).

energy inputs and emission output. The selected base year 2019 data has been used to explore the potential energy resources of the studied grids. The functional unit for this study has been defined as electricity (1 MW) received at the distribution power station.

The activity and emission factor data have been found from technical and scientific sources as well as electrical energy institutions, including *Rwanda Energy Group (REG)*, *Tanzania Electric Supply Company (TANESCO)*, *Eastern Africa Power Pool (EAPP)*, *Southern African Power Pool (SAPP)*, *Kenya Electricity Generating Company (KENGEN)* and *Kenya Electricity Transmission Company Limited (KETRACO)*. The data has been acquired from appropriate institutional actors through face-to-face discussions, and reviews of consistent published data. The developed LCCE background dataset has been replicated through Monte Carlo simulations with RStudio to obtain the probable LCCE values.

The perimeter and scope of the life cycle evaluation of the electrical power system, components, and series of processes chain involved is illustrated in Figure 2. The cradle-to-gate analysis for this study involves a series of activities starting from the extraction of raw energy materials (such as coal, biomass, gas and diesel) and then continuing to the pre-processing stages before finally getting to the stages of power generation and transmission of the final power product. The gate-to-gate assessment involves the use of raw energy materials or resources for generating and transmission power, the gate-to-gate omits the energy extraction stages from the studied system boundary).

The cradle-to-grave power systems boundary covers the whole series of activities involved in the extraction of raw energy resources delivered to power generation, power T&D, power use, reuse, recycling, and final disposal. However, the mathematical model for this study has adopted the gate-to-gate, and some grave analysis.

The main phases of the LCA presented by this piece of work are indicated in, the flow chart, Figure 3.

Based on the available activity and emission factor data, the elementary LCCE flows of the power product have been evaluated to obtain the environmental performance (neutrality) feedback for strategic power system design and operation. The simple descriptions of a process

have been used to calculate or predict the LCCE from the gate-to-gate, and some end-user's activities.

The elementary flows and basic formula have been presented and adopted to estimate the LCCE between the life cycle inventory and life cycle impact assessment phases of this study as expressed in Figure 4.

The series of the gate-to-gate, and some end-users, electrical power system, and activities for the studied elementary LCCE flow, have been calculated using both existing and assumed facts, and mathematical representations as indicated in equation (1) [22],

$$LCCE, t = Qm, t \times EFm, t + SP, t \times Efo, t + RR, t(1 - RC, t). \quad (1)$$

Where:

- $LCCE, t$: life-cycle carbon-emission values of studied power systems (kg) in the year t ,
- Qm, t : amount of newly added transmitted power capacity (MW) in the year t ,
- EFm, t : embodies the amount of carbon release factor of the power produced by the new installation, maintenance, and operation (kg/MW) in the year t ,
- SP, t : is a power capacity (MW) installed and persisted by the base year t ,
- Efo, t : embodies a carbon release factor of the electricity system capacity installed, maintained, operated, and persisted (kg/MW) by the base year t ,
- RR, t : embodies the residual amount of carbon releases from recycled and retired/substituted power (kg) in the year t , and
- RC, t : embodies the recycling coefficient of the residual power capacity (s) retired in the year t .

The data have been obtained within the established system boundary using parameters developed through a mathematical algorithm and coded in the MS Excel worksheets. The established worksheet parametric values have been assessed based on the recognised mathematical algorithm, key assumptions and scenarios, and the system boundary model. Some key parameters such as energy storage

