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Life Cycle Carbon Emission Modelling of Electrical Power Systems: the case of Kenya, Rwanda, and Tanzania

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College of Science and Technology

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By

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A PhD thesis Submitted in Fulfilment of the Requirements for the Degree of Doctor of Electrical Power Systems in the College of Science and Technology of the University of Rwanda

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November, 2022

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DEDICATION

I dedicate this thesis to God Almighty my creator, my strong pillar, my source of inspiration, wisdom, knowledge, and understanding. I also dedicate this work to my beloved father **Lumuliko Nogelitawa Chambile**, my lovely mother **Martha Kiyao**, my sweet wife **Mercy** Hallan, my Sons **Lufunyo** Enock and **Lewis** Enock and all who have been affected in every way possible by this journey; Thank you; God bless you.

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ABSTRACT

Life Cycle Carbon Emission Modelling of Electrical Power Systems: the case of Kenya, Rwanda, and Tanzania

By

Enock Lumuliko Chambile, PhD Electrical Power Systems
The University of Rwanda, 2022

This thesis has explored the extent to which grid electricity generation and transmission system drivers are designed and operated according to environmental governance (EG) factors, with Kenya, Rwanda, and Tanzania as case study countries. So far, much work exists on environmental life-cycle assessment approaches for electrical power systems neglecting the upstream processes, due to the lack of an effective model for the life cycle inventory (LCI) and method for data collection. This calls for the development of a more effective and simplified LCI model and method for carbon emission data collection including both upstream and downstream processes of the electrical power systems. Nonetheless, most studies use data that do not certainly reflect the country's existing status. This demands detailed investigations of the up-to-date situation in the study area. This thesis seeks to create awareness, in the electricity sub-sector, of the antagonistic relationship between technology and infrastructural advancements, and their environmental impacts both upstream and downstream. The selected countries are the most appropriate for the study of, both non-renewable and renewable electricity systems due to their environmental geographies, potential power trade, upcoming grid interconnection, different generation mixes, different transmission losses as well as different system capacities.

The thesis specifically attempts to answer the following questions: (i) "*Using LCI model, determine to what extent are grid electricity generation, transmission and distribution power system (downstream and upstream) drivers designed and operated according to environmental governance factors*?", (ii) "*Using LCI model, determine what would be the impact on the lifetime decarbonization performance of the downstream and upstream power systems if environmental governance factors were considered*?" and (iii) "*Is there lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power systems?"*.

The methodology is adopted from the life cycle assessment theoretical framework offered by the international standardisation organisation but expanded to include upstream process considering life cycle carbon emissions. The mixed methods research design is also adopted whereby both quantitative and qualitative techniques have been employed to offer a better thoughtful of epistemology (positivism and interpretivism). The data has been acquired through face-to-face discussions and reviews of consistent published data. All the data acquired has been documented and referenced. Authorisation to the actors and companies directly involved in the study has also been obtained. Where necessary, participant data or participants were fully anonymized while observing all data redistribution procedures from the platform(s). The presented data has been established within the determined system boundary using established life-cycle carbon-emission inventory Excel worksheets of different activity and emission factor data as well as the established base year, the lifetime, and the functional unit.

The thesis has been achieved to: Develop the life cycle carbon emissions (LCCE) estimation model of the studied electric power systems and compile an inventory (country-specific data and assumptions) database of an electrical product for a particular grid using the developed LCCE model, as well as carry out life-cycle carbon inventory analysis of both electric power generation sources and transmission losses of each studied grid. The carbon emissions inventory analysis results showed that only Kenyan generation and transmission systems revealed the lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power systems. Nevertheless, the results of this study should be taken as indicative and not a conclusive answer as with so many computer models.

The study has contributed to the body of knowledge by developing the LCCE model, the LCCE database, and the LCCE analysis results that could be used (by operators, researchers, and policymakers) for planning, estimating, and evaluating the environmental performance of the studied power generation and transmission systems. Further studies need to be conducted to cover more countries in all African power pools, more system dynamic impact analysis, and a wide range of environmental parameters such as wildlife species abundances and diversity (in both aquatic and terrestrial environment systems), and non-greenhouse gases emission.

Keywords: Environmental life-cycle assessment, lifetime decarbonization performance, power generation, and transmission systems, technology and infrastructural advancements

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
BAU	Business as Usual
BESS	Battery Energy Storage Systems
CAES	Compressed Air Energy Storage
DC	Direct Current
DPSIR	Drivers, Pressure, State, Impact and Responses
EAPP	Eastern Africa Power Pool
EG	Environmental Governance
HV	High Voltage
HVDC	High Voltage Direct Current
IAS	Industrial Application Society
IEEE	Institute of Electrical and Electronics Engineering
KenGen	Kenya Electricity Generating Company
KETRACO	Kenya Electricity Transmission Company Limited
LCA	Life-Cycle Assessment
LCCE	Life Cycle Carbon Emission
LCCEI	Life Cycle Carbon Emission Inventory
LCCEA	Life Cycle Carbon Emission Analysis
LCI	Life Cycle Inventory
LCIA	Life-Cycle Impact Assessment
PES	Power and Energy Society
PHS	Pumped Hydro Storage
REG	Rwanda Energy Group
ROW	Right-Of-Way
SAPP	Southern African Power Pool
SDG	Sustainable Development Goal
T&D	Transmission and Distribution
TANESCO	Tanzania Electricity Supply Company Limited

SYMBOLS AND NOTATIONS

Adef	Area of land deforested [ha]
AE	Average flow of electricity over the life of the project [MWh]
At	Filling quantity of a particular pollutant per unit of added electrical power
$A,_{2049}$	Filling quantity of a carbon emission per unit of added electrical power system capacity
BD	Biomass density per unit area (above ground, below ground, soil carbon, litter, and dead biomass) [tCO2/ha]
EFm,t	Emission factor for a particular pollutant of the electrical product system owing to the new installation, operation, and maintenance of systems in year t [kg/MW]
EFo,t	Emission factor for a particular pollutant of the electrical power system capacity currently installed, operated, maintained, and surviving [kg/MW]
GHG	Direct non-generation T&D greenhouse gas emissions [kg/MWh] in year t [kg]
LCCE,t	Overall amount of a specific emission in year t [(kg)/(kg/MW]
NR,t-j	Fraction of the newly added electrical power system in year t - j (%)
$NR,_{2048}$	Retirement fraction of the newly added electrical power system in the year 2048
Nt	Newly added electrical power system capacity in year t [MW], and is equal to the net newly installed electrical power system capacity plus the retired electrical power system capacity
$N,_{2049}$	Newly added electrical power system capacity in the year 2049
PE_{LC}	Direct non-generation emissions from land clearing [tCO_2] system capacity [kg/MW]
$PR,_{2049}$	Ratio of a carbon emission remaining in the retired electrical power system by the year 2049
Qm,t	Quantity of a particular pollutant from electrical power system capacity owing to the new installation, operation, and maintenance of electrical product systems [kg/MW]
$Qm,_{2049}$	Quantity of carbon emitted in the newly added electrical power (generation and transmission) systems capacity in the year 2049
$Qm,_{2048}$	Product of the quantity of carbon emitted in the newly added electrical power (generation and transmission) systems capacity in the year 2048

RC,t	Recycling coefficient for the residual pollutants emitted from the electrical power systems retired in year t (%)
$1-RC,_{2049}$	Residual carbon emission fraction from the electrical power systems retired in the year 2049
RR,t	Remaining quantity of a particular pollutant from retired and recycled electrical product systems, in kg (t)
$RR,_{2049}$	Carbon emissions remaining from the retired and recycled electrical product systems in the year 2049
SA,t	Ratio of the particular pollutants substituted into the newly added electrical power system (%)
$1-SA,_{2049}$	Ratio of the carbon emission substituted remaining into the newly added electrical power system in the year 2049
SP,t	Electrical power system capacity currently installed and surviving in the year t [MW]

CHAPTER ONE

1.1 Background to the study

The development of new, more clean, efficient and affordable electrical power systems technologies is required to achieve sustainability targets. Knowledge of the environmental sciences is important for a comprehensive understanding of the total impact of electrical power systems [1]. Modern electricity grids development allows a significant integration of renewable resources in energy production [2]. However, research is required to continuously improve on the understanding of the use of the life assessment tools for targeting and observing the local (national), regional and global electricity grids development to ensure sustainable politics, economic and biophysical environment. There is an increasing concern worldwide by engineers, technologists, and environmental scientists about the negative impacts caused by electrical power generation, transmission and distribution (T&D) to the environment.

Sustainability of the environment has for a long period been a key objective in energy policies. However, the kind of environmental problems considered have been increased over time. As problems concerning local pollutants (produced air, water or land pollutants which may cause acid rain, corrosion in the area around the power generation facilities or impair of agricultural/ecological/health systems) have decreased, the main focus has shifted to climate change [3]. With growing concerns over environmental governance (EG) for sustainable electrical power systems development, an appropriate understanding of the consequences of energy production, T&D to the environmental resource and their attributes arise. However, there is limited information specifically on the environmental impacts caused by electrical power generation and T&D in African countries, especially from sub-Saharan Africa [4], [5]. Electrical technologies are shifting from conventional generation based on fossil-fuels sources to renewable energy sources. The power systems are also moving in the direction of the use of highly efficient meter – based electronics. Efforts are necessary to increase the understanding of the use of the life-cycle assessment tools for directing and checking the local, regional and global electrical power systems for sustainable development. There is inadequate scientific data that shows how renewable energy sources decarbonise the electricity energy chain, especially in sub-Saharan Africa.

A better understanding of the environmental sustainability performance of electricity use in society must necessarily involve a thorough understanding of the power generation, transmission and distribution. The impact of T&D systems is caused by the development and operations of the infrastructures (including electricity losses). The assessments of the impact of electric power systems on the environment regularly fail to include T&D systems (they concentrate on power generation systems, especially on the power generation points), both types of impact and lifetime impact, thereby potentially leading to inappropriate results [4],[5]. Therefore, the previous methods of carrying out the environmental life-cycle assessment of the power systems are not sufficiently mature [7]–[9]. However, the advancement of a more comprehensive method for evaluating the impact of the power systems on the environment has little been studied, and there are limited efforts to advance the method that can be found [10].

Previous studies have also evaluated the Life cycle impact assessment (LCIA) of power generation and storage technologies [7], [9], [11] as well as T&D infrastructure[16] on the environment. Nonetheless, most studies use data that do not certainly reflect the country's specific context. This demands detailed investigations of the up to date situation in the study area. Moreover, most of these studies have not received the necessary attention to understand the environmental impact associated with the manufacture, installation, use, maintenance, and decommissioning of energy generation, T&D technologies [3]. The tools to make it happen are extensively lacking [12]. Therefore, despite the earnest efforts of previous studies, more gaps still exist that need to be addressed. So far, much work exists on environmental life cycle assessment approaches for electrical power systems neglecting the upstream processes such as vegetation removal (to pave rights of way for power T&D activities) and power loss during T&D activities [13], due to the lack of an effective model for the life cycle inventory (LCI) and method for data collection [3]. This calls for the development of a more effective and simplified LCI model and method for data collection including a series of process start from the extraction of raw energy materials (such as coal, biomass, gas and diesel) and then continue to the pre-processing stages before finally getting to the stages of electricity generation (downstream) and T&D, and use of the final electrical product (upstream) of the systems. The downstream processes for this study is ending at the transmission substations.

Limited understanding of the influence of environmental mitigation or enhancement measures on technology and infrastructural improvements is also prevailing. Inadequate knowledge of the future trends in the energy resources demands and the corresponding undue burden on the environment (Sustainable Development Goal (SDG) 12), incomplete information on the climate change mitigation through the future adoption of renewable resources and energy efficiency technologies (SDG 13), and the partial understanding of the sustainable ecological developments (SDG 15) hinder the sustainable power systems modelling. The limited consideration of the nexus of climate-resilient economies, access to affordable, reliable and clean electricity (SDG 7), and the African Development Agenda of the year 2063 will also lead to the un-sustainable future power systems model. Therefore, the overall problem addressed in this study is the insufficient understanding of the effective environmental emission inventory analysis to inform the future sustainable power systems model. An emissions inventory is a database that document, by source, the amount of pollutants (such as criteria and hazardous substances) discharged into the environment during a specific period. The outcomes of this research provided information to be used in developing electrical power systems policy, plans and design with maximum environmental sustainability.

The earlier study estimated the environmental emissions of electricity based on the power unit, i.e., kWh [9]. However, the power unit centred functional unit does not automatically reveal the T&D behaviour of an electrical energy system. Inadequate consideration of the use of extremely efficient power electronics in electricity generation, power T&D, and end-user applications has been reported in the assessment and management of electrical power systems [14]. Therefore, most of the tools used to carry out the environmental LCA of electrical power systems are not adequately mature. In some cases, the calculation covers emissions from material consumption by T&D systems [15]. However, the advance of a more considerable method for evaluating the impact of T&D lines on the environment has scarcely been discoursed, while some efforts to advance the method can be found. This necessitates the development of a life-cycle environmental emission study focused on the studied grids. 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.

1.1.1 Problem statement

The electrical energy value chain needs to be decarbonised. In observing transitions to decarbonised generation sources, effects from manufacture and fuel extraction are to be measured, similar to the effects from generation. The previous research evaluated the impact of low carbon scenarios, while they also regularly omit some carbon emissions (from such as land transformation) [4] or consider the inadequate set of life-cycle impacts or stages. Apart from impacts from different electricity generation plants, transmission and distribution (T&D) lines, transformers, substations and towers, generated electricity lost during transmission as heat and consumed to operate the facilities also contributes to the cumulative carbon emissions of the power delivered to customers [10], [11]. Most of the produced electric power is transferred from power stations to substations for supplying residential, commercial and industrial end-users [10]. However, most of the carbon decarbonisation study of the electrical energy value chain are not considering both downstream and upstream processes [10]. However, most of the carbon emission data, and estimation model on electrical generation, transmission and distribution process throughout the life cycle of the studied systems are also not readily available.

Carrying out the LCIA of both electric power generation and transmission systems is essential for providing information on the design of technologies related to clean electrical power systems. To date, little research has been conducted to check the environmental pressure of studied grids. The most relevant methods for impact assessments of both electric power generation [16] and transmission systems did not consider different life span, remains pollutants from the recycling capacity, and retired rate of the present and newly installed power system components. The conventional impact assessment of electrical power systems has covered electric power T&D systems [17], as well as electric power generation [4], [18]. Few studies have been conducted to undertake LCIA for both electric power systems in the studied countries. Limited understanding of the LCIA for evaluating and monitoring global, regional, and local electrical power generation and transmission systems is noticeable. Little has been studied in previous studies about the improvement of more substantial LCIA results appropriate for achieving the optimum environmentally sustainable goals of the studied grids.

1.1.2 Purpose and objectives of the research

The overall objective of the study was to explore and contribute to an improved understanding of the environmental pressure caused by electric power systems in Kenya, Rwanda and Tanzania with a life cycle approach.

The study specifically aimed to:

(i) Develop the life cycle carbon emissions (LCCE) model of the electric power systems in the study areas,

(ii) Compile carbon emissions data of relevant inputs and outputs of a product for a particular grid electricity power generation and transmission systems using the developed LCCE model and the country-specific data, and assumptions, and

(iii) Carry-out the life-cycle carbon emission analysis (LCCEA) of both electric power generation and transmission designs and operations of each country.

1.1.3 Research questions

This study attempted to answer the questions:

(i) *"Using LCI model, determine to what extent are grid electricity generation, transmission and distribution power system (downstream and upstream) drivers designed and operated according to environmental governance factors?",*

(ii) *"What would be the impact on the lifetime decarbonization performance of the downstream and upstream power systems if environmental governance factors were considered?"* and

(iii) *"Is there lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power systems?".*

1.1.4 Significance of the study and justification

This study has created awareness in the electricity sub-sector, of the antagonistic relationship between technology and infrastructural advancements, and environmental impacts. Considering their future grid interconnection, different system capacity operation levels, different transmission scales, different grid mixes and different environmental characteristics, make Tanzania, Rwanda, and Kenya the perfect samples for the manipulation of both renewable and non-renewable energy sources as well as electricity generation and transmission developments in Southern Africa and Eastern Africa power pools. The information found by this study can be used to develop superior power systems policy design, plans and practice with minimum environmental impact. The model established in this research could be used to develop efficient environmentally sustainable electrical power systems. The developed model could also be a reference and example for similar researches. The thesis could also supply data and theory references for environmental impact control in the studied grids.

1.1.5 Research framework overview

The potential environments to be affected by electrical power systems include but are not limited to air, water, soil and natural resources. The environmental impacts of different electrical generation mix scenarios and transmission have been studied. The environmental considerations can manipulate infrastructural design and technologies, and hence influence the electrical power systems performance. Therefore, the environmental considerations (across the electrical power systems components) have been evaluated. The overview of the conceptual framework is indicated in Figure 1.1.

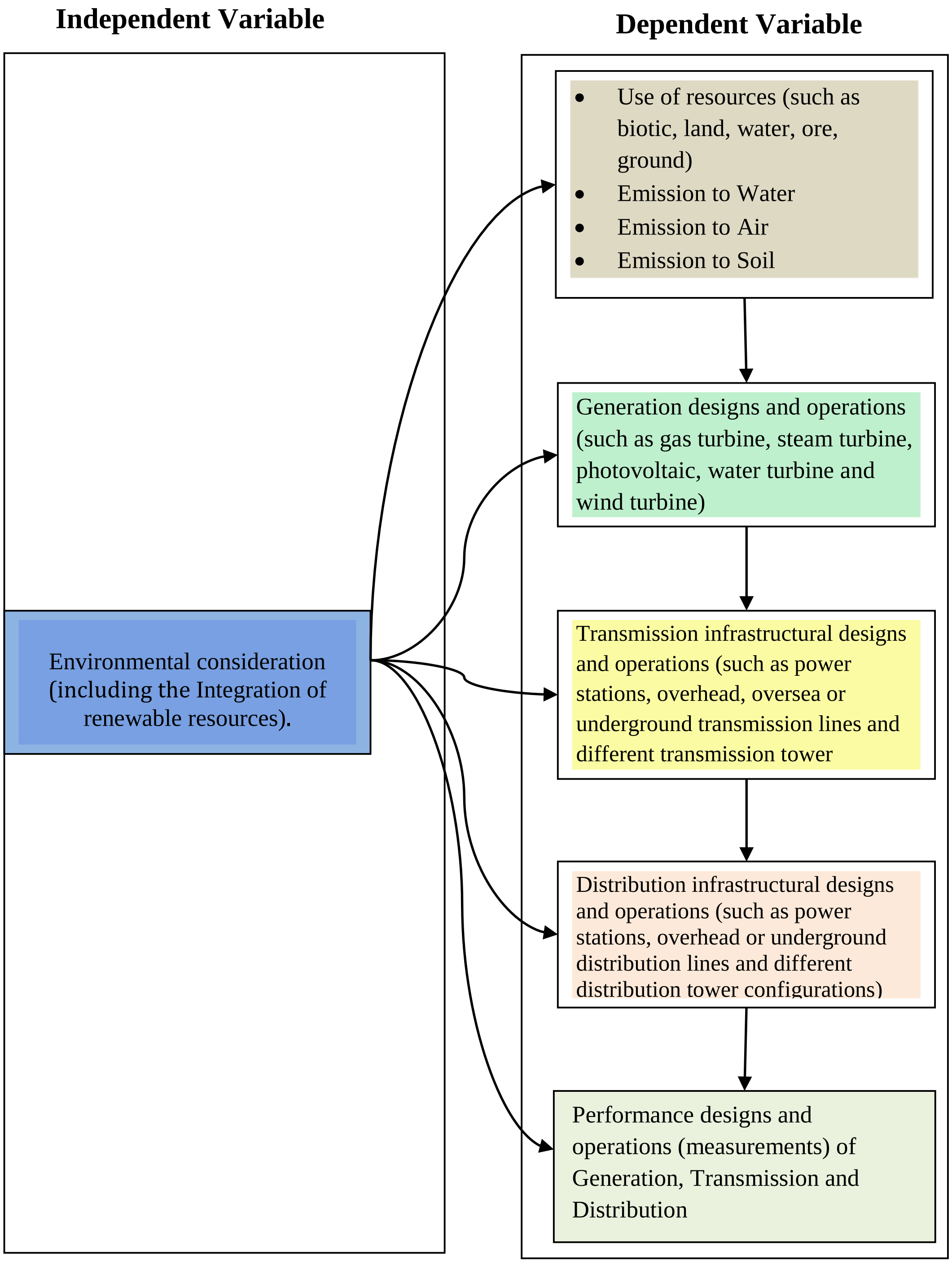


Fig.1. 1. Framework overview

Source: Authors' analysis

A summary of the techniques and modes of measurement to attain the set objectives are presented in Table 1.1.

Table 1. 1. Technique and mode of the study to attain the objectives

Serial number	Objective	Research questions	Mode of verification	Method of Analysis
i	Develop the LCCE model of the electric power systems in the study area	*(i) "Using LCI model, determine to what extent are grid electricity generation, transmission and distribution power system (downstream and upstream) drivers designed and operated according to environmental governance factors?",* *(ii) "What would be the impact on the lifetime decarbonization performance of the downstream and upstream power systems if environmental governance factors were considered?"*	Preliminary questionnaire designed to validate the general inventory approach to ensure developed research data is against any potential bias; Two set of variables were considered (dependent and independent variables); Electricity generated, transmitted and distributed (MW) and Carbon emission (kg), assumptions developed based on the pre-defined elementary flows, intermediate flows and reference flows, Function unit, Scenarios and systems boundaries	- Developed instrument/ model to guide the consequent data collection -Spreadsheet format used to allow the user to examine in detail, the data and assumptions employed -MS Excel calculation -Monte Carlo simulation using simple Excel - Developed graphs/plots/ curves
ii	Compile carbon emissions data of relevant inputs and outputs of electric product for a particular grid electricity power generation, and transmission systems using the developed LCCE model, country-specific assumptions and data	-not applicable	-Country specific activity data (generation activities, transmission losses, emission factors) and assumptions developed based on the pre-defined elementary flows, intermediate flows and reference flows	- Developed spreadsheet format life cycle carbon emission inventory (LCCEI) prototype
iii	Carry out the LCCEA of both electric power generation and transmission design and operations of each country.	*"Is there lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power systems?"*	LCCEI verified results two set of variables were considered (dependent and independent variables) Electricity generated, transmitted and distributed (MW), power loss and carbon emission (kg) Scenarios and systems boundaries	- Developed LCCEI dataset -Monte Carlo simulation using R studio - Developed graphs/ curves/plots

1.1.6 Research philosophy

The ontology of this study attempted to develop the science of the impact on the lifetime decarbonisation performance of the electrical power system systems if environmental governance factors are considered in both grid electricity generation and transmission systems drivers designed and operated, impact on the lifetime decarbonization performance of the downstream and upstream power systems if environmental governance factors were considered, and the lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power system. Appropriate methodologies have been addressed, with the hope of conveying to the fore ontological dialogues required to foster epistemic discourse for the lifetime environmental performance of the generation and transmission systems of the studied countries and Africa as a whole. Therefore, positivism (including case studies, surveys, and forecasting) and interpretivism (including descriptive, case studies, review, argumentative, and future research) epistemology were adopted. A mixture of quantitative and qualitative methods was also employed.

1.2 Some related work

Environment impacts along all life-cycle of power systems occur in different intensities and ways [2]. The practice related to the power generation, T&D of electricity cause climate change, resource depletion, acidification, land transformation, eutrophication, and impair water quality /quantity [3], [4]. The power generation involved the use of scarce energy resources and increasing demand of scarce environmental resources.

Electricity generation can also involve an emission (especially when fossil fuel is burnt) that directly or indirectly leads to a number of adverse local and global impacts. Deprived air quality resulting from fossil fuel emissions affect public health and socio-economic status at the local level. Fossil fuel use also contributes significantly to global warming caused by its greenhouse gases (GHGs) emissions. "*The Earth's atmosphere accumulates solar heat due to GHG concentrations and raises the temperature"* [5]. The previous research shows that direct emissions from the electricity generated from fossil fuels represent about 83–99% of the total GHG emissions, while infrastructure accounts for minor emissions. However, the infrastructures represent about 97–99% of the total emissions for wind, Solar PV and hydropower systems [6]. The life cycle assessment is, therefore, recommended to be conducted to prevent or control global warming [7], However, GHG emissions might not be applied as the only sign to characterize the sustainability performance of a system [6].

The generation of electricity causes thermal pollution into water bodies as well as many other types of pollution. For example, water gets heated to above the natural temperature, which affects plant and animal organisms. Other types of pollution may include hazardous waste such as oil, conductors and cables insulators to soil and water from land/sea cables oil-impregnated paper, mineral oil to the soil and water due to leakages of consumed diesel oil in the process of excavation and transport and power generation [8], [9]; residual biomass and nuclear waste [6].

Generation, transmission and distribution systems affect land use in ways such as pollution of flora and fauna by fuel consumption waste; reduction of usable land by the installation of electric transmission and distribution infrastructures (e.g. pylons, poles and conductors and insulators). For example, impoverishment of the vegetation along the entire right-of-way (ROW) width cleared for the lifetime of the transmission project(s). The long term experience to low-frequency electromagnetic fields may also distress individuals and the health of crops in the immediate proximity of transmission lines [17]. High voltage transmission lines also generate radio interference (RI) noise due to corona effects and electro-magnetic fields.

Superconductor high voltage (SCHV) technologies such as underground superconducting cables are potential alternatives to standard high-voltage (HV) transmission and might also impair environmental sustainability[19], particularly in terms of electromagnetic fields and visibility [13]. The local and global environmental costs that take place mainly peripheral to the power sector, are more challenging to account for, and thus have been excluded in the developing model. However, in the 21st century, all power system policy and planning with an environmental concern are obtain subsidies [14].

Electricity supply companies strive to manage the environment of the communities in which they operate. The companies spend billions of dollars each year on best practices, operational measures, and technologies, to protect the environment and human health. They are constantly examining new and advanced ways to generate electricity and to use it wisely while also managing the environment. Renewable electricity sources such as geothermal, solar power, wind, and biomass have been reported to produce maximum environmental sustainability and generally have also low or no fuel costs [15]. Reducing environmental emissions, which are harmful to the environment, by the electric power sector, requires infrastructure investments and changes in the operations of power systems as well as mitigation technologies employed [16]. Effects on the ecology are uncertain, due to its sensitivity to the design of specific infrastructure and geographical location. Electricity networks infrastructure development has environmental effects spread across a wider area due to the linear nature of electricity lines [17].

Rivals of the innovative transmission projects have also named the resultant towers visual pollutants, as intrusive or unsightly. The adoption of the high-voltage underground lines, superconducting cables, and higher-capacity-conducting materials may cause some impact on sighting, taking into account the present transmission project(s)corridors. A promising development is ready on higher-capacity conductors' technologies for the future towers and underground high voltage direct current cables. "*These technologies should be considered and used when appropriate*" [18]. The early research on the superconductor and standard high-voltage transmission systems lead to multiple technological innovations that could provide a novel long-distance transmission option with different efficiency.

Electricity generation technologies are superlatively linked by the procedure of life-cycle thinking with transparent and reliable metrics. A metric is traced during the course of the life-cycle which includes the physical unit of quantity and the ways of data collection and analysis. Previous studies proposed the metrics to be as objective and consistent as possible to create accurate life-cycle assessment (LCA) comparisons. Most of the majority of LCA researchers and practitioners adopted the metrics of kg CO_2-eq yr−1 for GHG emissions. Other categories of an environmental impact lack the previously well-defined metrics and missing harmony between LCA researchers and practitioners. Similarly, some of the environmental sustainability impacts are not well understood [19].

1.3.1 Life cycle assessment for electrical power systems

The ISO defines four phases of an LCA (Figure 1.2). Those phases include (1) Defining Goal and scope such as the objective of the study, defining functional unit and the system boundaries; (2) Life cycle inventory (LCI) data (input/output) from the studied system components is gathered; (3) LCIA, where system data are aggregated and characterized to well recognize their environmental consequence; and (4) Interpretation, where the outcomes are discussed according to the pre-defined objective (including research questions) and scope of the study.

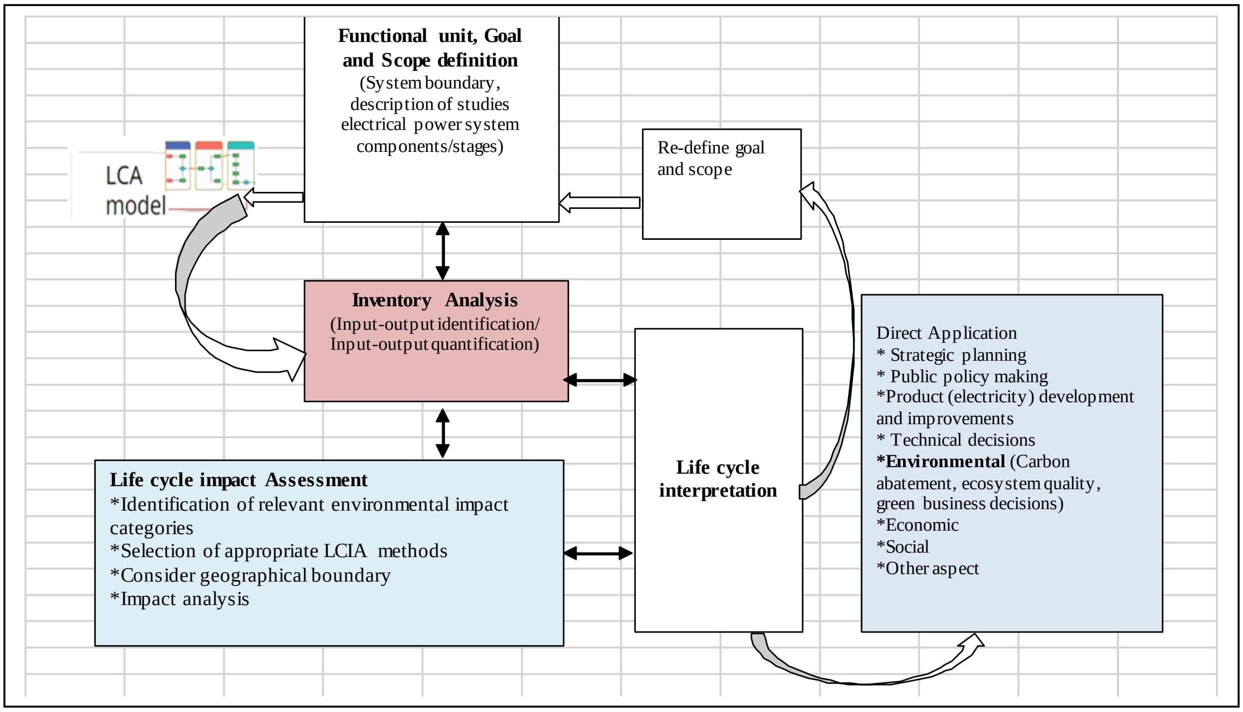


Fig.1. 2. Phases of a life cycle assessment

Source: Adapted and modified from [20]

Present LCA literature offers substantial attention to the environmental impact of power generation[4], [9], [18], but gives relatively less attention to the environmental impact of T&D systems[7], [17]. The power industry is exceptional in LCA and policy examination for the reason that while it is straightforward to quantify electricity consumed, it is difficult to trace the electricity produced in a given power plant(s) through the T&D system to specific customers. For this motivation, it is basic in LCA to create and employ emissions factors, or the average quantity of a pollutant per unit activity. These factors represent the combined estimate of emissions from a wide-ranging electrical power system(s) [21].

The capacity for transmitting electricity from power generation plants to customers differs in different locations along with the national and regional grids. So far, the kWh-based assessment is not independently reflecting the transmission capacity to ensure the environmental effect of electricity transmission reflects the different transmission distances. Different transmission facility occupancy rates should be allocated to different environmental impacts since each customer uses different transmission facilities. Figure 1.3 shows the platform of the value chain for power supply, beginning with the acquisition of fuel for electricity generation station(s), through electricity generation operations, transmission operations and distribution operations, and lastly utilization operations. Whether it is a power station(s), transmission line(s), or fuel mine(s), all of these facilities have input/output material(s), the construction and operational phases, and lastly a decommissioning phase. The whole life-cycle may cover decades and be associated with the production and transfer of power and energy. Each of the boxes in Figure 1.3 has environmental pollutants emissions from a wide range of energy sources. Figure. 1.3 also shows the potential environmental pollutants emission sources to be considered by this study. Impact indicators are estimated per unit of total electricity brought by the national T&D grid for each country.

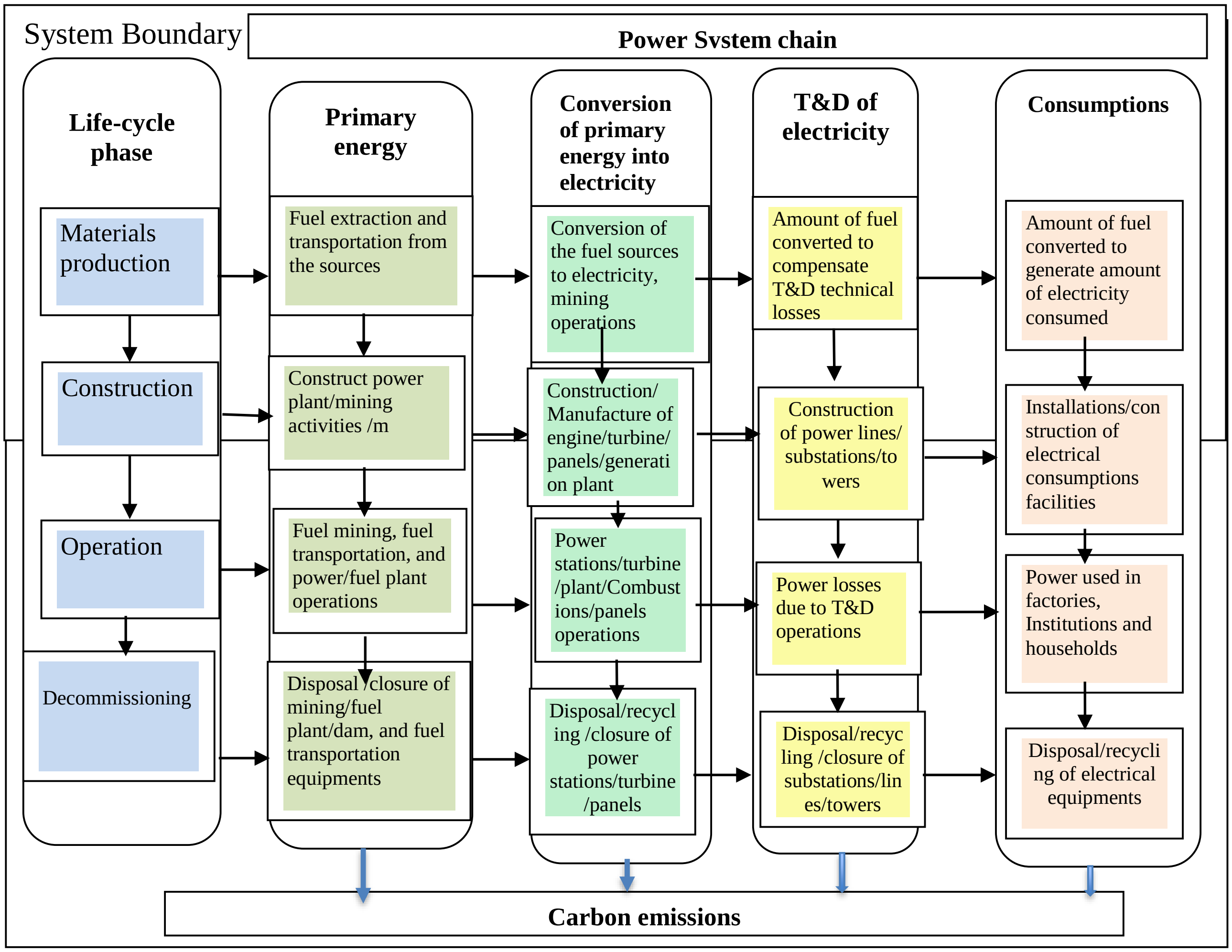


Fig.1. 3. Overview of the LCA for electricity power system

Source: (Adapted from [17] and reviewed by author)

Literature shows the average grid power systems capacity flow in Kenya, Tanzania and Rwanda as 7,826.4GWh/year [22], 5,740.84 GWh/year [22] and 170 GWh/year [23] respectively. The life-time of most of the prevailing transmission systems equipment is fifty (50) years[24]. This research model used the LCI data for the current national electrical generation, transmission and distribution infrastructure to estimate the environmental sustainability of supplying electricity to Kenya, Rwanda and Tanzania.

1.3.2 Grid infrastructures

The emerging concept of the architecture of the grid describes the grid not just as a physical configuration, but one that holds a range of performers and requirements. The design of the grid is shaped by factors such as public policy, business models, and technological practices. Electric power grids have four major components including: generation plants, transmission and distribution plants (which include main equipment such as transformers, switchgear, conductors and supporting towers, as well as insulators) and utilization equipment. Electricity generation plant(s) produce power using several forms of energy such as fossil fuels, solar, nuclear, geothermal and water. Step-up transformers raise the generated voltages to higher voltage levels required for efficient transfer to remote areas. Normally, a few transmission transformers backing a generation plant, which implies that the loss of (two or more of) these large power transformers can lead to substantial electric power outages over a large area. Distribution transformer(s) step down the voltages to lower levels that are appropriate for use in homes, businesses and industry. The distribution transformers are regularly knocked out or damaged during weather events. However, they are easily replaced or repaired depending on how widespread the damage is [25]**.**

1.3.2.1 Grid electricity generation

Methods for the generation of electric power can be broadly divided into renewable or non-renewable based on the primary energy sources. The non-renewable energy sources (i.e. coal, gas, petrol, peat, and diesel) have a limited supply and can be exhausted over a period of time, whereas renewable-based use primary energy sources are inexhaustible because they can be continuously renewed. These include hydroelectric, biomass and biofuels, geothermal, wind, and solar. Steam turbines can typically be powered by oil and coal resources (two non-renewables); and solar power, solid waste, geothermal, and biomass energy resources (four renewables). Other energy generation technologies are related to two forms or only one form of renewable energy, such as photovoltaic (relate to solar-power) and water turbines (hydropower and hydro-kinetic energy) and wind (wind-power and hydro-kinetic energy) [26].

1.4 Status of the power supply sector in the case study countries

The total installed on-grid electricity generation capacity in Kenya stands at 2,370 MW as of 2017 [27]. This generation energy mix comprises 52.1% from hydro, 32.5% from fossil-fuels, 1.8% from biogas co-generation, 0.4% from wind, and 13.2% from geo-thermal [27], [28]. Rwanda has the lowest electricity use and generation per capita compared to other studied countries. Total installed on-grid electricity generation capacity as of 2017 was 160 MW of which about 40% came from diesel-powered generators and 60% came from hydrological resources. Recently about 20% of Rwanda's households were connected to the grid [29]. The previous work showed that by 2015 about 26% of Kenyan's households were connected to the grid [30]. Formerly, Tanzania had an installed on-grid electricity generation capacity of around 1,520 MW (as of 2016)[31]. "*Presently, annual electricity demand has been growing at a rate of 10-15%*", although by 2015 only 24% of Tanzania's (both mainland and island) households were connected to the grid [32].

Earlier work showed that, by 2016, only 24.6% of Tanzania's mainland households were connected to the grid [33]. In 2013, approximately 40% of electricity generation were from renewable sources, predominantly hydropower, while the residual sources were from non-renewables (including natural gas and other fossil fuels). Operational renewables are including Hydro and Biomass and Waste, while non-renewables are fossil fuels including natural Gas Turbines, Diesel and Oil. Previous reports showed that Tanzania imported a total of about 16 MW of power from Kenya (via Namanga), Uganda and Zambia while electricity accounted for only about four per cent (4%) of primary energy consumed, and biomass accounting for about 85% of primary energy use [32], [34]. Rwanda has a vision of exporting electricity to the network (Rwanda-Uganda, Rwanda-Tanzania, Rwanda-Burundi, Rwanda-DRC) while also importing electricity when the most sustainable supplies can be available from sources like the hydro plants in Lower Kafue Gorge of Zambia (to be imported via Tanzania)[35], the hydro plants in Ethiopia (to be imported via Uganda and Kenya), and the developing Julius Nyerere Hydropower Station of Tanzania. The generation speculation "future" will be influenced by technologies such as high geothermal, high nuclear, high natural gas, high wind, high clean-coal, and high solar[36].

The study conducted in Tanzania revealed that increasing share of hydro-power would considerably help to minimize the environmental toxicity potentials, and enhance the environmental profile of the power system(s)[28]. However, this research attempted to describe a wider scope of the power systems and provided a wider picture of the energy mix generated in Rwanda, Tanzania and Kenya. The energy mix generation impacts are, therefore, studied and compared with non-power generation impacts.

1.4.1 Transmission and distribution process

Transmission substations at the generating sources facilitate to step up the electric power that leaves generation points for transmission. The substation receives power generated in power stations and its transformers increase the voltage to a level that can vary from 155 kV to 765kV (depending on the distance that the electricity has to travel and the transmission line design) in order to minimize transmission losses. The switches and circuits breakers also allow power to particular lines to be turned off and on as desired. The substation also has converters to convert the direct-current (DC) to alternating-current (AC)[26], particularly if the electricity generated is DC, as from direct-drive wind and photovoltaic cells.

The voltage must be stepped down before the electric power is distributed to the end-users, as indicated in Figure 1.4. Other types of equipment in substation include voltage regulators to avoid lower (under) and higher (over) voltage conditions, bus bars that provide connections for multiple lines to distribute off in multiple distribution lines [26].

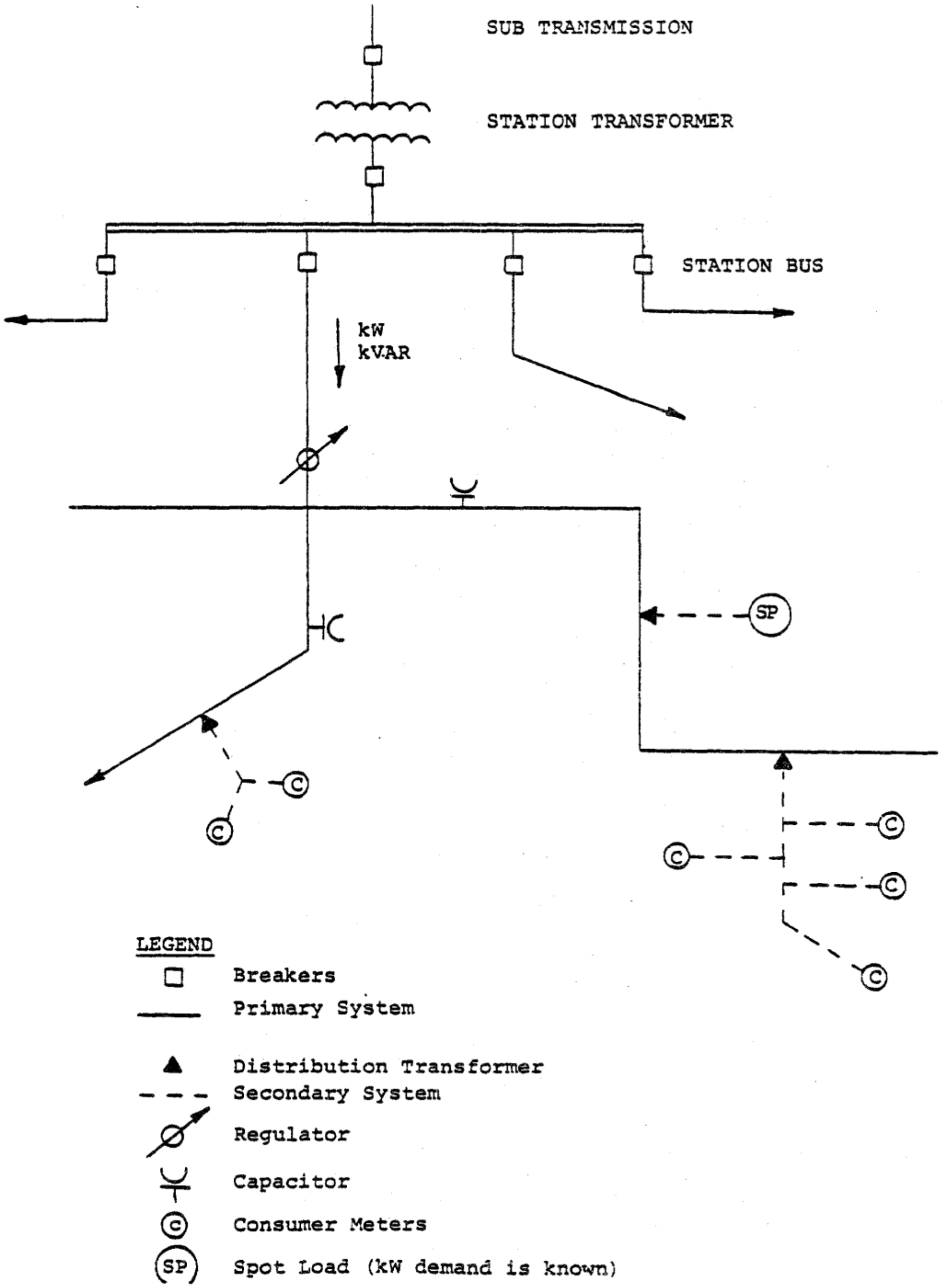


Fig.1. 4. Schematic power distribution system

Source: [37]

A simple distribution substation may take less than one acre. Other types of substations may take up to six acres or more.

1.4.2 Electric power transmission and distribution losses

The power is typically transmitted at HV (110 kV or above) to minimize the energy lost. However, most of the existing electric power delivery systems existing in the study area are ageing infrastructure and largely reflect technology developed in the 1950s that either currently needs or will soon need replacement [38]. The ageing of T&D infrastructure pushes the power system to be extremely vulnerable and causes high distribution and transmission losses [38]. The electricity T&D losses are often ignored in electricity LCAs. The impacts of T&D are likely to become more significant compared to the impact of electricity generation itself. Previous studies explored the possibilities of developing new infrastructural designs to enhance the efficient transmission systems from the remote areas with distributed generation such as wind and PV power. The distributed generation systems are connected directly to low voltage lines. However, the developed LCAs for the previous studies did not account for both electricity generation and transmission [9], [39]. The prevailing average T&D losses data (refer Figure 1.5), shows that, Tanzanian power transmission and distribution losses of 25% (with regular power outages) is among the highest in Africa and the world, and improving transmission efficiency or reducing losses is the foremost concern in the electric power systems development [35].