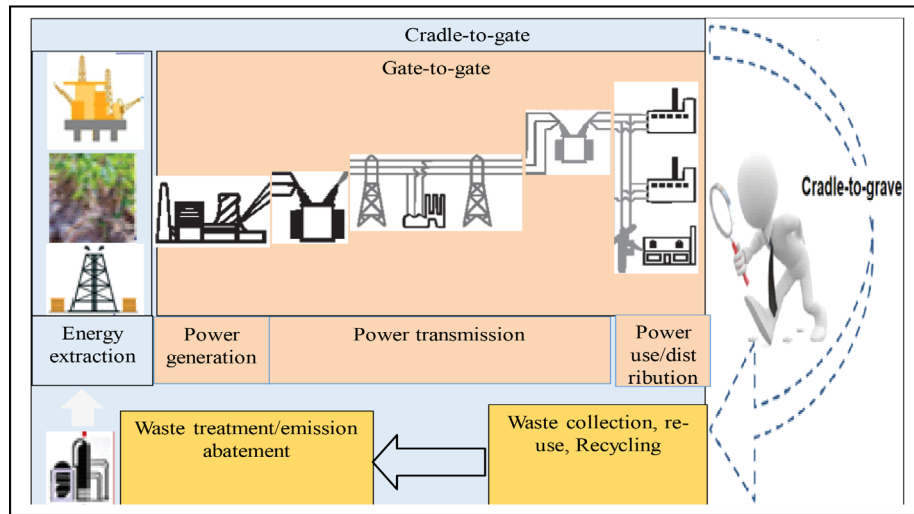


Fig. 2. LCA system boundary settings for the studied, electrical power systems, series of activities (Modelled after [18, 25]).

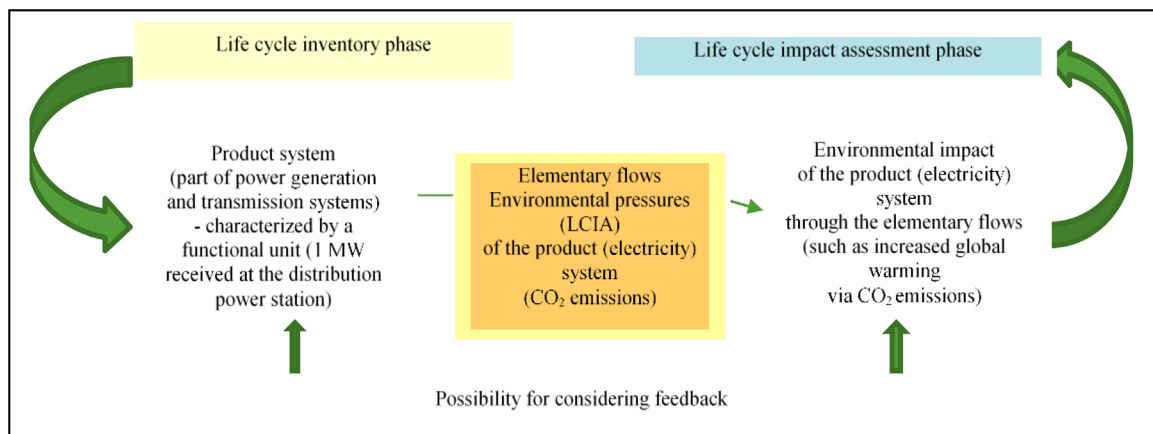


Fig. 3. LCCE flow of the studied series of electrical power system activities (Modelled after [26]).

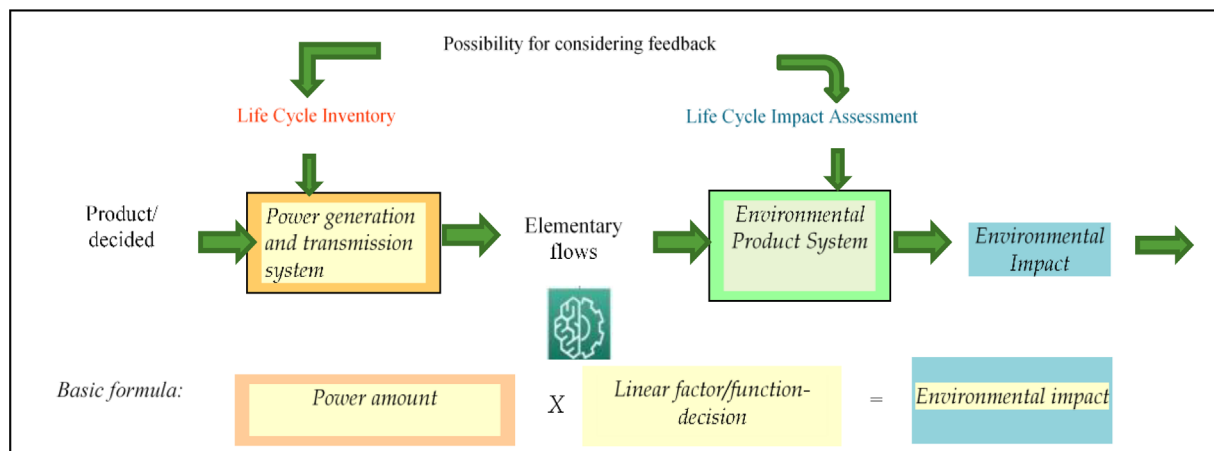


Fig. 4. Model representation for the LCCE evaluation adopted by the study (Modelled after [13, 26]).

Table 1. The numerical information of the BAU and EG scenarios for the studied grids by the year 2049 (Modelled after [8]).

Model parameters	Unit	BAU			EG		
		Kenya	Rwanda	Tanzania	Kenya	Rwanda	Tanzania
SP, t	MW	2819.00	216.20	1567.00	2819.00	216.20	1567.00
EFo, t	kg/MW	0.02	26.80	0.06	0.02	26.80	0.06
Qm, t	MW	600.50	70.40	1914.50	0.26	3.50E-03	0.70
EFm, t	kg/MW	0.03	0.94	0.07	1.86E-03	1.63E-03	1.38E-03
RR, t	kg	4.58	0.54	9.89	1.9E-03	2.54E-05	4.66E-03
RC, t	%	27.00	51.00	50.00	62.00	62.00	55.00

equipment, e-mobility, power electronics, distribution power loss, and grid stability have been omitted to streamline analysis. The chosen parameters have been selected to provide a detailed sustainability assessment, emphasizing long-term impacts, and have proven sensitive to result variations upon value changes.

2.2 Evaluation scenarios and assumptions

The study compared emissions between generation and transmission power systems in three sub-Saharan countries from the base year 2019 to 2049. For easiness, only business as usual (BAU), and EG scenarios have been studied. The BAU scenario has assumed a low amount of recycled emissions, due to the presently comfortable renewable energy policies and regulations. The BAU scenario assumed the expansions in hydropower, geothermal, photovoltaic, and wind power have been considered to rise gently; the advances in electricity generation technology have been anticipated to remain constant, and the electricity demand and LCCE per unit electricity produced persisted as established in the current design. The recycling, efficiency as well as replacement ratios have also been established as insubstantial. The BAU scenario predicts sluggish renewables growth, stable technology, steady demand, and limited recycling under existing policies. Conversely, the EG scenario anticipates continuous renewable expansion, smart grid integration, efficient energy utilization, decentralized generation, minimized transmission losses, and a balanced consumption-generation dynamic, aiming for a net-zero future by 2050 or earlier. The BAU assumption underestimated the urgency of transitioning to renewable energy, potentially leading to higher LCCE. Conversely, the EG assumption promoted renewables, likely resulting in lower LCCE compared to BAU. The numerical information of BAU and EG scenarios has been provided in Table 1. The grid LCCE dynamics for the Kenyan, Rwandan, and Tanzanian power systems have been calculated by adding together all aspects of the LCCE from the diverse generation technologies. The current activity data (operational power system capacities) and power generation grid-specific LCCE factors have been obtained from both primary and secondary sources, professionally assumed, and calculated.

The installed generation capacity for the case studies by the year 2049 was gradually tuned from the previous year of prediction existing on the most newly modernised power

master plan(s). The sizes of new power generation plants have been established according to the Eastern Africa power pool and the current master plans obtained in the studied grids [27–29]. The data on electricity mixes and capacity have been assumed from the current restructured national power systems designs of the studied countries. The specific emission factor of the transmission has been sourced from the published power data and method. The assumed EG scenario for the specific case comprised the reflection of cleaner power production measures in the perspective of present and upcoming power system development, *e.g.* by enhancing approval of wind farms, solar roof-top technologies, energy-saving technologies, mini-hydro technologies, biomass technologies, interconnections, and regional electricity trades, ever-changing from non-renewable to renewables, power transmission loss control, and smart grid integration [8, 13]. The EG scenario anticipated that the power system capacity and upcoming per capita grid-electricity demand amplified somewhat gently in contrast with the BAU scenario, due to the assumption of efficient power use measures. Dispersed generators have been presumed to be present at both the consumption and generation sides of the electrical power system, comprising wind, mini or small hydropower, large-hydropower, geothermal power, and solar systems generation units. Smart grid theories have been presumed, to balance consumption and generation.