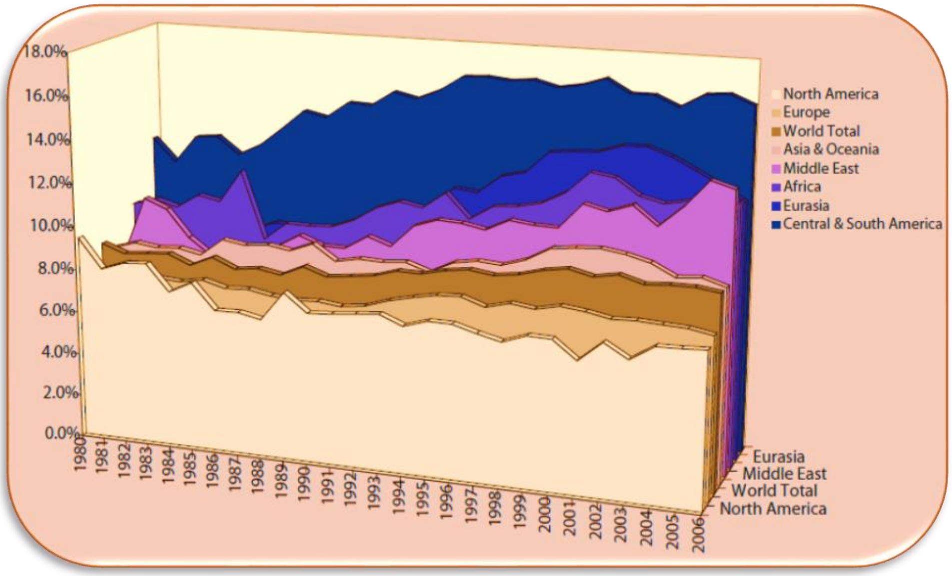


Fig.1. 5. Average T&D losses by region for both technical and nontechnical

Source:[40]

About 49% of power is produced by hydro. Most of the hydro-power plants are found in the southern part of Tanzania while maximum load centres are in the northern part. High losses in the distribution lines are mostly due to the ageing of the lines, with poor investments and unplanned extensions for a long time, causing overloading of system equipment such as conductors and transformers [35]. The previous Kenya power sector assessment report also reported that as of 2015, Kenya had total transmission losses of 4.5% [36]. The distribution network in regions outside Nairobi is less interconnected, and generally with long distances between transmission substations or bulk supply points with many radial 33kV and 11kV feeders, with average losses of 13.5%. [37]. In Rwanda, the overall losses figure from generation to the distribution system was 23% at the end of 2011[41]. The Tanzanian T&D losses are extremely high because electrical power generation and T&D technical losses of 22.5% [42] are acceptable in Asia and Oceania. The higher T&D losses reported in Tanzania and Rwandan depends on the network characteristics such as existing 33 kV, 11 kV, and 400-volt lines in rural areas are extended over long distances to feed loads scattered over large areas. However, figure 1.5 shows the average African T&D losses ranges from 9%-13%.

1.5 Contributions of the Thesis

The main contributions of this thesis are summarised as follows:

a. Contribution to an improved understanding of the life-cycle carbon emission values produced due to various electrical power T&D designs and operations (including removal of vegetation for the right of ways);

b. Contribution to the development of the “Life-cycle carbon-emission (LCCE) estimation model for electrical power systems”, hence improving the knowledge on the optimal electricity generation mix and transmission plan(s) for environmentally sustainable power systems design and monitoring;

c. Demonstration of how to apply the LCCE estimation tool to a case study to develop a dataset for the LCCE for the electrical power systems of the studied countries;

d. Provision of online data link to allow decision-makers, researchers, and practitioners to explore more the application of best practices in the studied grids;

e. Published scientific articles to support the design, and operations of electrical power systems with minimum environmental impact; and

f. Proposed theories on the life cycle assessment, and hence bridge the knowledge gap on the level of understanding of the environmental sustainability performance of the power systems designs, operations, and objectives anticipated by different system operators, researchers and policymakers.

1.6 List of publications developed from the research and Thesis preparation work

The following listed four (4) scientific papers have been published in the course of the research and preparation of the thesis. These include two (2) articles published in peer-reviewed journals, and two (2) articles published in peer-reviewed Conference proceedings. One (1) manuscript has been submitted for publication. The proposed research model presented in this thesis is based on these papers. This means that three (3) thesis chapters out of the six (6) chapters have been published. The version of papers presented in this thesis differs only in slightly formatting and minor errata. In all the papers I am the main author supported by my three supervisors, as co-authors

Publication 1:

E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, 'Impact of Electrical Power Systems on the Environment in Kenya, Rwanda, and Tanzania'. *Article presented at the* postgraduate (energy systems) forum session (hosted by Tshwane University of Technology) of the 2018 IEEE PES/IAS PowerAfrica *Conference on Affordable and Clean Emerging Energy Solutions for Sustainable Development* in Cape Town, South Africa, published in the ***IEEE Xplore***,

(https://doi.org/10.1109/PowerAfrica.2018.8521092)

Publication 2:

E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, 'Grid Electricity Generation Systems Comparisons Using the Life Cycle Carbon Emission Inventory'. *Article presented at the* 2020 IEEE PES/IAS PowerAfrica *Conference on Sustainable and Smart Energy Revolutions for Powering Africa* in Nairobi, Kenya, published in the ***IEEE Xplore***, (https://doi.org/10.1109/PowerAfrica49420.2020.9219876*)*

Publication 3:

E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, 'Modelling of environmental emission in Kenyan, Rwandan, and Tanzanian electrical power systems', *J. Clean. Prod.*, p. 127830, Vol.312, Aug. 2021.

(https://doi.org/10.1016/j.jclepro.2021.127830)

Publication 4:

E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, 'Data on the life-cycle carbon-emission in Kenyan, Rwandan, and Tanzanian grid electricity generation and transmission systems', *Data Br. J.*, p. 107692, Vol. 40, Feb. 2022.

(https://doi.org/10.1016/j.dib.2021.107692)

Manuscript:

E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, 'Assessment of Grid Electricity Systems Using the Life-Cycle Carbon-Emission Model', Completed Journal manuscript number EPSR-D-22-03388, under *Review*

1.7 Thesis layout

The first two chapters of this thesis provide an introduction and review of the status of existing, and operational electrical power generation, T&D systems, and the associated environmental life cycle emissions (particularly the life-cycle carbon-emission) methods. The three original chapters of the thesis (chapter three, chapter four, and chapter five) were developed following the three specific objectives of the research presented in chapter one of the thesis.

The first section of the **chapter two** presents a review of the baseline status of the studied national T&D systems and their associated greenhouse gas emissions. The sub-chapter has been presented in the 2018 IEEE PES/IAS PowerAfrica Conference and published by IEEE and is available in IEEE Xplore. The second section of this chapter developed the baseline status of the studied grid electricity generation systems; it proposes an environmental life-cycle inventory model. The sub-chapter has been presented at the 2020 IEEE PES/IAS PowerAfrica Conference and also published by IEEE and available in IEEE Xplore.

Chapter three presents the compiled relevant life cycle carbon emissions data for the studied grids. It also presents an online data link. The presented data allows researchers, practitioners and policymakers to move away from overly basic assertions concerning the comparative environmental advantages of the different electricity system plan(s), and to focus on the comprehensive image, especially the serious roles of technology variety and the use of best practices. It also presents the research design as well as some ethical considerations. The chapter also demonstrates how developed mathematical algorithms have been applied to the study area. The work done in this chapter has been published as data article in the Data in Brief journal (Elsevier).

Chapter four of the thesis presents a model for estimating the dynamic life-cycle carbon-emission of the studied power system components. In this chapter, a method is proposed to bridge the existing knowledge gap regarding the feasibility of the eco-labelled electricity composition designs assumed by electric power systems researchers. An evidence-based assessment model for influencing innovations, infrastructural eco-designs and technology transfers for sustainable electrical power systems, has been developed in this chapter. In this chapter theories (using the developed research questions) related to science, technology, environment, policy and society concerning the infrastructural design and operations of electrical power systems, have been advanced. Results produced in this chapter have been published as research article in the Journal of Cleaner Production (Elsevier).

Chapter five presents the life cycle impact assessment of carbon emitted from the studied electrical power generation and HV transmission systems. The chapter also presents life-cycle inventory-analysis (LCIA) from the developed parameters, data collected and calculated using Microsoft Excel. An analysis is made of the pre-defined research question that "There is no lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power system" in Tanzania and Rwanda using R codes developed from the data generated in the course of this research. The work done in this chapter has been submitted for publication in the journal of Electrical Power Systems Research (Elsevier).

Chapter six of the thesis provides answers to the research questions. It also presented some research limitations which may impair the neatness and usability of the obtained results. The chapter also proposes the areas of further research for targeting and observation of both global and local policy interventions for environmentally sustainable power systems development.

List of References

[1] I. B. Hauan, "Life Cycle Assessment of Electricity Transmission and Distribution," Norwegian University of Science and Technology, 2014.

[2] J. Klimstra and M. Hotakainen, *Smart Power Generation*, 4th ed. Helsinki: Avain Publishers, 2011.

[3] F. Iannone and D. Zaninelli, "Life cycle assessment applications to electrical energy production: a possible sustainability analysis tool," *2007 IEEE Power Eng. Soc. Gen. Meet.*, pp. 0–5, 2007, doi: 10.1109/PES.2007.385958.

[4] M. Felix and S. H. Gheewala, "Environmental assessment of electricity production in Tanzania," *Energy Sustain. Dev.*, vol. 16, no. 4, pp. 439–447, 2012, doi: 10.1016/j.esd.2012.07.006.

[5] G. Falchetta, M. Hafner, and S. Tagliapietra, "Pathways to 100% Electrification in East Africa by 2030," *Energy J.*, vol. 41, no. 3, 2020, doi: 10.5547/01956574.41.3.gfal.

[6] E. G. H. Raquel S.Jorge, "Grid infrastructure for renewable power in Europe: The environmental cost," *Energy*, no. May, pp. 760–768, Vol. 69, 2014, doi: 10.1016/j.energy.2014.03.072.

[7] A. Arvesen, I. B. Hauan, B. M. Bolsøy, and E. G. Hertwich, "Life cycle assessment of transport of electricity via different voltage levels: A case study for Nord-Trøndelag

county in Norway," *Appl. Energy*, p. 20, 2015, doi: 10.1016/j.apenergy.2015.08.013.

[8] M. Felix and S. H. Gheewala, "Environmental assessment of electricity production in Tanzania," *Energy Sustain. Dev.*, vol. 16, no. 4, pp. 439–447, 2012, doi: 10.1016/j.esd.2012.07.006.

[9] R. Turconi, A. Boldrin, and T. Astrup, "Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations," *Renew. Sustain. Energy Rev.*, vol. 28, pp. 555–565, 2013, doi: 10.1016/j.rser.2013.08.013.

[10] H. Chum, "Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," in *October*, no. October, J. S. (UK) Kirit Parikh (India), Ed. New York, NY, USA: Cambridge University Press, Cambridge, United Kingdom, 2004, pp. 511–598.

[11] M. Felix and S. H. Gheewala, "Environmental toxicity potential from electricity generation in Tanzania," pp. 1424–1432, 2014, doi: 10.1007/s11367-014-0748-8.

[12] N. Komendantova, M. Vocciante, and A. Battaglini, "Can the BESTGRID process improve stakeholder involvement in electricity transmission projects?," *Energies*, vol. 8, no. 9, pp. 9407–9433, 2015, doi: 10.3390/en8099407.

[13] World Energy Council, "Comparison of Energy Systems Using Life Cycle Assessment: A Special Report of the World Energy Council," London W1B, 2004.

[14] F. Blaabjerg and J. M. Guerrero, "Smart grid and renewable energy systems," in *International Conference on Electrical Machines and Systems, ICEMS*, 2011, pp. 1–10, doi: 10.1109/ICEMS.2011.6073290.

[15] R. S. Jorge, T. R. Hawkins, and E. G. Hertwich, "Life cycle assessment of electricity transmission and distribution-part 1: Power lines and cables," *Int. J. Life Cycle Assess.*, vol. 17, no. 1, pp. 9–15, 2012, doi: 10.1007/s11367-011-0335-1.

[16] C. Ghenai and M. Bettayeb, "Data analysis of the electricity generation mix for clean energy transition during COVID-19 lockdowns," *Energy Sources, Part A Recover. Util. Environ. Eff.*, pp. 1–21, Feb. 2021, doi: 10.1080/15567036.2021.1884772.

[17] E. Chambile, N. Ijumba, B. Mkandawire, and J. Hakizimana, "Impact of Electrical Power Systems on the Environment in Kenya, Rwanda and Tanzania," in *2018 IEEE PES/IAS PowerAfrica Conference*, 2018, no. 18261617, pp. 885–889, doi: 10.1109/PowerAfrica.2018.8521092.

[18] E. Chambile, N. Ijumba, B. Mkandawire, and J. Hakizimana, "Grid Electricity

Generation Systems Comparisons Using the Life Cycle Carbon Emission Inventory," in *2020 IEEE PES/IAS PowerAfrica Conference*, 2020, pp. 1–5, doi: 10.1109/PowerAfrica49420.2020.9219876.

[19] A. Chervyakov, M. Ferrari, A. Marian, S. Stückrad, and H. Thomas, "Superconducting Electric Lines," 2015. doi: 10.2312/iass.2015.028.

[20] H. H. Khoo and R. B. H. Tan, "Life Cycle Assessment Methodology : Ongoing Developments and Outlook," 2022 World Scientific Publishing Company, 2022, pp. 1–21.

[21] ISO, "Environmental management — Life cycle assessment — Principles and framework," *ISO 14040*, vol. 2006, Art. no. Reference number ISO 14040:2006(E), 2003.

[22] E. A. Nyari, T. Pogrebnaya, and L. Wilson, "Energy Sector and Solar Energy Potential in Tanzania," 2015. [Online]. Available: www.ijete.org.

[23] Lahmeyer International, "Analysis and Projection of Rwandas Electricty Demand," Kigali, 2004. doi: http://www.devpartners.gov.rw/fileadmin/templates/docs/EDPRS/Key%20Analytical%20Studies/Sectoral%20Studies/Energy_Demand_Analysis_%26_Projection_2004.pdf.

[24] V. Zongo, "Iringa-Shinyanga Transmission Line Project Country : Tanzania," Dar es Salaam, 2010. [Online]. Available: https://docplayer.net/6269043-Project-appraisal-report.html.

[25] M. Madrigal and R. Spalding-Fecher, "Impacts of Transmission and Distribution Projects on Greenhouse Gas Emissions," Washington, D.C, N O . 2 1, 2010.

[26] United States Environmental Protection Agency, "EIA Technical Review Guidelines: Energy Generation and Transmission," 2011. [Online]. Available: http://www2.epa.gov/sites/production/files/2014-04/documents/energyvol1.pdf.

[27] K. E. G. C. Limited, "Powering a Sustainable Future," Nairobi, 2017.

[28] SE4All, "Sustainable Energy for All (SE4All) Kenya's Investment Prospectus," Nairobi, 2016.

[29] Republic of Rwanda, "Energy Sector Strategic Plan," Kigali, 2015. [Online]. Available: http://www.mininfra.gov.rw/rw/fileadmin/user_upload/new_tender/ESSP_17th_March_2015.pdf.

[30] K. Lee *et al.*, "Electrification for 'under Grid' households in Rural Kenya," *Dev. Eng.*, vol. 1, pp. 26–35, 2016, doi: 10.1016/j.deveng.2015.12.001.

[31] D. Peng and R. Poudineh, “Sustainable electricity pricing for Tanzania,” London, E-40305-TZA-1, 2016. [Online]. Available: http://www.theigc.org/wp-content/uploads/2016/08/Peng-Poudineh-2016-Working-Paper.pdf.

[32] J. F. Kitonga and E. Bonafe, “Tanzanian energy sector under the universal principles of the International Energy Charter,” 2015. [Online]. Available: http://www.energycharter.org/fileadmin/DocumentsMedia/CONEXO/20150827-Tanzania_Pre-Assessment_Report.pdf.

[33] Rural Energy Agency, “Energy Access Situation Report, 2016; Tanzania Mainland,” Dodoma, 2017. [Online]. Available: https://www.nbs.go.tz/nbs/takwimu/rea/Energy_Access_Situation_Report_2016.pdf.

[34] Andrew, K. S. and R. Herscowitz, and Donovan, “Investment Brief for the Electricity Sector in Tanzania,” 2014. [Online]. Available: https://www.usaid.gov/sites/default/files/documents/1860/Tanzania _IG_2015_05_03.pdf.

[35] United Nations Development Programme, “Rapid Assessment Gap Analysis Pakistan,” Kigali, 2012.

[36] U.S. DOE, “Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities,” 2015. [Online]. Available: http://energy.gov/sites/prod/files/2015/09/f26/Quadrennial-Technology-Review-2015_0.pdf.

[37] M. Munasinghe and W. Scott, “Energy Efficiency: Optimization of Electric Power Distribution System Losses (Final Report of Research Project No. R633),” Washington, D.C., 1982.

[38] H. Williams and C. W. Paper, “Transmission & Distribution Infrastructure Transmission & Distribution Infrastructure,” 2010.

[39] R. Turconi, “Life Cycle Assessment of Electricity Systems,” Technical University of Denmark, Copenhagen, 2014.

[40] M. Madrigal and R. Spalding-Fecher, “Impacts of Transmission and Distribution Projects on Greenhouse Gas Emissions. Review of Methodologies and a Proposed Approach in the Context of World Bank Lending Operations,” Washington, D.C., 2010. doi: 10.1596/27755.

[41] Rwanda Energy Group, “Brief Note on Loss Reduction Project Funded by European Union,” 2017. [Online]. Available:

http://reg.rw/images/pdf/BRIEFNOTEONPROJECTS002. pdf.

[42] Electrical India, “Losses in Distribution & Transmission Lines _ Electrical India Magazine,” *Electrical India Magazine*, 2018. https://www.electricalindia.in/losses-in-distribution-transmission-lines/#:~:text=Technical losses are normally 22.5,30%25 of the total losses (accessed Nov. 02, 2022).

CHAPTER TWO

2.1.0 Carbon Emission from Transmission and Distribution Right of Passage

2.1.1 Abstract

The understanding of the impacts caused by electrical power systems on the environment is important in order to mitigate the environmental impacts. A literature review on the direct non-generation greenhouse gas emissions in the construction and operation of the national electrical power transmission and a distribution (T&D) system was conducted in order to understand its impact on climate change. The results revealed that the impact of the length of T&D lines to the greenhouse gas emissions, due to vegetation removal, is insignificant. The findings show that, Kenya is the lowest emitter of carbon in study area with the highest average flow of electricity; compared to Rwanda with the lowest average flow of electricity. The study contributes to an improvement of the understanding of the life cycle emission inventory and the impacts caused by electrical power T&D on greenhouse gases due to vegetation removal in particular. However, further studies are recommended, to cover a wider scope of the environmental impact and electrical power systems backed by primary data on materials consumption by the power systems and power losses in the system.

Key words: Direct non-generation emission, land clearing, life cycle assessment, electrical power systems, greenhouse gases.

2.1.2 Background

An electricity network comprises a system in which electricity is generated, transmitted and distributed to consumers [1]. This system consists of power stations, transmission and distribution lines, transformers, converters, storage units, electrical appliances and access road. Power stations produce electricity from other energy forms and carriers, such as fossil fuels, nuclear, natural gas and renewables. In order to minimize transmission losses, electricity is typically converted to a high voltage level by transformers and transmitted at this level from power plant to a distribution system, where it is converted to the distribution voltage level by other transformers. In case of long distances, usually starting at about 400-800 km, DC is used for transmission, which lowers demand placed on conductors and removes the need for reactive power compensation, thereby offsetting the high costs of AC/DC converters[1], [2]. The activities entailed in the generation, transmission and distribution of electricity impair environmental resources and their attributes.

Generally, electricity generation can result into environmental impacts including but not limited to: acidification, eutrophication, resource depletion, land transformation, and water quantity/quality and climate change[3][4]. The generation of electricity entails the consumption of natural resources (mainly fuels) and consumption of water (an increasingly scarce resource).

The carbon emissions of delivering electricity to consumers is estimated to be 90% attributed to power production, 8% to distribution and 2% to transmission [5]. The carbon emissions of new transmission and distribution lines on an area may depend on the topography, land cover, and existing land uses. In forested areas for example, the entire right-of-way width is cleared and maintained free of tall-growing trees for the life of the transmission line. The result is a permanent change to the right-of-way land cover. Few consumers receive electricity directly from power plants. Hence, a good understanding of the environmental impacts of electricity use in society must necessarily involve a sound understanding of T&D. The impacts of T&D are known to be due to both infrastructure and electricity losses, however, environmental assessments of electricity generation often fail to include the impacts of T&D, thereby potentially leading to incorrect results [6], [7].

2.1.3 Literature review

Review of literature suggests that a number of studies have been carried out to study the environmental life cycle assessment of electrical power generation and storage technologies as well as transmission and distribution infrastructure [7]–[9]. Nevertheless, most studies employ data that do not necessarily reflect the country’s current status. This requires a detailed investigation of the up to date power systems in the study area. However, the development of a more convincing method for assessing the impact of T&D to the environment have little been discussed, while a few attempts to improve the method can be found [3], [7], [9]. In some cases the assessments have covered emissions from material consumption by the T&D systems[7].

2.1.4 Outcomes

The findings of this research provides information to be used to develop electrical power system policies, plans and designs with minimal environmental impacts. The model established in this research could be used for environmental impact assessment of electrical power systems, and act as empirical reference material for similar research in future. The obtained data information could also supply theory and data reference for climate change impact control in electrical power systems of the study area.

2.1.5 Methodology

The data analysis has been covered the power generation, transmission and distribution grids of Kenya, Rwanda and Tanzania. However, this chapter was designed to cover the literature review of the direct non-generation greenhouse gas emissions of T&D infrastructures, based on emission sources in the construction, operation and maintainance of the T&D systems in the study area. The study also did not cover the carbon emissions from materials consumption by the T&D systems and on-site energy use in construction, primarily in the form of transport fuel for construction vehicles and the shipping of components. This source of emissions was neglected due to the fact that it is likely to be very small compared to the lifetime energy and emission impacts of the T&D system. The corona discharge was also excluded from this study due to the fact that they are only present on very high voltage lines, and thus would not be applicable to distribution investments or many transmission lines in the study area. Due to the absence of data required to calculate the fugitive emissions of Sulfur hexafluoride (SF^6) during decommissioning, the study did not estimate that component.The baseline emissions from the importing and exporting grid were also neglected due to the fact that a very small amount (less than 5%) of electricity is currently exported and/ imported to the grids of the countries of study [10].

Impact indicators were measured per unit of total electricity delivered by the distribution and transmission for each country. The study was limited to evaluation of carbon dioxide (CO_2) as the main greenhouse gas. It was also limited to estimation of the carbon emission from transmission and distribution right of passage.

The average flow of electricity (AE) on T&D system in Kenya, Tanzania and Rwanda are 7,826.4GWh/year [11], 5,740.84 GWh/year[11] and 170 GWh/year [12], respectively. The lifetime of most of the transmission equipment is 50 years[13]. However, the average life of the T&D system adopted by this study is 20 years[10].In order to ensure the quality of results, reasonableness of the data was checked before processing it.

Equation (1) and (2) were applied to calculate direct non-generation emissions from land clearing for the T&D systems.

$$PE_{LC} = Ad_{ef} \times BD \qquad (1)$$

Where

PE_{LC}= Direct non-generation emissions from land clearing (tCO_2)

$Adef$= Area of land deforested (ha)

BD = Biomass density per unit area (above ground, below ground, soil carbon, litter, and dead biomass) (tCO_2/ha)

$$GHG = PE_{LC}/AE \qquad (2)$$

Where

AE= Average flow of electricity over the life of the project (MWh),

$PELC$ = Direct non-generation emissions from land clearing (tCO2)

GHG=Direct non-generation T&D greenhouse gas emissions (kg/MWh)

The transmission lines were assumed to transverse along the natural forests. The Rwanda's landscape is characterized as a tropical mountainecosystem while Kenya's and Tanzania's landscapes are characterized as a tropical rainforest ecosystem [10]. The distribution lines were assumed to tranverse on the farmlands. The farmlands can be developed through replacement of forests, grasslands, or desert shrublands. However, its biomass is usually similar to grasslands [14].

2.1.6 Current status

The data extrated and compiled in Tables 2.1.1, 2.1.2, and 2.1.3 were applied to calculate the total land area cleared to pave the way for the transmission and distribution lines in Kenya, Rwanda and Tanzania.

Table 2.1. 1. The land clearing subsystem modeled (T&D), with information on references in Kenya [15]–[18]

Transmission voltage level	66kV	132kV	220kV
Transmission line	580km	2436km	1331km
Transmission width of right of way	6.7m	27m	35m
Distribution voltage level	40kV	11kV	-
Distribution line	5,488km	13,879km	-
Distribution width of right of way	6m	6m	-

Table 2.1. 2.The land clearing sub-system modelled (T&D), with information on references in Rwanda [12], [16], [18], [19]

Transmission voltage level	70kV	110kV
Transmission line	253 km	96km
Transmission width of right of way	6.7m	22m
Distribution voltage level	30kV	15kV/V
Distribution line(km)	2,801 km	8,361 km
Distribution width of right of way	6m	6m

Table 2.1. 3. The land clearing subsystem modeled (T&D), with information on references in Tanzania [16], [18], [20]

Transmission voltage level	66kV	132kV	220kV
Transmission line	546km	1538km	2732km
Transmission width of right of way	6.7m	27m	35m
Distribution voltage level	33kV	11kV	400/230 V
Distribution line	12,602km	6,392km	26,565km
Distribution width of right of way	6m	6m	3.7m

Tables 2.1.4 and 2.1.5 show carbon emission results broken down by grid segments (representing national transmission and distribution systems). As is evident from Table 2.1.4, the delivery of 1 MWh of electricity by the transmission grid causes emissions of about 223 tCO_2, 157 tCO_2 and 368 tCO_2 in Kenya, Rwanda and Tanzania, respectively. Table 2.1.5 also shows that, distribution of 1 MWh of electricity by the transmission grid to consumers causes

emissions of about 52 tCO_2, 1379 tCO_2 and 129 tCO_2 in Kenya, Rwanda and Tanzania, respectively. Figure 2.1.1 revealed that, generally distribution lines emit more (almost double) than transmissions lines in the specific study area. However, the literatures shows that, upon consideration of the other factors such as the total power losses in the grid—or overall grid system efficiency, the distribution lines causes more emissions (almost four times) than transmissions lines [5]. Figure 2.1.2 shows that Rwanda is the highest carbon dioxide emitter in the study area with 1378835 kg CO_2/MWh, while Figure 2.1.3 indicates that Rwanda is dominating in T&D emission at 79%, followed by Tanzania at 14%.

Table 2.1. 4. Direct non-generation emissions from land clearance for the Transmission systems for 20 years' life span

	Kenya	Rwanda	Tanzania
Adef(ha)	116243000	3807100	140804200
BD(tCO_2/ha)	300 [10]	140 [10]	300 [10]
PE_{LC}(tCO_2)	34872900000	532994000	42241260000
GHG Transmission line emissions (kg/MWh)	222790	156763	367901

Table 2.1. 5. Direct non-generation emissions from land clearance emissions for the distribution systems for 20 years' life span

	Kenya	Rwanda	Tanzania
Adef(ha)	116202000	66972000	212254500
BD(tCO_2/ha)	70[10]	70[10]	70[10]
PE_{LC}(tCO_2)	8134140000	4688040000	14857815000
GHG Distribution line emissions (kg/MWh)	51966	1378835	129405

The results show that Kenya is the lowest emitter in the study area with the highest average flow of electricity (7,826.4GWh/year) compared to Rwanda with the lowest average flow of electricity (170 GWh/year). The study therefore revealed that, the grid infrastructural design, technology and the average flow of electricity are the dominant factors of the direct non-generation greenhouse gas emissions. However, other factors such as the length of transmission and distribution lines, and biomass density per unit area contribute less.

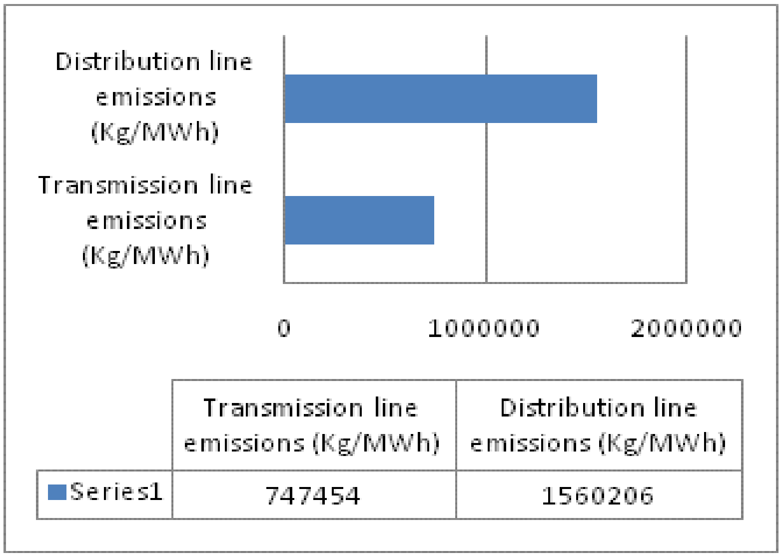


Fig.2.1. 1.Transmission and distribution lines emissions (Kg/MWh) from land clearing in study area

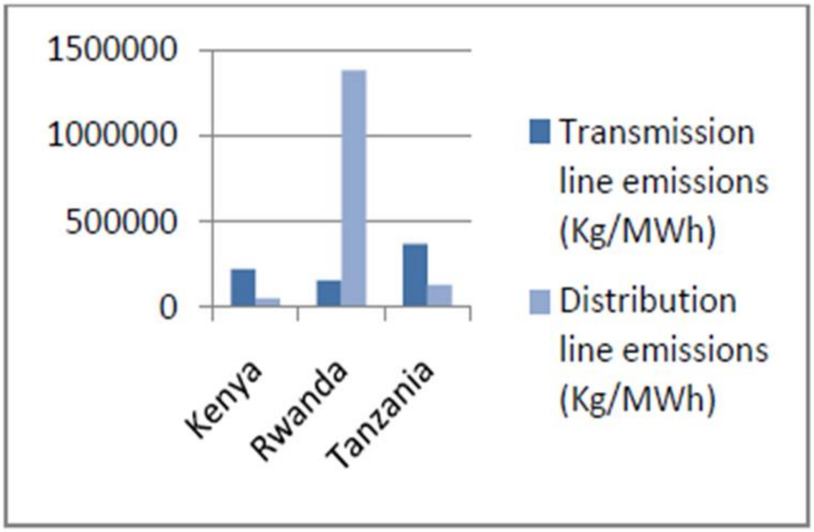


Fig.2.1. 2. Separate transmission and distribution lines emissions (Kg/MWh) from land clearing

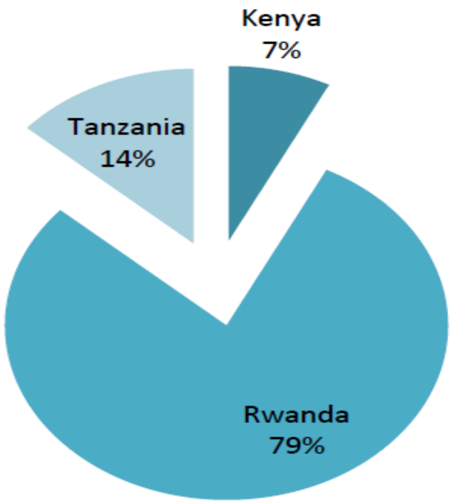


Fig.2.1. 3. Combined transmission and distribution line emissions (Kg/MWh) from land clearing

2.1.7 Conclusion and recommendation

The overall, electricity T&D can represent 10% of environmental impacts for the complete power generation and supply chain [5]. However, the current article adds to the body of knowledge on the Greenhouse gas emissions of electricity T&D, by examining the case of electricity supply in Kenya, Rwanda and Tanzania. The study contributes to an improvement of the understanding of the life cycle emission inventory and the impacts of electrical power T&D on greenhouse gases due to vegetation removal in particular. The study concludes that, the technologically advanced grid infrastructure with the larger average flow of electricity emit less while those grids with inferior technology and lower average flow of electricity emit more.

The study also developed some new life cycle carbon emissions data for electricity transmission and distribution that were not found in the previous literature especially for the vegetation removal. The data could be used to model networks in other countries within the region with similar environmental and technological conditions. The study also revealed that, there is no direct consequence on the distance of the T&D lines to the carbon emissions per average flow of electricity. However, further studies are recommended under this research to be backed by primary data and cover a wider scope of the environmental impact and electrical power systems.

The life cycle system boundary has been expanded in Chapter 3, 4 and 5 to take into account the generation and transmission of electricity. Thesis also considered other variables apart from the biomass density of the area cleared for T&D lines; covered environmental emissions associated with materials consumption by the power generation systems and power transmission losses in the system. Computer based simulations has been applied for the propagation of uncertainty.

References

[1] U. C. D. Chemwiki, C. C. A. Alike, and U. S. License, *Electric Power Systems: A Conceptual Introduction*. New Jersey: IEEE Press and John Wiley & Sons, Inc., Hoboken.

[2] A. Arvesen *et al.*, “Green Energy Choices: the benefits, risks and trade-offs of low-carbon technologies for electricity production,” Paris, France, 2016. [Online]. Available: http://www.un-expo.org/wp-content/uploads/2017/06/Green_energy_choices_The_benefits_risks_and_trade-offs_of_low-carbon_technologies_for_electricity_production-2016UNEP_GEC_web.pdf.pdf.

[3] M. Felix and S. H. Gheewala, “Environmental assessment of electricity production in Tanzania,” *Energy Sustain. Dev.*, vol. 16, no. 4, pp. 439–447, 2012, doi: 10.1016/j.esd.2012.07.006.

[4] C. V. A. and M. J. B. Paul J. Miller, “North American Power Plant Air Emissions,” Montréal (Québec) Canada, 2004.

[5] R. S. Jorge, T. R. Hawkins, and E. G. Hertwich, “Life cycle assessment of electricity transmission and distribution-part 1: Power lines and cables,” *Int. J. Life Cycle Assess.*, vol. 17, no. 1, pp. 9–15, 2012, doi: 10.1007/s11367-011-0335-1.

[6] E. G. H. Raquel S.Jorge, “Grid infrastructure for renewable power in Europe: The environmental cost,” *Energy*, no. May, pp. 760–768, Vol. 69, 2014, doi: 10.1016/j.energy.2014.03.072.

[7] A. Arvesen, I. B. Hauan, B. M. Bolsøy, and E. G. Hertwich, “Life cycle assessment of transport of electricity via different voltage levels: A case study for Nord-Trøndelag

county in Norway," *Appl. Energy*, p. 20, 2015, doi: 10.1016/j.apenergy.2015.08.013.

[8] M. Felix and S. H. Gheewala, "Environmental toxicity potential from electricity generation in Tanzania," pp. 1424–1432, 2014, doi: 10.1007/s11367-014-0748-8.

[9] R. Turconi, A. Boldrin, and T. Astrup, "Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations," *Renew. Sustain. Energy Rev.*, vol. 28, pp. 555–565, 2013, doi: 10.1016/j.rser.2013.08.013.

[10] M. Madrigal and R. Spalding-Fecher, "Impacts of Transmission and Distribution Projects on Greenhouse Gas Emissions," Washington, D.C, N O . 2 1, 2010.

[11] E. A. Nyari, T. Pogrebnaya, and L. Wilson, "Energy Sector and Solar Energy Potential in Tanzania," 2015. [Online]. Available: www.ijete.org.

[12] Lahmeyer International, "Analysis and Projection of Rwandas Electricty Demand," Kigali, 2004. doi: http://www.devpartners.gov.rw/fileadmin/templates/docs/EDPRS/Key%20Analytical%20Studies/Sectoral%20Studies/Energy_Demand_Analysis_%26_Projection_2004.pdf.

[13] V. Zongo, "Iringa-Shinyanga Transmission Line Project Country : Tanzania," Dar es Salaam, 2010. [Online]. Available: https://docplayer.net/6269043-Project-appraisal-report.html.

[14] D. Turney and V. Fthenakis, "Environmental impacts from the installation and operation of large-scale solar power plants," *Renew. Sustain. Energy Rev.*, vol. 15, no. 6, pp. 3261–3270, 2011, doi: 10.1016/j.rser.2011.04.023.

2.2.0 Grid Electricity Generation Systems Comparisons using the Life Cycle Carbon Emission Inventory (LCCEI)

2.2.1 Abstract

The study compared electricity generation systems using the life cycle carbon emission among the studied Kenyan, Rwandan and Tanzanian grids. The article presents the possible grid electricity generation mixes and purchase which can offer the lowest grid carbon emission. The developed inventory workbooks were adopted to account for residue carbon emissions related to the capacity survival lifetime, retired generation capacity, recycling rate and the current power trade planned in the study area. The current installed and operated grid electricity generation systems-process revealed to be a dominant emission factor in the studied grids. The study revealed the carbon reduction potential from the current grid upon the adoption of 100% renewable (grid electricity generation) mixes in the study area. The specific monitoring of the electricity generation capacity survival and retirement rates recommended for the future electrical science–policy research.

Index Terms: Grid electricity generation systems, low carbon emission energy resources, renewable electricity resources

2.2.2 Introduction

The modern electrical power systems grow towards more distributed generation points and shifting from the use of conventional and fossil-based energy sources to the use of renewable energy sources through the use of highly efficient power electronics[1],[2]. The power generation system have been changed from being just a down-streamed, large power-producing units into grid structure where the power is dispersed produced in many cases closer to the location of consumption [3]. Emission of carbon in electrical power generation systems is driven by the electricity demand, the share of renewable energy, smart and efficient technologies, substitution ratio, retirement ratio and the recovery ratio of the installed capacity [1], [3], [4]. The carbon emission driven factors are independent variables whereby, the dependent variables are carbon emission volumes. Building Life Cycle Carbon Emission Inventory (LCCEI) database is essential to provide information for 'clean technologies' design rather than investing in 'cleaning technologies'. The CO_2 taxation enhances minimization of climate impacts and hence recently caused electrical power system master plans to integrate CO_2 management issues.

The Southern Africa Power Pool (SAPP) and Eastern Africa Power Pool (EAPP) fostering regional interconnections to maximize the integration of renewable electricity into national grids[5]. The studied grids are within the EAPP. However, Tanzanian grid is also connected to the SAPP. The studied grids are interconnected by the lines presented in Table 2.2.1.

Table 2.2. 1. The interconnection lines in the studied grids [6]

From/To	From/To	Voltage (kV)	Committed Capacity (MW)
Kenya	Tanzania	400	1300
Rwanda	Tanzania	220	320

The previous study revealed the average flow of electricity in Kenya, Tanzania and Rwanda to be 7,826.4GWh/year, 5,740.84GWh/year and 170GWh/year respectively [6]. It was also identified some carbon emissions due to vegetation removal (through the total biomass removed, and carbon sink loss supposed to be done by the removed vegetation) to pave the right of ways for the electrical power transmission and distribution lines in the study area.

Considering their environmental characteristics, different system capacity levels and grid mixes make Kenya, Rwanda and Tanzania the perfect candidates for the exploitation of the renewable energy resources at different scales in both Eastern Africa and Southern Africa power pools [7],[8]. Providing life cycle Green House Gases (GHGs) inventories of electricity technologies and systems is a particularly challenging task, because of the complexity of the system being analyzed including the wide variation among generation technologies in emissions and inputs per unit generation across and even within fuel types. The component-related environmental impacts are essential for a thorough understanding of the total impacts of energy systems [9], [10]. The development of research to assess the most efficient, clean and affordable electricity generation technologies is required to achieve political, economic and environmental targets.

This study backs an objective to explore and contribute to an improved understanding of, the impacts of electrical power generation systems on the environment. It also aimed to compile an inventory of relevant inputs and outputs of the potential power generation systems of Kenya, Rwanda and Tanzania using the country and regionally specific data, and best practice assumptions. The study also designed to examine the basics of the mix of renewable power generation systems needed to pursue a sustainable future. The next section of this article addresses the dynamic interconnection potentials of energy and environment, and developing a possible comparison base for establishing recommendations and alternatives for action on, new grid power generation installation, regional power purchase and retirement of the current installed capacity. It is also providing useful information to compare the electricity generation system sustainability among the studied countries.

The electricity generation potentials from ocean waves existing in the study area have not covered. Therefore, the change of the power system generation flow for this particular study will be attributed by the adoption of solar rooftops projects, wind farms, geothermal and hydro. The developed conceptual framework of a particular research is presented in Figure 2.2.1.

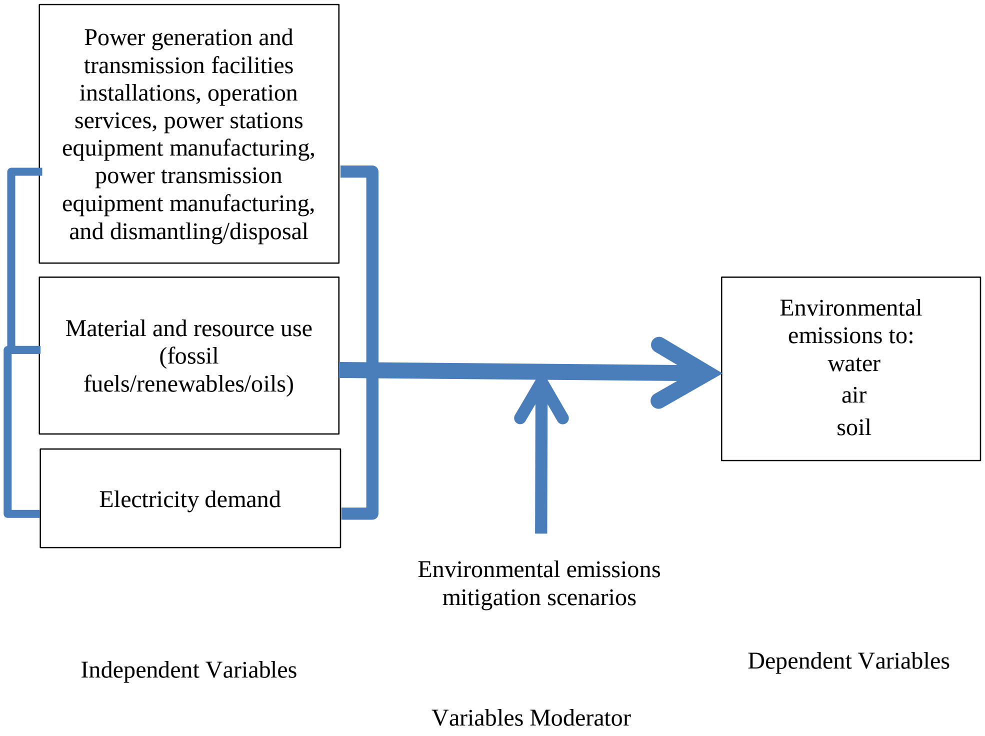


Fig.2.2. 1. Conceptual research framework

The carbon in biomass and bagasse has not been evaluated since they are part of the global carbon cycle. The finding of this study provides an idea about the possible carbon accounting of electricity generation systems and technologies. The study covered carbon emissions mainly from materials consumption by the systems. The limited understanding of the life cycle inventory analysis for targeting and monitoring of the local, regional and global grid-electricity generation systems is prevailing. Little has been discussed, in the previously studies, for the development of a more convincing carbon emission inventory results suitable to achieve the maximum environmental sustainability targets of the studied grids electricity generation technologies [6], [11]. Most relevant methods of the life cycle carbon emission inventory of the grid electricity generation systems lack the consideration of the different survival lifetime, residue emissions from the retired capacity and recycling rate of the current and newly installed grid electricity generation system components for the estimation of the grid carbon emissions.

2.2.3 Values of various parameters of the developed LCCEI

The future impact of the increased electricity efficiency was ignored just for simplification. The electricity generated from wind, solar, hydro, geothermal plants have been accounted for into grid since they are already incorporated in the prevailing electrical power systems. The current targeted grid carbon emission rate provided by the least-cost power development plan of Rwanda was about 0.05 kg/MW by the base year 2019 [2] while the value calculated through this study was about 26.75 kg/MW, the current carbon emission in Rwanda has been highly contributed by the use of peat energy resources and technology pools [7]. The Rwandan grid carbon emission factor of 0.00164 kg/MW has been obtained (from the LCCEI for the generation part of the power systems for each country) during the course of this study, under the maximum renewable electricity purchase and installed generation systems; the obtained grid carbon emission is equal to 3% of the baseline targeted value provided in the prevailing Rwanda Least Cost Power Development Plan. However, no clear grid carbon emission reduction targeted values identified in the prevailing Kenyan and Tanzanian power development plans; in the current sustainability campaigns when scientists', economists' and government leaders' around the world have recognized the need to lower carbon emissions. The mathematical representation of the LCCEI refined to accommodate a wide range of independent variables parameters have been studied and explained in chapter 3.

2.2.3.1 Life cycle carbon emission inventory workbooks

The MS Excel workbooks containing spreadsheets translated from the modified algorithm have been applied to compute the carbon emission volumes. The variable values for survival and retirement parameters time incorporated into workbooks were obtained from the pre-established standard curve [11]. The activity data incorporated into workbooks were obtained from the national electric power generation institutions including Kenya Electricity Generation Company (KenGen), Tanzania Electricity Supply Company Limited (TANESCO) and Rwanda Energy Group (REG). The technology-specific carbon emission factors were sourced from the published scientific and technical papers [12]–[14] The overall grid carbon emission factor for Rwandan, Tanzanian and Kenyan power systems have been revealed by summing the fractions of all carbon emission factors from different operational generation mix technologies by the year 2019. The grid installed capacity by the year 2049 has been linearly adjusted from the last year of projection presented on the most recently updated national and regional power systems plans [2], [4], [7], [15]–[18]. The workbooks were not considered the carbon emission prevention and control technologies beyond the available potential renewable technologies since the maximum sustainability is attained upon the maximum environment-energy conservation.

2.2.3.3 Uncertainty reduction

The study established the function unit of MW to comply with pre-established international life cycle assessment standards [19], [20]. The LCCEI uncertainty reduced by considering the recycling possibilities for some newly installed generation capacities, technology choices based on carbon emission substitution levels; retirement and survival ratio in the mathematical algorithm, and planned capacity for the regional power trade in the studied electrical power generation systems [7], [13], [17], [21]. The real data from the existing, committed and candidate plants obtained within the defined power pools and the electric power systems boundary. The article compared the life-cycle carbon emissions values obtained through the proposed mathematical algorithm (considering established life cycle carbon emission inventory) against the carbon emissions obtained through conversional method using the product of the country-specific grid emission factor and the projected grid electricity generation activity data.

2.2.4 Carbon emission results and discussion

The lifetime evaluation of 30 years (as the average lifetime of electric power systems) has been assumed from the base year 2019 to establish the presented results for each life cycle carbon emission parameter.

2.2.4.1 The proposed 100% renewable electricity purchase and installed generation systems

The current data explored the renewable potentials of the grid electricity mix in the study area as presented in Figure 2.2.2. The results indicated a significant potential use of geothermal energy by 56% in Rwanda upon the optimal implementation of the current potential installed capacity of 700MW available onsite and optimal planned purchase of about 240MW within the EAPP.

The current explored potential geothermal resources use for the newly installed grid electricity in the study area is about 15700MW whereby more than 64% of it is from the Kenyan grid.