The power mixes of upcoming power generated under the EG scenario have been presumed to be controlled by renewable power sources. The EG scenario in the study area reflected the peak use of geothermal power resources to develop electricity power systems that are resistant to climate change impact. The EG scenario also reflected the optimal use of mini-hydropower plants and small-hydropower plants (compared to large-hydropower plants) to improve the dispersed generation and community involvement. On the other hand, the extreme carrying capacity for the hydro-power generation capacity development plans by 2049 has been recognised as less than 70% of the grid electricity combinations, to ensure environmental sustainability [8]. A recycling factor regarding the residual CO₂ measurements of the capacity transferred and retired from one generation plant to another has been combined in the established algorithm. The specialized decision has been engaged to arrive at appropriate outcomes for a specific grid.

2.3 Grid electricity systems evaluation using the simulated LCCE MS Excel dataset

The LCA technique has been adopted to evaluate the carbon emissions of the studied grids. The MS Excel workbooks have been developed and used to calculate the carbon-emission levels. The carbon-emission-determined elements were considered as independent variables, whereas the dependent variables are carbon-emission.

The adopted workbooks have considered the available potential renewable and clean technologies, given that the maximum sustainability of the power system is achieved upon total environmental-energy conservation. Parameters such as the new setting up, operation, and maintenance in the year 2049; system capacity set up and persisted by the base year 2019; LCCE factor of the electricity generation system capacity set up, functioned, retained, and persisted by the base year 2019; residual amount of carbon emissions from recycled and retired electrical power systems in the year 2049; leftover of the substituted recycling portion from the power system components retired in the year 2049; newly added power system capacity (components) in the year 2049; amount of a carbon emission per unit of additional electricity generated and transmitted capacity in the year 2049; ratio of the carbon production replaced into the newly added system capacity in the year 2049; fraction of a carbon-emission left behind in the retired system components, quantity of carbon released in the newly added power generated and transmitted in the year 2048; and the retirement ratio of the newly added system components in the year 2048 [8, 22, 30] were studied.

The Monte Carlo simulated histograms (showing the life-cycle carbon-emission values) were developed using RStudio for both EG and BAU scenarios of the intended and operated drivers of the power systems. The developed Monte Carlo simulated histograms were in turn used to study the EG factors in the design of the drivers and operations of the studied grids by 2049. The LCCE was used to study the performance of the designed electrical power system while considering EG factors, within 30 years of transition of the grid electricity system(s) dominated by efficient transmission technologies, and the cleanest renewable energy sources. Based on the obtained life cycle carbon emission inventory (LCCEI) data, the probable life-cycle carbon-emission-values histograms were developed using RStudio.

The extract of those calculations spreadsheets whereby the key assumptions and scenarios, system boundary model, formulas, equation, and references are also provided through a Mendeley data repository (<https://data.mendeley.com/datasets/pcc8vhbv wz/2>).

2.4 Data quality and uncertainty

The results of this assessment should be interpreted as a guide rather than a definitive solution. However, the confidence levels regarding the certainty of the environmental assessment undertaken have been elevated owing to the performance of the developed graphs. The performance of the presented impact assessment Figures was also revealed to be sound with the authors' "best practice" prospects. Furthermore, the LCCE values have been checked for

double counting and overlooking, through the adoption of the linearity and partitioning of multifunctional processes per 1 MW.

3 Results and discussion

The presented results provide insight into the probable relationship between renewable-dominated power systems and lifetime decarbonization performance in the studied grids. The evaluation results of grid electricity systems emission from the developed LCCE dataset and Monte Carlo simulation are also presented in the next sub-sections. The explored electrical power systems components established life cycle carbon-emissions values, tested hypotheses, and limitations were presented and discussed against the prevailing research, policy, plans, and best practise for cleaner grid electricity systems.

3.1 Baseline energy resources

The explored cumulative capacity of the studied electrical power generation systems is dominated by hydropower, followed by natural gas, diesel, and geothermal power. Hydropower generation is dominant in Rwanda, followed by Tanzania and Kenya, as shown in Figure 5. The Tanzanian grid is powered predominantly by natural gas and hydro resources, while the Kenyan grid is powered mainly by geothermal, hydro, and diesel resources. However, there is potential to supply the regional grid with geothermal resources because they are considered to be both cleaner and renewable resources.

3.2 LCCE calculated from the studied generation and transmission systems

The life cycle grid carbon emissions levels from the currently operated (studied) grids were established and presented in Figure 6. In particular, Figure 6 shows that peat power contributed more emissions per unit of power in Rwanda as well as in the study area, in general, for the base year 2019. It also shows that natural gas and diesel are the major emission sources in Tanzania and Kenya, respectively. Figure 6 also explored that the cumulative carbon-emission contribution from the prevailing capacity of electrical power systems is dominated by peat power, followed by natural gas and diesel. It may be used to demonstrate that the majority of the LCCE was contributed by the peat power capacity (in the Rwandan grid), natural gas power capacity (in the Tanzanian grid), and diesel power capacity (in the Kenyan grid). The obtained results also revealed other sources of power, integrated into the electrical generation mixes, contributed insignificant carbon emissions in the study area.

The LCCE for electricity generation and HV transmission have been established, based on the developed LCCE intensity database for electricity generation, and the high-voltage (HV) power transmission loss for the studied grids, and presented in Figure 7. The LCCE contributions from the studied components and area were assessed for the base year 2019.

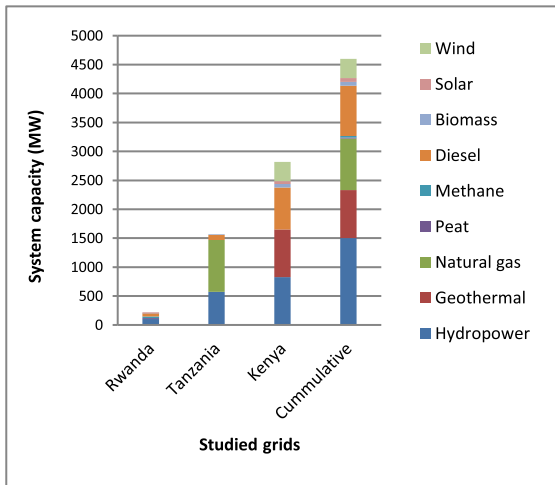


Fig. 5. Contribution of the different energy resources utilised to generate grid electricity for the base year 2019.

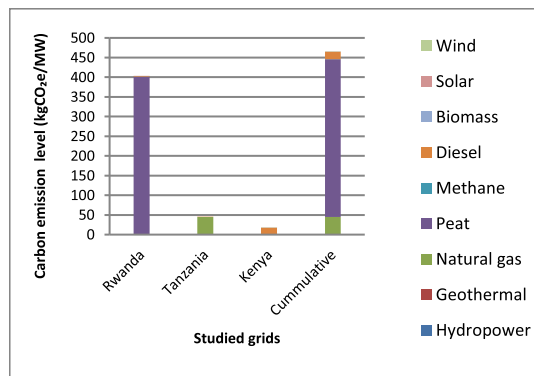


Fig. 6. LCCE contributions from different energy resources employed to generate grid electricity for the base year 2019.

Figure 7 shows that the Rwandan grid generated higher emissions per unit of electricity, followed by the Tanzanian grid.

The LCCE obtained from the developed MS Excel data and presented in Figure 8 also shows that the baseline level of LCCE per unit of power is much higher in the Rwandan grid than in the Tanzanian and Kenyan grids.

The emissions come mainly from power generation sources rather than transmission line sources.

3.3 Evaluations of the LCCE calculated from the studied generation and transmission systems

The collected, estimated and calculated LCCE (in MS Excel dataset) was simulated using RStudio to obtain the presented Monte Carlo histograms (Fig. 9). The presented histograms do not show the probability or trend of carbon-emission (environmental performance) increase or decrease obtained in electrical generation and transmission systems designed under EG scenarios (as opposed to BAU scenarios) by 2049. The presented histograms, therefore,

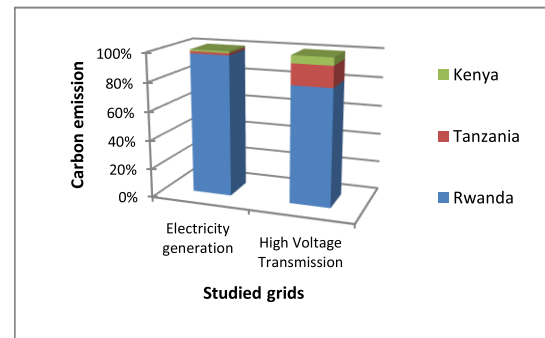


Fig. 7. LCCE contributions from the studied electrical power system components for the base year 2019.

therefore, revealed the absence of the lifetime decarbonization performance relationship between renewable energy sources dominated power systems and non-renewable energy sources dominated power systems. The results also revealed that the prevailing Rwandan BAU-modelled power system is dominated by relatively high emitting sources (including peat) while its EG-modelled power systems can also potentially be dominated by relatively higher emitting sources compared to Kenyan and Rwandan grids.