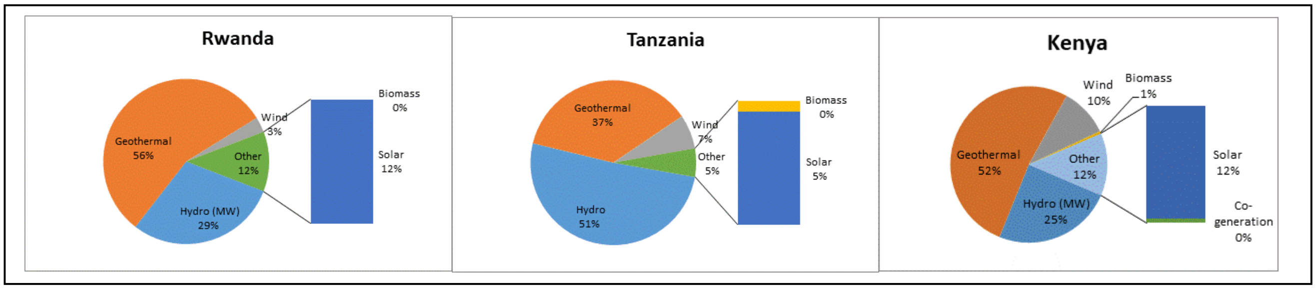


Fig.2.2. 2. The proposed 100% renewable electricity purchase and installed generation systems to offer the lowest possible life cycle carbon emission contribution in the studied grids by the year 2049

The hydro resources revealed to have a potential of contributing up to about 51% in Tanzania; however, the data about the optimal available water resources carrying capacity for grid electricity generation while ensuring other environmental services are not endanger is still lacking. The results indicated a significant wind resources contribution potential in Kenya and lesser contribution in Rwanda due to environmental reasons. The solar resources contribution potential shown to be higher in both Kenya and Rwanda compared to Tanzania.

2.2.4.2 The carbon emission from the currently operated grid electricity generation Capacity

The study has established an emission intensities database for lowering emissions and stabilizing atmospheric CO_2 levels to avoid the worst predicted effects of climate change. The evaluation results of grid carbon emission from the current installed electricity generation mixes of the proposed case study were presented in Figure 2.2.3.

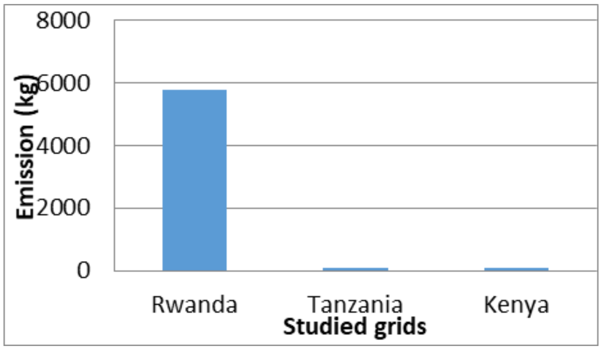


Fig.2.2. 3. Carbon emission intensity from the current operational grid electricity generation mixes

Currently, the Rwandan installed grid stands out to be the highest carbon emitter per unit electricity generation capacity in the study area, followed by Tanzania and Kenya.

2.2.3 Life cycle carbon emission inventory of the proposed 100% renewable electricity purchase and installed generation systems

The integration of, renewable electricity generation and, renewable electricity trade into the grid has been considered for the new grid installed electricity generation. The transfer of electricity loads from the region of low carbon emission to the region of high carbon emission was assumed to be established by the newly systems operators to enhance the grid electricity carbon reduction performance in specific country. The current installed and operated grid electricity generation systems process revealed to be a dominant emission factor in the studied grids. The Tanzanian results indicated a significant residual quantity of the carbon emission intensities due to its higher quantity in the electricity generation systems capacity retired by the year 2049. The results also found insignificant residual quantity of the carbon emissions due to the significant recycling of residual carbon emitted by the Kenyan grid power generation system because of its substantial integration potential of the PV technology [21]. However, the Kenyan grid electricity mix suggested by this study anticipated to develop a significant carbon emission from the newly added grid electricity capacity compared to other grids in the study area.

The developed LCCEI has been taken into account; the residue carbon emissions related survival lifetime, retired capacity and recycling rate of the potential grid electricity generation mix from different renewable energy resources. However, the carbon emission intensity can be reduced further upon the consideration of other carbon emission prevention and control technologies beyond the renewable technologies which are locally available or planned. The newly installed grid electricity generation systems, especially the capacity survived and recycled are recommended to consider the adaption to climate rather than investing on mitigations. The percentage of the life cycle carbon emission contribution for the studied cases is presented in Figure 2.2.4.

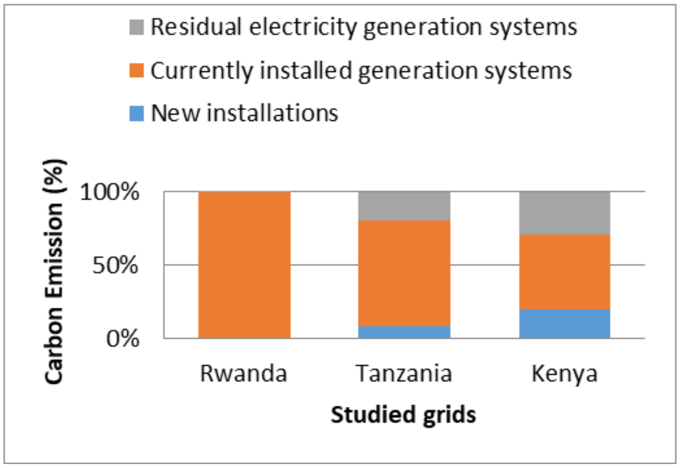


Fig.2.2. 4. The lowest possible life cycle carbon emission intensity contribution offered by 100% renewable electricity generation system process in the studied grids by the year 2049

2.2.5 Conclusion

The chapter presented the life cycle inventory case results suitable for the planning of the integration of the renewable energy resources in the studied grids electricity generation mixes. The potential adoption of the 100% renewable grid electricity generation mixes alternatives planned by this study revealed to sustain the Rwandan grid while generating emission of just about 3% of the baseline grid carbon emission value targeted by the years 2040. The current installed and operated grid electricity generation systems-process showed to be a dominant emission factor in the studied grids. Further study is recommended to include the cumulative electricity inventory data and the analysis of a wide range of environmental pollutants. However, further site-specific monitoring of the electricity generation capacity survival and retirement ratios are also required for future electrical science–policy research.

References

[1] F. Blaabjerg and J. M. Guerrero, “Smart grid and renewable energy systems,” in *International Conference on Electrical Machines and Systems, ICEMS*, 2011, pp. 1–10,

doi: 10.1109/ICEMS.2011.6073290.

[2] Rwanda Energy Group, "Rwanda Least Cost Power Development Plan (LCPDP) 2019 – 2040," Kigali, 2019. [Online]. Available: https://www.reg.rw/fileadmin/user_upload/LCPDP_REPORT_June_2019.pdf.

[3] S. Kihwele, K. Hur, and A. Kyaruzi, "Visions, scenarios and action plans towards next generation tanzania power system," *Energies*, vol. 5, no. 10, pp. 3908–3927, 2012, doi: 10.3390/en5103908.

[4] United Republic of Tanzania, "Power System Master Plan 2016 Update," Dodoma, 2016. [Online]. Available: https://www.infoafrica.it/wp-content/uploads/2017/02/Power-System-Master-Plan-PSMP-2016-Update.pdf.

[5] G. Falchetta, M. Hafner, and S. Tagliapietra, "Pathways to 100% Electrification in East Africa by 2030," *Energy J.*, vol. 41, no. 3, 2020, doi: 10.5547/01956574.41.3.gfal.

[6] E. Chambile, N. Ijumba, B. Mkandawire, and J. Hakizimana, "Impact of Electrical Power Systems on the Environment in Kenya, Rwanda and Tanzania," in *2018 IEEE PES/IAS PowerAfrica Conference*, 2018, no. 18261617, pp. 885–889, doi: 10.1109/PowerAfrica.2018.8521092.

[7] Eastern Africa Power Pool, "EAPP Regional Master Plan Volume I: Main Report," Addis Ababa, Ethiopia, 2014. [Online]. Available: https://www.ea-energianalyse.dk/wp-content/uploads/2020/02/1332_eapp_master_plan_2014_volume_1_main_report.pdf.

[8] B. Musara, "The Southern African Power Pool Market Operations," Nairobi, Kenya, 2019. doi: 10.4324/9780429424526-3.

[9] A. F. Zobaa and B. K. Bose, "Renewable Energy, Global Warming Problem and Impact of Power Electronics (Invited Paper) World Energy Outlook Key words," in *International Conference on Renewable Energies and Power Quality*, 2011, pp. 1–10, doi: https://doi.org/10.24084/repqj09.003.

[10] E. Chambile, "Emission of Air Pollutants from the Energy Sector in Tanzania," University of Dar es Salaam, Dar es Salaam, 2008.

[11] S. Zhou, F. Teng, and Q. Tong, "Mitigating Sulfur Hexafluoride (SF6) Emission from Electrical Equipment in China," *Sustainability*, vol. 10, no. 2402, pp. 1–17, 2018, doi: 10.3390/su10072402.

[12] R. Turconi, A. Boldrin, and T. Astrup, "Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations," *Renew. Sustain.*

Energy Rev., vol. 28, pp. 555–565, 2013, doi: 10.1016/j.rser.2013.08.013.

[13] Eastern Africa Power Pool, “Eastern Africa Power Pool Regional Master Plan Volume II: Data Report,” Addis Ababa, Ethiopia, 2014. [Online]. Available: http://www.ea-energianalyse.dk/reports/1332/1332_eapp_master_plan_2014_volume_2_data_report.pdf.

[14] C. L. John Gale, R. W. John Bradshaw, Zhenlin Chen, Amit Garg, Dario Gomez, Hans-Holger Rogner, Dale Simbeck, C. Ferenc Toth, and E. R. Ismail El Gizouli, Jürgen Friedrich Hake, “IPCC Special Report on Carbon dioxide Capture and Storage,” Cambridge, United Kingdom, 2018.

[15] Ö. S. Berggren Anna, “Kenya meeting the electricity demand of 2030, An assessment of how Kenya Vision 2030 and climate change impact the optimal electricity generation mix,” KTH Royal Institute of Technology, Stockholm, Sweden, 2017.

[16] African Development Bank Group, “Rwanda Energy Sector Review and Action Plan,” Tunis, 2013. [Online]. Available: https://www.afdb.org/fileadmin/uploads/afdb/Documents/Project-and-Operations/Rwanda_-_Energy_Sector_Review_and_Action_Plan.pdf.

[17] S. I. Kajugus, K. T. Kabaka, and T. T. Mnjokava, “Geothermal Development in Tanzania - a Country Update,” 2018, no. November, p. 11, [Online]. Available: http://theargeo.org/fullpapers/C7/Geothermal Development in Tanzania - a Country Update-converted.pdf.

[18] KPMG, “Renewable Energy in Africa: Tanzania - Country profile,” Abidjan, 2015. [Online]. Available: https://www.afdb.org/fileadmin/uploads/afdb/Documents/Generic-Documents/Renewable_Energy_in_Africa_-_Tanzania.pdf.

[19] W. C. Edwards, “Life Cycle Assessment: Best Practices of ISO 14040 Series,” Suwon, ISBN 981-05-0590-6, 2004. [Online]. Available: file:///C:/Users/user/AppData/Local/Temp/04_cti_scsc_lca_rev.pdf.

[20] I. Standard, “Environmental management — Life cycle assessment — Principles and framework,” Geneva, ISO 14040:2006(E), 2006. [Online]. Available: http://www.cscses.com/uploads/2016328/20160328110518251825.pdf.

[21] United Nations Development Programme, “Rapid Assessment Gap Analysis Pakistan,” Kigali, 2012.

CHAPTER THREE

3.0 Data on the Life Cycle Carbon Emission in Kenyan, Rwandan, and Tanzanian Grid Electricity Generation and Transmission Systems

3.1 Abstract

This chapter presents data for the estimation of the life cycle carbon emission in Kenyan, Rwandan, and Tanzanian grid electricity generation and transmission systems. Data was collected and estimated using the developed life-cycle carbon emission inventory (LCCEI) algorithm implemented through Excel tabs (LCCEI Excel worksheets). The data acquired through the LCCEI modelled parameters[1]. The presented dataset shows the results of the developed data collection model. The activity data were obtained from specialized data sources. Some information was obtained through meetings with relevant institutional actors and experts of national and regional power institutions as well as expert judgement. However, most of the data were also obtained from the reviewed published reputable sources, such as the scientifically indexed Conference proceedings and journals. The obtained data are presented in this article and in a Mendeley data repository. The compiled data can also be customised and coded to commonly used evaluation software to enhance its open use by scientists, practitioners, and policymakers at national, regional and global levels.

Keywords: Clean technologies, Electrical power system capacity, Carbon emissions data, Life cycle carbon emission estimation parameters

3.2 Specifications Table

Subject	Energy
Specific subject area	Energy and Environmental Sciences, Engineering, and Technology
Type of data	Table, text, Excel Spreadsheet and figure.
How data were acquired	The existing primary and secondary data, and developed new case-specific data were obtained, within the developed system boundary, using the life cycle carbon emission (LCCE) model made through the mathematical algorithm and coded in Microsoft Excel worksheets (*see the supplementary life cycle carbon emission inventory (LCCEI) data file*). The developed LCCE data collection model was adopted to acquire the presented data [1].
Data format	*Raw and Calculated*
Parameters for data collection	The parameters for 'activity and emission factor' data collection are presented in excel. Those parameters are including calculated life cycle carbon emissions of the electrical power systems (LCCE,$_{2049}$) in the year 2049, the quantity of carbon emitted in the newly added electrical power (generation and transmission) systems capacity (Qm,$_{2049}$) in the year 2049, the carbon emission factor of the electrical product system caused by the new installation, operation, and maintenance (EFm,$_{2049}$) in the year 2049, an electrical power system capacity (SP,$_{2019}$) installed and survived by the base year 2019, the carbon emission factor of the electrical power system capacity installed, operated, maintained, and surviving (EFo,$_{2019}$) in the base year 2019, the remaining quantity of carbon emissions from retired and recycled electrical product systems (RR,$_{2049}$) in the year 2049, and remaining of the substituted recycling fraction from the electrical power systems retired (RC,$_{2049}$) in the year 2049. The parameters related to the newly added electrical power system capacity (N,$_{2049}$), filling quantity of a carbon emission per unit of added electrical power system capacity (A,$_{2049}$), ratio of the carbon emission substituted into the newly added electrical power system (SA,$_{2049}$) in the year 2049 and ratio of a carbon emission remaining in the retired electrical power system (PR,$_{2049}$,) in the year 2049 were also studied. The data was also collected using the parameters such as the quantity of carbon emitted in the newly added electrical power (generation and transmission) systems capacity (Qm,$_{2048}$) in the year 2048, and the retirement fraction of the newly added electrical power system (NR,$_{2048}$) in year 2048. The established parameters have been externally peer reviewed using established questions through field

	survey (8 respondents), workshops, seminars, university and scientific Conferences (10 respondents), and journal editors and reviewers (12 respondents).
Description of data collection	The minimum and maximum temporal data points were selected to comply with the average electrical power systems life span of 30 years from the base year 2019. The data was collected and generated for the base year 2019, the year 2048 and the year 2049. The power loss due to distribution was not included for data collection and generation just for simplification of the study. The data collection process also ignored activity and emission factor data related to the raw material acquisition (extraction and processing) and raw material transportation of the electrical power systems studied. The carbon emission data from biomass and bagasse energy sources was not generated since it is part of the global carbon cycle. The parameters developed from the mathematical algorithm, coded in Microsoft excel, were applied to collect existing data and developed new data. The modified mathematical representation is linked to logical relationships identified through a hypothetical LCCE approximation for the generation and transmission systems[1]. The production or reviews of activity data included information from the primary sources such as the relevant institutional actors and experts from national and international power organisations, information from secondary sources, and expert judgement. The secondary information was collected from reputable sources, such as indexed Conference proceedings and journals. The collected and estimated data were re-arranged and checked for completeness, consistency, and accuracy by ensuring that the current and newly installed capacities balanced in a particular electrical power system for a targeted year. The data have also been acquired through sharing and exchange of existing, transformed, and new data through workshops and seminar presentations at the African Centre of Excellence in Energy for Sustainable Development, University of Rwanda, the postgraduate (systems) forum of the 2018 IEEE PES/IAS PowerAfrica Conference and the technical session, on the advances in energy systems, of the 2020 IEEE PES/IAS PowerAfrica Conference.
Data source location	The primary data sources were the actors of the specialised national electrical power systems institutions including: Tanzania Geothermal Company Limited (TGDC) and Tanzania Electric Supply Company (TANESCO) in Tanzania; Rwanda Energy Group (REG), Energy Utility Corporation (EUCL) and the Energy Development Corporation (EDCL) in Rwanda; and Kenya Electricity Generating Company (KenGen), Geothermal Development Company (GDC) and Kenya Electricity Transmission Company Limited (KETRACO) in Kenya. The secondary data sources used in acquiring information include: Universities' reports, especially the additional data related to power demand in Kenya [2]; International specialised

	electrical power systems institutional reports, especially the additional data related to power demand in Tanzania [3]; National energy and environment reports, especially the additional data related to renewable electricity potentials in Tanzania [4]; International energy and environment reports, especially the additional data related to the hydropower potentials in Kenya [5], [6]; National power systems master plans, especially the additional data related to power demand in Rwanda [7], [8] International power systems master plans, especially the additional data related to the potential power sources and trade in Kenya, Rwanda and Tanzania[9]; National and international experts presentations, especially the additional activity data related to the geothermal potentials Tanzania[10]; web searches, journals and reports; Scientific and technical articles in energy and environment, especially the additional data related to the carbon emission factors for: large hydro, natural gas, geothermal[11], diesel, wind and solar [12], small hydro[13], and coal[14] potentials.
Data accessibility	Data is in this chapter and in a Mendeley data repository (https://data.mendeley.com/datasets/pcc8vhbvwz/2).
Related research article	E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, 'Modelling of environmental emission in Kenyan, Rwandan, and Tanzanian electrical power systems', *J. Clean. Prod.*, p. 127830, Aug. 2021.

3.3 Value of the data

- The acquired data can be used to evaluate the carbon intensity of the power supply systems within the established systems limits and algorithm. The obtained data can also be useful for evaluating the extent to which grid electricity generation and transmission system drivers are designed and operated in the context of environmental governance (EG) factors;

- The compiled LCCEI data can also be customised and exported to commonly used evaluation software to enhance its use for scientists, practitioners, developers and policymakers at national, regional, and global scales;

- The generated data can also enhance learnability and carbon emission monitoring of electrical power systems and sustainable sub-region and regional grid interconnections design;

- Besides it is easy to replicate the collected (existing and new) data, collected data can also openly be used by anyone who has interest in conducting a life cycle assessment of electrical power systems;
- The developed data can be openly-used for targeting and monitoring of local, regional, and global institutions for environmentally sustainable electrical power system development, and
- The data can also be openly-used to generate additional knowledge for guiding clean technologies and the design of environmentally sustainable electricity production and transmission systems.

3.4 Data description

The quantitative data have been collected since the obtained pilot survey data showed the developed 'gate to gate LCCEI' system boundaries is acceptable for the collection of both up and downstream inventory data for electrical power systems in the study area. The installed capacity and transmission loss data has been obtained from EAPP, SAPP, REG, EDCL, EUCL, TANESCO, TGDC, KenGen, GDC and KETRACO reports and/actor(s). The technology-specific carbon emission factors have been obtained from published scientific and technical papers. The electrical power system capacity in the year 2049 has been linearly adjusted from the last year of projection presented on the most recently updated national and regional power systems master plans. The dataset was compiled after modelled life-cycle carbon emission inventory (LCCEI) parameters administration from the studied national grids for, the base year 2019 and, the projected year 2049. The dataset files in the repository provide the carbon emission factors ($EFo,_{2019}$) of both the electrical product system capacity installed, operated, maintained, and surviving in a studied national grid for the base year 2019. The EFo, 2019 were calculated from different energy sources and presented in the dataset B1 (Cell K 8), B3. (Cell L 8) and B2 (Cell B 16). The dataset provides the carbon emission factor ($EFm,_{2049}$) of the electrical product system caused by the new installation, operation, and maintenance in the year 2049 product presented in dataset C1 (Cell H 10), C2. (Cell G 10), and C3 (Cell J 13). The $EFm,_{2049}$ were calculated from different energy sources and transmission loss designed for different scenarios. The power transmission system loss capacity of 0.03% has been considered. The electrical power system capacity installed and survived ($SP,_{2019}$) values of 1565.72 MW

(Tanzania), 216.23 MW (Rwanda) and 2819 MW (Kenya) have been presented for the base year 2019.

The quantity of carbon emitted in the newly added electrical power (generation and transmission) systems capacity ($Qm,_{2049}$) in the year 2049 has been calculated in dataset D (as the product of the newly added electrical power system capacity ($N,_{2049}$) in the year 2049, filling quantity of a carbon emission per unit of added electrical power system capacity ($A,_{2049}$) and the ratio of the carbon emission substituted remaining into the newly added electrical power system ($1\text{-}SA,_{2049}$) in the year 2049. The dataset D also present the carbon emissions ($RR,_{2049}$) data remaining from the retired and recycled electrical product systems in the year 2049, as a product of the quantity of carbon emitted in the newly added electrical power (generation and transmission) systems capacity ($Qm,_{2048}$) in the year 2048, retirement fraction of the newly added electrical power system ($NR,_{2048}$) in the year 2048, and the ratio of a carbon emission remaining in the retired electrical power system ($PR,_{2049}$) by the year 2049. Dataset D (Column H) presents the remaining data of the substituted recycling coefficient/the residual carbon emission fraction from the electrical power systems retired ($1\text{-}RC,_{2049}$) in the year 2049. The higher the percentage of solar composition in the grid the lower the residual emission. The systems compose of long-lived hazardous wastes was also allocated (perceived to have) greater than 50% residue carbon emission. Dataset E presents the calculated $LCCE,_{2049}$ (kg/MW) database of the studied grid electricity generation and transmission systems for the year 2049. Apart from the text data and Table provided by this chapter, the supplementary LCCEI data file (including questions, raw anonymized original responses to questions, data references, calculation toolkit, and LCCE data) is also provided through the Mendeley data repository (https://data.mendeley.com/datasets/pcc8vhbvwz/2).

3.5 Experimental design, materials and methods

The mixed methods research design was adopted whereby both qualitative and quantitative data were used to provide a better understanding of research problems as indicated in Figure 3.1. This included exploratory sequential design to describe variables that are necessary for the study. The qualitative phase was used to develop the instruments and model to guide the quantitative data presented by this study. The presented data have been collected within the determined system boundary using developed LCCEI Excel worksheets of different activity and emission factor such as use of different fuel and available energy potentials, different generation technologies, different storage technologies, different transmission technologies and established functional unit. The data acquired were documented and referenced. The life cycle carbon emission data have been converted into a common unit (kg/MW).

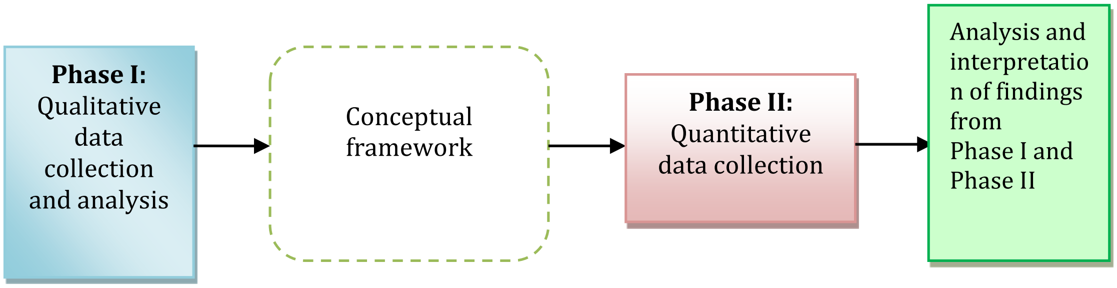


Fig.3. 1. Overview of the Exploratory Sequential Design (Authors' analysis)

The possible sources of both qualitative and quantitative grid-specific life cycle carbon emission data are presented in Table 3.1. The grid codes, developed in Excel, have been used to collect the life cycle carbon emission data by the year 2049.

Table 3. 1. Possible sources of grid-specific life cycle carbon emission data obtained from the studied countries

National	International	Others
Specialised electrical power systems institutional actors (KenGen, KETRACO, KPLC, GDC, REG, EUCL, EDCL, TANESCO, TGDC)	Specialised electrical power systems institutional actors (Southern African Power Pool (SAPP) and Eastern Africa Power Pool (EAPP))	Scientific and technical articles in energy and environment
Energy and Environment reports	Energy and Environment reports	Journal and reports
Powers systems master plans	Powers systems master plans	Universities reports
Energy and/environmental experts, national grid systems operators	Energy and/environmental experts, sub-region grid systems operators	Web search

The preliminary survey questions planned in the content of the developed research framework and boundaries have been piloted (administered through interviews and literature review) in the sources of data identified by the researcher. The survey questions have been designed to validate the general inventory approach and assumptions. The survey has also ensured the developed research data is suitable for research question testing and avoid any potential bias. The obtained pilot survey data showed the developed 'gate to gate LCCE' system boundaries is acceptable for the collection of both up and downstream inventory data for electrical power systems in the study area.

The dataset format (spreadsheets) and structure were obtained from established system limits and algorithm. The assumptions regarding power systems coverage, representative year, technology/management level were described [1]. The external peer review process and expert opinion regarding the developed research questions, system boundary, mathematical algorithm, and its underlying data were adopted to ensure database validity and utility. The use of expert judgment has been applied to determine the appropriate way to apply a model, appropriate mix of technologies, appropriate activity and emission factor data, and appropriate regression techniques to reduce possible bias and increase accuracy.

The use of national data has been preferred since sources are typically more up to date and provide better links to the originators of data. In some cases, directly applicable data was not available, therefore physically and statistically related alternative data that have a correlation with the missing data were applied to develop the LCCEI spreadsheet database. The Excel worksheets B1, B2, B3, C1, C2 and C3, of the LCCEI data file presented in a Mendeley data repository linked to this article, were applied to collect and/calculate grid electricity generations/consumptions data (for each fuel type for each end-use), transmission systems loss data (for each studied grid), and their respective life cycle carbon emission factor data. Excel worksheets D, of the presented LCCEI data file, has been used to calculate $LCCE,_{2049}$ of a particular year using the parametric values ($N,_{2049}$, $A,_{2049}$, $NR,_{2049}$, $SA,_{2049}$, $RC,_{2049}$, $RR,_{2049}$, $SP,_{2019}$, $Qm,_{2049}$, $Qm,_{2048}$, $EFo,_{2019}$, and $EFm,_{2049}$) estimated based on the established mathematical algorithm, system boundary model, scenarios, and the key assumptions. The LCCE data have been computed from the available and assumed data using equation (1) slightly modified from the previously published research article[1], and expressed as follows:

$$LCCE,2049 = Qm,2049 \times EFm,2049 + SP,2019 \times EFo,2019 + RR,2049\,(1 - RC,2049) \qquad (1)$$

Where:

- $LCCE_{,2049}$ calculated life cycle electrical power systems amount of carbon emission (kg) in the year 2049,
- $Qm_{,2049}$ represents the quantity of carbon emitted in the newly added electrical power (generation and transmission) systems capacity (kg/MW) in the year 2049,
- $EFm_{,2049}$ represents a carbon emission factor (kg/MW) of the electrical product system caused by the new installation, operation, and maintenance in the year 2049,
- $SP_{, 2019}$ is an electrical power system capacity (MW) installed and survived by the base year 2019,
- $EFo_{,2019}$ represents a carbon emission factor (kg/MW) of the electrical power system capacity installed, operated, maintained, and survived by the base year 2019,
- $RR_{,2049}$ represents the remaining quantity of carbon emissions (kg/MW) from retired and recycled electrical product systems in the year 2049, and
- $RC_{,2049}$ represents a remaining of the substituted recycling coefficient/the residual carbon emission fraction from the electrical power systems retired in the year 2049.

The $Qm_{,2049}$ data have been computed from the available and assumed data using equation (2) slightly modified from the previously published research article [1], and expressed as follows:

$$Qm,2049 = N,2049 \times A,2049\ (1 - SA,2049) \tag{2}$$

Where:

- $N_{,2049}$ represents the newly added electrical power system capacity (MW) in the year 2049,
- A_{2049} represents the filling quantity of a carbon emission per unit of added electrical power system capacity (kg/MW) in the year 2049, and
- $SA_{,2049}$ represents the ratio of the carbon emission substituted into the newly added electrical power system in the year 2049.

The $RR_{,2049}$ data have also been computed from the available and assumed data using equation (3) slightly modified from the previously published research article [1], and expressed as follows:

$$RR,2049 = \sum_{j=1}^{n} Qm,2048 \times NR,2048 \times PR,2049 \qquad (3)$$

- Where:
- $PR_{,2049}$ represents the ratio of a carbon emission remaining in the retired electrical power system,
- $Qm_{,2048}$ represents the quantity of carbon emitted in the newly added electrical power (generation and transmission) systems capacity (kg/MW) in the year 2048, and
- $NR_{,2048}$ is the retirement fraction of the newly added electrical power system in the year 2048.

3.6 Ethics statement

The respective ethical operation guidelines, and procedures, were considered during the research and publication process[1]. This data section reports raw and calculated data recorded at the developed LCCE inventory model. No data collected from social media platforms were presented. The contribution of all authors is well mentioned. Ethics approval for survey studies is not mandatory, since this work does not involve the use of human subjects or animal experiments. However, the ethics of this study was approved by the doctoral committee, of the African Centre of Excellence in Energy for Sustainable Development at the College of Science and Technology, of the University of Rwanda, in Rwanda and also approved by the Sokoine University of Agriculture in Tanzania. Permission to the companies and actors directly involved in the study has also been granted. Where necessary, participants or participant data were fully anonymized while complying with all data redistribution policies from the platform(s).

References

[1] E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, "Modelling of environmental emission in Kenyan, Rwandan, and Tanzanian electrical power systems," *J. Clean. Prod.*, vol. 312, Aug. 2021, doi: 10.1016/J.JCLEPRO.2021.127830.

[2] Ö. S. Berggren Anna, "Kenya meeting the electricity demand of 2030, An assessment of how Kenya Vision 2030 and climate change impact the optimal electricity generation mix," KTH Royal Institute of Technology, Stockholm, Sweden, 2017.

[3] B. Musara, "The Southern African Power Pool Market Operations," Nairobi, Kenya, 2019. doi: 10.4324/9780429424526-3.

[4] KPMG, "Renewable Energy in Africa: Tanzania - Country profile," Abidjan, 2015. [Online]. Available: https://www.afdb.org/fileadmin/uploads/afdb/Documents/Generic-Documents/Renewable_Energy_in_Africa_-_Tanzania.pdf.

[5] D. Marks, J. Hamilton, Richardson Ivan, and N. Carn, "African Energy Data Book," East Sussex, 2018. [Online]. Available: africa-energy.com/live-data.

[6] International Energy Agency, "Africa Energy Outlook 2019," 2019. [Online]. Available: https://webstore.iea.org/africa-energy-outlook-2019.

[7] Rwanda Energy Group, "Rwanda Least Cost Power Development Plan (LCPDP) 2019 – 2040," Kigali, 2019. [Online]. Available: https://www.reg.rw/fileadmin/user_upload/LCPDP_REPORT_June_2019.pdf.

[8] United Republic of Tanzania, "Power System Master Plan 2016 Update," Dodoma, 2016. [Online]. Available: https://www.infoafrica.it/wp-content/uploads/2017/02/Power-System-Master-Plan-PSMP-2016-Update.pdf.

[9] Eastern Africa Power Pool, "Eastern Africa Power Pool Regional Master Plan Volume II: Data Report," Addis Ababa, Ethiopia, 2014. [Online]. Available: http://www.ea-energianalyse.dk/reports/1332/1332_eapp_master_plan_2014_volume_2_data_report.pdf.

[10] S. I. Kajugus, K. T. Kabaka, and T. T. Mnjokava, "Geothermal Development in Tanzania - a Country Update," 2018, no. November, p. 11, [Online]. Available: http://theargeo.org/fullpapers/C7/Geothermal Development in Tanzania - a Country Update-converted.pdf.

[11] H. Hondo, "Life cycle GHG emission analysis of power generation systems: Japanese case," *Energy*, vol. 30, no. 11-12 SPEC. ISS., pp. 2042–2056, 2005, doi: 10.1016/j.energy.2004.07.020.

[12] R. Turconi, A. Boldrin, and T. Astrup, “Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations,” *Renew. Sustain. Energy Rev.*, vol. 28, pp. 555–565, 2013, doi: 10.1016/j.rser.2013.08.013.

[13] D. Weisser, “A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies,” *Energy*, vol. 32, no. 9, pp. 1543–1559, 2007, doi: 10.1016/j.energy.2007.01.008.

[14] P. E. Hardisty, T. S. Clark, R. G. Hynes, S. Kensington, G. Terrace, and N. S. Wales, “Life Cycle Greenhouse Gas Emissions from Electricity Generation: A Comparative Analysis of Australian Energy Sources,” *Energies*, no. 5, pp. 872–897, 2012, doi: 10.3390/en5040872.

CHAPTER FOUR

4.0 Life Cycle Carbon Emission (LCCE) Modelling of Electrical Power Systems in Kenya, Rwanda, and Tanzania

4.1 Abstract

There is limited information on environmental (especially carbon) emissions in African grid electricity generation and transmission systems, especially from the sub-Saharan African countries. The developed parameters are useful for evaluating the extent to which grid electricity generation and transmission system drivers are designed and operated in the context of environmental governance (EG) factors. The environmental pressure caused by the studied power systems was evaluated in terms of carbon emission levels. To simplify the study, variable parameters were sampled from the national power grids of three sub-Saharan countries, namely: Kenya, Rwanda, and Tanzania. The developed inventory workbooks accounted for the residual carbon emissions related to the grid generation and transmission capacity survival lifetime, retired system capacity, and recycling rate, aiming to reduce the uncertainty in grid emissions in the study area. The obtained area of the curve for the business as usual and EG models reveals that Rwanda has the potential to contribute more emissions per unit power, followed by Tanzania and Kenya. The higher carbon emission uncertainty levels (65%–75%) obtained from the EG simuland and life cycle carbon emissions revealed that only limited EG factors were considered during the design and operation of the studied grid electricity generation and transmission systems. However, the possibility of significant lifetime decarbonisation performances from generation and transmission systems was also shown in the EG-modelled output, owing to its lower carbon emission uncertainty levels (15%–25%). The logarithmic regression trend lines presented by this research show a higher R_2 value for the EG modelled life cycle carbon emission (LCCE) output ($R_2 = 0.8689$) and EG simuland LCCE output ($R_2 = 0.9209$), compared to EG modelled LCCE output ($R_2 = 0.7526$) and EG simuland LCCE output ($R_2 = 0.8223$) obtained from the linear regression trend lines, implying a very good relationship between the structural assumptions and simplifications constituting the model itself for case studied by the year 2049. The study suggests monitoring of a wide range of environmental parameters (apart from carbon) and associated energy storage technologies, considering both cumulative data and expanded systems.

Keywords: Electricity generation, Hybrid electrical power systems, Life cycle carbon emission inventory, Net-zero emission, Transmission systems

4.2 Introduction

The African power sector is facing challenges in ensuring energy reliability and security at the minimal cost to existing consumers and in meeting increasing demand, thereby adversely affecting sustainability [1]. The electrical energy consumption in Africa has continued to increase. The environmental challenges linked with energy resource utilisation have created key sustainability challenges in 21st century Africa, owing to insufficient indigenous knowledge system-based institutions and practices [2]. Currently, electricity accounts for only approximately 4% of primary energy usage; the total electric power installed capacity in Africa is 236.2 GW, with a renewable capacity of 49.5 GW [3]. Electrical power systems technologies are changing from relying only on electrical power generation using fossil-based energy sources to integrating renewable energy sources into the power mix. They are also changing towards the use of renewable sources enabled by highly efficient power electronics devices for power generation, transmission, distribution, and end-user applications [4].

Transitioning the world’s energy economy to a lower carbon future will require significant investments in a variety of cleaner technologies, including renewables and nuclear power. However, in the short term, improving the efficiency of fossil fuel combustion for energy generation can provide an important contribution [5]. The generation and distribution of electricity is the cause of nearly 40% of the CO_2 emissions in the United States, as well as large shares of SO_2, NOx, small particulates, and other toxins [6]. To limit global warming to 1.5 °C, net global CO_2 emissions must drop by 45% between 2010 and 2030, and must reach net zero by approximately 2050 [7]. The prompt deployment of renewables will have a greater impact on power generation, as their share could possibly reach 71% in 2050 [8]. Globally, power generation emits approximately 37% of the total global CO_2 emissions. In 2018, the African continent accounted for 4% of global energy-related CO_2 emissions, despite being home to approximately 17% of the world population. North Africa accounted for the largest share of the continent’s energy-related emissions at 40%, followed by South Africa at 35%. The studied countries in this thesis currently account for the lowest shares of carbon emissions from electricity generation and transmission systems in the region. As of 2019, East Africa has an electricity access level of 36%, with over 140 million people without access [9]. Nevertheless, the power sector is the sector with the most emissions in Africa (480 Mt), followed by transport (355 Mt) and manufacturing industry (150 Mt). Sub-Saharan Africa, which has more than 600 million people living without electricity, is among the regions that are the most exposed to the effects of climate change [10].

This study aims to provide an overview of the CO_2 emissions from both grid electricity generation and transmission in the studied sub-Saharan African countries. It is vital to understand the nexus of environmentally sustainable and climate-resilient economies and communities (SDG 7 of the African Agenda 2063)[11], access to clean, affordable, and reliable electricity (SDG 7), demands for resource consumption owing to increased production and the corresponding undue burden on environmental resources (SDG 12), actions to mitigate climate change through energy efficiency and renewable resources (SDG 13), and sustainable ecological developments (SDG 15) [7].

CO_2 taxation enhances the minimisation of environmental impacts, and has recently led to the integration of environmental governance (EG) issues in electrical power generation and transmission plans. Access to electricity, energy efficiency, and use of renewable energy are increasing in the studied countries [12]. Additional efforts are required to improve the understanding of targets and the monitoring of local, regional, and global electrical power systems using life cycle inventory (LCI) methods. There is inadequate research evidence showing how considerations of environmental emissions reductions have influenced the performances of grid electricity generation and transmission systems, especially in the African region [13]. Considering their environmental characteristics and grid mixes, Kenya, Rwanda, and Tanzania are good candidates for the exploitation of both renewable and non-renewable energy sources, and for facilitating electricity transmission processes at different levels in Eastern and Southern Africa power pools. The findings of this study provide concepts regarding the possible carbon emission effects from electricity production and transmission systems and technologies.

The electricity industry is unique in regards to LCIs and policy analyses, as it is impossible to trace the electricity generated in a given power plant through the transmission and distribution system to a specific electricity consumer. Therefore, to develop the LCI, the average amount of a pollutant per unit activity has been created and utilised. Emission factors are used to represent an aggregated estimate of emissions from a broader system. Efforts are being made worldwide to obtain comparable results from LCI studies developed in different countries using different algorithms [14]. The common gCO_2e/kWh-based functional unit does not necessarily reflect the transmission and distribution behaviours of an electrical energy system [15]. Carbon emissions from transmission lines for delivering electricity from power generation plants to consumers vary according to their geographical locations in the electric power grid. An integrated environmental assessment of electricity transmission systems also needs to reflect the different transmission distances, voltage levels, and technologies. Most existing LCI models suffer from problems regarding subjective boundary definitions, inflexibility, and high inventory costs [16]. They also omit sensitive factors contributing to environmental impacts. Examples of such omitted sensitivity factors include, but are not limited to, the substitution ratio, recovery ratio, residual pollutant remaining at retirement, survival of newly added electrical power systems, and capacity of a retired electrical power system.

The current understanding regarding life cycle environmental simulations for assessing the environmental sustainability of electrical power generation [17], grid extensions for the integration of variable renewable energies [18], transmission and distribution [19] elements is relatively disjointed. Thus, electrical power systems require the development of an effective approach for conducting a simplified life cycle carbon emission inventory (LCCEI). There remains a significant amount of work required to ensure that there is an improved understanding of how grid electricity generation and transmission system drivers are designed and operated, while considering the EG requirements. Conducting an LCCEI for electric power systems is a particularly challenging task, owing to the complexity of the systems being analysed. These systems include wide variations among inputs and emissions per unit generation across (and even within) fuel types, as well as in the inputs and emissions per unit generation transmitted to the distributors and users. The system contains the quantities of pollutants released into the environment and amounts of energy and materials consumed in the life cycle of the product [20].

The service life is known to influence the impacts of electrical power generation and transmission systems. This study assumed the lifetime of electric power systems to be 30 years on average. Thermal power plants, on average, have an economic life span of twenty (20) years; however, the life span can be extended by proper maintenance and interim replacement of major parts [21]. The lifetime of other components of electricity systems is assumed as 40 years, except for transformers (30 years) [22]. Therefore, the lifetime of each component in the proposed system is modelled with a lifetime of 30 years on average [23]. The main focus of this study is to develop a methodology for estimating the consumption of embodied materials and energy resources and the quantities of environmental emissions caused by (or otherwise attributable) to a grid electric product's life cycle. Previous studies have indicated that the maximum electrical power system sustainability is attained by maximising electrical resource conservation and diversifying power systems beyond hydro-electricity [18]. Thus, this study accounts for the electricity generated from wind, solar, hydro, and geothermal plants and transmitted into the grid. The installed generation and transmission system capacities and future per capita electricity demand are assumed to decrease with the implementation of energy efficiency and interconnectivity policies in the study area. The study, therefore, hopes to offer some solutions through developments in environmental, energy, and systems engineering sciences, aiming to eventually realise sustainable development goal (SDG) 7 of the African Agenda 2063, and the United Nations SDGs 7, 12, 13, and 15.

The goal of this study is to contribute to the available literature and to the tools for evaluating the impacts of electrical power generation and transmission systems on the environment. The study examines the basics of possible mixes of electricity generation and transmission systems, and the corresponding designs needed to pursue a sustainable future. The conceptual framework of the study (Figure 4.1) lays the foundation for testing speculative variations of electrical power system drivers with associated environmental pressures. This study attempts to answer the following research questions. First, to what extent are grid electricity generation and transmission system (downstream and upstream) drivers designed and operated according to environmental governance (EG) factors? Second, what would the impacts on the lifetime decarbonisation performances of the generation and transmission systems be from considering EG factors? MS Excel workbooks containing spreadsheets translated from a modified algorithm are applied to compute the carbon emission volumes. The r-squared (R^2) values obtained from the carbon emission outputs simulated in Monte Carlo simple Excel [24] are studied to provide answers to the aforementioned research questions. The extract of those workbooks are provided as Appendix 6 of this thesis and in a Mendeley data repository (https://data.mendeley.com/datasets/pcc8vhbvwz/2).

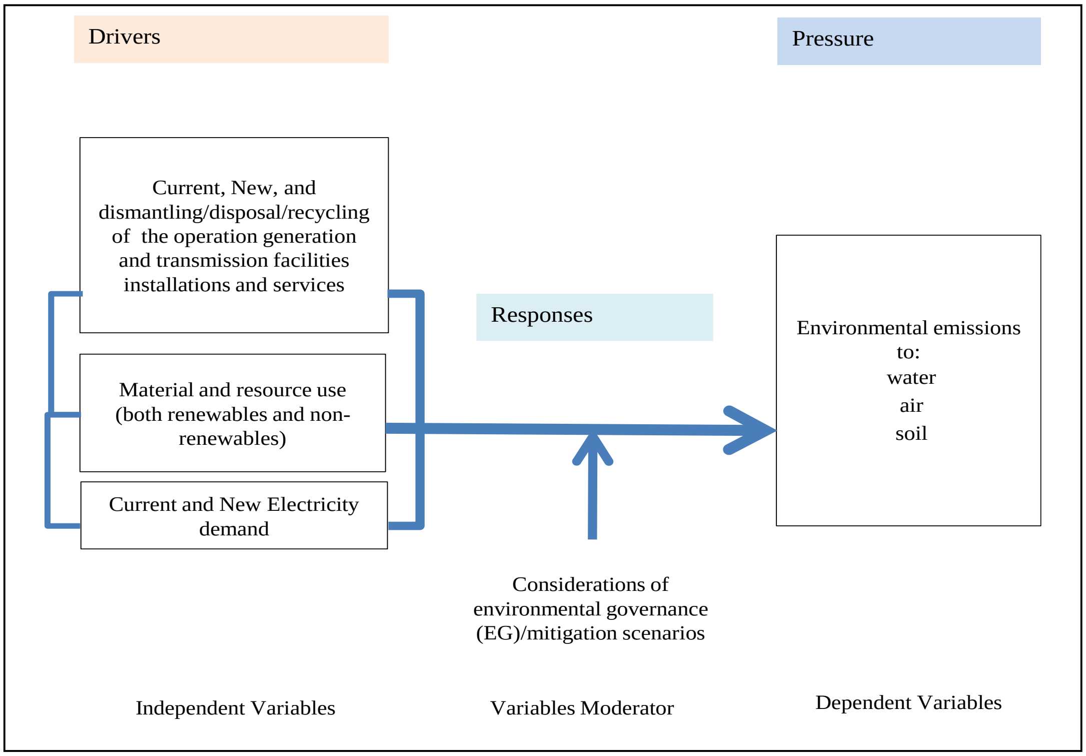


Fig.4. 1. Conceptual framework of the study

The major output of this study is a simplified (user friendly) mathematical LCCEI model for analysis that can be employed by different stakeholders, such as practitioners, researchers, and decision-makers, as a reference for evaluating the sustainability of developed hybrid electrical power generation and transmission systems in a studied region. The study also provides a sound basis for the selection of the data and methodology for the LCI of electricity generation and transmission in the study area. The techniques used can also be applied to other electric power systems beyond the study area. Thus, the information herein can be useful for assessments of the environmental changes caused by grid electricity resource utilisation in the study area. This study also provides a database that can be used to analyse the levels of carbon emissions in different electrical power system expansion scenarios, through calculation sheets.

This study provides evidence-based data and tools for influencing technology transfers, innovations, and infrastructural eco-designs aimed towards the development of sustainable electrical power systems. It lays the foundation for an electrical power systems development model for ensuring that water supplies for cities and irrigation systems in agricultural areas are not endangered. It also develops a database which allows decision-makers to move away from overly simplistic assertions regarding the relative environmental merits of certain generation and transmission plans and to focus on the complete picture, especially the critical roles of technology selection and the application of best practices in the study area. Further technical knowledge regarding how to construct a verbal scale for assessment of the environmental impacts caused by energy system growth and the state of the environment is required, i.e. to supplement the prevailing research [25] for guidance in hybrid power system development.

The next section of this chapter presents the system boundaries, system processes, 'Drivers, Pressure, State, Impact and Responses' (DPSIR) analytical structure, along with an algorithm for life cycle carbon emission (LCCEs). Furthermore, it provides a possible comparison base for establishing regional recommendations and alternatives regarding how electrical power system drivers can be designed and operated while considering EG factor for reducing environmental pressure. This chapter concludes with a simplified model for evaluating pollution prevention regulatory strategies, including those concerning important life cycle electrical power systems design and operation elements for sustainable African region development.

4.3 Materials and Methods

4.3.1. System boundary modelling

The electrical power system boundary of the study was limited to power generation and transmission systems. The supplied load was assumed to grow at an annual rate of 3% after 100% electrification; hence, the population growth needed to be managed so as to maintain the 100% target. The baseline for the evaluation was 2019 and a lifetime of 30 years, i.e. ending in 2049. The functional unit of a MW was used, so as to comply with international standards [26]. Different power generation and transmission systems were modelled in relation to the same functional unit. Cut-off rules were applied to model the unit processes of the study. The general up- and downstream components prior to refinement during the development of the studied LCI model are outlined in Figure 4.2.

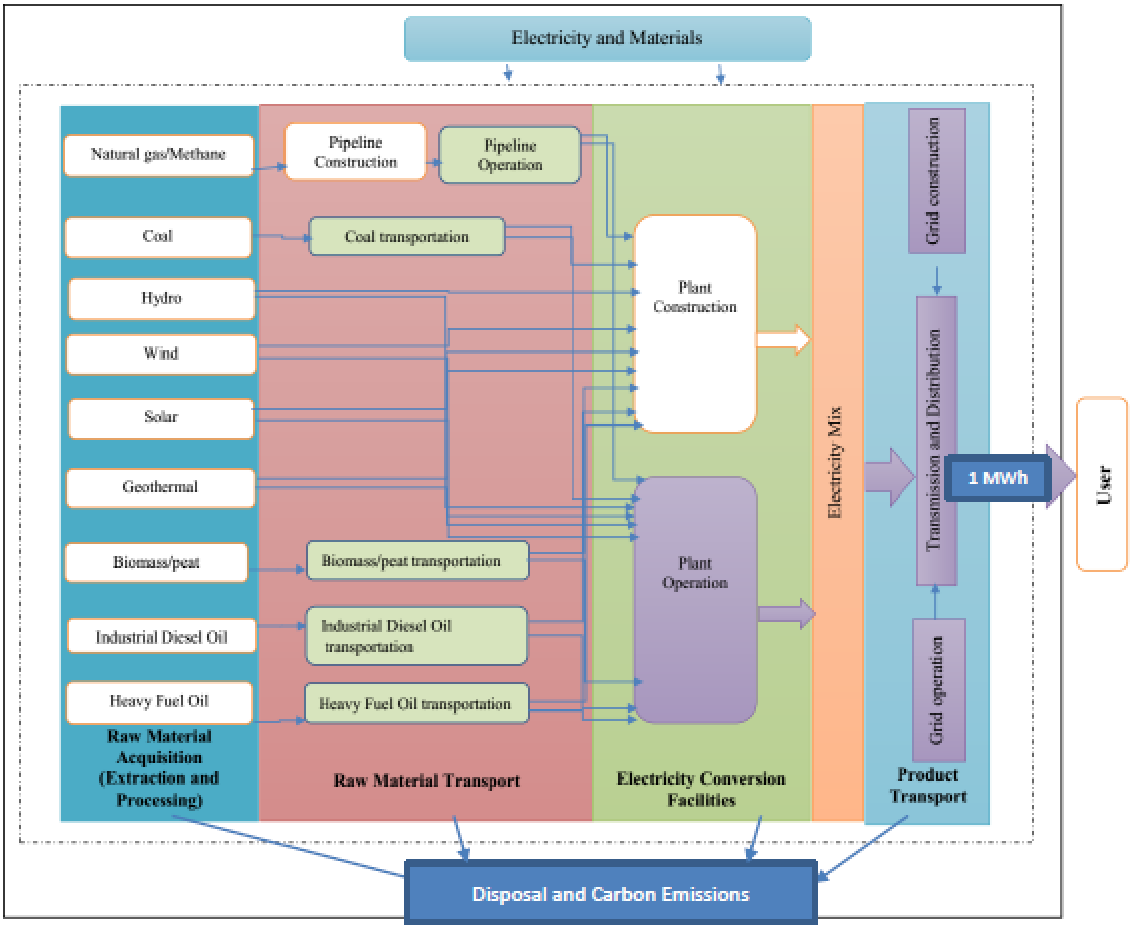


Fig.4. 2. System boundaries of life cycle inventory (LCI) for grid electricity generation and transmission in the study area

Source: Modelled after [27]

4.3.1.1. Power generation systems

The LCI model incorporated electricity generation activity data obtained from technical articles [10], [28] scientific papers [29] and energy institutions such as Southern African Power Pool (SAPP), Eastern Africa Power Pool (EAPP), Tanzania Electric Supply Company (TANESCO), Rwanda Energy Group (REG), and Kenya Electricity Generating Company (KenGen). The approaches for the electricity mixes adopted in the study areas (modelled after [14]) are presented in Equation 4.

$$Electricity\ supply\ mix = \ electricity\ domestic\ production + electricity\ exports\ + electricity\ imports \qquad (4)$$

The domestic production included all power plants situated within the political borders of a country [30] and the planned electricity trades (especially from geothermal, wind, and hydro sources) with foreign countries. The different power system technologies modelled in the study area are presented in Figure 4.2. The domestic power production mix in the study area is shown in Table 4.1.

Table 4. 1. Installed electricity generation mix in the studied systems by the year 2019

Electricity generation mix (MW)	Rwanda	Tanzania	Kenya
Natural gas	0.00	892.70	0.00
Hydro	103.16	573.70	826.00
Wind	0.00	0.00	335.00
Geothermal	0.00	0.00	828.00
Solar	12.80	0.00	50.00
Peat	15.00	0.00	0.00
Methane	26.40	0.00	0.00
Biomass	0.07	10.50	32.00
Bagasse co- generation	0.00	0.00	28.00
Diesel oil	58.80	88.80	720.00
Total electricity generation amount	216.23	1567.00	2819.00

4.3.1.2. Power transmission systems

The LCI model in this study was developed to accommodate electricity transmission activity data. The power transmission loss from generating stations to load centres was modelled. Presently, the Kenya–Tanzania transmission line is planned to be interconnected at 400 kV with a committed capacity of 1300 MW, whereas the Rwanda–Tanzania transmission line is currently planned to be interconnected at 220 kV with a committed capacity of 320 MW [31]. The initial power transmission activity secondary data were obtained from technical articles [32], the new power transmission loss data were developed using the ideas obtained from the scientific papers [33] and primary data were obtained from energy institutions, including TANESCO, REG, Kenya Electricity Transmission Company Limited (KETRACO), SAPP, and EAPP.

The developed LCCEI was designed to measure the environmental emissions values for the transmission grid per unit of electricity delivered by the system, for both the current and newly installed transmission capacities [16]. The currently installed high-voltage transmission sections with different voltage levels in the study area are described in Table 4.2. For simplification, the environmental emissions per distance covered for different transmission and distribution voltage levels were not modelled. For the same reason, the estimated future power system capacity estimated ignored the impacts of electricity efficiency increasing with time, and the anticipated future impacts of the upcoming grid electricity pressures required to facilitate electro-mobility.

Table 4. 2. Installed high voltage transmission lines in study area by the year 2019

Geographical scope	**Typical voltage levels (kV)**	**Total line length (km)**		**Source**
		High voltage (HV)AC	**HVDC**	
Rwanda	110	642.30	0.00	Rwanda Energy Group (REG)
	132	0.00	0.00	REG
	220	401.10	0.00	REG
	400	0.00	0.00	REG
	500	0.00	0.00	REG
Tanzania	110	0.00	0.00	Tanzania Electric Supply Company (TANESCO)
	132	1697.50	0.00	TANESCO
	220	2940.70	0.00	TANESCO
	300	0.00	0.00	TANESCO
	400	670.00	0.00	TANESCO
Kenya	110	0.00	0.00	TANESCO
	132	2650.00	0.00	Kenya Electricity Transmission Company Limited (KETRACO)
	220	2700.00	0.00	KETRACO
	400	2000.00	0.00	KETRACO
	500	0.00	612.00	KETRACO

4.3.1.3. Foreground and background systems

The concept of foreground and background systems was applied to capture the inventories of selected environmental indicators. A background emissions inventory system was modelled so as to account for the indirect emissions of grid electricity associated with the use of land [13], natural gas, methane, diesel oil, coal, peat, nuclear, hydro pumping and storage, hydro, geothermal, solar, wind, and embodied materials during power generation and transmission processes. The foreground emissions inventory system was modelled so as to account for the direct emissions associated with the installations and operations of the selected power generation and transmission processes. The foreground emissions were also associated with the processes of retirement and dismantling, recycling, survival ratios, and residual emissions from abandonment and disposal [34]. The background and foreground system boundaries processes within the life cycles of the grid electric products and the associated material and energy flows were modelled, and are presented in Figure 4.3.

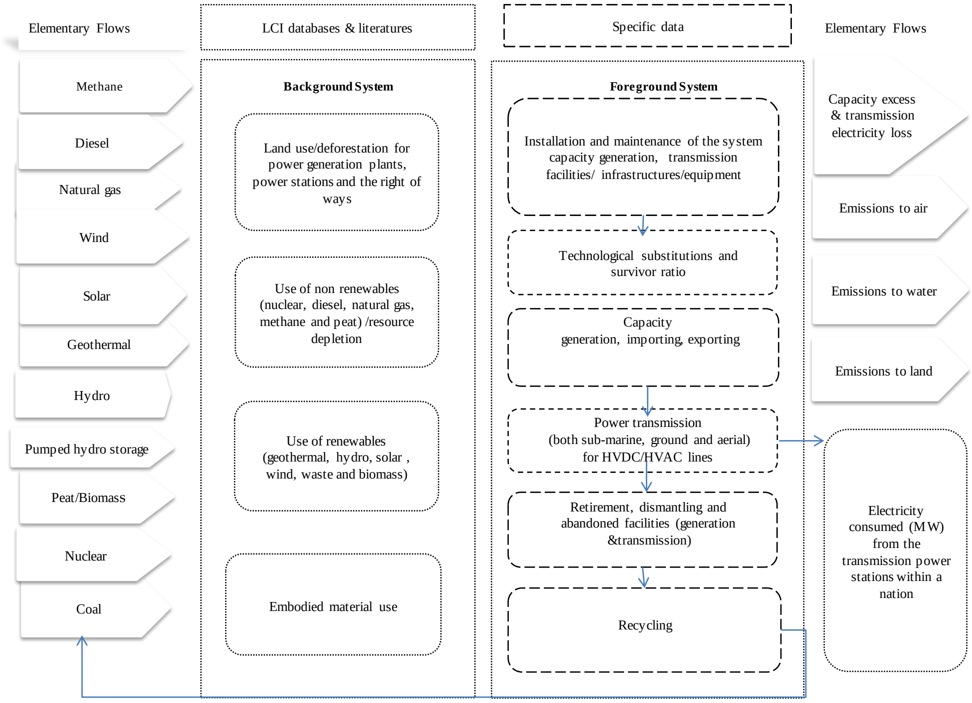


Fig.4. 3. System boundaries model for the studied grid electricity generation and transmission in study area

Source: Modelled after [35]

4.3.1.4. Processes included in the system boundary

Model adjustments were made to ensure that the appropriate parameters were considered. This process required that the power supply and electricity demand remained in balance at all times (system balancing), that adequate generation capacity was installed within a region to meet residual demand (capacity adequacy), and that the transmission network infrastructure was sufficient to deliver generated power to end-users. To gain a good understanding of the dynamics of the system, the DPSIR theoretical framework was adopted for this study, as presented in Figure 4.4. The conceptual structure focused on the responses as the variable moderators, drivers (grid electricity power generation and transmission) as independent variables, and pressures (environmental emissions) as dependent variables; these were studied within the DPSIR theory, using a developed linear algorithm suitable for the LCCEI for the studied cases.

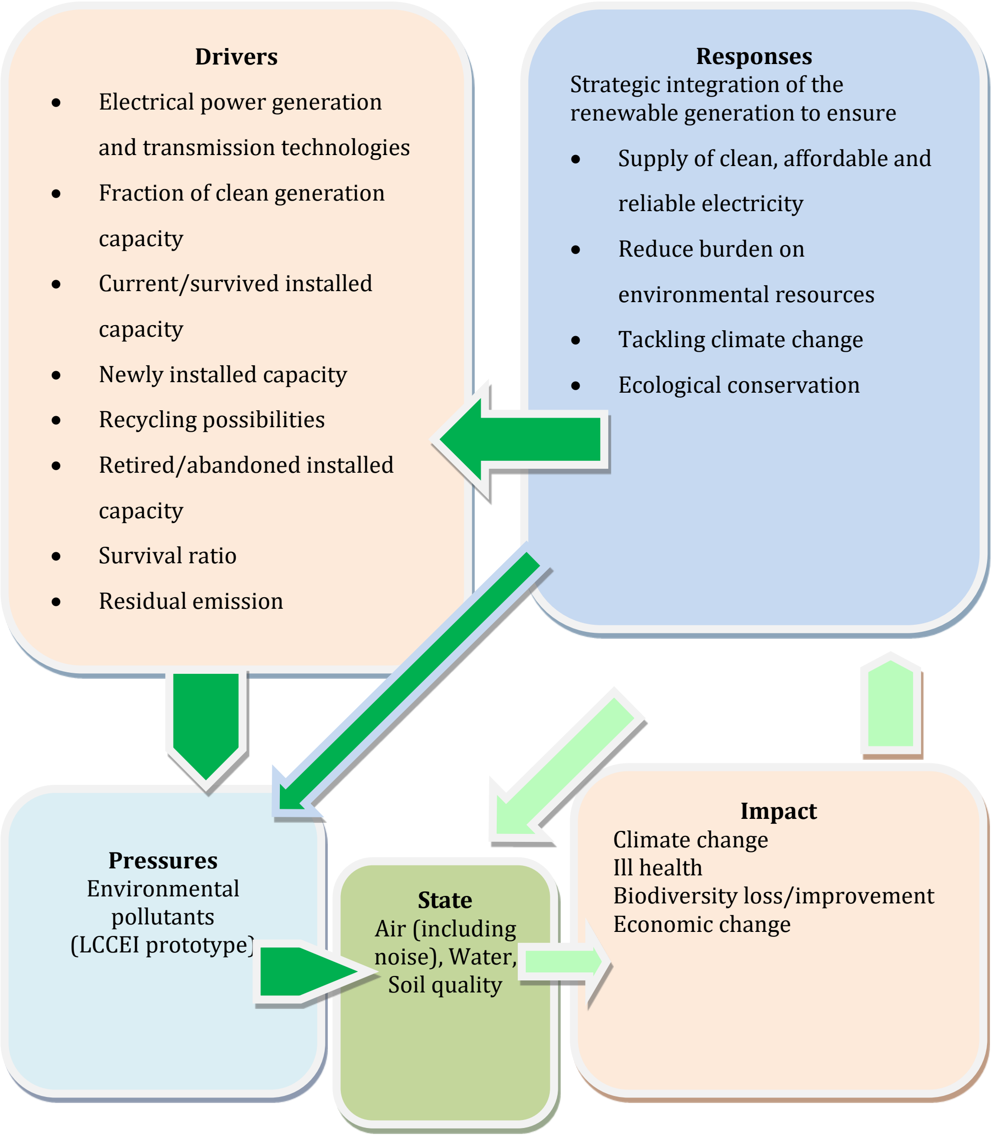


Fig.4. 4. 'Drivers, Pressure, State, Impact and Responses' (DPSIR) structure

Source: Modelled after [36]

The sensitivity parameters of the study included the share of low-carbon energy sources, substitution ratio, recovery ratio, residual pollutant remaining at retirement, survival of a newly added electrical power system, capacity of a retired electrical power system, and pollutant substituted in the newly added electrical power system [34]. The LCCEI was developed while considering the parameters of the independent sensitivity variables. The environmental emission results were useful for guiding the design and operation optimisation of the energy resource usage, transmission, and exchange in the region. The calculated inventory results regarding the carbon from different power systems' modelled structures were related to the proposed functional unit (i.e. MW) for a lifetime of 30 years; thus, the year 2019 was considered as a base year. The electrical product system flowchart (Figure 4.5) was modelled to indicate the unit processes interconnecting the inputs and outputs. The sub-processes included the usages of energy resources and of specific embedded materials, and the environmental emissions associated with the production and transmission of 1 MW of power to a power transmission sub-station [17]. Studies have acknowledged the difficulties in operating a power system including only renewable generation units, i.e. without any load control (both base load and inertia [4]. However, for simplification, the environmental pollutants associated with several energy storage equipment elements, power electronics, and operations required for enabling the transition to power systems installed with renewable generation units were not modelled herein. For the same reason, some downstream activities, such as energy material acquisitions and transportations of gas, oil, peat, and coal from extraction sources to power generation points, and upstream activities, such as vegetation removal (to pave rights of way for power transmission activities) [13] and power generation plants, were not modelled herein. The carbon in the biomass and bagasse was not evaluated, as it is part of the global carbon cycle [37]. The power consumed directly from a plant and distribution power station was also not modelled. The environmental pollutants emitted owing to embodied power transmission and distribution materials, and labour for delivery were not included in the systems studies. The environmental pollutants emitted owing to machinery, infrastructure, facilities, and equipment related to energy material acquisition and transportation were also not modelled, as the environmental loads associated with them were considered negligible owing to their long-term life spans.

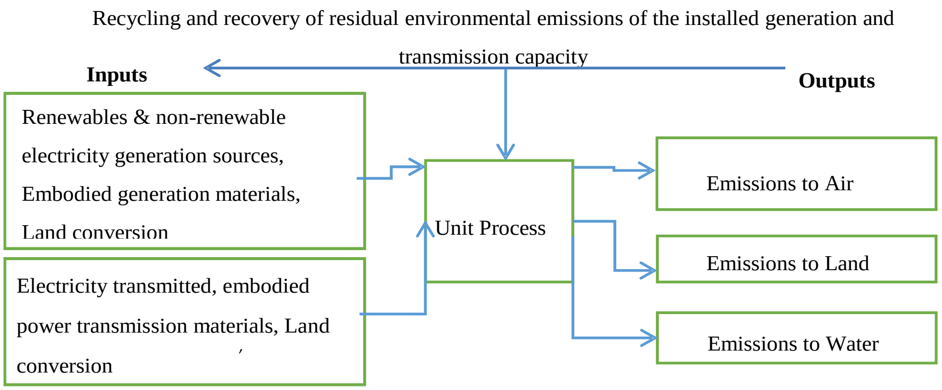


Fig.4. 5. Unit processes within the system boundary of the study

Source: Modelled after [38]

4.3.2. Algorithm and parameters

The choices of the algorithm and model were influenced by the authors' knowledge of the various 'families' of models already existing and previously applied in similar research. The emissions from each unit process within the system boundary were considered as equivalent to the product of the grid-specific emission factor (kg/MW) and grid electricity generated (MW) and transmitted, as follows.

$$\textit{Grid Emissions} = \textit{Grid Emission factor x Activity data} \qquad (2)$$

The modified mathematical representation was physically linked to logical relationships identified through a hypothetical LCCE approximation for the generation and transmission systems. This study also attempted to present MS Excel LCCEI spreadsheet prototype and polynomial regression tests. The mathematical algorithm was adopted as a reasonable computation, and for gaining inventory results as a table, i.e. listing the geographical coverages, system capacities, systems technologies, and emissions outputs associated with the functional unit [39]. The LCCE outputs were computed from available and assumed data, and the mathematical algorithm was a slightly modified version from previous relevant scientific articles [40] and expressed as Appendix 6 and in a Mendeley data repository.

The mathematical algorithm was modified to make it flexible in time, and to accommodate wide ranges of independent variable parameters (installed power capacity) and dependent variable parameters (carbon emissions). The modified mathematical algorithm presented in this study can be used as an LCCEI tool to account for the residual environmental pollutants emitted from the installed and retired capacity, newly added capacity, and currently installed capacity, using grid electricity generation and transmission activity data.

4.3.3 Case study scenario setting and key assumptions

A case study was conducted to undertake the LCCEI, and to represent other environmental pollutants from the Kenyan, Rwandan, and Tanzanian grid electricity generation systems. The study evaluated the business as usual (BAU) and EG scenarios for the power system master plans of the studied grids. For simplicity, only two scenarios were considered. Power generation under the BAU scenario was assumed to occur only at the generation side of the power system. The BAU scenario adopted the prevailing modelled plans, whereby the use of non-renewable energy sources and absence of smart appliances were assumed; the developments in geothermal, hydropower, wind, and photovoltaic power were considered to increase slowly; the improvements in power generation technology were assumed to be frozen at their current levels; and the power consumption and emission rates per unit power generated remained as presented in the prevailing plans and institutions.

The substitution, efficiency, and recycling ratios were also assumed as insubstantial. A low quantity of recycled pollutants was assumed in the BAU scenario, owing to the currently relaxed policies and regulations concerning particular pollutants. In the LCCEI model, it was assumed that once the new installed capacity was operational, the facility survival ratio became high and the retirement ratio became low during the first 20 years. An assumption was also made that, as the age of the new installed capacity reached 30 years, the retirement ratio reached its peak. Therefore, the retirement ratio was gradually reduced as the proportion of the surviving new installed capacity was reduced. After 40 years, both the survival and retirement ratios were assumed as zero, as presented in Figure 4.6.

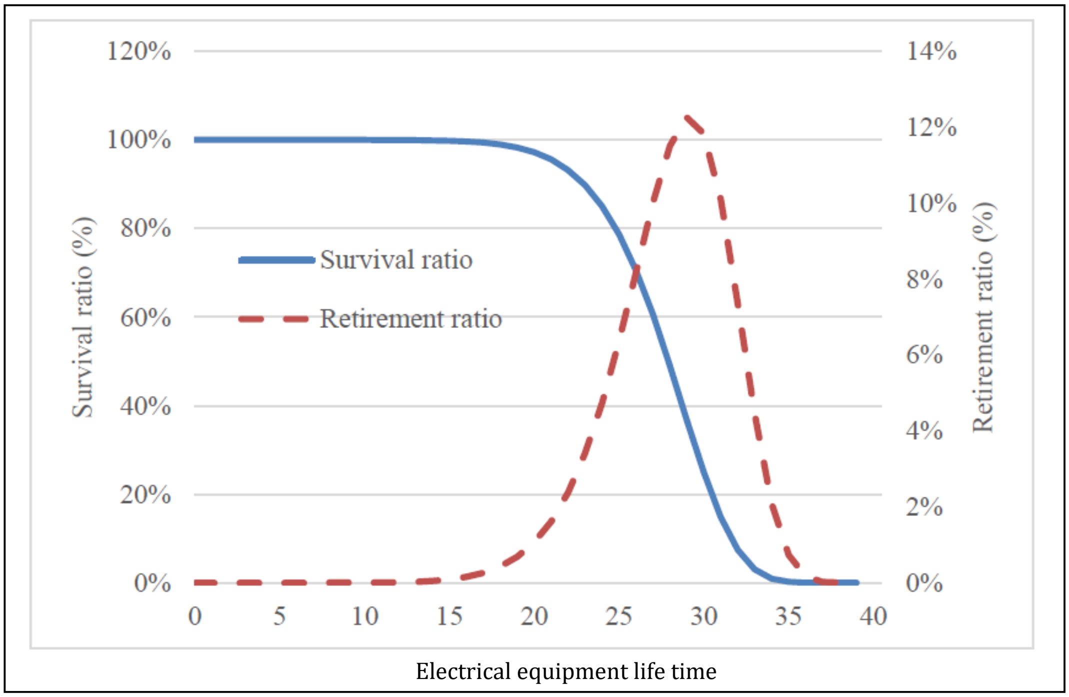


Fig.4. 6. Illustration of the equipment survival and retirement curves

Source: Modified from[34]

The current installed capacity was obtained from data published by national electric power generation institutions, including KenGen, TANESCO, and REG. Power generation technology-specific carbon emission factors for nuclear, oil, wind, solar, natural gas [22], small hydropower [17], geothermal, large hydropower [20], and coal [5] were obtained from published scientific and technical papers. The carbon emission factors for peat and methane power generation technology were obtained from published technical papers [41].The overall grid carbon emission factors for the Rwandan, Tanzanian, and Kenyan power systems were obtained by summing the fractions of all of the carbon emission factors from the different installed generation technology mixes by the year 2019. The grid installed capacity (Nt) by the year 2049 was linearly adjusted from the last year of projection presented on the most recently updated national and regional power system master plans. The capacities of new power plants were modelled according to the prevailing electrical power systems master plans in Rwanda [28] and Tanzania [32], and published scientific report in Kenya [12]. The estimated total installed capacities, including the addition of an electricity percentage to compensate for the electricity loss during transmission from generation plants to power transmission stations under the BAU scenario, were not considered imports and exports plans by the year 2049. The grid electricity mix data were adopted from the most updated national power systems' master plans. Power transmission technology-specific carbon emission factors were sourced from published technical and scientific method and data [42].

The adopted EG scenario for the particular case included the consideration of pollution prevention and control plans in the context of current and future power system capacity growth, e.g. through the adoption of energy-saving technologies, solar rooftop projects, wind farms, combined heat and power (biomass) projects, mini-hydro projects, regional power interconnections, power trades, smart grid integration [43], shifting from fossil fuels to renewables, and transmission power loss control. The EG scenario assumed that the installed capacity and future per capita electricity demand increased relatively slowly in comparison with the BAU scenario, owing to the adoption of an efficient energy use policy. Distributed generators were assumed to exist at both the generation and consumption sides of the power system, including small or mini hydro, wind, and solar systems and/or large hydropower and geothermal power generation units. Smart grid concepts were assumed, so as to balance generation and consumption. It was also assumed that there was substantial use of power generation and transmission system efficiency technologies and insulated home substitutions and recycling ratios [33], as governed by the policies and regulations concerning particular pollutants. The EG scenario also assumed the use of communication technology to control appliances at consumer’s side to save energy, reducing cost and increasing reliability and transparency [4].

The total estimated installed capacities, including an added electricity percentage to compensate for the electricity loss during transmission to power transmission stations, under the EG scenarios by the year 2049, were considered in the context of import and export plans for the year 2049 [44]. Activity information was obtained from relevant institutions through interviews, and through reviews of reliable secondary information from technical report in Eastern Africa [41], Rwanda [28], and Tanzania [21], and scientific studies in Kenya [12] and Tanzania [45]. The grid electricity mixes of future power generation systems under EG scenarios were assumed to be dominated by low-carbon energy sources. Previous studies have shown that the water availability in the studied countries will not be able to sufficiently meet the expected water demand in the future. The EG scenario assumes the strong implementation of national, regional, and global institutions to support the realisation of the United Nations SDGs 7, 12, 13, and 15, and Goal 7 of the African Agenda 2063. The EG scenario in the case studies considered the optimal use of geothermal resources to enhance the electrical power generation systems that are resilient to the impacts of climate change. It also considered the optimal use of small hydros and mini hydros (compared to large hydros) to enhance the distributed generation and community participation [46]. However, the maximum carrying capacity for the hydropower generation capacity expansion plans by 2049 was established as not more than 70% of the electricity mixes, so as to ensure a sustainable supply of clean water for cities, environmental conservation, and minimal negative impacts on agricultural areas [12].

Substitution for CO_2 volumes or for any environmental pollutant (SA,t) to achieve emissions reductions is a long-term process. The modified LCI algorithm incorporated parameters related to substitutions of CO_2 volumes in newly installed electric power systems technologies. A recycling coefficient concerning the residual CO_2 volumes (RC,t) of the installed capacity retired and transferred from one power plant to another (or sold to a different operator) was incorporated in the developed algorithm. The current (SP,t) installed capacity under the operation, newly installed capacity plus retired installed capacity (Nt), retirement fraction of newly added installed (NR,t) capacity, and fraction of residual carbon emissions (PR,t) in the retired/abandoned installed capacity were also estimated and calculated, with the aid of a prototype.

Professional judgement has been employed to arrive at applicable results for a particular grid. The findings were calculated by summing the fractions of all carbon emission factors from the different newly installed generation mixes and transmission technologies for the year 2049, using the developed inventory prototype. The modelled LCCE output of the grid electricity generation and high-voltage transmission systems were imported into Excel for Monte Carlo simulations [24]; the LCCE value obtained from the highest positive coefficient (checked for non-negativity) was considered as a simuland for the LCCE output.

4.3.4. Life cycle carbon emission (LCCE) calculation model

The evaluation of the performance of the existing and planned grid electricity generation and transmission systems, based on technology and resources assessments, was conducted using the developed LCCEI model. The Microsoft Excel spreadsheets and LCCEI were developed so as to enable the estimation of the carbon emitted from the life cycles of the systems designed and operated in the studied area using the developed mathematical algorithm. The capacity-based carbon emissions were accounted for, to ensure that the uncertain electrical demand and supply matched in real-time under different scenarios. The study presented an environmental emission model under both BAU and EG scenarios. The potential for low-carbon electricity generation technology mixes was developed based on the available scientific knowledge for the studied national grids studied, aiming to meet electricity demands in scenarios different from the current BAU. The study supported the idea that a significant recycling coefficient is attained in a grid electricity generation mix with relatively more solar power. The grid electricity generation systems identified as generating long-term hazardous waste were also assumed to have a poor recycling coefficient (<50%) by 2049. Therefore, the recycling coefficient for the residual pollutant of the installed/retired capacity was modelled to reflect the percentage compositions of both the solar power generation systems and residue emission generation potentials. The current Kenyan BAU scenario has been evaluated as having a poor recycling coefficient (27%) for residual pollutants, as a substantial amount of its grid electricity generation mix comes from coal and nuclear technology [12].

The researchers ensured that the prevailing algorithm was sufficiently improved so as to arrive at an appropriate algorithm for reflecting the uncertainty associated with the current and future changes of the aforementioned environmental and emission-driven factors. The carbon emissions per unit power were evaluated for the testing of a model developed in the course of this study. The detailed parameters developed and evaluated based on the proposed LCI algorithms are presented in Table 4.3. The obtained grid LCCE values were imported into Excel for Monte Carlo simulations [24]. The extract of those calculations spreadsheets are provided as Appendix 6 of this thesis 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/pcc8vhbvwz/2).

Table 4. 3. Life cycle carbon emission estimation parameters modelled from the grid electricity generation and transmission systems by the year 2049

Model parameters	Unit	Business as usual (BAU)			Environmental governance (EG)		
		Kenya	Rwanda	Tanzania	Kenya	Rwanda	Tanzania
SP,t	MW	2819.00	216.23	1567.00	2819.00	216.23	1567.00
EFo,t	kg/MW	0.02	26.75	0.06	0.02	26.75	0.06
Qm,t	kg	600.52	70.42	1914.51	0.26	3.50E-03	0.69
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
SA,t	%	8.70	96.50	28.20	92.20	99.90	97.50
N,t	MW	18974.20	1896.50	18161.00	18437.20	1809.20	17632.20
A,t	kg/MW	0.03	1.06	0.08	2.03E-04	1.90E-03	1.54E-03
NR,t	%	12.30	12.30	12.30	12.30	12.30	12.30
PR,t	%	6.20	6.20	4.20	5.90	5.90	5.50

4.3.5. Data quality, uncertainty reduction, and validation

The study established a function unit for complying with international life cycle assessment standards [26]. The uncertainty in the life cycle environmental inventory model developed in this study was both parametric (the quantitative data used in the model) and structural (the assumptions and simplifications constituting the model itself). The generated information was verified through interviews with relevant institutional stakeholders from both national and regional power organisations, including KenGen, TANESCO, REG, KETRACO, and SAPP. The data collected were checked for completeness, consistency, and accuracy by ensuring that the current and newly installed capacities were balanced in a particular electrical power system for a targeted year of study. The representation of the energy resource potentials existing in the real system was compared with data published by reputable sources, such as the websites of specialised electrical power systems institutions, and scientifically indexed conferences and journals.

The LCI uncertainty in the study was reduced by considering the parametric system data developed therein. The uncertainty was contributed to by, e.g. carbon emission factors not focused on global warming potentials, outdated adopted databases (or those not relevant to a particular geographical area), and the projected installed generation activity data. The uncertainty levels obtained from regression tests were adopted to facilitate scientific decisions for any choice of action, with a range of possible outcomes and probabilities. The results of this study, as with so many computer models [36], should be interpreted as guidance, and not a definitive answer.

The confidence level regarding the certainty was raised owing to the behaviour of the charts developed from the results. The behaviour of the charts was shown to be consistent with the authors' 'best practice' expectations. The emission methodology revised and adopted by this study was also regarded as more accurate because it accounted for the long lifetimes of the electrical equipment and associated delayed emission effects. The environmental and grid electricity data were identified to measure the effects of environmental changes. Most of the presented results were produced from secondary sources as combined with some limited primary data and, whenever necessary, estimates based on conservative assumptions. The developed inventory workbooks accounted for residual carbon emissions related to the grid generation capacity survival lifetime, retired system capacity, recycling rate, transmission loss, and power exchanges between utilities, thereby reducing the emissions uncertainty in the study area. However, a more refined and policy-relevant tool could be obtained with cumulative data, detailed simulation flow parameters, and expert knowledge in the fields of environmental, energy, and engineering sciences.

A more certain LCCEI model was developed by considering basic environmental emission uncertainty factors from previous studies [47]. Environmental pollutant (carbon) outputs with uncertainties owing to different scenarios of electrical power system design and operation were modelled for three African sub-Saharan nations. However, in the case studies, even a single case sufficed, as long as there were key lessons to be learnt [48]. The study also acknowledged the additional uncertainties introduced owing to the estimations of some model parameters.

4.3.6. Risks and ethics

The research was aligned to ensure that governance and ethics were core components [49]. The data collected were used ethically and transparently. The negative bias in the creation of the algorithm was also eliminated. The respective ethical operation guidelines and procedures were also considered during the research and publication process.

4.4 Results and discussions

The linear model for the independent variables (grid generation and transmission system capacities) was developed to represent their relationships with the dependent variable (carbon emission). Figure 4.7 shows that the carbon emissions from the grid electricity generation and transmission capacities decrease as designers and operators move away from the BAU model. The area of the curve for the BAU and EG models reveals that Rwanda has the potential to contribute more emissions per unit power, followed by Tanzania and Kenya. The obtained LCCEI results indicate that Kenyan electrical power systems have the specialised institutions to stand a better chance of supporting a relatively stronger incorporation of environmentally conscious engineering by 2049. In addition, upcoming national and regional hybrid power systems and trades offer an avenue for optimising the environmental pressure per unit power in the study area.

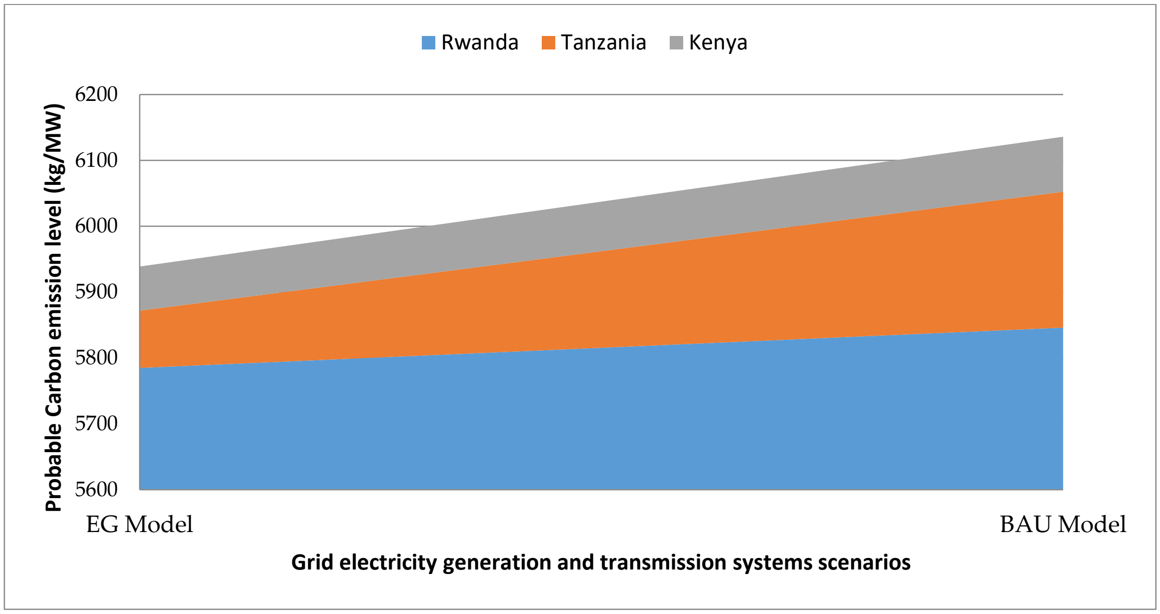


Fig.4. 7. Life cycle carbon emission (LCCE) levels from different electrical power systems modelled scenarios

Figure 4.8 shows the uncertainty range in the confidence levels for the grid electricity generation and transmission system scenarios studied through 2049. Error bars with one standard deviation are used to evaluate the uncertainties in the pollutant (carbon) emission intensity modelled flows for each studied electric power system. Based on the verbal scale assessment knowledge introduced by the Intergovernmental Panel on Climate Change [50], the observed EG simuland (i.e. the LCCE) uncertainty range of 65%–75% is likely to yield significant LCCEs from the designed and operated grid electricity generation and transmission system drivers. The uncertainty values in the LCCE indicate that only limited EG factors were considered during the grid electricity generation and transmission system driver design and operation in the study area. This is owing to inadequate consideration of pollution prevention (i.e. EG) regulatory and corrective strategies during the design and operation of the cheaper and less-sophisticated hybrid electrical power systems model in the study area. However, the portrayed error bars also show that the EG-modelled output uncertainty values range between 15%–25%, indicating that a significant lifetime decarbonisation performance can be attained from the generation and transmission systems if the EG factors proposed by this study are also considered. It is also possible to use the developed grid codes to predict how the systems will perform with time, e.g. aiming toward net-zero emissions in 2050. Simuland carbon emission values presented in this thesis are obtained after the estimated (using mathematical algorism) carbon emission values imported into simple Excel for Monte Carlo simulations.

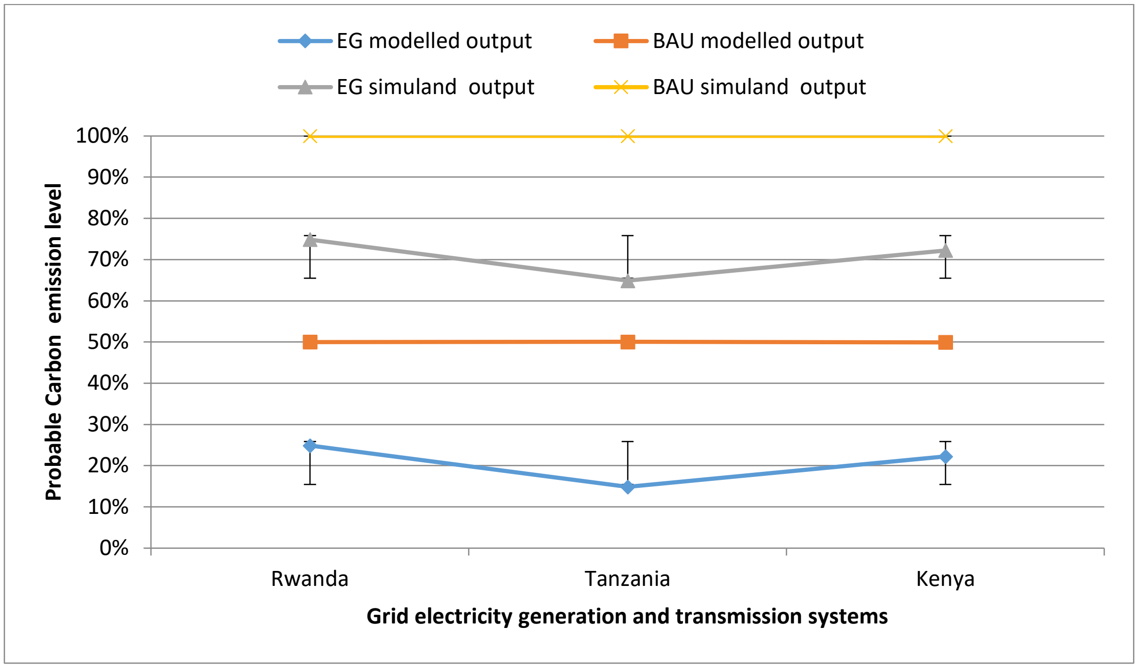


Fig.4. 8. LCCE uncertainty from different electrical power systems scenarios

Figure 4.9 presents various LCCE outputs and bounds from the different analysed scenarios. The obtained linear distribution curves portray distribution flows describing the possible carbon emission uncertainties among the studied scenarios. The obtained EG modelled LCCE output (R^2 = 0.7526) and EG simuland LCCE output (R^2 = 0.8223) reveal a good relationship between the structural assumptions and simplifications that constitute the linear approximation model itself, in the case studied for the year 2049. This means that at least 75% of the emitted carbon is explained by the hybrid (EG) generation and transmission systems model.

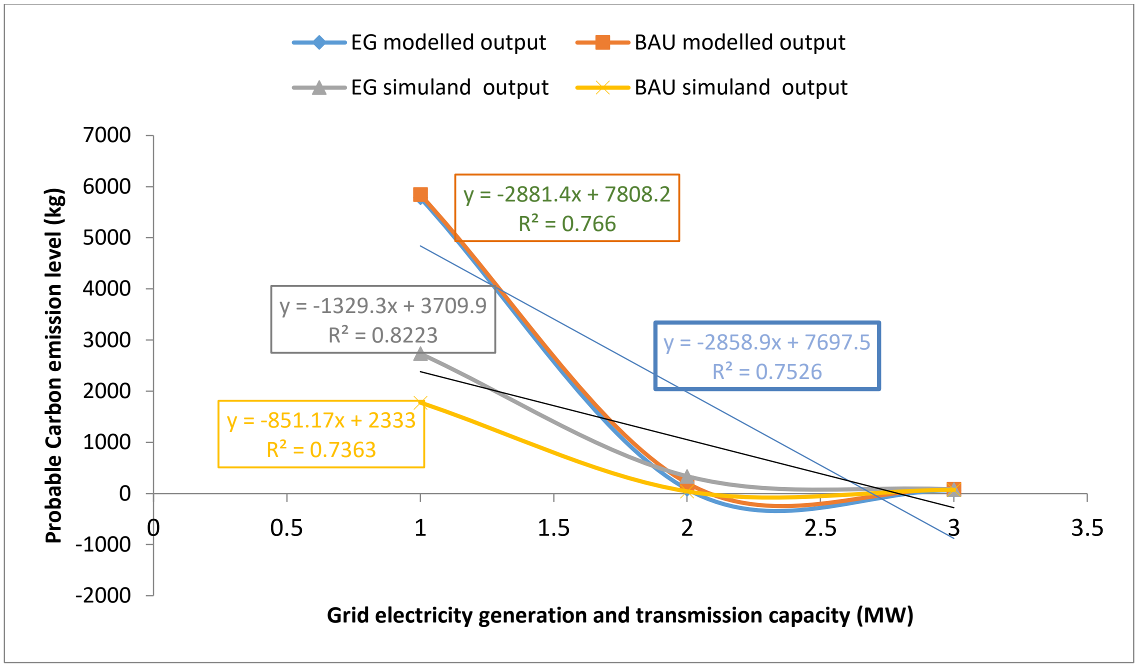


Fig.4. 9. LCCE levels from different electrical power systems scenarios evaluated using linear regression

In evaluating the accuracy of the results obtained from the polynomial liner regression method presented in Fig. 4.9, the logarithmic regression trend lines presented in Figure 4.10 show a higher R^2 value for the EG modelled LCCE output ($R^2 = 0.8689$) and EG simuland LCCE output ($R^2 = 0.9209$), implying a very good relationship between the structural assumptions and simplifications constituting the model itself for case studied by the year 2049. This means that up to 92% of the carbon emitted can be explained in the hybrid (EG) generation and transmission systems using the logarithmic regression trend lines. Therefore, the results reveal that a higher-order regression test offers a better fit line compared to a lower-order regression test. Accordingly, a hybrid electrical power systems testing model designed using a higher-order polynomial approximation, shuffling of the modelled parameters, and data obtained from additional countries is recommended for reducing the risk of being excessively optimistic during design and operation, so as to support the United Nations SDGs 7, 12, and 15, and Goal 7 of the African Agenda for 2063.

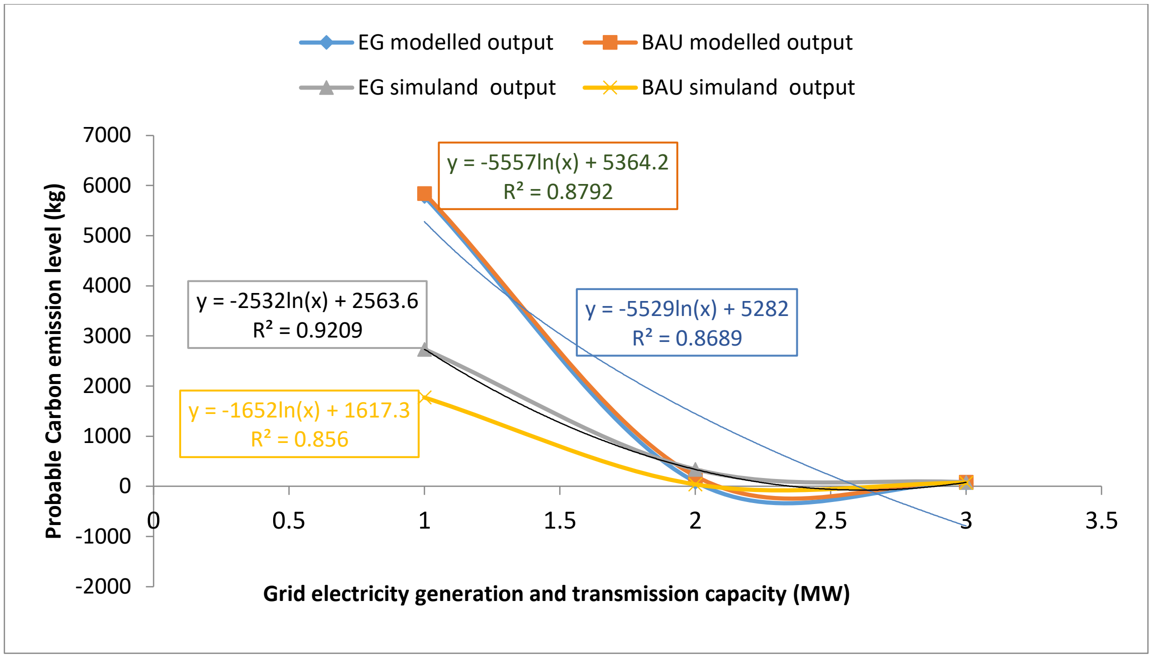


Fig.4. 10. LCCE levels from different electrical power systems scenarios evaluated using logarithmic regression

The developed LCCEI tool can also be customised, coded, and exported to commonly used evaluation software to enhance its open use for scientists, practitioners, and policymakers at national, regional, and global scales. The study can be used to generate additional knowledge for guiding clean technologies and the eco-design of electricity production and transmission systems in the study area. The generated knowledge can also enhance the effectiveness, efficiency, satisfaction, learnability, and monitoring of electrical power systems and grid interconnections in the study area. The developed model is therefore useful for targeting and monitoring local, regional, and global energy and environmental institutions for sustainable electrical power system development. Further studies on the Monte Carlo regression shape(s) obtained from particular defined dynamics of the hybrid electrical power systems process variables related to the impacts and states of the environment are therefore recommended.