The Monte Carlo simulated histograms obtained using RStudio (Fig. 10) also do not show the probability or trend of the carbon-emission (environmental performance) increase or reduction in the studied Tanzanian electricity systems designed under the EG scenarios (as opposed to BAU scenarios) by 2049. The presented histograms (Fig. 10), therefore, revealed the absence of the lifetime decarbonization performance relationship between renewable energy sources dominated power systems and non-renewable energy sources dominated power systems. The results reveal that the prevailing Tanzanian BAU-modelled power system is dominated by relatively fewer emitting sources (compared to the Rwandan grid) mostly natural gas, apart from the fact that its EG-modelled power systems can also potentially be dominated by lesser emitting sources, such as hydropower and some geothermal sources, while adopting the most efficient transmission technologies.

The Monte Carlo simulated histogram obtained using RStudio (Fig. 11) shows the probability of carbon-emission reduction (high environmental performance) under the EG scenarios (as opposed to BAU scenarios), through its current transition plan and operation of its grid electricity generation sources dominated by geothermal and hydropower technologies in the Kenyan electrical power systems designed by 2049, owing to its slightly distorted histograms (*i.e.*, *positively skewed*). Therefore, the Kenyan grid LCCE analysis revealed the lifetime decarbonization performance relationship between renewable energy sources dominated power systems and non-renewable energy sources dominated power systems under all studied grid operations. The results may also reveal the prevailing Kenyan BAU-modelled power systems to be dominated by the lesser emitting energy sources compared to other studies systems while its EG-modelled power systems can also potentially be

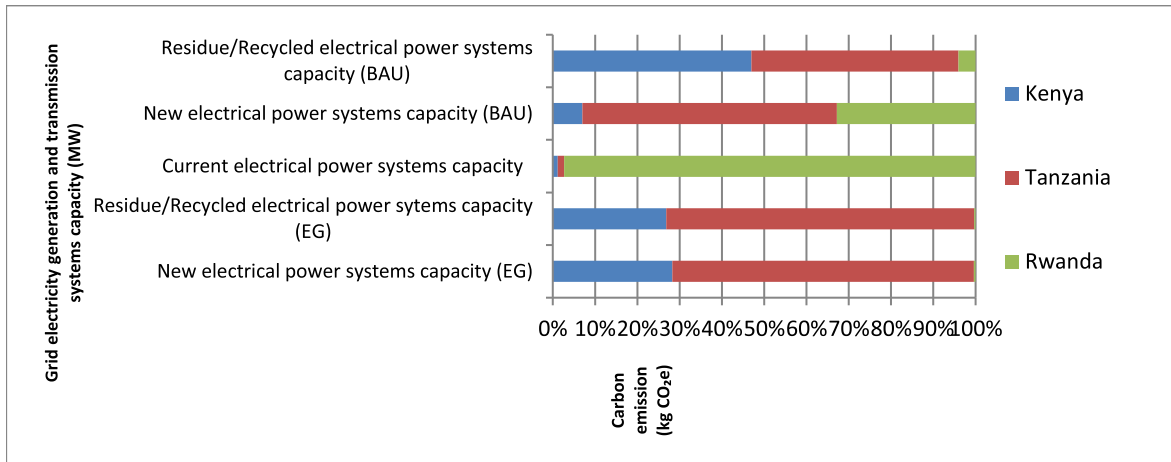


Fig. 8. LCCE from the electrical power system components designed and operated from the base year 2019 to 2049.