4.5 Conclusions

The study attempted to develop a linear algorithm equation and parameters for conducting an LCCEI for the studied electrical power systems. It also attempted to provide scientific evidence to model the optimal lifetime performance of electrical power systems if the proposed EG (decarbonised) factors were considered during design and operation. The developed LCCE prototype accounted for residual carbon emissions related to the grid-generation capacity survival lifetime, retired system capacity, recycling rate, planned power trades, and transmission efficiency, so as to reduce the uncertainty in grid emissions. This study provides an overview of the CO_2 emissions from both grid electricity generation and transmission in the studied sub-Saharan African countries. The obtained higher carbon emission uncertainty levels for the EG simuland revealed that limited EG factors were considered during the grid electricity generation and transmission system design and operation. The developed LCCE models revealed that the Rwandan grid could contribute more carbon per unit power, followed by the Tanzanian and Kenyan grids.

However, the lower carbon emission uncertainty levels obtained from the EG modelled output revealed the significant lifetime decarbonisation performance of the generation and transmission systems studied in the selected countries. Therefore, the developed linear approximation hybrid electrical power systems model can be useful for guiding and predicting the optimal lifetime performance of electrical power systems if the proposed EG factors are considered. The grid codes developed in this study can be used to predict how electrical power systems perform with time, aiming toward net-zero emissions. In order to improve energy and environmental systems technologies, the study is envisage the future African grid electricity systems to integrate pumped hydro storage (PHS) and compressed air energy storage (CAES) technologies since they emit less and has longer lifespan as opposed to advanced battery energy storage systems (BESS) with shorter lifespan and the use of electrolytes, which require energy intensive mining and ore processing. However, the study also foresee particular success for BESS, since CAES and PHS are mature technologies with little forecast improvement for either energy input or efficiency while BESS systems are still under extensive development and significant cost reductions are expected, which should correspond to decreases in energy input.

The regression model test reveals that the most accurate results are likely to be obtained using a higher-order polynomial approximation. Further hybrid electrical power systems model testing is recommended to reduce the risk of being overly optimistic during system design and operation, so as to support the United Nations SDGs 7, 12, and 15, and Goal 7 of the African Agenda for 2063. A higher-order regression study on the dynamics of the hybrid electrical power systems variables related to the particular impacts and states of the environment are recommended. The study also suggests monitoring a wide range of environmental parameters (apart from the carbon) and employing associated energy storage technologies, using both cumulative data and expanded systems.

References

[1] African Development Bank, "Energy Sector Policy of the AfDB Group," Tunisia, 2019.

[2] N. Ijumba and H. Kaya, "Energy Resources and Environmental Conflicts in Africa: Implications on Indigenous Knowledge Systems and Environmental Policy," *J. Hum. Ecol.*, vol. 53, no. 2, pp. 96–100, 2016, doi: 10.1080/09709274.2016.11906960.

[3] D. Marks, J. Hamilton, Richardson Ivan, and N. Carn, "African Energy Data Book," East Sussex, 2018. [Online]. Available: africa-energy.com/live-data.

[4] F. Blaabjerg and J. M. Guerrero, "Smart grid and renewable energy systems," in *International Conference on Electrical Machines and Systems, ICEMS*, 2011, pp. 1–10, doi: 10.1109/ICEMS.2011.6073290.

[5] P. E. Hardisty, T. S. Clark, R. G. Hynes, S. Kensington, G. Terrace, and N. S. Wales, "Life Cycle Greenhouse Gas Emissions from Electricity Generation: A Comparative Analysis of Australian Energy Sources," *Energies*, no. 5, pp. 872–897, 2012, doi: 10.3390/en5040872.

[6] R. S. Jorge, T. R. Hawkins, and E. G. Hertwich, "Life cycle assessment of electricity transmission and distribution-part 2: Transformers and substation equipment," *Int. J. Life Cycle Assess.*, vol. 17, no. 2, pp. 184–191, 2012, doi: 10.1007/s11367-011-0336-0.

[7] United Nations, "Report of the Secretary-General on SDG Progress 2019," New York, 2019. [Online]. Available: https://sustainabledevelopment.un.org/content/documents/24978Report_of_the_SG_on_SDG_Progress_2019.pdf.

[8] R. L. Santos, "Global Energy and Climate Outlook 2018: Sectoral mitigation options

towards a low-emissions economy," Luxembourg, 2018. doi: 10.2760/67475.

[9] G. Falchetta, M. Hafner, and S. Tagliapietra, "Pathways to 100 % Electrification in East Africa by 2030 Pathways to 100 % Electrification in East Africa by 2030," *Energy J.*, vol. Volume 41, no. May, 2020, doi: 10.5547/01956574.41.3.gfal.

[10] International Energy Agency, "Africa Energy Outlook 2019," 2019. [Online]. Available: https://webstore.iea.org/africa-energy-outlook-2019.

[11] African Peer Review Mechanism, "Agenda 2063 and SDGs Implementation in Africa," Midrand, 2020. [Online]. Available: https://www.google.com/search?q=agenda+2063+pdf&ei=vhG7YOasIsbwaKjKgJAD&start=20&sa=N&ved=2ahUKEwjmg4ic5__wAhVGOBoKHSglADI4ChDy0wN6BAgBEDY&biw=1366&bih=643.

[12] Ö. S. Berggren Anna, "Kenya meeting the electricity demand of 2030, An assessment of how Kenya Vision 2030 and climate change impact the optimal electricity generation mix," KTH Royal Institute of Technology, Stockholm, Sweden, 2017.

[13] E. Chambile, N. Ijumba, B. Mkandawire, and J. Hakizimana, "Impact of Electrical Power Systems on the Environment in Kenya, Rwanda and Tanzania," in *2018 IEEE PES/IAS PowerAfrica Conference*, 2018, no. 18261617, pp. 885–889, doi: 10.1109/PowerAfrica.2018.8521092.

[14] R. Itten, R. Frischknecht, M. Stucki, P. Scherrer, and I. Psi, "Life Cycle Inventories of Electricity Mixes and Grid," Uster, 2014.

[15] C. Weber, P. Jaramillo, J. Marriott, and C. Samaras, "Life cycle assessment and grid electricity: What do we know and what can we know?," *Environ. Sci. Technol.*, vol. 44, no. 6, pp. 1895–1901, 2010, doi: 10.1021/es9017909.

[16] A. Arvesen, I. B. Hauan, B. M. Bolsøy, and E. G. Hertwich, "Life cycle assessment of transport of electricity via different voltage levels: A case study for Nord-Trøndelag county in Norway," *Appl. Energy*, p. 20, 2015, doi: 10.1016/j.apenergy.2015.08.013.

[17] D. Weisser, "A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies," *Energy*, vol. 32, no. 9, pp. 1543–1559, 2007, doi: 10.1016/j.energy.2007.01.008.

[18] K. Schaber, F. Steinke, and T. Hamacher, "Transmission grid extensions for the integration of variable renewable energies in Europe: Who benefits where?," *Energy Policy*, vol. 43, no. 4, pp. 123–135, 2012, doi: https://doi.org/10.1016/j.enpol.2011.12.040.

[19] I. B. Hauan, “Life Cycle Assessment of Electricity Transmission and Distribution,” *Environ. Sci. Technol.*, vol. 44, no. 6, pp. 1895–1901, 2010, doi: https://doi.org/10.1021/es9017909.

[20] H. Hondo, “Life cycle GHG emission analysis of power generation systems: Japanese case,” *Energy*, vol. 30, no. 11-12 SPEC. ISS., pp. 2042–2056, 2005, doi: 10.1016/j.energy.2004.07.020.

[21] United Republic of Tanzania, “The Executive Summary of Power System Master Plan 2012 Update,” Dar es Salaam, 2013. [Online]. Available: http://www.tanesco.co.tz/index.php/investments/investment-report/23-the-executive-summary-of-power-system-master-plan-2012-update?format=html.

[22] R. Turconi, A. Boldrin, and T. Astrup, “Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations,” *Renew. Sustain. Energy Rev.*, vol. 28, pp. 555–565, 2013, doi: 10.1016/j.rser.2013.08.013.

[23] T. M. Valheim, “Environmental assessment of electricity transmission using input-output analysis,” Trondheim, 2016. [Online]. Available: http://hdl.handle.net/11250/2418199.

[24] T. Eriksson, “Simple Excel Visual Basic Application for Monte Carlo simulation with ad hoc made spreadsheet models,” in *5th Nordic Feed Science Conference*, 2014, pp. 138–142.

[25] Y. Liu, A. Syberfeldt, and M. Strand, “Review of simulation-based life cycle assessment in manufacturing industry,” *Prod. Manuf. Res.*, vol. 7, no. 1, pp. 490–502, 2019, doi: 10.1080/21693277.2019.1669505.

[26] I. Standard, “Environmental management — Life cycle assessment — Principles and framework,” Geneva, ISO 14040:2006(E), 2006. [Online]. Available: http://www.cscses.com/uploads/2016328/20160328110518251825.pdf.

[27] B. Atilgan and A. Azapagic, “An integrated life cycle sustainability assessment of electricity generation in Turkey,” *Energy Policy*, vol. 93, pp. 168–186, 2016, doi: 10.1016/j.enpol.2016.02.055.

[28] Rwanda Energy Group, “Rwanda Least Cost Power Development Plan (LCPDP) 2019 – 2040,” Kigali, 2019.

[29] S. Kihwele, K. Hur, and A. Kyaruzi, “Visions, scenarios and action plans towards next generation tanzania power system,” *Energies*, vol. 5, no. 10, pp. 3908–3927, 2012, doi: 10.3390/en5103908.

[30] P. N. Biskas, D. I. Chatzigiannis, and A. G. Bakirtzis, “Market coupling feasibility

between a power pool and a power exchange," *Electr. Power Syst. Res.*, vol. 104, no. September 2018, pp. 116–128, 2013, doi: 10.1016/j.epsr.2013.06.015.

[31] Eastern Africa Power Pool, "Eastern Africa Power Pool Regional Master Plan Volume II: Data Report," Addis Ababa, Ethiopia, 2014. [Online]. Available: http://www.ea-energianalyse.dk/reports/1332/1332_eapp_master_plan_2014_volume_2_data_report.pdf.

[32] United Republic of Tanzania, "Power System Master Plan 2016 Update," Dodoma, 2016. [Online]. Available: https://www.infoafrica.it/wp-content/uploads/2017/02/Power-System-Master-Plan-PSMP-2016-Update.pdf.

[33] R. S. Jorge, T. R. Hawkins, and E. G. Hertwich, "Life cycle assessment of electricity transmission and distribution-part 1: Power lines and cables," *Int. J. Life Cycle Assess.*, vol. 17, no. 1, pp. 9–15, 2012, doi: 10.1007/s11367-011-0335-1.

[34] S. Zhou, F. Teng, and Q. Tong, "Mitigating Sulfur Hexafluoride (SF6) Emission from Electrical Equipment in China," *Sustainability*, vol. 10, no. 2402, pp. 1–17, 2018, doi: 10.3390/su10072402.

[35] M. Felix and S. H. Gheewala, "Environmental assessment of electricity production in Tanzania," *Energy Sustain. Dev.*, vol. 16, no. 4, pp. 439–447, 2012, doi: 10.1016/j.esd.2012.07.006.

[36] M. Peirce, "Computer-Based Models in Integrated Environmental Assessment A report produced for the European Environment Agency," Warrington, 1998. [Online]. Available: https://www.eea.europa.eu/publications/TEC14.

[37] E. Chambile, "Emission of Air Pollutants from the Energy Sector in Tanzania," University of Dar es Salaam, Dar es Salaam, 2008.

[38] X. Gong, Z. Nie, Z. Wang, and F. Gao, "Calculation model of life cycle inventory for a product system," in *IEEE Proceedings of 4th International Conference on Computer Science and Education*, 2009, pp. 1208–1211, doi: 10.1109/ICCSE.2009.5228466.

[39] I. B. Hauan, "Life Cycle Assessment of Electricity Transmission and Distribution," Norwegian University of Science and Technology, 2014.

[40] E. Chambile, N. Ijumba, B. Mkandawire, and J. Hakizimana, "Grid Electricity Generation Systems Comparisons Using the Life Cycle Carbon Emission Inventory," in *2020 IEEE PES/IAS PowerAfrica Conference*, 2020, pp. 1–5, doi: 10.1109/PowerAfrica49420.2020.9219876.

[41] Eastern Africa Power Pool, "EAPP Regional Master Plan Volume I: Main Report," Addis

Ababa, Ethiopia, 2014. [Online]. Available: https://www.ea-energianalyse.dk/wp-content/uploads/2020/02/1332_eapp_master_plan_2014_volume_1_main_report.pdf.

[42] Paul Denholm and Gerald Kulcinski, "Net energy balance and greenhouse gas emissions from renewable energy storage systems," Madison, 2003.

[43] A. Arvesen *et al.*, "Green Energy Choices: the benefits, risks and trade-offs of low-carbon technologies for electricity production," Paris, France, 2016. [Online]. Available: http://www.un-expo.org/wp-content/uploads/2017/06/Green_energy_choices_The_benefits_risks_and_trade-offs_of_low-carbon_technologies_for_electricity_production-2016UNEP_GEC_web.pdf.pdf.

[44] R. A. Verzijlbergh, L. J. De Vries, G. P. J. Dijkema, and P. M. Herder, "Institutional challenges caused by the integration of renewable energy sources in the European electricity sector," *Renew. Sustain. Energy Rev.*, vol. 75, pp. 660–667, 2017, doi: 10.1016/j.rser.2016.11.039.

[45] M. Felix and S. H. Gheewala, "Environmental assessment of electricity production in Tanzania," *Energy Sustain. Dev.*, vol. 16, no. 4, pp. 439–447, 2012, doi: 10.1016/j.esd.2012.07.006.

[46] A. F. Zobaa and B. K. Bose, "Renewable Energy, Global Warming Problem and Impact of Power Electronics (Invited Paper) World Energy Outlook Key words," in *International Conference on Renewable Energies and Power Quality*, 2011, pp. 1–10, doi: https://doi.org/10.24084/repqj09.003.

[47] ECON, *WP1 Task 1 " The Drivers of Electricity Demand and Supply ,"* no. April. 2007, pp. 1–16.

[48] R. K. Yin, "Robert K . Yin . (2014). Case Study Research Design and Methods (5th ed .). Thousand Oaks , CA : Sage . 282 pages .," *Can. J. Progr. Eval.*, no. March 2016, pp. 1–5, 2018, doi: 10.3138/CJPE.BR-240.

[49] Institute of Electrical and Electronics Engineers, "Ethically Aligned Design, First Edition, A Vision for Prioritizing Human Well-being with Autonomous and Intelligent Systems," Nottingham, 2019.

[50] A. E. Milne, M. J. Glendining, R. M. Lark, S. A. M. Perryman, T. Gordon, and A. P. Whitmore, "Communicating the uncertainty in estimated greenhouse gas emissions from agriculture," *J. Environ. Manage.*, vol. 160, pp. 139–153, 2015, doi: 10.1016/j.jenvman.2015.05.034.

CHAPTER FIVE

5.0 Case studies: Assessment of Grid Electricity Systems Using the Life-Cycle Carbon-Emission (LCCE) Model

5.1 Abstract

The study attempted to assess the environmental pressure of the studied Kenyan, Rwandan, and Tanzanian grids by computing their life cycle carbon emission. The study fills the research gap outlined above by applying a life cycle assessment method and simulate the learning patterns using RStudio. 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 data (emission factors and activity) has been collected from the reports (scientific and technical) and national utility actors. The presented results showed that only Kenyan generation and transmission systems have the lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power systems. The study also recommended further research to use the most current data, including new technologies adopted from cradle-to-grave of the systems, and consider the interpretation of the environmental impact caused by the power systems.

Keywords: Grid electricity generation systems, Grid electricity transmission systems, Life-cycle carbon–emission, Renewable dominated power system

5.2 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. The installed renewable capacity in Africa is 49.5 GW out of the total installed capacity of 236.2 GW [1]. Plans are also moving in the direction of the adoption of more efficient power electronic devices for electrical power systems design and operations [1]. Africa accounts for a comparatively small but increasing share of the world's carbon emissions [2]. 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 $MtCO_2$), the next emitting sector is transport (355 Mt CO_2) followed by industry (150 $MtCO_2$) [2]. 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 production, transmission, and distribution of renewable power systems 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 Agenda 2063 [3] should be recognised. However, there is inadequate scientific evidence on the life-cycle environmental impact (particularly CO_2 emissions) from electrical power systems in African countries, especially in sub-Saharan Africa. 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 [3]. The process of accounting for energy and emissions is identified as a life cycle assessment (LCA) [4]. The LCA can also be defined as a logical valuation of probable environmental effects and natural resource use related with a product, such as electricity, taking into reflection the whole lifespan of the product itself as well as associate inputs [5].

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, hydro, and wind power, which are intermittent, is still a better option than burning it as quickly as possible [5]. Smart energy systems consider merging electricity with various storage options [6], heating, and transport sectors to create the required tractability to integrate large diffusions of unstable renewable energy [7]. Hence, good thought of the environmental impact of power use in society must also 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 maintenances). However, environmental sustainability assessments of the grid power generation regularly fail to contain the impact of T&D systems, possibly causing improper findings [8], [9]. The effect of new T&D lines on the studied grids may be determined by the land cover, topography, and prevailing land uses [10]. For example, in forested sites, the entire right-of-way (ROW) width is cleared and remained open for the life of the transmission line [11]. Previous results also revealed that the life-cycle carbon emission (LCCE) due to vegetation cleared in the operation of electrical power transmission and distribution[10] contribute less impact on climate change than LCCE due to power generation[12].

The overall problem talked in this study is an inadequate understanding of the lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power systems. This study aimed to carry out the life cycle carbon emission analysis of electric power generation and transmission in Kenya, Rwanda, and Tanzania using the carbon emissions data developed within the LCA system boundary sate in Chapter four. The causal relationship, renewable energy systems, studies explained in the literature in the form of research questions, neutrality hypothesis, growth hypothesis, feedback hypothesis and, conservation hypothesis [17]. However, the chapter has been answered the research question “Is there lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power systems?”.

In view of 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 renewable and non-renewable electricity generation sources, and transmission practises 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 intensities. The LCA is among the most promising method for sustainability assessment of designed plans and policies of an electrical power system. This study presents the valuation of studied grids by means of the life cycle carbon emission inventory (LCCEI). The research findings are used to propose superior plans, policies, and designs of electrical power systems with higher environmental performance. The study contributes to the development of knowledge of the different environmental performance of the power systems designs and operations, and objectives anticipated by different system operators, researchers, and policymakers. The obtained assessment information could also provide a system for climate-change impact control in the studied grids.

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 and Monte Carlo simulations with RStudio for the studied grids of three sub-Saharan countries, from the base year 2019 to 2049. Section 3 provide results and discusses the obtained relationship between renewable dominated power system and environmental improvement and its policy, design and practise implications. The study concludes with the pre-defined research questions that could be used to develop the clean electrical power systems flows within the studied countries and the region as a whole.

5.3 Methods

5.3.1 Goal, scope, boundary settings, elementary flows, and data collection

The methodology overview of this study is shown in Fig. 5.1. Each life cycle sub-component process involves energy inputs and emission output. The selected base year 2019 data were used to explore the potential energy resources of the studied grids. The functional unit for this study has been defined as an electricity (1 MW) received at the distribution sub-station. The activity and emission factor data have been found from the technical and scientific sources as well as electrical energy institutions, including Tanzania Electric Supply Company (TANESCO), Rwanda Energy Group (REG), Kenya Electricity Generating Company (KENGEN), Eastern Africa Power Pool (EAPP), and Southern African Power Pool (SAPP). The data has been acquired from appropriate institutions 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.

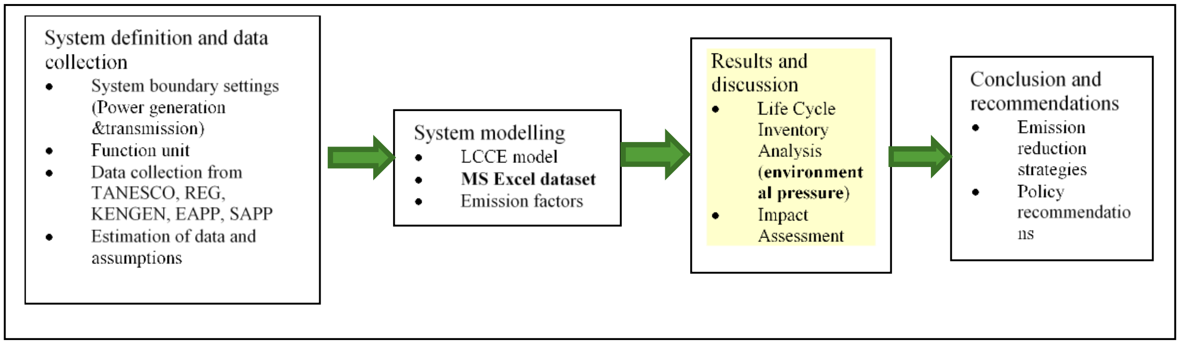


Fig.5. 1. Methodology overview for assessing the LCCE of the studied, electrical power systems, series of activities

(Modelled after [16]).

The perimeter and scope of the life cycle evaluation of the electrical power system, components, series of processes chain involved is illustrated as Figure 5.2. The cradle-to-gate analysis for this study involves the series of activities start from the extraction of raw energy materials (such as coal, biomass, gas and diesel) and then continue 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 omit 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 the power generation, power T&D, power use, re-use, recycling, and final disposal. However, the adopted mathematical model for this study has been adopted the gate-to-gate, and some grave analysis.

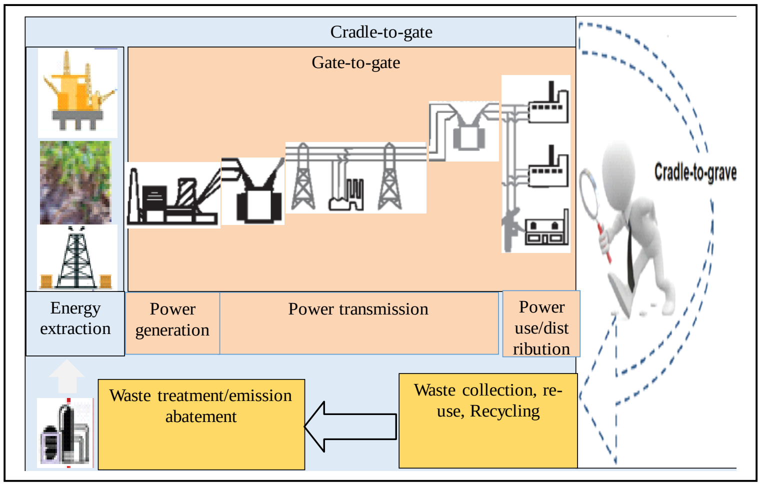


Fig.5. 2. LCA system boundary settings for the studied, electrical power systems, series of activities

(Modelled after [11], [18]).

The main phases of the LCA presented by this piece of work are indicated in, flow chart, Figure 5.3. Base 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.

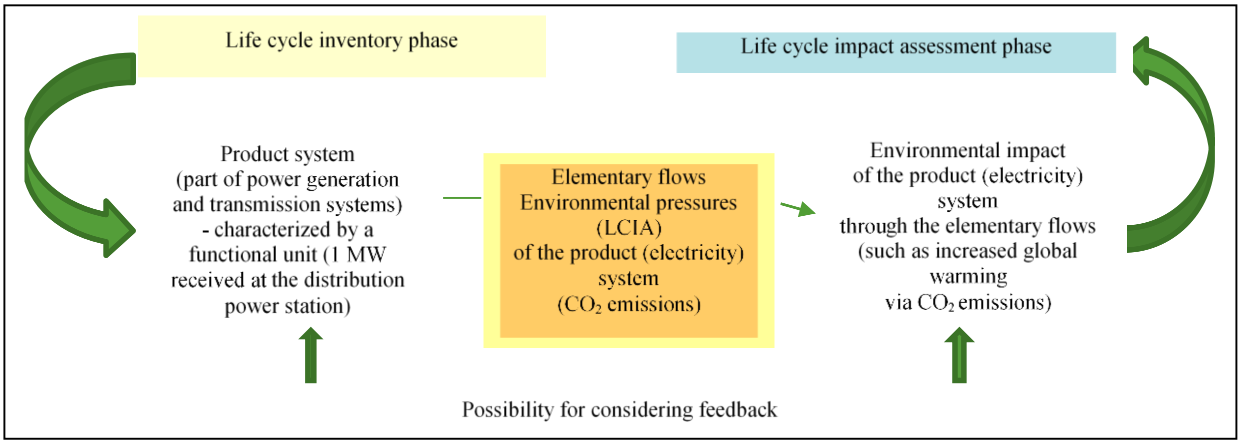


Fig.5. 3. LCCE flow of the studied series of electrical power system activities

(Modelled after [19]).

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 life cycle inventory and life cycle impact assessment phases and of this study as expressed in Figure 5.4:

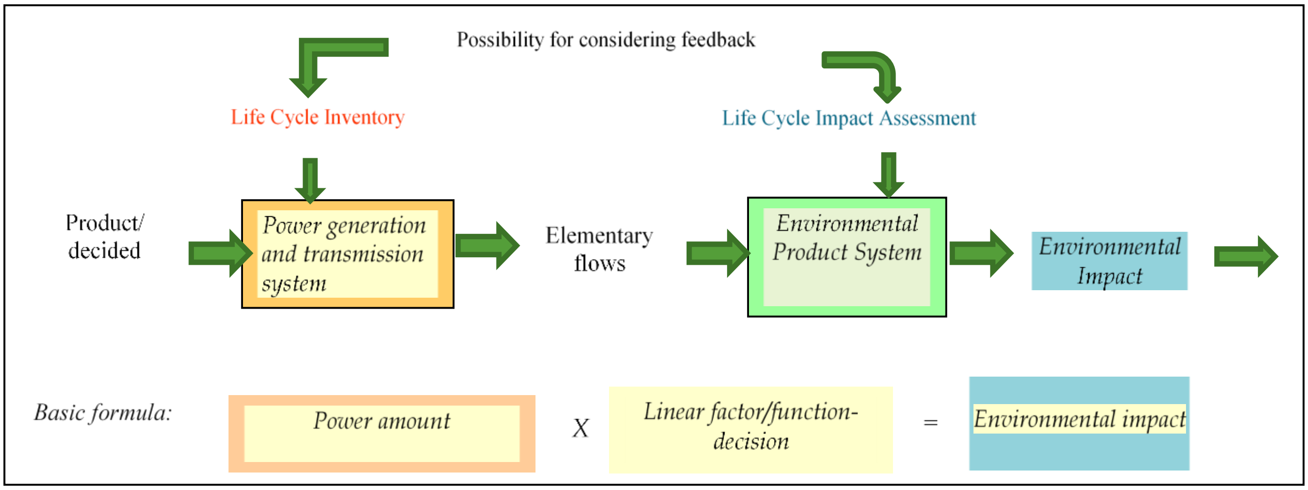


Fig.5. 4. Model representation for the LCCE evaluation adopted the study (Modelled after [19]).

The series of the gate-to-gate, and some end-users, electrical power system, activities for the studied elementary LCCE flow, have been calculated using both existing and assumed facts, and mathematical representations as explained in Chapter four of the thesis.

The (existing and new case-specific) data have been obtained within the established system boundary by means of parameters developed through a mathematical algorithm and coded in the MS Excel worksheets (presented as Appendix 6).

5.3.2 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 BAU and EG scenarios have been studied. The BAU scenario has also assumed a low amount of recycled emissions, due to the presently comfortable renewable energy policies and regulations. The BAU scenario has been 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 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 collected 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 [21]–[23]. 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 -have 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[6]. 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, so as to balance consumption and generation.

The power mixes of upcoming power generated under EG scenarios have been presumed to be controlled by renewable power sources. The EG scenario adopts the resilient operation of global, regional and national institutions to upkeep the understanding of the United Nations SDGs 15, 13, 12, and 7, and Goal 7 of the African Agenda 2063. The EG scenario in the study area reflected the peak use of geo-thermal power resources to develop electricity power systems that are resistant to the 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 seventy per cent (70%) of the grid electricity combinations, so as to ensure environmental sustainability[6]. A recycling factor regarding the residual CO_2 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.

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

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 been 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 [6], [20] were studied.

The Monte Carlo simulated histograms (showing the life-cycle carbon-emission-values) were developed using RStudio for both EG and business-as-usual (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 studied LCCE was also used to study the performance of the designed electrical power system while considering EG factors, within thirty (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 LCCEI data, the probable life-cycle carbon-emission histograms were developed using RStudio.

5.3.4. 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 environmental assessment has been considered the established strategic power capacity for the studied grids. The LCCE values have been checked for double counting and overlooking, through the adoption of the linearity and partitioning of multifunctional processes per 1MW.

5.4 Results and discussion

The presented results provide insight about the probable relationship between renewable dominated power system 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-emission, research questions, and limitations were presented and discussed against the prevailing research, policy, plans, and best practise for cleaner grid electricity systems.

5.4.1 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 5.5. 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.

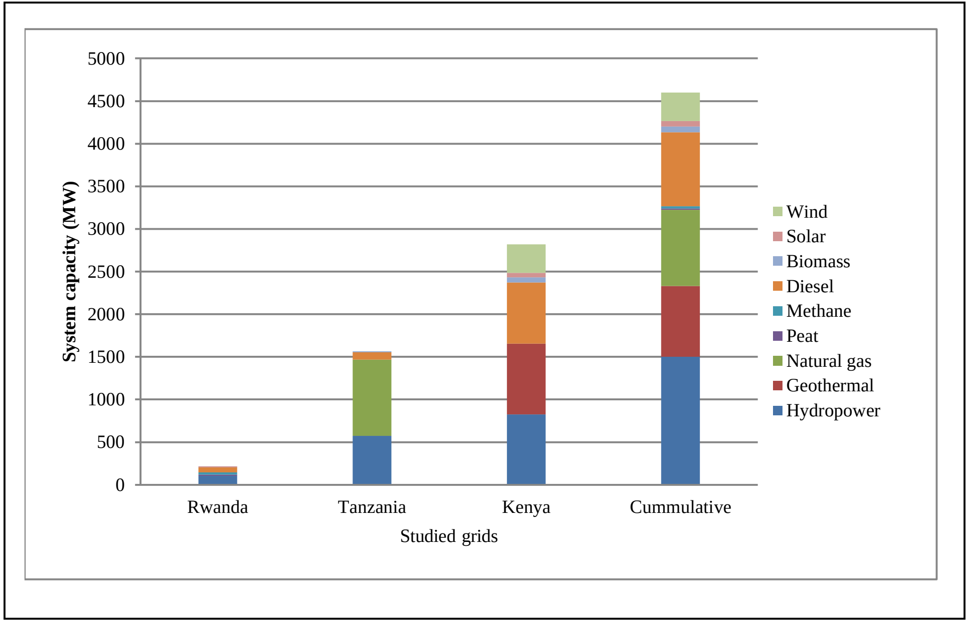


Fig.5. 5. Contribution of the different energy resources utilised to generate grid electricity for the base year 2019.

5.4.2 LCCE calculated from the studied generation and transmission systems

The life cycle grid carbon emission 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 5.6 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 were contributed by the peat power capacity (in Rwandan grid), natural gas power capacity (in Tanzanian grid), and diesel power capacity (in Kenyan grid). The obtained results also revealed other sources of power, integrated into the electrical generation mixes, contributed insignificant carbon emission in the study area.

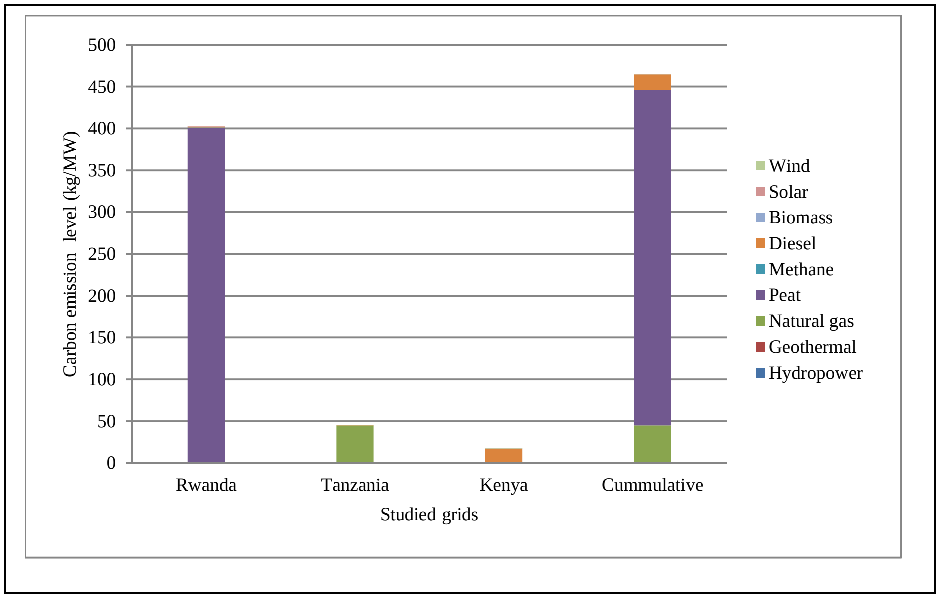


Fig.5. 6. LCCE contributions from different energy resources employed to generate grid electricity for the base year 2019.

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 as Figure 7. The LCCE contributions from the studied components and area were assessed for the base year 2019. Figure 7 shows that the Rwandan grid generated higher emission per unit of electricity, followed by the Tanzanian grid.

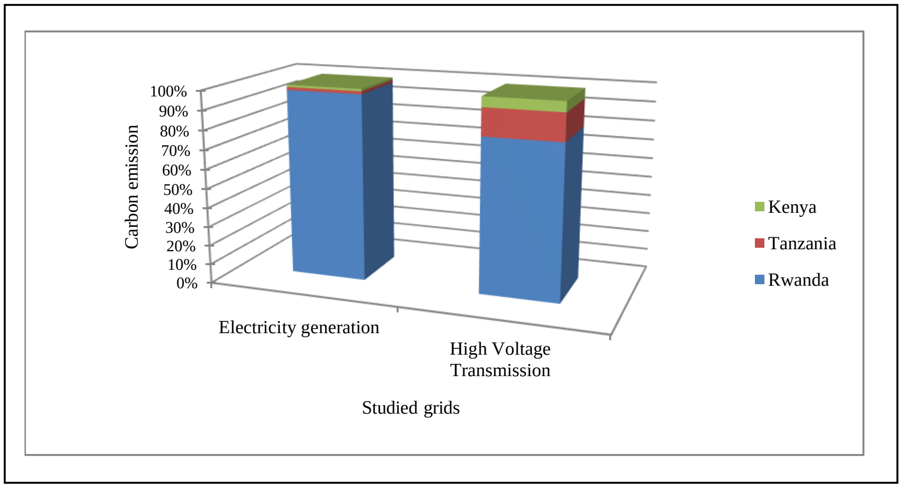


Fig.5. 7. LCCE contributions from the studied electrical power system components for the base year 2019.

The LCCE obtained from the developed MS Excel data and presented as Figure 5.8 also shows that, the baseline level of life-cycle carbon emission per unit power is much higher in the Rwandan grid than in the Tanzanian and Kenyan grids.

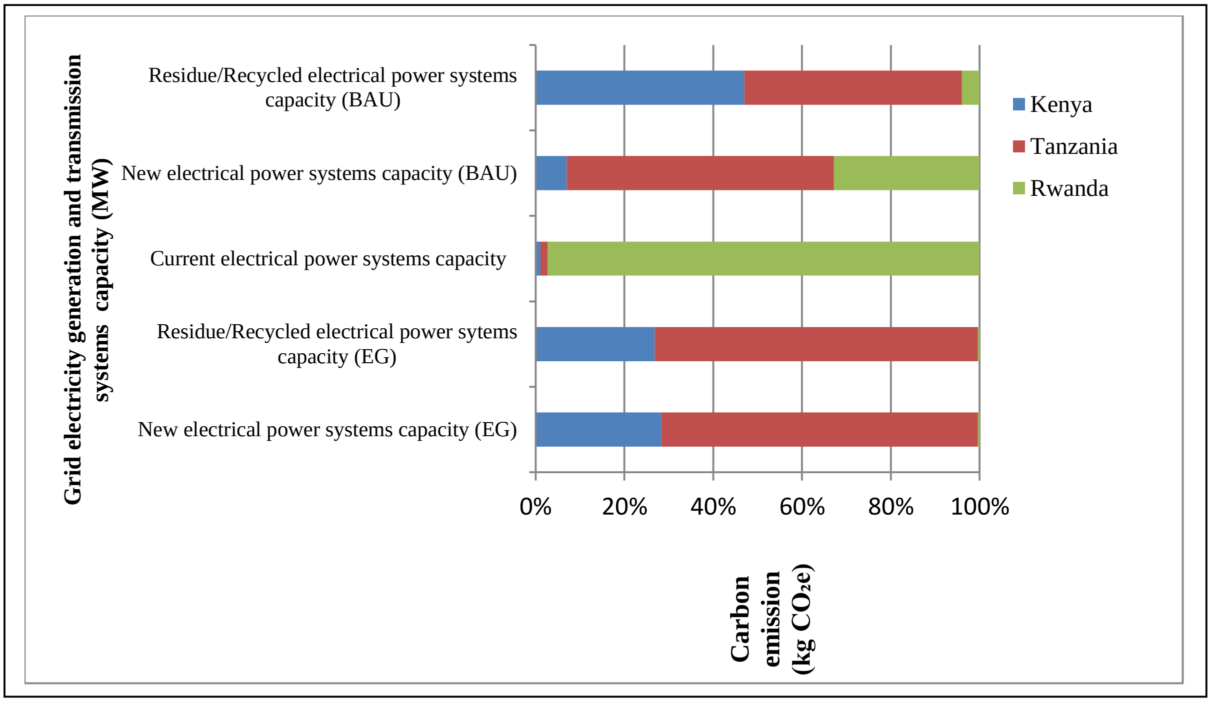


Fig.5. 8. LCCE from the electrical power system components designed and operated from the base year 2019 to 2049.

5.4.3 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 (Figure 5.9). The presented histograms do not show the probability or trend of carbon-emissions (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 (Figure 5.9), therefore, revealed the absence of the lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power systems. The results also revealed that the prevailing Rwandan BAU modelled power system is dominated with relatively high emitting source (including peat) while its EG modelled power systems can also potentially be dominated with relatively higher emitting sources compared to Kenyan and Rwandan grids.

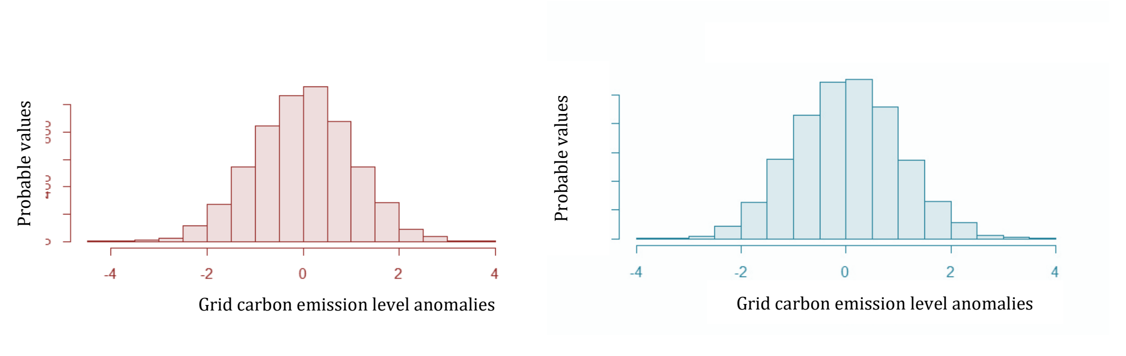


Fig.5. 9. Histogram of simulated normal LCCE data (kg CO_2e /MW) from the Rwandan grid electricity systems designed under both BAU (left side, *negatively skewed*) and EG (right side, *symmetrical distribution*) scenarios, by 2049.

The Monte Carlo simulated histograms obtained using RStudio (Figure 5.10) 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 (Figure 5.10), therefore, revealed the absence of the lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power systems. The results reveal that, the prevailing Tanzanian BAU modelled power system is dominated by relatively less emitting sources (compared to Rwandan grid) mostly natural gas, apart from the fact that its EG modelled power systems can also potential be dominated with lesser emitting sources, such as hydropower and some geothermal sources, while adopting the most efficient transmission technologies.

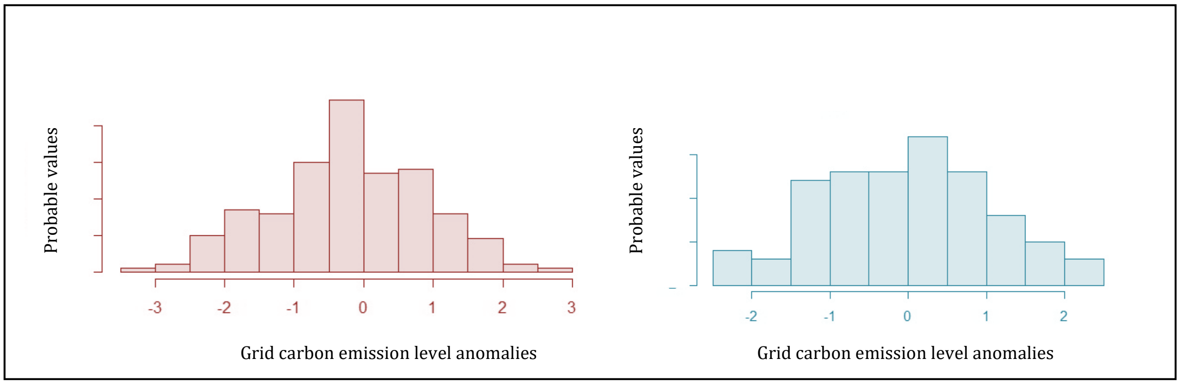


Fig.5. 10. Histogram of simulated normal LCCE data (kg CO_2e /MW) from the Tanzanian grid electricity systems designed under both BAU (left histogram, *negatively skewed*) and EG (right histogram, *symmetrical distribution*) scenarios by 2049.

The Monte Carlo simulated histogram obtained using RStudio (Figure 5.11) 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 system and non-renewable energy sources dominated power systems under among all studied grids operations. The results may also reveal the prevailing Kenyan BAU modelled power systems to be dominated by the more lesser emitting energy sources compared to others studies systems while its EG modelled power systems can also potentially be dominated with more lesser emitting geothermal power and hydropower, while adopting the most efficient transmission technologies.

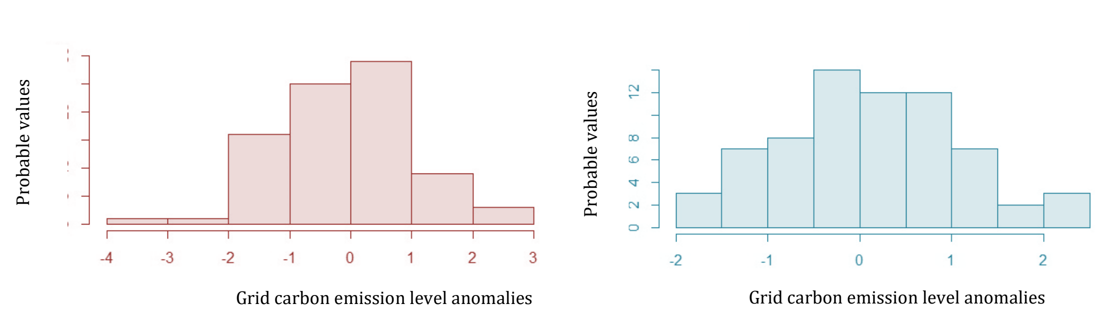


Fig.5. 11. Histogram of simulated normal LCCE data (kg CO_2e /MW) from the Kenyan grid electricity systems designed under both BAU (left histogram, *negatively skewed*) and EG (right histogram, *positively skewed*) scenarios by 2049.

5.4.4 Further life cycle impact management and monitoring implications

This study recommends the 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 policy, 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 penetration of low-emission sources such as solar, geothermal, wind, and hydropower. The study also recommends further research to comprise cumulative data and the examination of a wide range of environmental parameters assessed from cradle to grave. Further impact assessment studies are also required, to facilitate the interpretation of the environmental impact caused by the electrical power systems, in the study area.

The limitations of the field survey and the availability of the current internal data sources were revealed during the research. Most of the presented results are also 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 as reasonable a selection, estimation, and calculation of data.

5.5 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 system 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 more lesser emitting energy sources compared to others studies grids while its EG modelled power systems can also potentially be dominated with more lesser emitting geothermal power, and followed by hydropower.

Future research should 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, geo-thermal, 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 the 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 impact assessment studies were recommended, to facilitate the interpretation of the environmental impact caused by the power systems, in the study area.

References

[1] F. Blaabjerg and J. M. Guerrero, "Smart grid and renewable energy systems," in *International Conference on Electrical Machines and Systems, ICEMS*, 2011, pp. 1–10, doi: 10.1109/ICEMS.2011.6073290.

[2] International Energy Agency, "Africa Energy Outlook 2019," 2019. [Online]. Available: https://webstore.iea.org/africa-energy-outlook-2019.

[3] I. Standard, "Environmental management — Life cycle assessment — Principles and framework," Geneva, ISO 14040:2006(E), 2006. [Online]. Available: http://www.cscses.com/uploads/2016328/20160328110518251825.pdf.

[4] S. Philip, "Assessing the potential for photovoltaic technology to mitigate greenhouse gas emissions: Life cycle analysis and energy systems modelling for electricity access in rural India," Imperial College London, 2017.

[5] J. Klimstra and M. Hotakainen, *Smart Power Generation*, 4th improv. Helsinki: Avain Publishers, 2011.

[6] E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, "Modelling of environmental emission in Kenyan, Rwandan, and Tanzanian electrical power systems," *J. Clean. Prod.*, vol. 312, Aug. 2021, doi: 10.1016/J.JCLEPRO.2021.127830.

[7] B. V. Mathiesen *et al.*, "Smart Energy Systems for coherent 100% renewable energy and transport solutions," *Appl. Energy*, vol. 145, pp. 139–154, 2015, doi: 10.1016/j.apenergy.2015.01.075.

[8] A. Arvesen, I. B. Hauan, B. M. Bolsøy, and E. G. Hertwich, "Life cycle assessment of transport of electricity via different voltage levels: A case study for Nord-Trøndelag county in Norway," *Appl. Energy*, p. 20, 2015, doi: 10.1016/j.apenergy.2015.08.013.

[9] B. Atilgan and A. Azapagic, "An integrated life cycle sustainability assessment of electricity generation in Turkey," *Energy Policy*, vol. 93, pp. 168–186, 2016, doi: 10.1016/j.enpol.2016.02.055.

[10] E. Chambile, N. Ijumba, B. Mkandawire, and J. Hakizimana, "Impact of Electrical Power Systems on the Environment in Kenya, Rwanda and Tanzania," in *2018 IEEE PES/IAS*

PowerAfrica Conference, 2018, no. 18261617, pp. 885–889, doi: 10.1109/PowerAfrica.2018.8521092.

[11] M. Madrigal and R. Spalding-Fecher, “Impacts of Transmission and Distribution Projects on Greenhouse Gas Emissions,” Washington, D.C., 2010. doi: 10.1596/27755.

[12] E. Chambile, N. Ijumba, B. Mkandawire, and J. Hakizimana, “Grid Electricity Generation Systems Comparisons Using the Life Cycle Carbon Emission Inventory,” in *2020 IEEE PES/IAS PowerAfrica Conference,* 2020, pp. 1–5, doi: 10.1109/PowerAfrica49420.2020.9219876.

[13] R. Turconi, A. Boldrin, and T. Astrup, “Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations,” *Renew. Sustain. Energy Rev.*, vol. 28, pp. 555–565, 2013, doi: 10.1016/j.rser.2013.08.013.

[14] R. S. Jorge, T. R. Hawkins, and E. G. Hertwich, “Life cycle assessment of electricity transmission and distribution-part 1: Power lines and cables,” *Int. J. Life Cycle Assess.*, vol. 17, no. 1, pp. 9–15, 2012, doi: 10.1007/s11367-011-0335-1.

[15] C. Ghenai and M. Bettayeb, “Data analysis of the electricity generation mix for clean energy transition during COVID-19 lockdowns,” *Energy Sources, Part A Recover. Util. Environ. Eff.*, pp. 1–21, Feb. 2021, doi: 10.1080/15567036.2021.1884772.

[16] M. Felix and S. H. Gheewala, “Environmental assessment of electricity production in Tanzania,” *Energy Sustain. Dev.*, vol. 16, no. 4, pp. 439–447, 2012, doi: 10.1016/j.esd.2012.07.006.

[17] N. Singh, R. Nyuur, and B. Richmond, “Renewable energy development as a driver of economic growth: Evidence from multivariate panel data analysis,” *Sustain.*, vol. 11, no. 8, 2019, doi: 10.3390/su11082418.

[18] H. H. Khoo and R. B. H. Tan, “Life Cycle Assessment Methodology : Ongoing Developments and Outlook,” 2022 World Scientific Publishing Company, 2022, pp. 1–21.

[19] T. Schaubroeck, S. Schaubroeck, R. Heijungs, A. Zamagni, M. Brand, and E. Benetto, “Attributional & Consequential Life Cycle Assessment : Definitions , Conceptual Characteristics and Modelling Restrictions,” *Sustainability*, pp. 1–47, 2021, doi: https://doi.org/ 10.3390/su13137386.

[20] E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, “Data on the life cycle carbon emission in Kenyan, Rwandan, and Tanzanian grid electricity generation and transmission systems,” *Data Br. J.*, vol. 40, 2022, doi:

https://doi.org/10.1016/j.dib.2021.107692.

[21] Rwanda Energy Group, “Rwanda Least Cost Power Development Plan (LCPDP) 2019 – 2040,” Kigali, 2019. [Online]. Available: https://www.reg.rw/fileadmin/user_upload/LCPDP_REPORT_June_2019.pdf.

[22] Eastern Africa Power Pool, “Eastern Africa Power Pool Regional Master Plan Volume II: Data Report,” Addis Ababa, Ethiopia, 2014. [Online]. Available: http://www.ea-energianalyse.dk/reports/1332/1332_eapp_master_plan_2014_volume_2_data_report.pdf.

[23] United Republic of Tanzania, “Power System Master Plan 2016 Update,” Dodoma, 2016. [Online]. Available: https://www.infoafrica.it/wp-content/uploads/2017/02/Power-System-Master-Plan-PSMP-2016-Update.pdf.

CHAPTER SIX

6.0 Conclusions and Recommendations

6.1 Conclusions

The general objective of the study was to explore and contribute to an improved understanding of the environmental pressure caused by electric power systems in Kenya, Rwanda, and Tanzania with a life cycle approach. The specific objectives were to develop the environmental life cycle inventory (LCI) model of the electric power systems in the study areas; compile an inventory of relevant inputs and outputs of a product for particular electrical power systems using the developed environmental LCI model and the country-specific data, and assumptions; as well as and carry-out the life-cycle carbon emission inventory analysis of both electric power generation and transmission designs and operations of each country.

This thesis has explored and contributed to an improved understanding of the environmental impact caused by electric power generation and transmission systems in Kenya, Rwanda, and Tanzania with a life cycle approach. The life cycle carbon emissions estimate of related inputs and outputs of electricity products for particular power system components, established using the country-specific data and assumptions, has been presented in chapter three of the thesis. Chapter four of the thesis has attempted to develop the life-cycle carbon emission inventory model of the studied power systems components. The life cycle carbon emission inventory analysis of both electric power generation and transmission designs and operations undertaken for each country, is covered in chapter five of the thesis.

The thesis has answered three research questions posed in Chapter 1 as follows: (i) Limited environmental governance factors were considered during the grid electricity generation and transmission system design and operation in the selected countries, and (ii) Significant lifetime decarbonisation performance of the studied generation and transmission systems revealed in the selected countries. The obtained carbon analysis results also revealed lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power systems only in Kenyan generation and transmission systems.

The study does not cover the full life cycle assessment nor other environmental impacts such as air pollutants apart from the greenhouse gases, wildlife and loss of habitats, biodiversity loss, and land and water pollution (including hazardous wastes from transformer oils, conductors and cables) just for simplification. It is proposed that the environmental LCI model proposed by this thesis be used by operators, researchers, and policymakers as a tool for planning, estimating and assessing the environmental performance of the studied electrical grids. However, the results of this study should be interpreted as indicative rather than providing conclusive answers, as is the case with many computer models.

6.2 Recommendations

To improve the environmental sustainability of electrical power systems designs and operations, system planners and operators need to ensure that:

a) Both regional and national power generation policies and practices take into consideration the suppression of the highest emitting sources such as peat and diesel while enhancing the penetrations of the lowest emitting sources such as geothermal, hydropower, wind and solar.
b) There is an application of highly efficient technologies in power generation, transmission, distribution, and end-user (using several strategies such as trading schemes; regulatory directives; taxes and credit).
c) Future electrical power systems plans and operations take cognisance of the objectives of Goal 7 of the African Agenda for 2063 and the United Nations SDGs goals 7, 12, 13, 15.

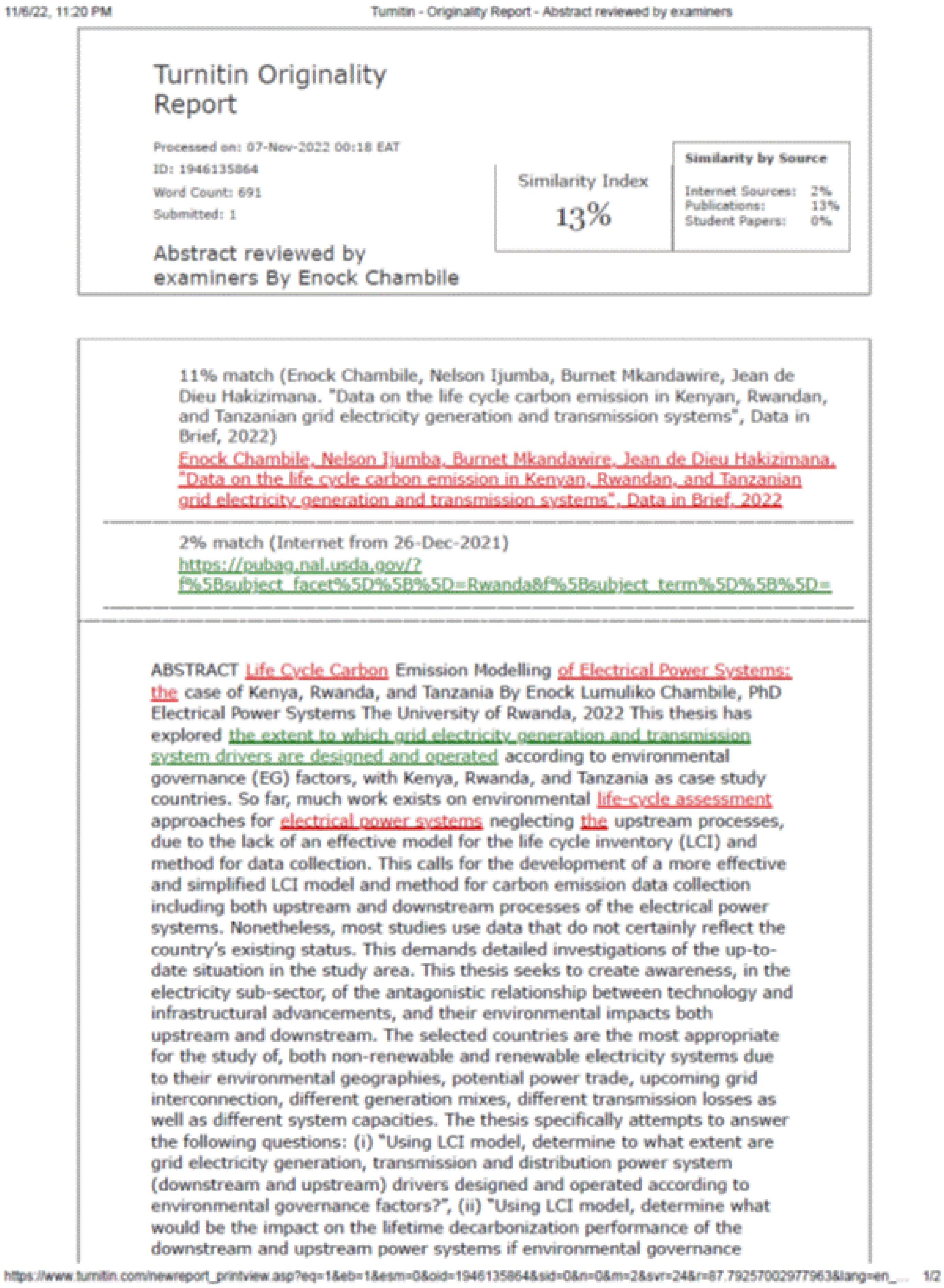
To enhance the understanding of the environmental impact of electrical power systems designs and operations, it is further recommended that:

a) A full dynamic life cycles environmental (a cradle to grave) emission investigation of the grid be carried out in the future.
b) Further impact assessment studies should be done, to facilitate the interpretation of the environmental impact caused by the electrical power systems, in a study area.

c) Additional studies be conducted to cover more countries, in all the African power pools, and a wider scope of environmental indicators (such as wildlife species abundances and diversity in both aquatic and terrestrial environment systems and non-greenhouse gases emission) be considered.
d) Further studies be made to enhance the understanding of the emission estimation equations (1&2) which have been adopted by this research to calculate carbon emissions from land clearing for the transmission and distribution systems.
e) More data verifications (particularly for High Voltage Direct Current lines are needed (such as the ongoing infrastructural development projects currently implemented onsite) prior to any further conclusive or practical action.
f) More advanced dynamic life cycle investigations (such as adoption of Stella Architect System Dynamic model) should be conducted while considering the most updated electrical power systems plans prevailing in the studied grids.

APPENDICES

Appendix 1. Turnitin originality report for an Abstract



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ABSTRACT Life Cycle Carbon Emission Modelling of Electrical Power Systems: the case of Kenya, Rwanda, and Tanzania By Enock Lumuliko Chambile, PhD Electrical Power Systems The University of Rwanda, 2022 This thesis has explored the extent to which grid electricity generation and transmission system drivers are designed and operated according to environmental governance (EG) factors, with Kenya, Rwanda, and Tanzania as case study countries. So far, much work exists on environmental life-cycle assessment approaches for electrical power systems neglecting the upstream processes, due to the lack of an effective model for the life cycle inventory (LCI) and method for data collection. This calls for the development of a more effective and simplified LCI model and method for carbon emission data collection including both upstream and downstream processes of the electrical power systems. Nonetheless, most studies use data that do not certainly reflect the country's existing status. This demands detailed investigations of the up-to-date situation in the study area. This thesis seeks to create awareness, in the electricity sub-sector, of the antagonistic relationship between technology and infrastructural advancements, and their environmental impacts both upstream and downstream. The selected countries are the most appropriate for the study of, both non-renewable and renewable electricity systems due to their environmental geographies, potential power trade, upcoming grid interconnection, different generation mixes, different transmission losses as well as different system capacities. The thesis specifically attempts to answer the following questions: (i) "Using LCI model, determine to what extent are grid electricity generation, transmission and distribution power system (downstream and upstream) drivers designed and operated according to environmental governance factors?", (ii) "Using LCI model, determine what would be the impact on the lifetime decarbonization performance of the downstream and upstream power systems if environmental governance

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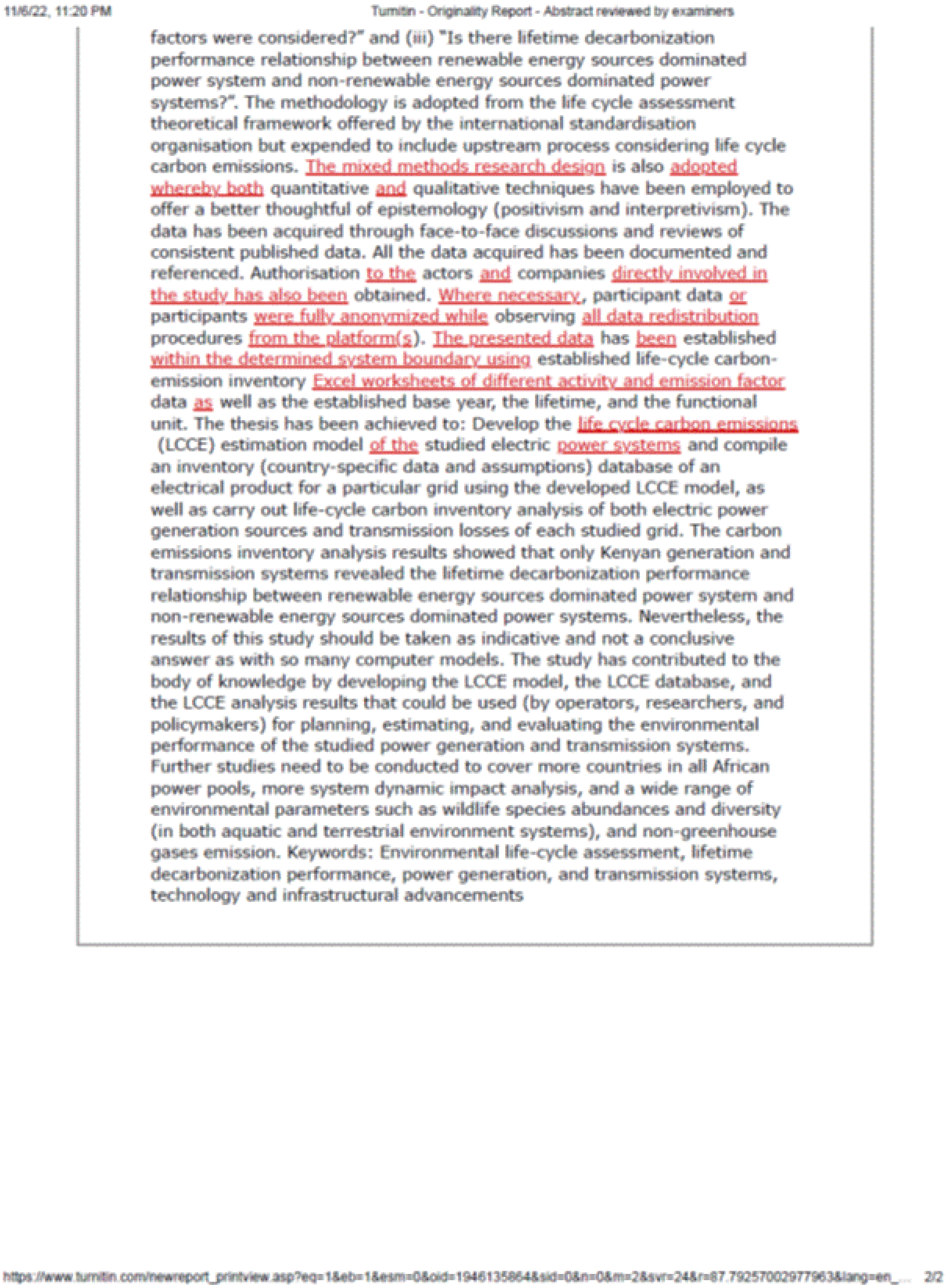
Appendix 1. Turnitin originality report for an Abstract…..continued



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factors were considered?" and (iii) "Is there lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power systems?". The methodology is adopted from the life cycle assessment theoretical framework offered by the international standardisation organisation but expended to include upstream process considering life cycle carbon emissions. The mixed methods research design is also adopted whereby both quantitative and qualitative techniques have been employed to offer a better thoughtful of epistemology (positivism and interpretivism). The data has been acquired through face-to-face discussions and reviews of consistent published data. All the data acquired has been documented and referenced. Authorisation to the actors and companies directly involved in the study has also been obtained. Where necessary, participant data or participants were fully anonymized while observing all data redistribution procedures from the platform(s). The presented data has been established within the determined system boundary using established life-cycle carbon-emission inventory Excel worksheets of different activity and emission factor data as well as the established base year, the lifetime, and the functional unit. The thesis has been achieved to: Develop the life cycle carbon emissions (LCCE) estimation model of the studied electric power systems and compile an inventory (country-specific data and assumptions) database of an electrical product for a particular grid using the developed LCCE model, as well as carry out life-cycle carbon inventory analysis of both electric power generation sources and transmission losses of each studied grid. The carbon emissions inventory analysis results showed that only Kenyan generation and transmission systems revealed the lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power systems. Nevertheless, the results of this study should be taken as indicative and not a conclusive answer as with so many computer models. The study has contributed to the body of knowledge by developing the LCCE model, the LCCE database, and the LCCE analysis results that could be used (by operators, researchers, and policymakers) for planning, estimating, and evaluating the environmental performance of the studied power generation and transmission systems. Further studies need to be conducted to cover more countries in all African power pools, more system dynamic impact analysis, and a wide range of environmental parameters such as wildlife species abundances and diversity (in both aquatic and terrestrial environment systems), and non-greenhouse gases emission. Keywords: Environmental life-cycle assessment, lifetime decarbonization performance, power generation, and transmission systems, technology and infrastructural advancements

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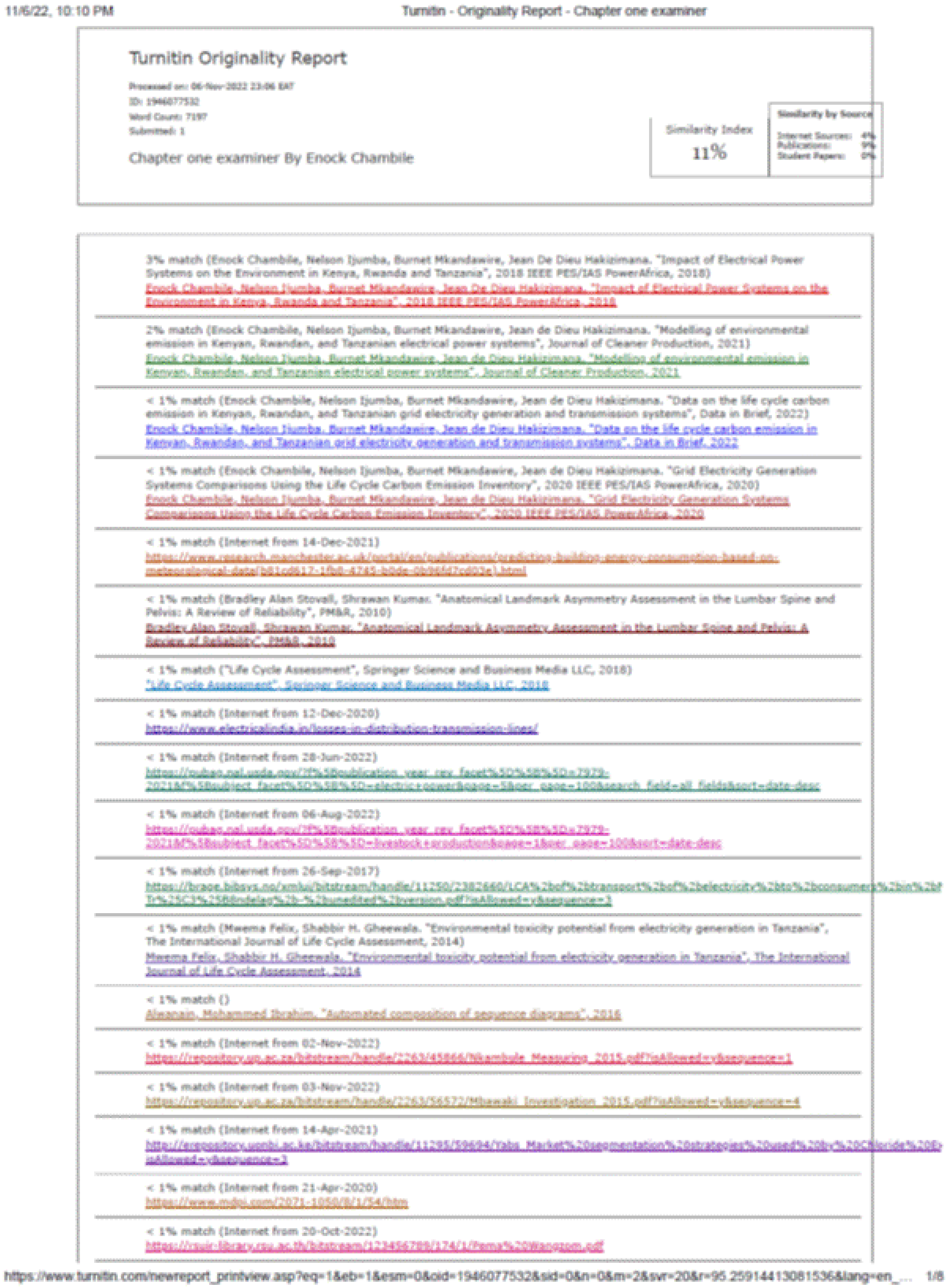
Appendix 2. Turnitin originality report for chapter one



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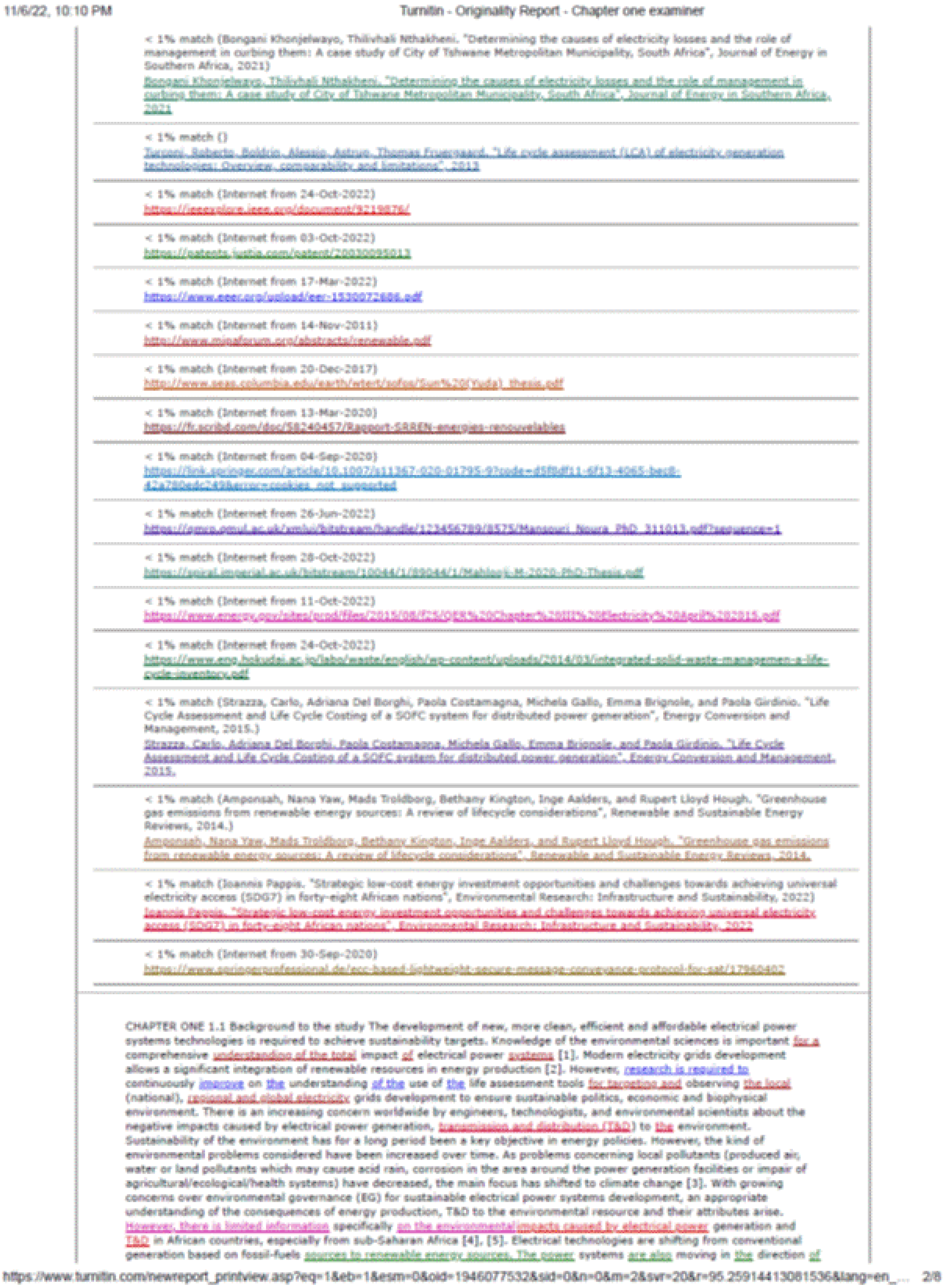

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Strazza, Carlo, Adriana Del Borghi, Paola Costamagna, Michela Gallo, Emma Brignole, and Paola Girdinio. "Life Cycle Assessment and Life Cycle Costing of a SOFC system for distributed power generation", Energy Conversion and Management, 2015.

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CHAPTER ONE 1.1 Background to the study The development of new, more clean, efficient and affordable electrical power systems technologies is required to achieve sustainability targets. Knowledge of the environmental sciences is important for a comprehensive understanding of the total impact of electrical power systems [1]. Modern electricity grids development allows a significant integration of renewable resources in energy production [2]. However, research is required to continuously improve on the understanding of the use of the life assessment tools for targeting and observing the local (national), regional and global electricity grids development to ensure sustainable politics, economic and biophysical environment. There is an increasing concern worldwide by engineers, technologists, and environmental scientists about the negative impacts caused by electrical power generation, transmission and distribution (T&D) to the environment. Sustainability of the environment has for a long period been a key objective in energy policies. However, the kind of environmental problems considered have been increased over time. As problems concerning local pollutants (produced air, water or land pollutants which may cause acid rain, corrosion in the area around the power generation facilities or impair of agricultural/ecological/health systems) have decreased, the main focus has shifted to climate change [3]. With growing concerns over environmental governance (EG) for sustainable electrical power systems development, an appropriate understanding of the consequences of energy production, T&D to the environmental resource and their attributes arise. However, there is limited information specifically on the environmental impacts caused by electrical power generation and T&D in African countries, especially from sub-Saharan Africa [4], [5]. Electrical technologies are shifting from conventional generation based on fossil-fuels sources to renewable energy sources. The power systems are also moving in the direction of

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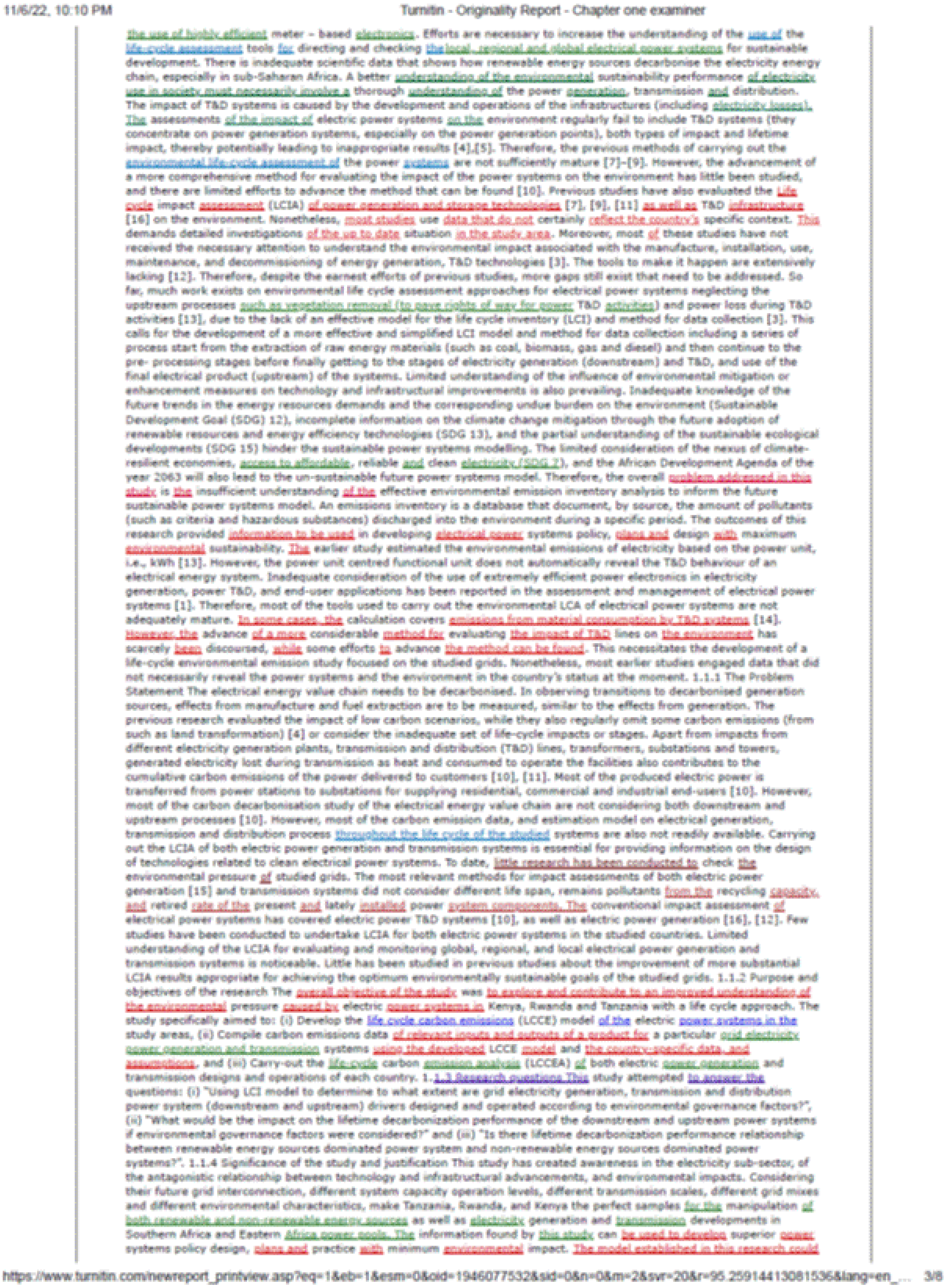

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the use of highly efficient meter – based electronics. Efforts are necessary to increase the understanding of the use of the life-cycle assessment tools for directing and checking the local, regional and global electrical power systems for sustainable development. There is inadequate scientific data that shows how renewable energy sources decarbonise the electricity energy chain, especially in sub-Saharan Africa. A better understanding of the environmental sustainability performance of electricity use in society must necessarily involve a thorough understanding of the power generation, transmission and distribution. The impact of T&D systems is caused by the development and operations of the infrastructures (including electricity losses). The assessments of the impact of electric power systems on the environment regularly fail to include T&D systems (they concentrate on power generation systems, especially on the power generation points), both types of impact and lifetime impact, thereby potentially leading to inappropriate results [4],[5]. Therefore, the previous methods of carrying out the environmental life-cycle assessment of the power systems are not sufficiently mature [7]–[9]. However, the advancement of a more comprehensive method for evaluating the impact of the power systems on the environment has little been studied, and there are limited efforts to advance the method that can be found [10]. Previous studies have also evaluated the Life cycle impact assessment (LCIA) of power generation and storage technologies [7], [9], [11] as well as T&D infrastructure [16] on the environment. Nonetheless, most studies use data that do not certainly reflect the country's specific context. This demands detailed investigations of the up to date situation in the study area. Moreover, most of these studies have not received the necessary attention to understand the environmental impact associated with the manufacture, installation, use, maintenance, and decommissioning of energy generation, T&D technologies [3]. The tools to make it happen are extensively lacking [12]. Therefore, despite the earnest efforts of previous studies, more gaps still exist that need to be addressed. So far, much work exists on environmental life cycle assessment approaches for electrical power systems neglecting the upstream processes such as vegetation removal (to pave rights of way for power T&D activities) and power loss during T&D activities [13], due to the lack of an effective model for the life cycle inventory (LCI) and method for data collection [3]. This calls for the development of a more effective and simplified LCI model and method for data collection including a series of process start from the extraction of raw energy materials (such as coal, biomass, gas and diesel) and then continue to the pre- processing stages before finally getting to the stages of electricity generation (downstream) and T&D, and use of the final electrical product (upstream) of the systems. Limited understanding of the influence of environmental mitigation or enhancement measures on technology and infrastructural improvements is also prevailing. Inadequate knowledge of the future trends in the energy resources demands and the corresponding undue burden on the environment (Sustainable Development Goal (SDG) 12), incomplete information on the climate change mitigation through the future adoption of renewable resources and energy efficiency technologies (SDG 13), and the partial understanding of the sustainable ecological developments (SDG 15) hinder the sustainable power systems modelling. The limited consideration of the nexus of climate-resilient economies, access to affordable, reliable and clean electricity (SDG 7), and the African Development Agenda of the year 2063 will also lead to the un-sustainable future power systems model. Therefore, the overall problem addressed in this study is the insufficient understanding of the effective environmental emission inventory analysis to inform the future sustainable power systems model. An emissions inventory is a database that document, by source, the amount of pollutants (such as criteria and hazardous substances) discharged into the environment during a specific period. The outcomes of this research provided information to be used in developing electrical power systems policy, plans and design with maximum environmental sustainability. The earlier study estimated the environmental emissions of electricity based on the power unit, i.e., kWh [13]. However, the power unit centred functional unit does not automatically reveal the T&D behaviour of an electrical energy system. Inadequate consideration of the use of extremely efficient power electronics in electricity generation, power T&D, and end-user applications has been reported in the assessment and management of electrical power systems [1]. Therefore, most of the tools used to carry out the environmental LCA of electrical power systems are not adequately mature. In some cases, the calculation covers emissions from material consumption by T&D systems [14]. However, the advance of a more considerable method for evaluating the impact of T&D lines on the environment has scarcely been discoursed, while some efforts to advance the method can be found. This necessitates the development of a life-cycle environmental emission study focused on the studied grids. 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. 1.1.1 The Problem Statement The electrical energy value chain needs to be decarbonised. In observing transitions to decarbonised generation sources, effects from manufacture and fuel extraction are to be measured, similar to the effects from generation. The previous research evaluated the impact of low carbon scenarios, while they also regularly omit some carbon emissions (from such as land transformation) [4] or consider the inadequate set of life-cycle impacts or stages. Apart from impacts from different electricity generation plants, transmission and distribution (T&D) lines, transformers, substations and towers, generated electricity lost during transmission as heat and consumed to operate the facilities also contributes to the cumulative carbon emissions of the power delivered to customers [10], [11]. Most of the produced electric power is transferred from power stations to substations for supplying residential, commercial and industrial end-users [10]. However, most of the carbon decarbonisation study of the electrical energy value chain are not considering both downstream and upstream processes [10]. However, most of the carbon emission data, and estimation model on electrical generation, transmission and distribution process throughout the life cycle of the studied systems are also not readily available. Carrying out the LCIA of both electric power generation and transmission systems is essential for providing information on the design of technologies related to clean electrical power systems. To date, little research has been conducted to check the environmental pressure of studied grids. The most relevant methods for impact assessments of both electric power generation [15] and transmission systems did not consider different life span, remains pollutants from the recycling capacity, and retired rate of the present and lately installed power system components. The conventional impact assessment of electrical power systems has covered electric power T&D systems [10], as well as electric power generation [16], [12]. Few studies have been conducted to undertake LCIA for both electric power systems in the studied countries. Limited understanding of the LCIA for evaluating and monitoring global, regional, and local electrical power generation and transmission systems is noticeable. Little has been studied in previous studies about the improvement of more substantial LCIA results appropriate for achieving the optimum environmentally sustainable goals of the studied grids. 1.1.2 Purpose and objectives of the research The overall objective of the study was to explore and contribute to an improved understanding of the environmental pressure caused by electric power systems in Kenya, Rwanda and Tanzania with a life cycle approach. The study specifically aimed to: (i) Develop the life cycle carbon emissions (LCCE) model of the electric power systems in the study areas, (ii) Compile carbon emissions data of relevant inputs and outputs of a product for a particular grid electricity power generation and transmission systems using the developed LCCE model and the country-specific data, and assumptions, and (iii) Carry-out the life-cycle carbon emission analysis (LCCEA) of both electric power generation and transmission designs and operations of each country. 1. 1.3 Research questions This study attempted to answer the questions: (i) "Using LCI model to determine to what extent are grid electricity generation, transmission and distribution power system (downstream and upstream) drivers designed and operated according to environmental governance factors?", (ii) "What would be the impact on the lifetime decarbonization performance of the downstream and upstream power systems if environmental governance factors were considered?" and (iii) "Is there lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power systems?". 1.1.4 Significance of the study and justification This study has created awareness in the electricity sub-sector, of the antagonistic relationship between technology and infrastructural advancements, and environmental impacts. Considering their future grid interconnection, different system capacity operation levels, different transmission scales, different grid mixes and different environmental characteristics, make Tanzania, Rwanda, and Kenya the perfect samples for the manipulation of both renewable and non-renewable energy sources as well as electricity generation and transmission developments in Southern Africa and Eastern Africa power pools. The information found by this study can be used to develop superior power systems policy design, plans and practice with minimum environmental impact. The model established in this research could

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Appendix 2. Turnitin originality report for chapter one …continued

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be used to develop efficient environmentally sustainable electrical power systems. The developed model could also be a reference and example for similar researches. The thesis could also supply data and theory references for environmental impact control in the studied grids. 1.1.4 Research framework overview The potential environments to be affected by electrical power systems include but are not limited to air, water, soil and natural resources. The environmental impacts of different electrical generation mix scenarios and transmission have been studied. The environmental considerations can manipulate infrastructural design and technologies, and hence influence the electrical power systems performance. Therefore, the environmental considerations (across the electrical power systems components) have been evaluated. The overview of the conceptual framework is indicated in Figure 1.1. Independent Variable Dependent Variable ? Use of resources (such as biotic, land, water, ore, ground) ? ? ? Emission to Water Emission to Air Emission to Soil Generation designs and operations (such as gas turbine, steam turbine, photovoltaic, water turbine and wind turbine) Transmission infrastructural designs Environmental consideration and operations (such as power stations, overhead, oversea or (including the Integration of underground transmission lines and different transmission tower Distribution infrastructural designs and operations (such as power stations, overhead or underground distribution lines and different distribution tower configurations) Performance designs and operations (measurements) of Generation, Transmission and Distribution Fig.1. 1. Framework overview Source: Authors' analysis A summary of the techniques and modes of measurement to attain the set objectives are presented in Table 1.1. Table 1.1. Technique and mode of the study to attain the objectives Serial number Objective Research questions/ postulations Mode of verification Method of Analysis i Develop the LCCE model of the electric power systems in the study area (i) "Using LCI model to determine to what extent are grid electricity generation, transmission and distribution power system (downstream and upstream) drivers designed and operated according to environmental governance factors?", (ii) "What would be the impact on the lifetime decarbonization performance of the downstream and upstream power systems if environmental governance factors were considered?" Preliminary questionnaire designed to validate the general inventory approach to ensure developed research data is against any potential bias; Two set of variables were considered (dependent and independent variables); Electricity generated, transmitted and distributed(MW) and Carbon emission (kg), assumptions developed based on the pre-defined elementary flows, intermediate flows and reference flows, Function unit, Scenarios and systems boundaries - Developed instrument/ model to guide the consequent data collection -Spreadsheet format used to allow the user to examine in detail, the data and assumptions employed -MS Excel calculation -Monte Carlo simulation using simple Excel - Developed graphs/plots/ curves ii Compile carbon emissions data of relevant inputs and outputs of electric product for a particular grid electricity, power generation, and transmission systems using the developed LCCE model, country-specific assumptions and data -not applicable -Country specific activity data (generation activities, transmission losses, emission factors) and assumptions developed based on the pre-defined elementary flows, intermediate flows and reference flows - Developed spreadsheet format life cycle carbon emission inventory (LCCEI) prototype iii Carry out the LCCEA of both electric power generation and transmission design and operations of each country. "Is there lifetime decarbonization performance relationship between renewable energy sources dominated power system and non- renewable energy sources dominated power systems?" LCCEI verified results two set of variables were considered (dependent and independent variables) Electricity generated, transmitted and distributed (MW), power loss and carbon emission (kg) Scenarios and systems boundaries - Developed LCCEI dataset -Monte Carlo simulation using R studio - Developed graphs/ curves/plots 1.1.5 Research philosophy The ontology of this study attempted to develop the science of the impact on the lifetime decarbonisation performance of the electrical power system systems if environmental governance factors are considered in both grid electricity generation and transmission systems drivers designed and operated, impact on the lifetime decarbonization performance of the downstream and upstream power systems if environmental governance factors were considered, and the lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power system. Appropriate methodologies have been addressed, with the hope of conveying to the fore ontological dialogues required to foster epistemic discourse for the lifetime environmental performance of the generation and transmission systems of the studied countries and Africa as a whole. Therefore, positivism (including case studies, surveys, and forecasting) and interpretivism (including descriptive, case studies, review, argumentative, and future research) epistemology were adopted. A mixture of quantitative and qualitative methods was also employed. 1.2 Some related work Environment impacts along all life-cycle of power systems occur in different intensities and ways [2]. The practice related to the power generation, T&D of electricity cause climate change, resource depletion, acidification, land transformation, eutrophication, and impair water quality /quantity [3], [4]. The power generation involved the use of scarce energy resources and increasing demand of scarce environmental resources. Electricity generation can also involve an emission (especially when fossil fuel is burnt) that directly or indirectly leads to a number of adverse local and global impacts. Deprived air quality resulting from fossil fuel emissions affect public health and socio-economic status at the local level. Fossil fuel use also contributes significantly to global warming caused by its greenhouse gases (GHGs) emissions. "The Earth's atmosphere accumulates solar heat due to GHG concentrations and raises the temperature" [5]. The previous research shows that direct emissions from the electricity generated from fossil fuels represent about 83–99% of the total GHG emissions, while infrastructure accounts for minor emissions. However, the infrastructures represent about 97–99% of the total emissions for wind, Solar PV and hydropower systems [6]. The life cycle assessment is, therefore, recommended to be conducted to prevent or control global warming [7]. However, GHG emissions might not be applied as the only sign to characterize the sustainability performance of a system [6]. The generation of electricity causes thermal pollution into water bodies as well as many other types of pollution. For example, water gets heated to above the natural temperature, which affects plant and animal organisms. Other types of pollution may include hazardous waste such as oil, conductors and cables insulators to soil and water from land/sea cables oil-impregnated paper, mineral oil to the soil and water due to leakages of consumed diesel oil in the process of excavation and transport and power generation [8], [9]; residual biomass and nuclear waste [6]. Generation, transmission and distribution systems affect land use in ways such as pollution of flora and fauna by fuel consumption waste; reduction of usable land by the installation of electric transmission and distribution infrastructures (e.g. pylons, poles and conductors and insulators). For example, impoverishment of the vegetation along the entire right-of-way (ROW) width cleared for the lifetime of the transmission project(s). The long term experience to low- frequency electromagnetic fields may also distress individuals and the health of crops in the immediate proximity of transmission lines [14]. High voltage transmission lines also generate radio interference (RI) noise due to corona effects and electro-magnetic fields. Superconductor high voltage (SCHV) technologies such as underground superconducting cables are potential alternatives to standard high-voltage (HV) transmission and might also impair environmental sustainability[15], particularly in terms of electromagnetic fields and visibility [13]. The local and global environmental costs that take place mainly peripheral to the power sector, are more challenging to account for, and thus have been excluded in the developing model. However, in the 21st century, all power system policy and planning with an environmental concern are obtain subsidies [14]. Electricity supply companies strive to manage the environment of the communities in which they operate. The companies spend billions of dollars each year on best practices, operational measures, and technologies, to protect the environment and human health. They are constantly examining new and advanced ways to generate electricity and to use it wisely while also managing the environment. Renewable electricity sources such as geothermal, solar power, wind, and biomass have been reported to produce maximum environmental sustainability and generally have also low or no fuel costs [15]. Reducing environmental emissions, which are harmful to the environment, by the electric power sector, requires infrastructure investments and changes in the operations of power systems as well as mitigation technologies employed [16]. Effects on the ecology are uncertain, due to its sensitivity to the design of specific infrastructure and geographical location. Electricity networks infrastructure development has environmental effects spread across a wider area due to the linear nature of electricity lines [17]. Rivals of the innovative transmission projects have also named the resultant towers visual pollutants, as intrusive or unsightly. The adoption of the high-voltage underground lines, superconducting cables, and higher-capacity-conducting materials may cause some impact on sighting, taking into account the present

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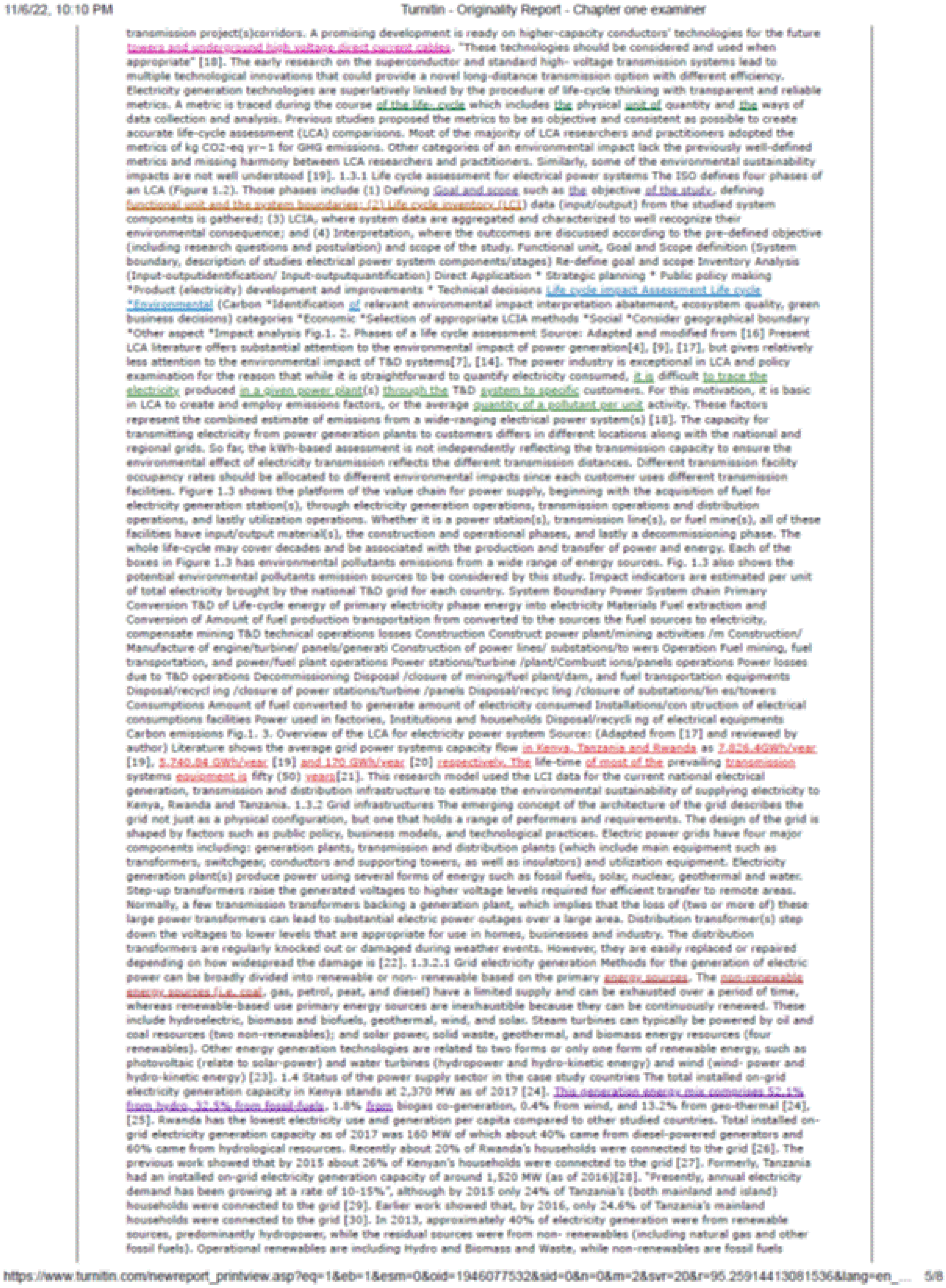