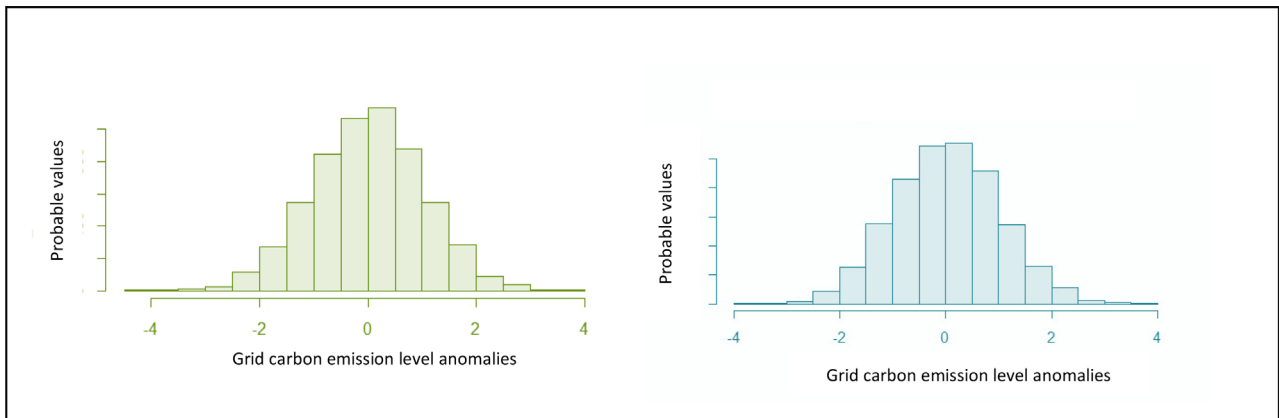


Fig. 9. Histogram of simulated normal LCCE data (kg CO₂e /MW) from the Rwandan grid electricity systems designed under both BAU (left side, *negatively skewed*) and EG (right side, *symmetrical distribution*) scenarios, by 2049.

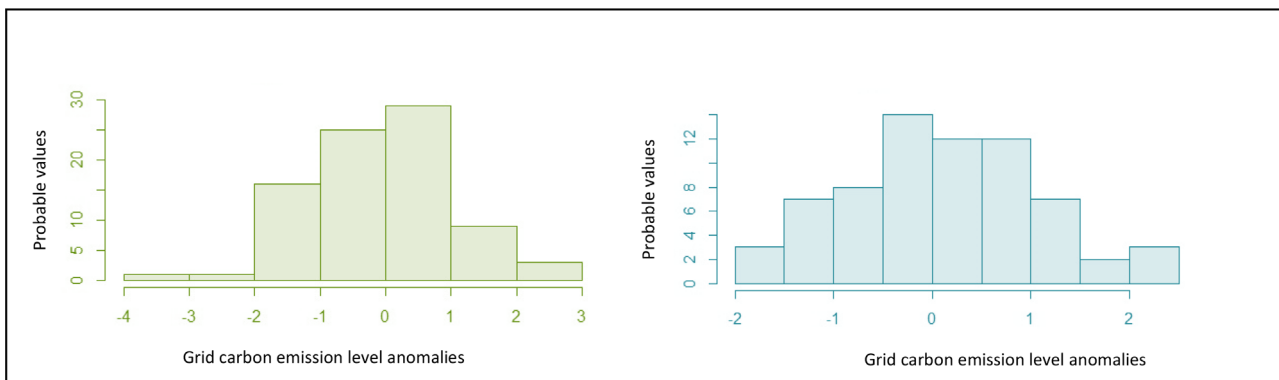


Fig. 10. Histogram of simulated normal LCCE data (kg CO₂e /MW) from the Tanzanian grid electricity systems designed under both BAU (left histogram, *negatively skewed*) and EG (right histogram, *symmetrical distribution*) scenarios by 2049.