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transmission project(s)corridors. A promising development is ready on higher-capacity conductors' technologies for the future towers and underground high voltage direct current cables. "These technologies should be considered and used when appropriate" [18]. The early research on the superconductor and standard high- voltage transmission systems lead to multiple technological innovations that could provide a novel long-distance transmission option with different efficiency. Electricity generation technologies are superlatively linked by the procedure of life-cycle thinking with transparent and reliable metrics. A metric is traced during the course of the life- cycle which includes the physical unit of quantity and the ways of data collection and analysis. Previous studies proposed the metrics to be as objective and consistent as possible to create accurate life-cycle assessment (LCA) comparisons. Most of the majority of LCA researchers and practitioners adopted the metrics of kg CO2-eq yr−1 for GHG emissions. Other categories of an environmental impact lack the previously well-defined metrics and missing harmony between LCA researchers and practitioners. Similarly, some of the environmental sustainability impacts are not well understood [19]. 1.3.1 Life cycle assessment for electrical power systems The ISO defines four phases of an LCA (Figure 1.2). Those phases include (1) Defining Goal and scope such as the objective of the study, defining functional unit and the system boundaries; (2) Life cycle inventory (LCI) data (input/output) from the studied system components is gathered; (3) LCIA, where system data are aggregated and characterized to well recognize their environmental consequence; and (4) Interpretation, where the outcomes are discussed according to the pre-defined objective (including research questions and postulation) and scope of the study. Functional unit, Goal and Scope definition (System boundary, description of studies electrical power system components/stages) Re-define goal and scope Inventory Analysis (Input-outputidentification/ Input-outputquantification) Direct Application * Strategic planning * Public policy making *Product (electricity) development and improvements * Technical decisions Life cycle impact Assessment Life cycle *Environmental (Carbon *Identification of relevant environmental impact interpretation abatement, ecosystem quality, green business decisions) categories *Economic *Selection of appropriate LCIA methods *Social *Consider geographical boundary *Other aspect *Impact analysis Fig.1. 2. Phases of a life cycle assessment Source: Adapted and modified from [16] Present LCA literature offers substantial attention to the environmental impact of power generation[4], [9], [17], but gives relatively less attention to the environmental impact of T&D systems[7], [14]. The power industry is exceptional in LCA and policy examination for the reason that while it is straightforward to quantify electricity consumed, it is difficult to trace the electricity produced in a given power plant(s) through the T&D system to specific customers. For this motivation, it is basic in LCA to create and employ emissions factors, or the average quantity of a pollutant per unit activity. These factors represent the combined estimate of emissions from a wide-ranging electrical power system(s) [18]. The capacity for transmitting electricity from power generation plants to customers differs in different locations along with the national and regional grids. So far, the kWh-based assessment is not independently reflecting the transmission capacity to ensure the environmental effect of electricity transmission reflects the different transmission distances. Different transmission facility occupancy rates should be allocated to different environmental impacts since each customer uses different transmission facilities. Figure 1.3 shows the platform of the value chain for power supply, beginning with the acquisition of fuel for electricity generation station(s), through electricity generation operations, transmission operations and distribution operations, and lastly utilization operations. Whether it is a power station(s), transmission line(s), or fuel mine(s), all of these facilities have input/output material(s), the construction and operational phases, and lastly a decommissioning phase. The whole life-cycle may cover decades and be associated with the production and transfer of power and energy. Each of the boxes in Figure 1.3 has environmental pollutants emissions from a wide range of energy sources. Fig. 1.3 also shows the potential environmental pollutants emission sources to be considered by this study. Impact indicators are estimated per unit of total electricity brought by the national T&D grid for each country. System Boundary Power System chain Primary Conversion T&D of Life-cycle energy of primary electricity phase energy into electricity Materials Fuel extraction and Conversion of Amount of fuel production transportation from converted to the sources the fuel sources to electricity, compensate mining T&D technical operations losses Construction Construct power plant/mining activities /m Construction/ Manufacture of engine/turbine/ panels/generati Construction of power lines/ substations/to wers Operation Fuel mining, fuel transportation, and power/fuel plant operations Power stations/turbine /plant/Combust ions/panels operations Power losses due to T&D operations Decommissioning Disposal /closure of mining/fuel plant/dam, and fuel transportation equipments Disposal/recycl ing /closure of power stations/turbine /panels Disposal/recyc ling /closure of substations/lin es/towers Consumptions Amount of fuel converted to generate amount of electricity consumed Installations/con struction of electrical consumptions facilities Power used in factories, Institutions and households Disposal/recycli ng of electrical equipments Carbon emissions Fig.1. 3. Overview of the LCA for electricity power system Source: (Adapted from [17] and reviewed by author) Literature shows the average grid power systems capacity flow in Kenya, Tanzania and Rwanda as 7,826.4GWh/year [19], 5,740.84 GWh/year [19] and 170 GWh/year [20] respectively. The life-time of most of the prevailing transmission systems equipment is fifty (50) years[21]. This research model used the LCI data for the current national electrical generation, transmission and distribution infrastructure to estimate the environmental sustainability of supplying electricity to Kenya, Rwanda and Tanzania. 1.3.2 Grid infrastructures The emerging concept of the architecture of the grid describes the grid not just as a physical configuration, but one that holds a range of performers and requirements. The design of the grid is shaped by factors such as public policy, business models, and technological practices. Electric power grids have four major components including: generation plants, transmission and distribution plants (which include main equipment such as transformers, switchgear, conductors and supporting towers, as well as insulators) and utilization equipment. Electricity generation plant(s) produce power using several forms of energy such as fossil fuels, solar, nuclear, geothermal and water. Step-up transformers raise the generated voltages to higher voltage levels required for efficient transfer to remote areas. Normally, a few transmission transformers backing a generation plant, which implies that the loss of (two or more of) these large power transformers can lead to substantial electric power outages over a large area. Distribution transformer(s) step down the voltages to lower levels that are appropriate for use in homes, businesses and industry. The distribution transformers are regularly knocked out or damaged during weather events. However, they are easily replaced or repaired depending on how widespread the damage is [22]. 1.3.2.1 Grid electricity generation Methods for the generation of electric power can be broadly divided into renewable or non- renewable based on the primary energy sources. The non-renewable energy sources (i.e. coal, gas, petrol, peat, and diesel) have a limited supply and can be exhausted over a period of time, whereas renewable-based use primary energy sources are inexhaustible because they can be continuously renewed. These include hydroelectric, biomass and biofuels, geothermal, wind, and solar. Steam turbines can typically be powered by oil and coal resources (two non-renewables); and solar power, solid waste, geothermal, and biomass energy resources (four renewables). Other energy generation technologies are related to two forms or only one form of renewable energy, such as photovoltaic (relate to solar-power) and water turbines (hydropower and hydro-kinetic energy) and wind (wind- power and hydro-kinetic energy) [23]. 1.4 Status of the power supply sector in the case study countries The total installed on-grid electricity generation capacity in Kenya stands at 2,370 MW as of 2017 [24]. This generation energy mix comprises 52.1% from hydro, 32.5% from fossil-fuels, 1.8% from biogas co-generation, 0.4% from wind, and 13.2% from geo-thermal [24], [25]. Rwanda has the lowest electricity use and generation per capita compared to other studied countries. Total installed on-grid electricity generation capacity as of 2017 was 160 MW of which about 40% came from diesel-powered generators and 60% came from hydrological resources. Recently about 20% of Rwanda's households were connected to the grid [26]. The previous work showed that by 2015 about 26% of Kenyan's households were connected to the grid [27]. Formerly, Tanzania had an installed on-grid electricity generation capacity of around 1,520 MW (as of 2016)[28]. "Presently, annual electricity demand has been growing at a rate of 10-15%", although by 2015 only 24% of Tanzania's (both mainland and island) households were connected to the grid [29]. Earlier work showed that, by 2016, only 24.6% of Tanzania's mainland households were connected to the grid [30]. In 2013, approximately 40% of electricity generation were from renewable sources, predominantly hydropower, while the residual sources were from non- renewables (including natural gas and other fossil fuels). Operational renewables are including Hydro and Biomass and Waste, while non-renewables are fossil fuels

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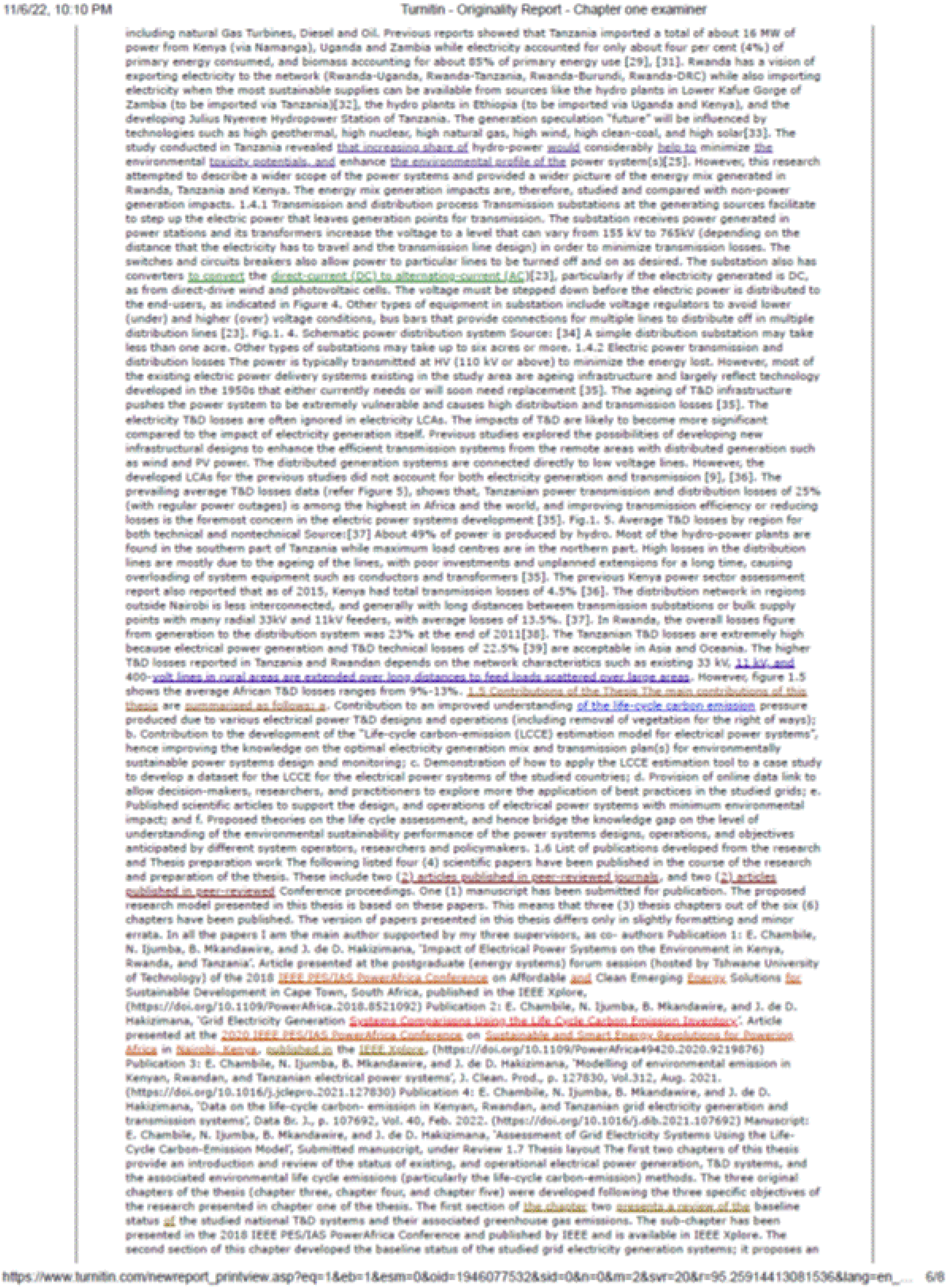

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including natural Gas Turbines, Diesel and Oil. Previous reports showed that Tanzania imported a total of about 16 MW of power from Kenya (via Namanga), Uganda and Zambia while electricity accounted for only about four per cent (4%) of primary energy consumed, and biomass accounting for about 85% of primary energy use [29], [31]. Rwanda has a vision of exporting electricity to the network (Rwanda-Uganda, Rwanda-Tanzania, Rwanda-Burundi, Rwanda-DRC) while also importing electricity when the most sustainable supplies can be available from sources like the hydro plants in Lower Kafue Gorge of Zambia (to be imported via Tanzania)[32], the hydro plants in Ethiopia (to be imported via Uganda and Kenya), and the developing Julius Nyerere Hydropower Station of Tanzania. The generation speculation "future" will be influenced by technologies such as high geothermal, high nuclear, high natural gas, high wind, high clean-coal, and high solar[33]. The study conducted in Tanzania revealed that increasing share of hydro-power would considerably help to minimize the environmental toxicity potentials, and enhance the environmental profile of the power system(s)[25]. However, this research attempted to describe a wider scope of the power systems and provided a wider picture of the energy mix generated in Rwanda, Tanzania and Kenya. The energy mix generation impacts are, therefore, studied and compared with non-power generation impacts. 1.4.1 Transmission and distribution process Transmission substations at the generating sources facilitate to step up the electric power that leaves generation points for transmission. The substation receives power generated in power stations and its transformers increase the voltage to a level that can vary from 155 kV to 765kV (depending on the distance that the electricity has to travel and the transmission line design) in order to minimize transmission losses. The switches and circuits breakers also allow power to particular lines to be turned off and on as desired. The substation also has converters to convert the direct-current (DC) to alternating-current (AC)[23], particularly if the electricity generated is DC, as from direct-drive wind and photovoltaic cells. The voltage must be stepped down before the electric power is distributed to the end-users, as indicated in Figure 4. Other types of equipment in substation include voltage regulators to avoid lower (under) and higher (over) voltage conditions, bus bars that provide connections for multiple lines to distribute off in multiple distribution lines [23]. Fig.1. 4. Schematic power distribution system Source: [34] A simple distribution substation may take less than one acre. Other types of substations may take up to six acres or more. 1.4.2 Electric power transmission and distribution losses The power is typically transmitted at HV (110 kV or above) to minimize the energy lost. However, most of the existing electric power delivery systems existing in the study area are ageing infrastructure and largely reflect technology developed in the 1950s that either currently needs or will soon need replacement [35]. The ageing of T&D infrastructure pushes the power system to be extremely vulnerable and causes high distribution and transmission losses [35]. The electricity T&D losses are often ignored in electricity LCAs. The impacts of T&D are likely to become more significant compared to the impact of electricity generation itself. Previous studies explored the possibilities of developing new infrastructural designs to enhance the efficient transmission systems from the remote areas with distributed generation such as wind and PV power. The distributed generation systems are connected directly to low voltage lines. However, the developed LCAs for the previous studies did not account for both electricity generation and transmission [9], [36]. The prevailing average T&D losses data (refer Figure 5), shows that, Tanzanian power transmission and distribution losses of 25% (with regular power outages) is among the highest in Africa and the world, and improving transmission efficiency or reducing losses is the foremost concern in the electric power systems development [35]. Fig.1. 5. Average T&D losses by region for both technical and nontechnical Source:[37] About 49% of power is produced by hydro. Most of the hydro-power plants are found in the southern part of Tanzania while maximum load centres are in the northern part. High losses in the distribution lines are mostly due to the ageing of the lines, with poor investments and unplanned extensions for a long time, causing overloading of system equipment such as conductors and transformers [35]. The previous Kenya power sector assessment report also reported that as of 2015, Kenya had total transmission losses of 4.5% [36]. The distribution network in regions outside Nairobi is less interconnected, and generally with long distances between transmission substations or bulk supply points with many radial 33kV and 11kV feeders, with average losses of 13.5%. [37]. In Rwanda, the overall losses figure from generation to the distribution system was 23% at the end of 2011[38]. The Tanzanian T&D losses are extremely high because electrical power generation and T&D technical losses of 22.5% [39] are acceptable in Asia and Oceania. The higher T&D losses reported in Tanzania and Rwandan depends on the network characteristics such as existing 33 kV, 11 kV, and 400-volt lines in rural areas are extended over long distances to feed loads scattered over large areas. However, figure 1.5 shows the average African T&D losses ranges from 9%-13%. 1.5 Contributions of the Thesis The main contributions of this thesis are summarised as follows: a. Contribution to an improved understanding of the life-cycle carbon emission pressure produced due to various electrical power T&D designs and operations (including removal of vegetation for the right of ways); b. Contribution to the development of the "Life-cycle carbon-emission (LCCE) estimation model for electrical power systems", hence improving the knowledge on the optimal electricity generation mix and transmission plan(s) for environmentally sustainable power systems design and monitoring; c. Demonstration of how to apply the LCCE estimation tool to a case study to develop a dataset for the LCCE for the electrical power systems of the studied countries; d. Provision of online data link to allow decision-makers, researchers, and practitioners to explore more the application of best practices in the studied grids; e. Published scientific articles to support the design, and operations of electrical power systems with minimum environmental impact; and f. Proposed theories on the life cycle assessment, and hence bridge the knowledge gap on the level of understanding of the environmental sustainability performance of the power systems designs, operations, and objectives anticipated by different system operators, researchers and policymakers. 1.6 List of publications developed from the research and Thesis preparation work The following listed four (4) scientific papers have been published in the course of the research and preparation of the thesis. These include two (2) articles published in peer-reviewed journals, and two (2) articles published in peer-reviewed Conference proceedings. One (1) manuscript has been submitted for publication. The proposed research model presented in this thesis is based on these papers. This means that three (3) thesis chapters out of the six (6) chapters have been published. The version of papers presented in this thesis differs only in slightly formatting and minor errata. In all the papers I am the main author supported by my three supervisors, as co- authors Publication 1: E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, 'Impact of Electrical Power Systems on the Environment in Kenya, Rwanda, and Tanzania'. Article presented at the postgraduate (energy systems) forum session (hosted by Tshwane University of Technology) of the 2018 IEEE PES/IAS PowerAfrica Conference on Affordable and Clean Emerging Energy Solutions for Sustainable Development in Cape Town, South Africa, published in the IEEE Xplore, (https://doi.org/10.1109/PowerAfrica.2018.8521092) Publication 2: E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, 'Grid Electricity Generation Systems Comparisons Using the Life Cycle Carbon Emission Inventory'. Article presented at the 2020 IEEE PES/IAS PowerAfrica Conference on Sustainable and Smart Energy Revolutions for Powering Africa in Nairobi, Kenya, published in the IEEE Xplore, (https://doi.org/10.1109/PowerAfrica49420.2020.9219876) Publication 3: E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, 'Modelling of environmental emission in Kenyan, Rwandan, and Tanzanian electrical power systems', J. Clean. Prod., p. 127830, Vol.312, Aug. 2021. (https://doi.org/10.1016/j.jclepro.2021.127830) Publication 4: E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, 'Data on the life-cycle carbon- emission in Kenyan, Rwandan, and Tanzanian grid electricity generation and transmission systems', Data Br. J., p. 107692, Vol. 40, Feb. 2022. (https://doi.org/10.1016/j.dib.2021.107692) Manuscript: E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, 'Assessment of Grid Electricity Systems Using the Life-Cycle Carbon-Emission Model', Submitted manuscript, under Review 1.7 Thesis layout The first two chapters of this thesis provide an introduction and review of the status of existing, and operational electrical power generation, T&D systems, and the associated environmental life cycle emissions (particularly the life-cycle carbon-emission) methods. The three original chapters of the thesis (chapter three, chapter four, and chapter five) were developed following the three specific objectives of the research presented in chapter one of the thesis. The first section of the chapter two presents a review of the baseline status of the studied national T&D systems and their associated greenhouse gas emissions. The sub-chapter has been presented in the 2018 IEEE PES/IAS PowerAfrica Conference and published by IEEE and is available in IEEE Xplore. The second section of this chapter developed the baseline status of the studied grid electricity generation systems; it proposes an

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environmental life-cycle inventory model. The sub- chapter has been presented at the 2020 IEEE PES/IAS PowerAfrica Conference and also published by IEEE and available in IEEE Xplore. Chapter three presents the compiled relevant life cycle carbon emissions data for the studied grids. It also presents an online data link. The presented data allows researchers, practitioners and policymakers to move away from overly basic assertions concerning the comparative environmental advantages of the different electricity system plan(s), and to focus on the comprehensive image, especially the serious roles of technology variety and the use of best practices. It also presents the research design as well as some ethical considerations. The chapter also demonstrates how developed mathematical algorithms have been applied to the study area. The work done in this chapter has been published as data article in the Data in Brief journal (Elsevier). Chapter four of the thesis presents a model for estimating the dynamic life-cycle carbon-emission of the studied power system components. In this chapter, a method is proposed to bridge the existing knowledge gap regarding the feasibility of the eco-labelled electricity composition designs assumed by electric power systems researchers. An evidence-based assessment model for influencing innovations, infrastructural eco-designs and technology transfers for sustainable electrical power systems, has been developed in this chapter. In this chapter theories (using the developed research questions) related to science, technology, environment, policy and society concerning the infrastructural design and operations of electrical power systems, have been advanced. Results produced in this chapter have been published as research article in the Journal of Cleaner Production (Elsevier). Chapter five presents the life cycle impact assessment of carbon emitted from the studied electrical power generation and HV transmission systems. The chapter also presents life-cycle inventory-analysis (LCIA) from the developed parameters, data collected and calculated using Microsoft Excel. An analysis is made of the pre-defined research question that "There is no lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power system" in Tanzania and Rwanda using R codes developed from the data generated in the course of this research. The work done in this chapter has been submitted for journal publication. Chapter six of the thesis provides answers to the research questions. It also presented some research limitations which may impair the neatness and usability of the obtained results. The chapter also proposes the areas of further research for targeting and observation of both global and local policy interventions for environmentally sustainable power systems development. List of References [1] I. B. Hauan, "Life Cycle Assessment of Electricity Transmission and Distribution," Norwegian University of Science and Technology, 2014. [2] J. Klimstra and M. Hotakainen, Smart Power Generation, 4th improv. Helsinki: Avain Publishers, 2011. [3] F. Iannone and D. Zaninelli, "Life cycle assessment applications to electrical energy production: a possible sustainability analysis tool," 2007 IEEE Power Eng. Soc. Gen. Meet., pp. 0–5, 2007, doi: 10.1109/PES.2007.385958. [4] M. Felix and S. H. Gheewala, "Environmental assessment of electricity production in Tanzania," Energy Sustain. Dev., vol. 16, no. 4, pp. 439–447, 2012, doi: 10.1016/j.esd.2012.07.006. [5] G. Falchetta, M. Hafner, and S. Tagliapietra, "Pathways to 100% Electrification in East Africa by 2030," Energy J., vol. 41, no. 3, 2020, doi: 10.5547/01956574.41.3.gfal. [6] E. G. H. Raquel S.Jorge, "Grid infrastructure for renewable power in Europe: The environmental cost," Energy, no. May, pp. 760–768, Vol. 69, 2014, doi: 10.1016/j.energy.2014.03.072. [7] A. Arvesen, I. B. Hauan, B. M. Bolsøy, and E. G. Hertwich, "Life cycle assessment of transport of electricity via different voltage levels: A case study for Nord-Trøndelag county in Norway," Appl. Energy, p. 20, 2015, doi: 10.1016/j.apenergy.2015.08.013. [8] M. Felix and S. H. Gheewala, "Environmental assessment of electricity production in Tanzania," Energy Sustain. Dev., vol. 16, no. 4, pp. 439–447, 2012, doi: 10.1016/j.esd.2012.07.006. [9] R. Turconi, A. Boldrin, and T. Astrup, "Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations," Renew. Sustain. Energy Rev., vol. 28, pp. 555–565, 2013, doi: 10.1016/j.rser.2013.08.013. [10] H. Chum, "Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," in October, no. October, J. S. (UK) Kirit Parikh (India), Ed. New York, NY, USA: Cambridge University Press, Cambridge, United Kingdom, 2004, pp. 511–598. [11] M. Felix and S. H. Gheewala, "Environmental toxicity potential from electricity generation in Tanzania," pp. 1424–1432, 2014, doi: 10.1007/s11367-014-0748-8. [12] N. Komendantova, M. Vocciante, and A. Battaglini, "Can the BESTGRID process improve stakeholder involvement in electricity transmission projects?," Energies, vol. 8, no. 9, pp. 9407–9433, 2015, doi: 10.3390/en8099407. [13] World Energy Council, "Comparison of Energy Systems Using Life Cycle Assessment: A Special Report of the World Energy Council," London W1B, 2004. [14] E. Chambile, N. Ijumba, B. Mkandawire, and J. Hakizimana, "Impact of Electrical Power Systems on the Environment in Kenya, Rwanda and Tanzania," in 2018 IEEE PES/IAS PowerAfrica Conference, 2018, no. 18261617, pp. 885–889, doi: 10.1109/PowerAfrica.2018.8521092. [15] A. Chervyakov, M. Ferrari, A. Marian, S. Stückrad, and H. Thomas, "Superconducting Electric Lines," 2015. doi: 10.2312/iass.2015.028. [16] H. H. Khoo and R. B. H. Tan, "Life Cycle Assessment Methodology : Ongoing Developments and Outlook," 2022 World Scientific Publishing Company, 2022, pp. 1–21. [17] E. Chambile, N. Ijumba, B. Mkandawire, and J. Hakizimana, "Grid Electricity Generation Systems Comparisons Using the Life Cycle Carbon Emission Inventory," in 2020 IEEE PES/IAS PowerAfrica Conference, 2020, pp. 1–5, doi: 10.1109/PowerAfrica49420.2020.9219876. [18] ISO, "Environmental management — Life cycle assessment — Principles and framework," ISO 14040, vol. 2006, Art. no. Reference number ISO 14040:2006(E), 2003. [19] E. A. Nyari, T. Pogrebnaya, and L. Wilson, "Energy Sector and Solar Energy Potential in Tanzania," 2015. [Online]. Available: www.ijete.org. [20] Lahmeyer International, "Analysis and Projection of Rwandas Electricty Demand," Kigali, 2004. doi: http://www.devpartners.gov.rw/fileadmin/templates/docs/EDPRS/Key Analytical Studies/Sectoral Studies/Energy_Demand_Analysis_&_Projection_2004.pdf. [21] V. Zongo, "Iringa-Shinyanga Transmission Line Project Country : Tanzania," Dar es Salaam, 2010. [Online]. Available: https://docplayer.net/6269043-Project-appraisal- report.html. [22] M. Madrigal and R. Spalding-Fecher, "Impacts of Transmission and Distribution Projects on Greenhouse Gas Emissions," Washington, D.C, N O . 2 1, 2010. [23] United States Environmental Protection Agency, "EIA Technical Review Guidelines: Energy Generation and Transmission," 2011. [Online]. Available: http://www2.epa.gov/sites/production/files/2014-04/documents/energyvol1.pdf. [24] [25] K. E. G. C. Limited, "Powering a Sustainable Future," Nairobi, 2017. SE4All, "Sustainable Energy for All (SE4All) Kenya's Investment Prospectus," Nairobi, 2016. [26] Republic of Rwanda, "Energy Sector Strategic Plan," Kigali, 2015. [Online]. Available: http://www.mininfra.gov.rw/rw/fileadmin/user_upload/new_tender/ESSP_17th_March_20 15.pdf. [27] K. Lee et al., "Electrification for 'under Grid' households in Rural Kenya," Dev. Eng., vol. 1, pp. 26–35, 2016, doi: 10.1016/j.deveng.2015.12.001. [28] D. Peng and R. Poudineh, "Sustainable electricity pricing for Tanzania," London, E-40305-TZA-1, 2016. [Online]. Available: http://www.theigc.org/wp- content/uploads/2016/08/Peng-Poudineh-2016-Working-Paper.pdf. [29] J. F. Kitonga and E. Bonafe, "Tanzanian energy sector under the universal principles of the International Energy Charter," 2015. [Online]. Available: http://www.energycharter.org/fileadmin/DocumentsMedia/CONEXO/20150827-Tanzania_Pre-Assessment_Report.pdf. [30] Rural Energy Agency, "Energy Access Situation Report, 2016; Tanzania Mainland," Dodoma, 2017. [Online]. Available: https://www.nbs.go.tz/nbs/takwimu/rea/Energy_Access_Situation_Report_2016.pdf. [31] Andrew, K. S. and R. Herscowitz, and Donovan, "Investment Brief for the Electricity Sector in Tanzania," 2014. [Online]. Available: https://www.usaid.gov/sites/default/files/documents/1860/Tanzania _IG_2015_05_03.pdf. [32] [33] United Nations Development Programme, "Rapid Assessment Gap Analysis Pakistan," Kigali, 2012. U.S. DOE, "Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities," 2015. [Online]. Available: http://energy.gov/sites/prod/files/2015/09/f26/Quadrennial-Technology-Review- 2015_0.pdf. [34] M. Munasinghe and W. Scott, "Energy Efficiency: Optimization of Electric Power Distribution System Losses (Final Report of Research Project No. R633)," Washington, D.C., 1982. [35] [36] [37] H. Williams and C. W. Paper, "Transmission & Distribution Infrastructure Transmission & Distribution Infrastructure," 2010. R. Turconi, "Life Cycle Assessment of Electricity Systems," Technical University of Denmark, Copenhagen, 2014. M. Madrigal and R. Spalding-Fecher, "Impacts of Transmission and Distribution Projects on Greenhouse Gas Emissions. Review of Methodologies and a Proposed Approach in the Context of World Bank Lending Operations," Washington, D.C., 2010. doi: 10.1596/27755. [38] Rwanda Energy Group, "Brief Note on Loss Reduction Project Funded by European Union," 2017. [Online]. Available: http://reg.rw/images/pdf/BRIEFNOTEONPROJECTS002. pdf. [39] Electrical India, "Losses in Distribution & Transmission Lines

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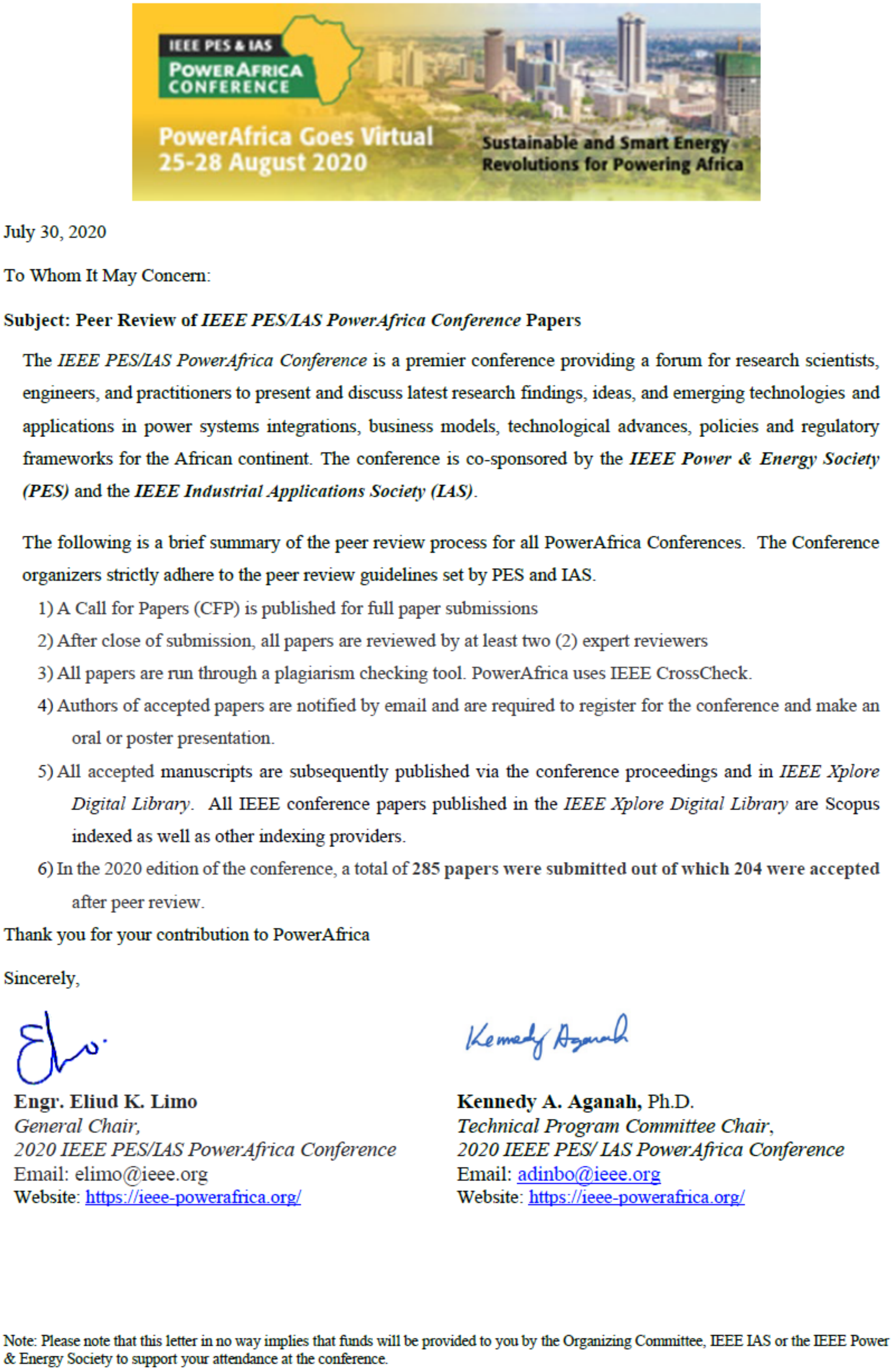

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Subject: Peer Review of *IEEE PES/IAS PowerAfrica Conference* Papers

The *IEEE PES/IAS PowerAfrica Conference* is a premier conference providing a forum for research scientists, engineers, and practitioners to present and discuss latest research findings, ideas, and emerging technologies and applications in power systems integrations, business models, technological advances, policies and regulatory frameworks for the African continent. The conference is co-sponsored by the ***IEEE Power & Energy Society (PES)*** and the ***IEEE Industrial Applications Society (IAS)***.

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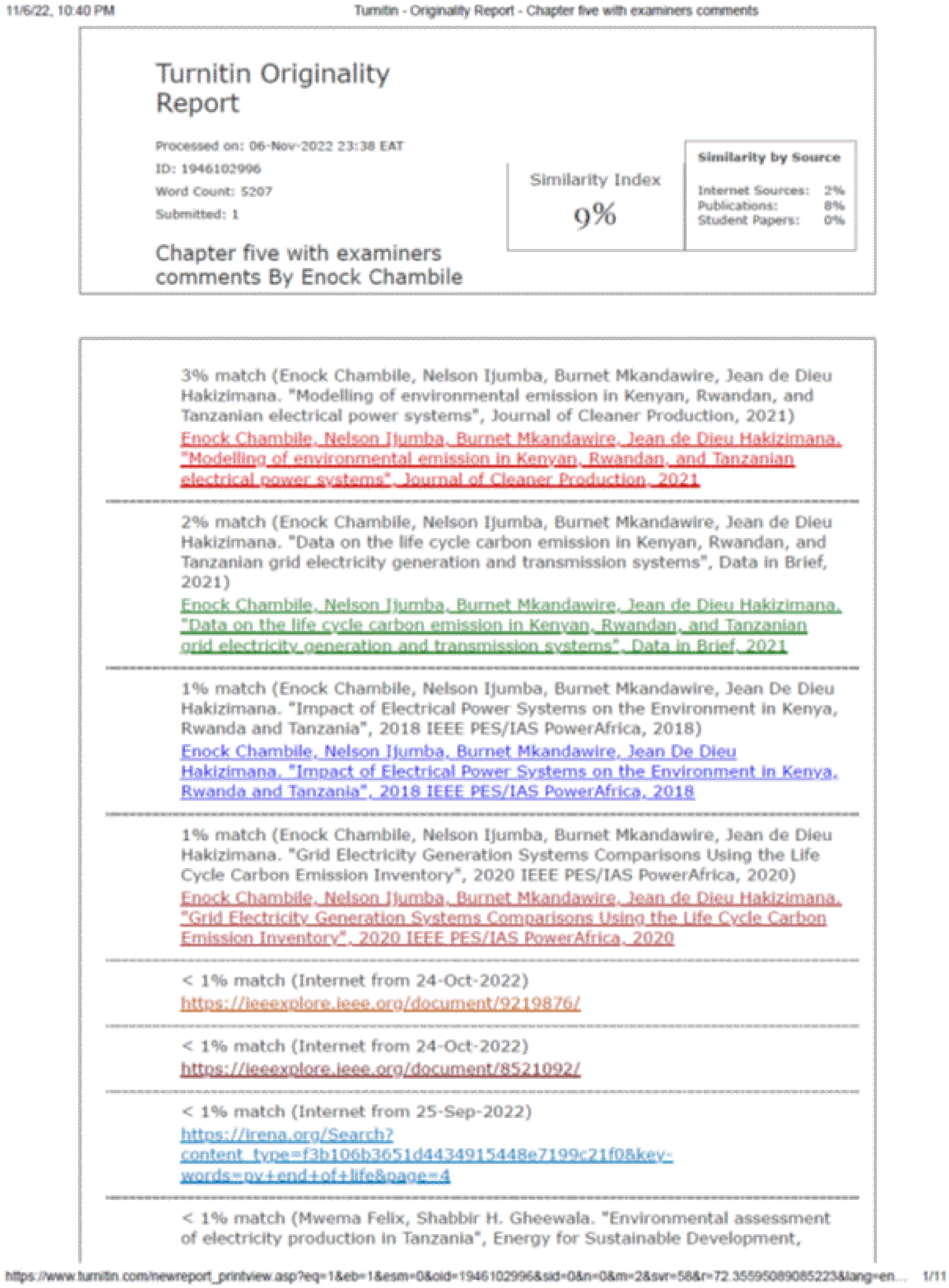

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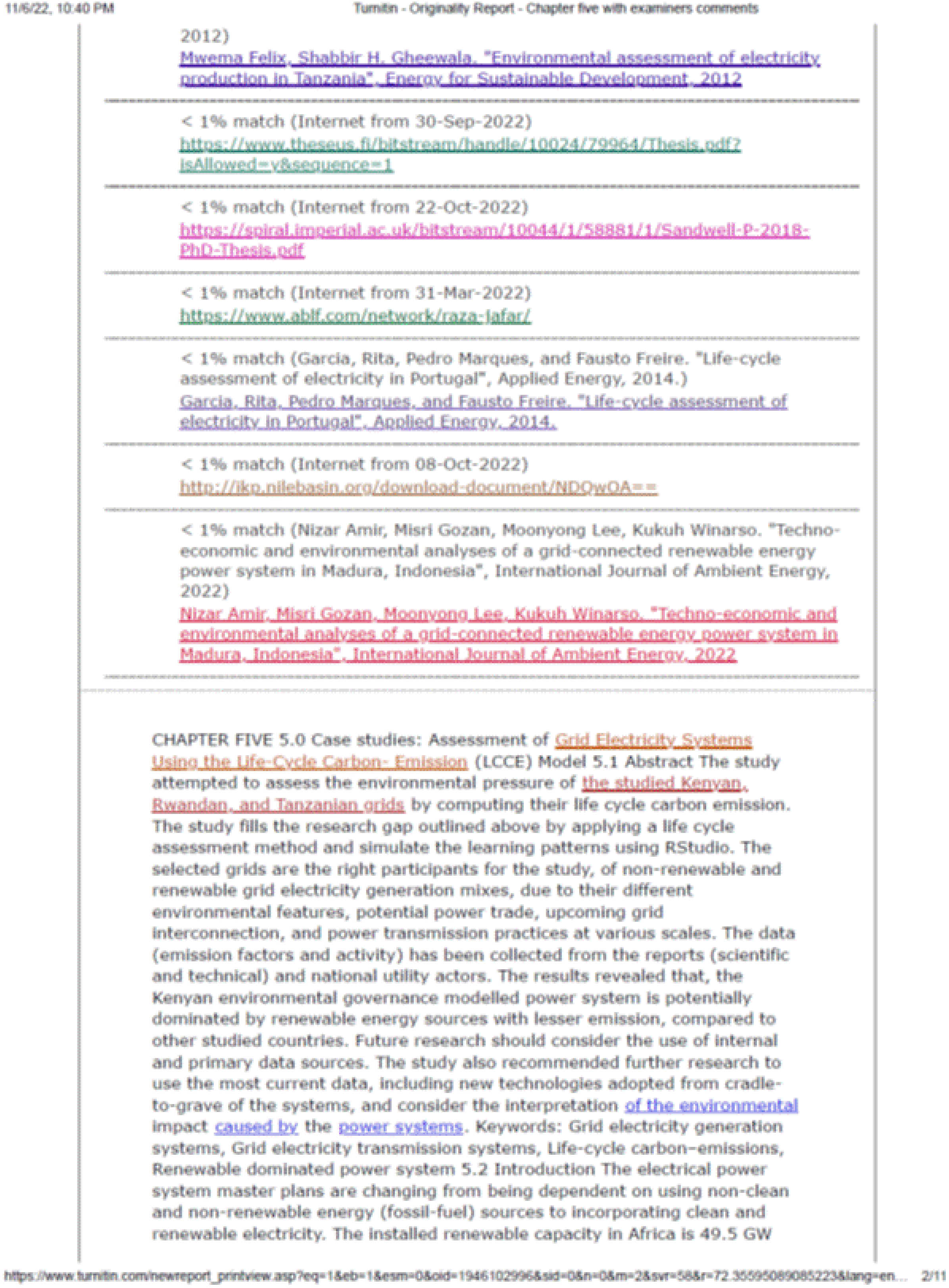

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CHAPTER FIVE 5.0 Case studies: Assessment of Grid Electricity Systems Using the Life-Cycle Carbon- Emission (LCCE) Model 5.1 Abstract The study attempted to assess the environmental pressure of the studied Kenyan, Rwandan, and Tanzanian grids by computing their life cycle carbon emission. The study fills the research gap outlined above by applying a life cycle assessment method and simulate the learning patterns using RStudio. 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 data (emission factors and activity) has been collected from the reports (scientific and technical) and national utility actors. The results revealed that, the Kenyan environmental governance modelled power system is potentially dominated by renewable energy sources with lesser emission, compared to other studied countries. Future research should consider the use of internal and primary data sources. The study also recommended further research to use the most current data, including new technologies adopted from cradle-to-grave of the systems, and consider the interpretation of the environmental impact caused by the power systems. Keywords: Grid electricity generation systems, Grid electricity transmission systems, Life-cycle carbon–emissions, Renewable dominated power system 5.2 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. The installed renewable capacity in Africa is 49.5 GW

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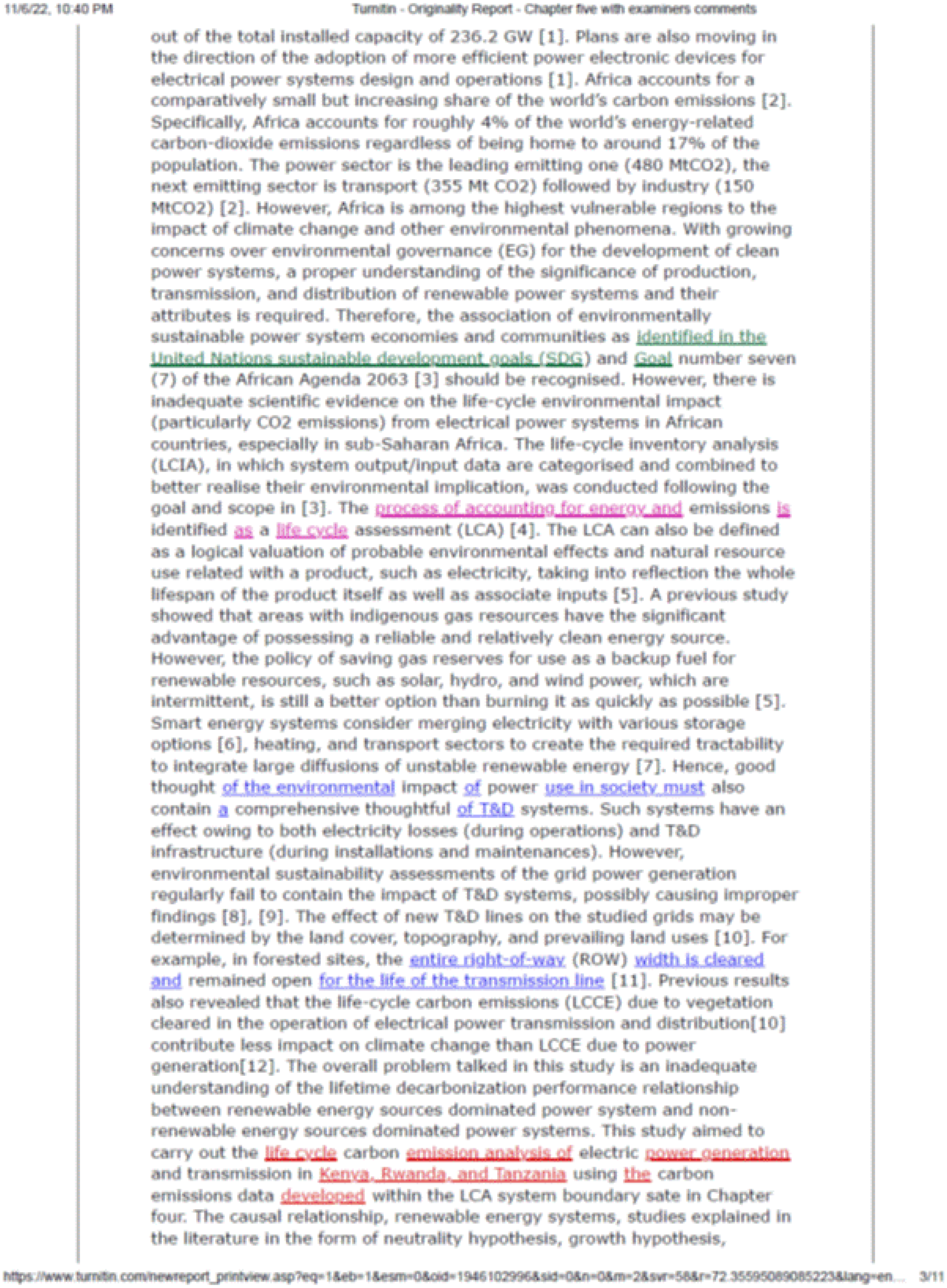