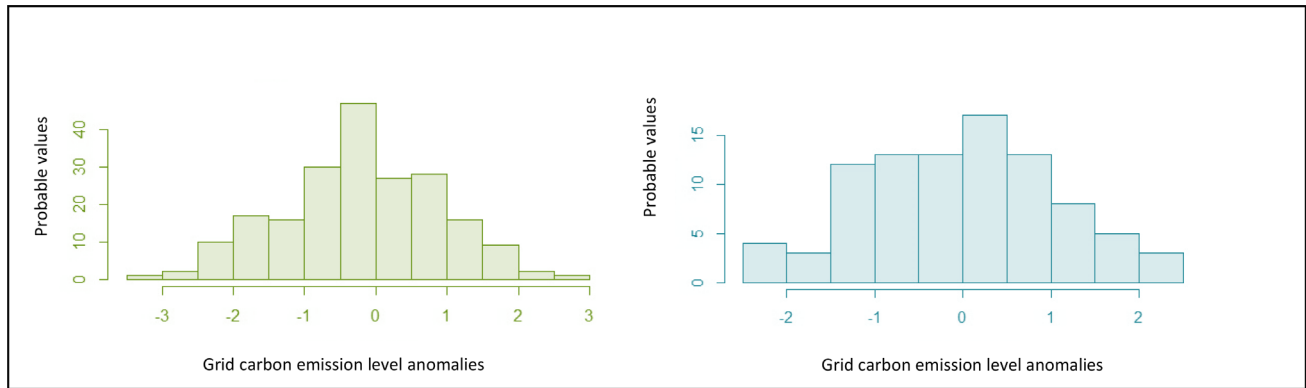


Fig. 11. Histogram of simulated normal LCCE data (kg CO₂e /MW) from the Kenyan grid electricity systems designed under both BAU (left histogram, *negatively skewed*) and EG (right histogram, *positively skewed*) scenarios by 2049.

dominated by lesser emitting geothermal power and hydropower while adopting the most efficient transmission technologies.

3.4 Further life cycle impact management and monitoring implications

The research findings may be used to evaluate the established postulation that “There is no relationship between the renewable dominated power system and environmental improvement” in the studied grid’s operations. The limitations of the field survey and the availability of the current internal data sources were also revealed during the research. The presented results are mostly obtained from secondary data sources and external sources. The high losses in the studied transmission systems, adopted during MS Excel and RStudio analysis, are mainly related to the ageing systems and the overloading of system equipment such as transformers and conductors. However, efforts were made to make reasonable a selection, estimation, and calculation of data.

This study recommends regional and national extension plans and designs to minimise losses in transmission lines by ensuring adequate investments in new technology for the coming years while avoiding the overloading of system equipment such as transformers and conductors. Given that the natural environments among the studied countries are not the same, the national, regional and global energy institutions are also recommended to speed up the interconnection of the transmission network to enhance the penetration of lower-emission energy sources in the grid electricity mixes through regional power trade. The study, therefore, recommends the use of efficient power electronics as well as sustainable electrical power system policies, plans and practices. To enhance the sustainability of the power generation systems, it is hereby recommended both national and regional electricity generation plans, designs, and policies to restrict the use of high-emission sources such as diesel and peat and support the penetration of low-emission sources such as solar, geothermal, wind, and hydropower. The study also recommends further research to comprise cumulative environmental and energy data and parameters

assessed from cradle to grave. Further impact assessment studies are also required, to facilitate the interpretation of the carbon emissions caused by the electrical power generation, transmission and distribution systems, in the study area.

4 Conclusions

This research presents an assessment of electrical power systems using the LCCE in Rwanda, Tanzania, and Kenya. The study explored and estimated carbon emission potentials from energy generation sources and transmission activities by the year 2049. The study contributed to the development of knowledge of the understanding of the environmental performance of the different power systems designs and operations anticipated by different system operators, researchers, and policymakers. The data was collected from the scientific and technical reports and national utilities actors. Furthermore, LCCE Monte Carlo simulated histograms were presented for both the EG and BAU scenarios. The presented results showed that only Kenyan generation and transmission systems have the lifetime decarbonization performance relationship between renewable energy sources dominated power systems and non-renewable energy sources dominated power systems. The presented results also reveal the prevailing Kenyan BAU-modelled power systems to be dominated by the lesser emitting energy sources compared to other studies grids while its EG-modelled power systems can also potentially be dominated with lesser emitting geothermal power, followed by hydropower.

The study is based on simulations, and its effectiveness needs to be validated through practical implementations. Future research should also be conducted using internal and primary data sources. The study implied that both national and regional power generation plans, designs, and policies should consider restricted use of high-emission sources, such as diesel and peat, and encourage the penetration of low-emission technologies, such as solar, wind, geothermal, and hydropower. The electrical institutions are also suggested to speed up the regional interconnection

of the transmission network to enhance the trade of lower-emission energy sources in the grid electricity mixes for a cleaner power system. However, site-specific (using internal and primary data sources) monitoring is required for future clean energy systems science-policy research. The study also recommended further research to consider the most current and cumulative data as well as the exploration of more environmental indicators, and the adoption of new technologies such as the use of green hydrogen made from renewable electricity, assessed from cradle to grave. Further life cycle carbon emissions studies were recommended, to facilitate the interpretation of the carbon emissions caused by the power generation, transmission and distribution systems, in the study-studied grids.

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Conflicts of interest

The author declares no conflict of interest.

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