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out of the total installed capacity of 236.2 GW [1]. Plans are also moving in the direction of the adoption of more efficient power electronic devices for electrical power systems design and operations [1]. Africa accounts for a comparatively small but increasing share of the world's carbon emissions [2]. 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), the next emitting sector is transport (355 Mt CO2) followed by industry (150 MtCO2) [2]. 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 production, transmission, and distribution of renewable power systems 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 Agenda 2063 [3] should be recognised. 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. 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 [3]. The process of accounting for energy and emissions is identified as a life cycle assessment (LCA) [4]. The LCA can also be defined as a logical valuation of probable environmental effects and natural resource use related with a product, such as electricity, taking into reflection the whole lifespan of the product itself as well as associate inputs [5]. 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, hydro, and wind power, which are intermittent, is still a better option than burning it as quickly as possible [5]. Smart energy systems consider merging electricity with various storage options [6], heating, and transport sectors to create the required tractability to integrate large diffusions of unstable renewable energy [7]. Hence, good thought of the environmental impact of power use in society must also 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 maintenances). However, environmental sustainability assessments of the grid power generation regularly fail to contain the impact of T&D systems, possibly causing improper findings [8], [9]. The effect of new T&D lines on the studied grids may be determined by the land cover, topography, and prevailing land uses [10]. For example, in forested sites, the entire right-of-way (ROW) width is cleared and remained open for the life of the transmission line [11]. Previous results also revealed that the life-cycle carbon emissions (LCCE) due to vegetation cleared in the operation of electrical power transmission and distribution[10] contribute less impact on climate change than LCCE due to power generation[12]. The overall problem talked in this study is an inadequate understanding of the lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power systems. This study aimed to carry out the life cycle carbon emission analysis of electric power generation and transmission in Kenya, Rwanda, and Tanzania using the carbon emissions data developed within the LCA system boundary sate in Chapter four. The causal relationship, renewable energy systems, studies explained in the literature in the form of neutrality hypothesis, growth hypothesis,

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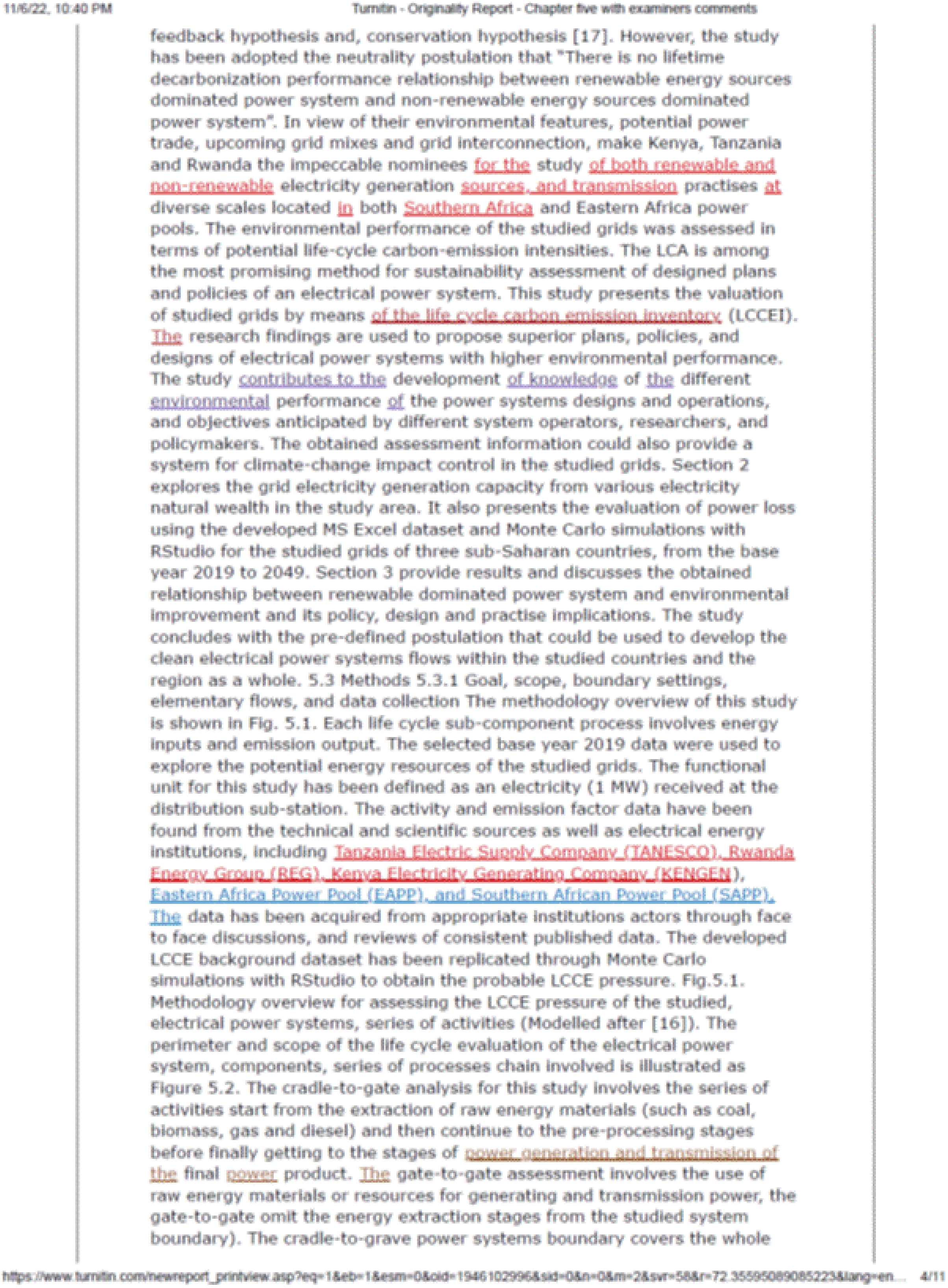

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feedback hypothesis and, conservation hypothesis [17]. However, the study has been adopted the neutrality postulation that "There is no lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power system". In view of 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 renewable and non-renewable electricity generation sources, and transmission practises 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 intensities. The LCA is among the most promising method for sustainability assessment of designed plans and policies of an electrical power system. This study presents the valuation of studied grids by means of the life cycle carbon emission inventory (LCCEI). The research findings are used to propose superior plans, policies, and designs of electrical power systems with higher environmental performance. The study contributes to the development of knowledge of the different environmental performance of the power systems designs and operations, and objectives anticipated by different system operators, researchers, and policymakers. The obtained assessment information could also provide a system for climate-change impact control in the studied grids. 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 and Monte Carlo simulations with RStudio for the studied grids of three sub-Saharan countries, from the base year 2019 to 2049. Section 3 provide results and discusses the obtained relationship between renewable dominated power system and environmental improvement and its policy, design and practise implications. The study concludes with the pre-defined postulation that could be used to develop the clean electrical power systems flows within the studied countries and the region as a whole. 5.3 Methods 5.3.1 Goal, scope, boundary settings, elementary flows, and data collection The methodology overview of this study is shown in Fig. 5.1. Each life cycle sub-component process involves energy inputs and emission output. The selected base year 2019 data were used to explore the potential energy resources of the studied grids. The functional unit for this study has been defined as an electricity (1 MW) received at the distribution sub-station. The activity and emission factor data have been found from the technical and scientific sources as well as electrical energy institutions, including Tanzania Electric Supply Company (TANESCO), Rwanda Energy Group (REG), Kenya Electricity Generating Company (KENGEN), Eastern Africa Power Pool (EAPP), and Southern African Power Pool (SAPP). The data has been acquired from appropriate institutions 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 pressure. Fig.5.1. Methodology overview for assessing the LCCE pressure of the studied, electrical power systems, series of activities (Modelled after [16]). The perimeter and scope of the life cycle evaluation of the electrical power system, components, series of processes chain involved is illustrated as Figure 5.2. The cradle-to-gate analysis for this study involves the series of activities start from the extraction of raw energy materials (such as coal, biomass, gas and diesel) and then continue 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 omit the energy extraction stages from the studied system boundary). The cradle-to-grave power systems boundary covers the whole

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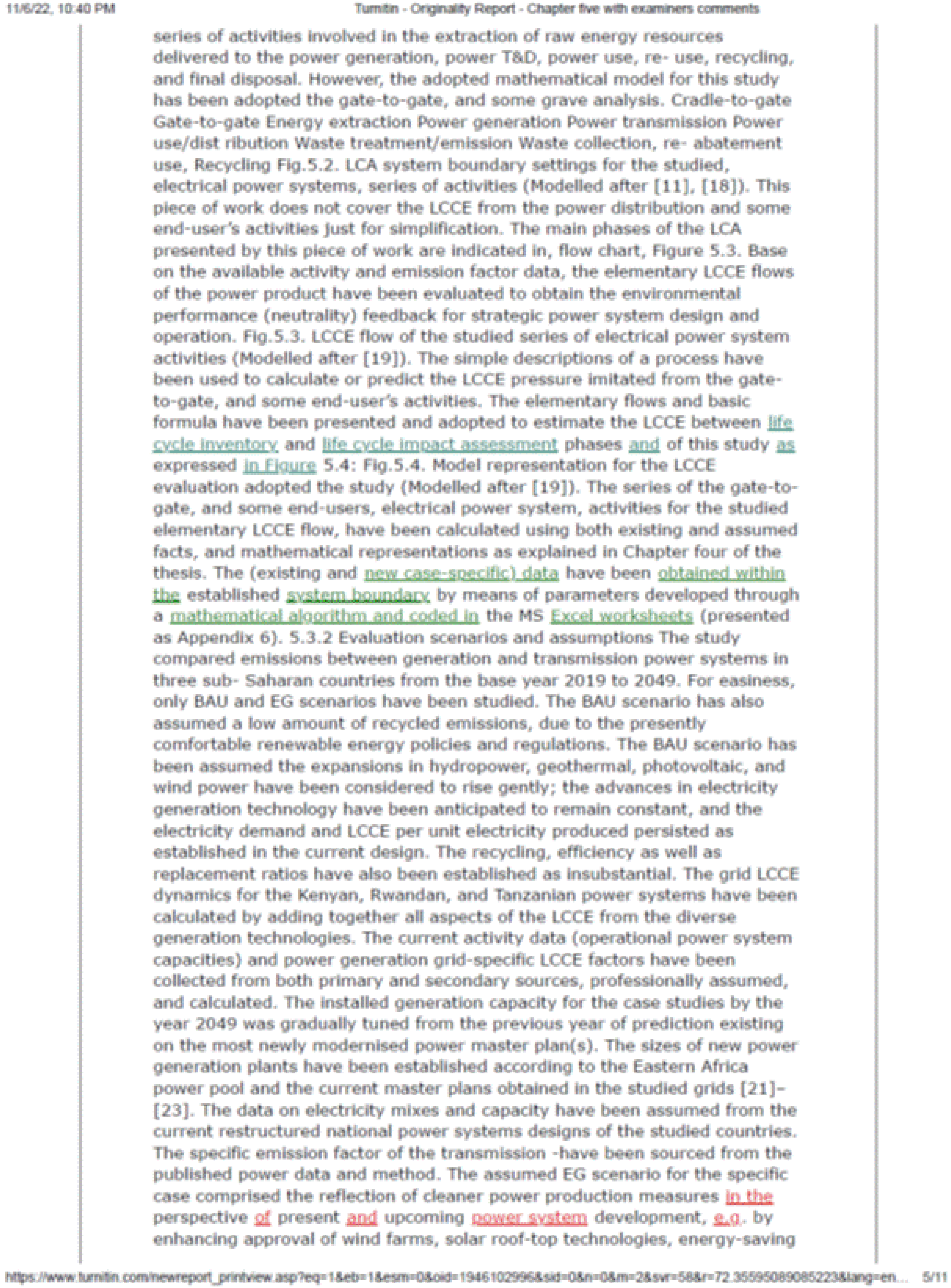

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series of activities involved in the extraction of raw energy resources delivered to the power generation, power T&D, power use, re- use, recycling, and final disposal. However, the adopted mathematical model for this study has been adopted the gate-to-gate, and some grave analysis. Cradle-to-gate Gate-to-gate Energy extraction Power generation Power transmission Power use/dist ribution Waste treatment/emission Waste collection, re- abatement use, Recycling Fig.5.2. LCA system boundary settings for the studied, electrical power systems, series of activities (Modelled after [11], [18]). This piece of work does not cover the LCCE from the power distribution and some end-user's activities just for simplification. The main phases of the LCA presented by this piece of work are indicated in, flow chart, Figure 5.3. Base 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. Fig.5.3. LCCE flow of the studied series of electrical power system activities (Modelled after [19]). The simple descriptions of a process have been used to calculate or predict the LCCE pressure imitated 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 life cycle inventory and life cycle impact assessment phases and of this study as expressed in Figure 5.4: Fig.5.4. Model representation for the LCCE evaluation adopted the study (Modelled after [19]). The series of the gate-to-gate, and some end-users, electrical power system, activities for the studied elementary LCCE flow, have been calculated using both existing and assumed facts, and mathematical representations as explained in Chapter four of the thesis. The (existing and new case-specific) data have been obtained within the established system boundary by means of parameters developed through a mathematical algorithm and coded in the MS Excel worksheets (presented as Appendix 6). 5.3.2 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 BAU and EG scenarios have been studied. The BAU scenario has also assumed a low amount of recycled emissions, due to the presently comfortable renewable energy policies and regulations. The BAU scenario has been 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 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 collected 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 [21]–[23]. 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 -have 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

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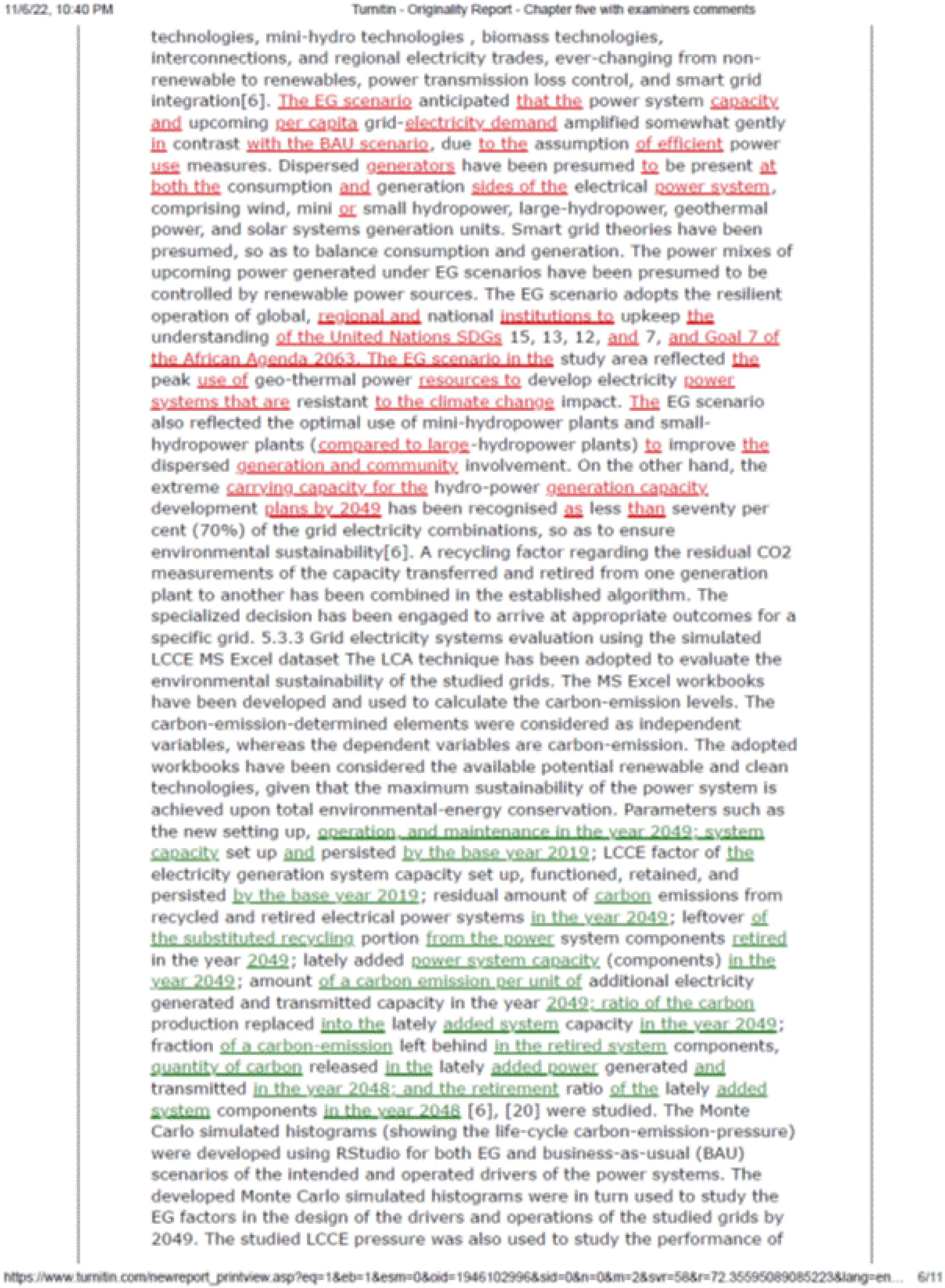

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technologies, mini-hydro technologies , biomass technologies, interconnections, and regional electricity trades, ever-changing from non-renewable to renewables, power transmission loss control, and smart grid integration[6]. The EG scenario anticipated 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, so as to balance consumption and generation. The power mixes of upcoming power generated under EG scenarios have been presumed to be controlled by renewable power sources. The EG scenario adopts the resilient operation of global, regional and national institutions to upkeep the understanding of the United Nations SDGs 15, 13, 12, and 7, and Goal 7 of the African Agenda 2063. The EG scenario in the study area reflected the peak use of geo-thermal power resources to develop electricity power systems that are resistant to the 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 seventy per cent (70%) of the grid electricity combinations, so as to ensure environmental sustainability[6]. 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. 5.3.3 Grid electricity systems evaluation using the simulated LCCE MS Excel dataset The LCA technique has been adopted to evaluate the environmental sustainability 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 been 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; lately 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 lately 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 lately added power generated and transmitted in the year 2048; and the retirement ratio of the lately added system components in the year 2048 [6], [20] were studied. The Monte Carlo simulated histograms (showing the life-cycle carbon-emission-pressure) were developed using RStudio for both EG and business-as-usual (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 studied LCCE pressure was also used to study the performance of

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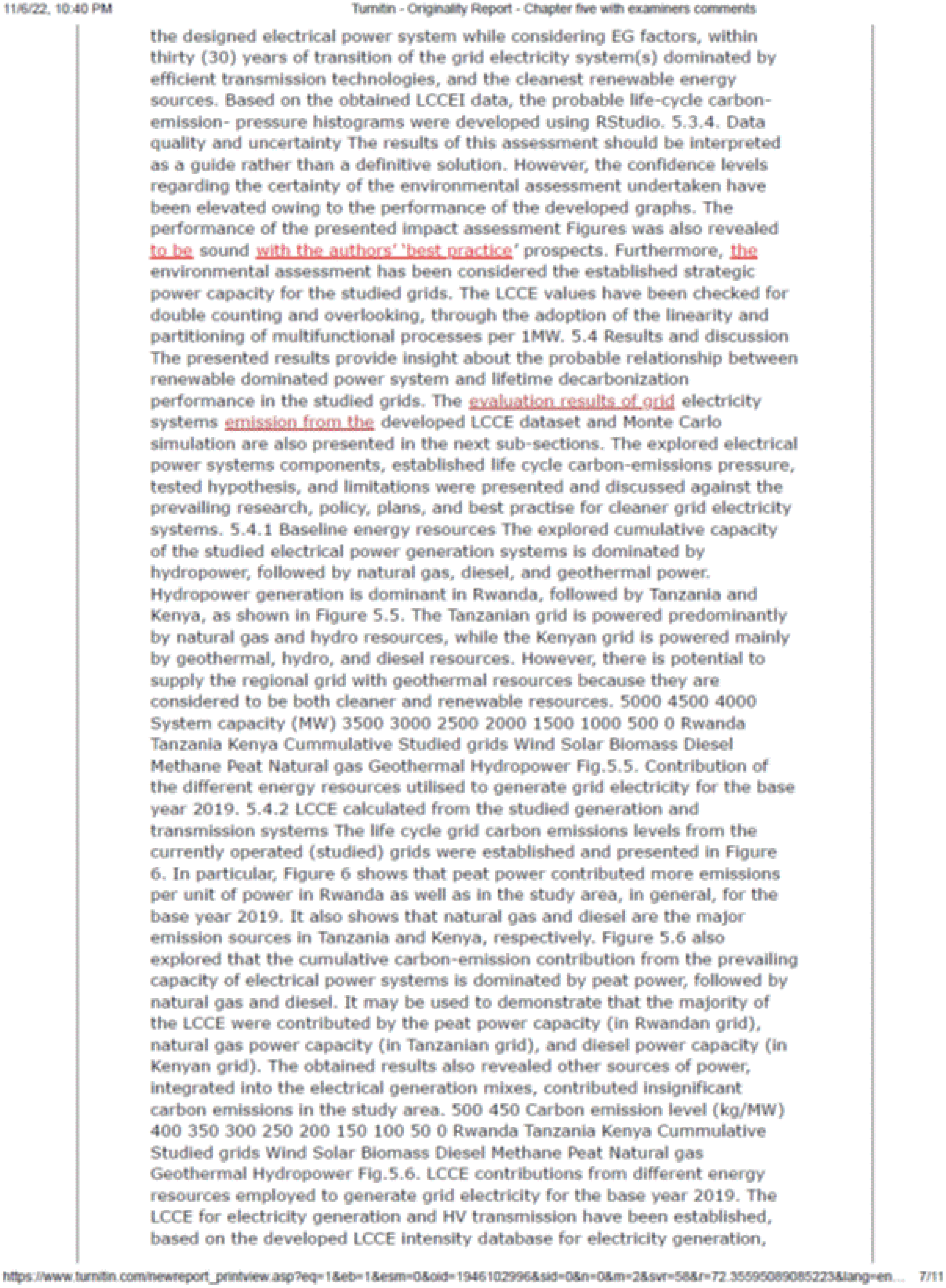

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the designed electrical power system while considering EG factors, within thirty (30) years of transition of the grid electricity system(s) dominated by efficient transmission technologies, and the cleanest renewable energy sources. Based on the obtained LCCEI data, the probable life-cycle carbon-emission- pressure histograms were developed using RStudio. 5.3.4. 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 environmental assessment has been considered the established strategic power capacity for the studied grids. The LCCE values have been checked for double counting and overlooking, through the adoption of the linearity and partitioning of multifunctional processes per 1MW. 5.4 Results and discussion The presented results provide insight about the probable relationship between renewable dominated power system 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 pressure, tested hypothesis, and limitations were presented and discussed against the prevailing research, policy, plans, and best practise for cleaner grid electricity systems. 5.4.1 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 5.5. 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. 5000 4500 4000 System capacity (MW) 3500 3000 2500 2000 1500 1000 500 0 Rwanda Tanzania Kenya Cummulative Studied grids Wind Solar Biomass Diesel Methane Peat Natural gas Geothermal Hydropower Fig.5.5. Contribution of the different energy resources utilised to generate grid electricity for the base year 2019. 5.4.2 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 5.6 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 were contributed by the peat power capacity (in Rwandan grid), natural gas power capacity (in Tanzanian grid), and diesel power capacity (in 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. 500 450 Carbon emission level (kg/MW) 400 350 300 250 200 150 100 50 0 Rwanda Tanzania Kenya Cummulative Studied grids Wind Solar Biomass Diesel Methane Peat Natural gas Geothermal Hydropower Fig.5.6. LCCE contributions from different energy resources employed to generate grid electricity for the base year 2019. The LCCE for electricity generation and HV transmission have been established, based on the developed LCCE intensity database for electricity generation,

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and the high-voltage (HV) power transmission loss for the studied grids, and presented as Figure 7. The LCCE contributions from the studied components and area were assessed for the base year 2019. Figure 7 shows that the Rwandan grid generated higher emissions per unit of electricity, followed by the Tanzanian grid. 100% 90% Carbon emission 80% 70% 60% 50% 40% Kenya 30% 20% Tanzania 10% 0% Rwanda Electricity generation High Voltage Transmission Studied grids Fig.5.7. LCCE contributions from the studied electrical power system components for the base year 2019. The LCCE obtained from the developed MS Excel data and presented as Figure 5.8 also shows that, the baseline level of life-cycle carbon emissions per unit power is much higher in the Rwandan grid than in the Tanzanian and Kenyan grids. Studied grid electricity generation and transmission systems Residue/Recycled electrical power systems capacity (BAU) Kenya Tanzania New electrical power systems capacity (BAU) Rwanda Current electrical power systems capacity Residue/Recycled electrical power sytems capacity (EG) New electrical power systems capacity (EG) 0% 20% 40% 60% 80% 100% Carbon emission (kg/MW) Fig.5.8. LCCE from the electrical power system components designed and operated from the base year 2019 to 2049. 5.4.3 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 (Figure 5.9). The presented histograms do not show the probability or trend of carbon-emission pressure (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, accept the postulation that "There is no lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power system". The results also revealed that the prevailing Rwandan BAU modelled power system is dominated with relatively high emitting source (including peat) while its EG modelled power systems can also potentially be dominated with relatively higher emitting sources compared to Kenyan and Rwandan grids. Probability pressure Probability pressure Grid carbon emission level anomalies Grid carbon emission level anomalies Fig.5.9. Histogram of simulated normal LCCE data (kg/MW) from the Rwandan grid electricity systems designed under both BAU (left side, negatively skewed) and EG (right side, symmetrical distribution) scenarios, by 2049. The Monte Carlo simulated histograms obtained using RStudio (Figure 5.10) also do not show the probability or trend of the carbon-emission pressure (environmental performance) increase or reduction in the studied Tanzanian electricity systems designed under the EG scenarios (as opposed to BAU scenarios) by 2049. This result can also accept the postulation that "There is no lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power system". The results reveal that, the prevailing Tanzanian BAU modelled power system is dominated by relatively less emitting sources (compared to Rwandan grid) mostly natural gas, apart from the fact that its EG modelled power systems can also potential be dominated with lesser emitting sources, such as hydropower and some geothermal sources, while adopting the most efficient transmission technologies. Probability pressure Probability pressure Grid carbon emission level anomalies Grid carbon emission level anomalies Fig.5.10. Histogram of simulated normal LCCE data (kg/MW) from the Tanzanian grid electricity systems designed under both BAU (left histogram, negatively skewed) and EG (right histogram, symmetrical distribution) scenarios by 2049. The Monte Carlo simulated histogram obtained using RStudio (Figure 5.11) shows the probability of carbon-emission pressure reduction (high environmental

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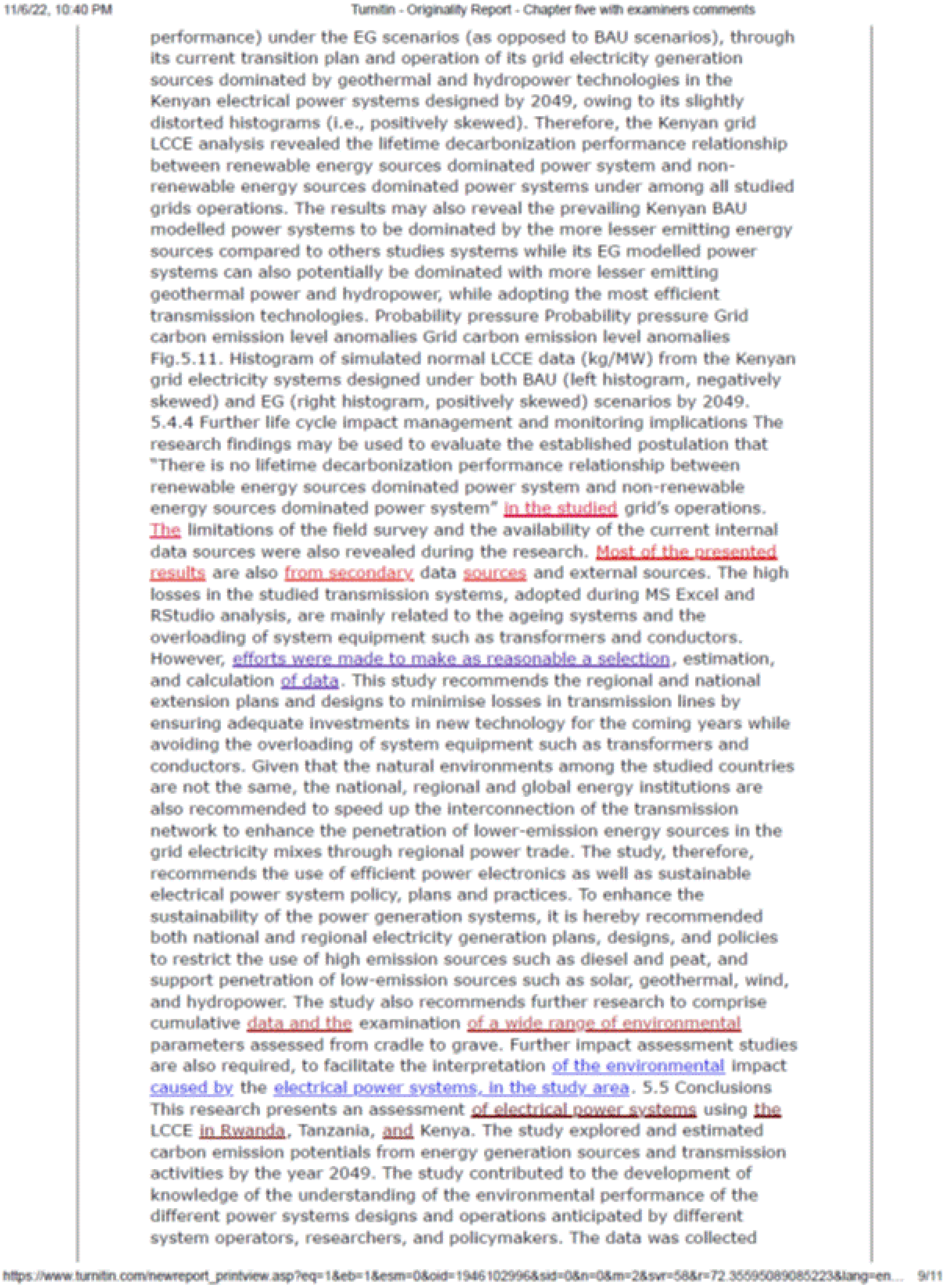

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performance) under the EG scenarios (as opposed to BAU scenarios), through its current transition plan and operation of its grid electricity generation sources dominated by geothermal and hydropower technologies in the Kenyan electrical power systems 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 system and non-renewable energy sources dominated power systems under among all studied grids operations. The results may also reveal the prevailing Kenyan BAU modelled power systems to be dominated by the more lesser emitting energy sources compared to others studies systems while its EG modelled power systems can also potentially be dominated with more lesser emitting geothermal power and hydropower, while adopting the most efficient transmission technologies. Probability pressure Probability pressure Grid carbon emission level anomalies Grid carbon emission level anomalies Fig.5.11. Histogram of simulated normal LCCE data (kg/MW) from the Kenyan grid electricity systems designed under both BAU (left histogram, negatively skewed) and EG (right histogram, positively skewed) scenarios by 2049. 5.4.4 Further life cycle impact management and monitoring implications The research findings may be used to evaluate the established postulation that "There is no lifetime decarbonization performance relationship between renewable energy sources dominated power system and non-renewable energy sources dominated power system" 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. Most of the presented results are also 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 as reasonable a selection, estimation, and calculation of data. This study recommends the 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 policy, 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 penetration of low-emission sources such as solar, geothermal, wind, and hydropower. The study also recommends further research to comprise cumulative data and the examination of a wide range of environmental parameters assessed from cradle to grave. Further impact assessment studies are also required, to facilitate the interpretation of the environmental impact caused by the electrical power systems, in the study area. 5.5 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

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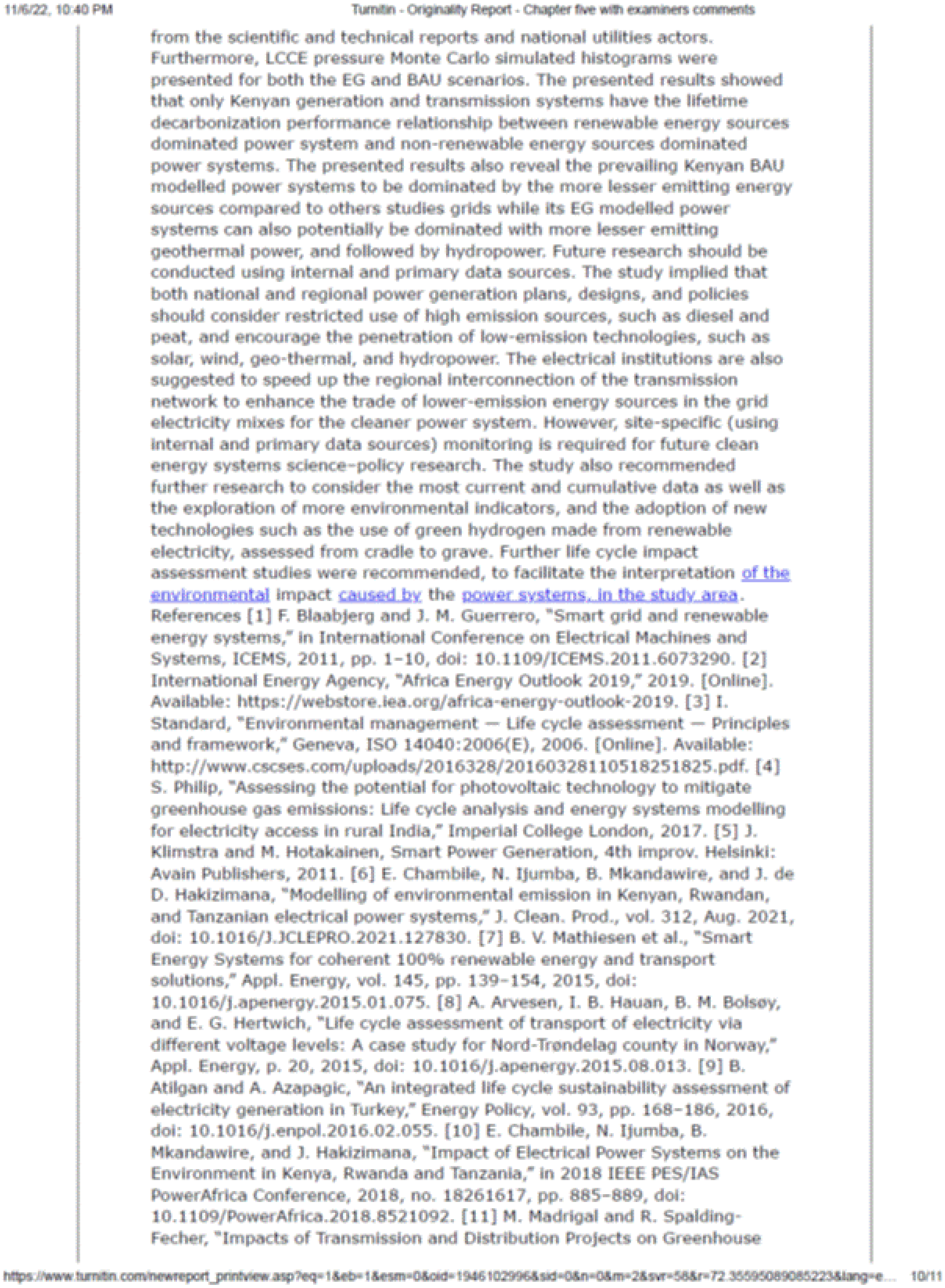

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from the scientific and technical reports and national utilities actors. Furthermore, LCCE pressure Monte Carlo simulated histograms were presented for both the EG and BAU scenarios. The presented results showed that only Kenyan generation and transmission systems have the lifetime decarbonization performance relationship between renewable energy sources dominated power system 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 more lesser emitting energy sources compared to others studies grids while its EG modelled power systems can also potentially be dominated with more lesser emitting geothermal power, and followed by hydropower. Future research should 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, geo-thermal, 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 the 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 impact assessment studies were recommended, to facilitate the interpretation of the environmental impact caused by the power systems, in the study area.

References [1] F. Blaabjerg and J. M. Guerrero, "Smart grid and renewable energy systems," in International Conference on Electrical Machines and Systems, ICEMS, 2011, pp. 1–10, doi: 10.1109/ICEMS.2011.6073290. [2] International Energy Agency, "Africa Energy Outlook 2019," 2019. [Online]. Available: https://webstore.iea.org/africa-energy-outlook-2019. [3] I. Standard, "Environmental management — Life cycle assessment — Principles and framework," Geneva, ISO 14040:2006(E), 2006. [Online]. Available: http://www.cscses.com/uploads/2016328/20160328110518251825.pdf. [4] S. Philip, "Assessing the potential for photovoltaic technology to mitigate greenhouse gas emissions: Life cycle analysis and energy systems modelling for electricity access in rural India," Imperial College London, 2017. [5] J. Klimstra and M. Hotakainen, Smart Power Generation, 4th improv. Helsinki: Avain Publishers, 2011. [6] E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, "Modelling of environmental emission in Kenyan, Rwandan, and Tanzanian electrical power systems," J. Clean. Prod., vol. 312, Aug. 2021, doi: 10.1016/J.JCLEPRO.2021.127830. [7] B. V. Mathiesen et al., "Smart Energy Systems for coherent 100% renewable energy and transport solutions," Appl. Energy, vol. 145, pp. 139–154, 2015, doi: 10.1016/j.apenergy.2015.01.075. [8] A. Arvesen, I. B. Hauan, B. M. Bolsøy, and E. G. Hertwich, "Life cycle assessment of transport of electricity via different voltage levels: A case study for Nord-Trøndelag county in Norway," Appl. Energy, p. 20, 2015, doi: 10.1016/j.apenergy.2015.08.013. [9] B. Atilgan and A. Azapagic, "An integrated life cycle sustainability assessment of electricity generation in Turkey," Energy Policy, vol. 93, pp. 168–186, 2016, doi: 10.1016/j.enpol.2016.02.055. [10] E. Chambile, N. Ijumba, B. Mkandawire, and J. Hakizimana, "Impact of Electrical Power Systems on the Environment in Kenya, Rwanda and Tanzania," in 2018 IEEE PES/IAS PowerAfrica Conference, 2018, no. 18261617, pp. 885–889, doi: 10.1109/PowerAfrica.2018.8521092. [11] M. Madrigal and R. Spalding-Fecher, "Impacts of Transmission and Distribution Projects on Greenhouse

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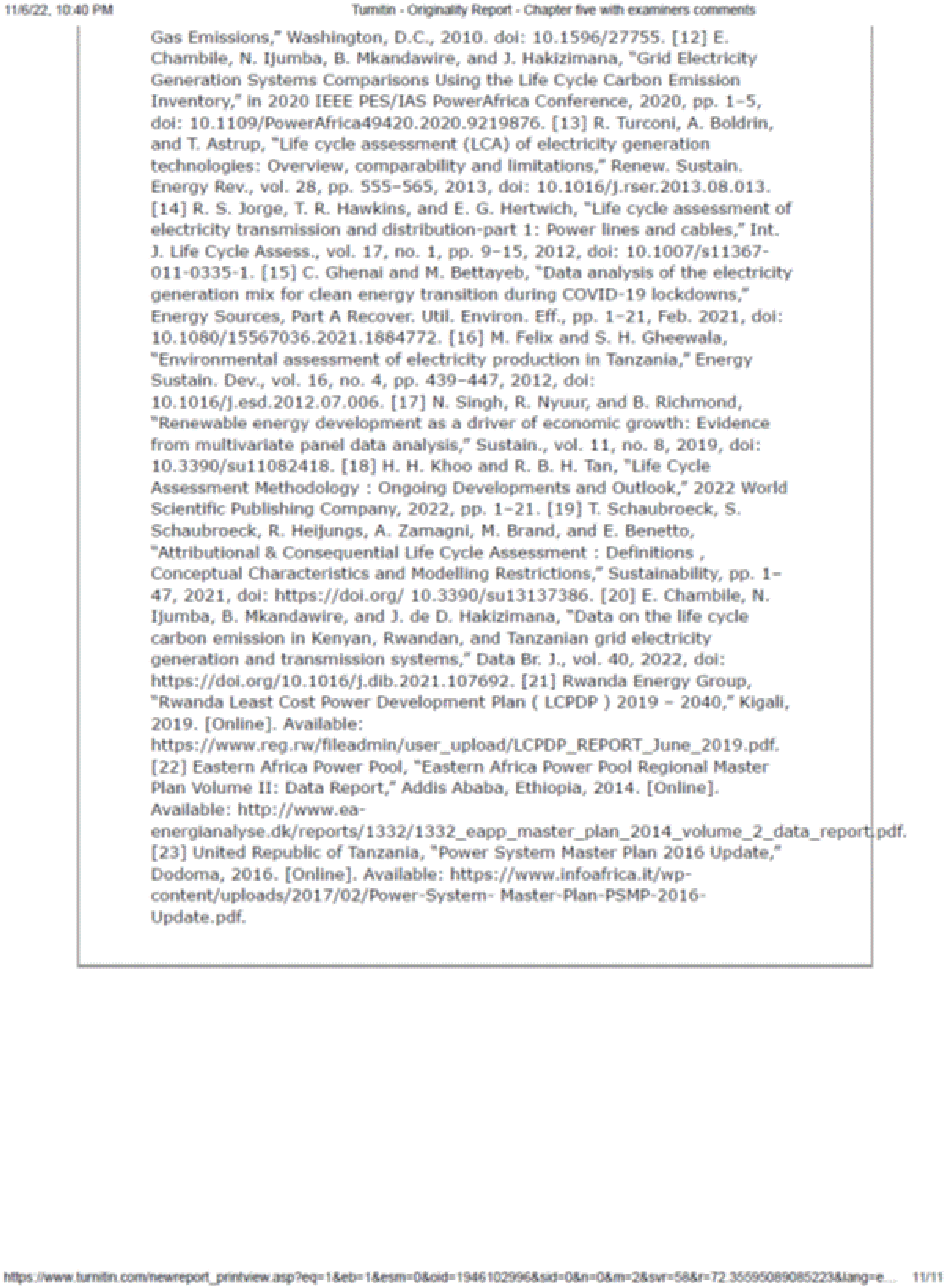

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Gas Emissions," Washington, D.C., 2010. doi: 10.1596/27755. [12] E. Chambile, N. Ijumba, B. Mkandawire, and J. Hakizimana, "Grid Electricity Generation Systems Comparisons Using the Life Cycle Carbon Emission Inventory," in 2020 IEEE PES/IAS PowerAfrica Conference, 2020, pp. 1–5, doi: 10.1109/PowerAfrica49420.2020.9219876. [13] R. Turconi, A. Boldrin, and T. Astrup, "Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations," Renew. Sustain. Energy Rev., vol. 28, pp. 555–565, 2013, doi: 10.1016/j.rser.2013.08.013. [14] R. S. Jorge, T. R. Hawkins, and E. G. Hertwich, "Life cycle assessment of electricity transmission and distribution-part 1: Power lines and cables," Int. J. Life Cycle Assess., vol. 17, no. 1, pp. 9–15, 2012, doi: 10.1007/s11367-011-0335-1. [15] C. Ghenai and M. Bettayeb, "Data analysis of the electricity generation mix for clean energy transition during COVID-19 lockdowns," Energy Sources, Part A Recover. Util. Environ. Eff., pp. 1–21, Feb. 2021, doi: 10.1080/15567036.2021.1884772. [16] M. Felix and S. H. Gheewala, "Environmental assessment of electricity production in Tanzania," Energy Sustain. Dev., vol. 16, no. 4, pp. 439–447, 2012, doi: 10.1016/j.esd.2012.07.006. [17] N. Singh, R. Nyuur, and B. Richmond, "Renewable energy development as a driver of economic growth: Evidence from multivariate panel data analysis," Sustain., vol. 11, no. 8, 2019, doi: 10.3390/su11082418. [18] H. H. Khoo and R. B. H. Tan, "Life Cycle Assessment Methodology : Ongoing Developments and Outlook," 2022 World Scientific Publishing Company, 2022, pp. 1–21. [19] T. Schaubroeck, S. Schaubroeck, R. Heijungs, A. Zamagni, M. Brand, and E. Benetto, "Attributional & Consequential Life Cycle Assessment : Definitions , Conceptual Characteristics and Modelling Restrictions," Sustainability, pp. 1–47, 2021, doi: https://doi.org/ 10.3390/su13137386. [20] E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, "Data on the life cycle carbon emission in Kenyan, Rwandan, and Tanzanian grid electricity generation and transmission systems," Data Br. J., vol. 40, 2022, doi: https://doi.org/10.1016/j.dib.2021.107692. [21] Rwanda Energy Group, "Rwanda Least Cost Power Development Plan (LCPDP) 2019 – 2040," Kigali, 2019. [Online]. Available: https://www.reg.rw/fileadmin/user_upload/LCPDP_REPORT_June_2019.pdf. [22] Eastern Africa Power Pool, "Eastern Africa Power Pool Regional Master Plan Volume II: Data Report," Addis Ababa, Ethiopia, 2014. [Online]. Available: http://www.ea-energianalyse.dk/reports/1332/1332_eapp_master_plan_2014_volume_2_data_report.pdf. [23] United Republic of Tanzania, "Power System Master Plan 2016 Update," Dodoma, 2016. [Online]. Available: https://www.infoafrica.it/wp-content/uploads/2017/02/Power-System- Master-Plan-PSMP-2016-Update.pdf.

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011-0335-1. [15] C. Ghenai and M. Bettayeb, "Data analysis of the electricity generation mix for clean energy transition during COVID-19 lockdowns," Energy Sources, Part A Recover. Util. Environ. Eff., pp. 1–21, Feb. 2021, doi: 10.1080/15567036.2021.1884772. [16] M. Felix and S. H. Gheewala, "Environmental assessment of electricity production in Tanzania," Energy Sustain. Dev., vol. 16, no. 4, pp. 439–447, 2012, doi: 10.1016/j.esd.2012.07.006. [17] N. Singh, R. Nyuur, and B. Richmond, "Renewable energy development as a driver of economic growth: Evidence from multivariate panel data analysis," Sustain., vol. 11, no. 8, 2019, doi: 10.3390/su11082418. [18] H. H. Khoo and R. B. H. Tan, "Life Cycle Assessment Methodology : Ongoing Developments and Outlook," 2022 World Scientific Publishing Company, 2022, pp. 1–21. [19] T. Schaubroeck, S. Schaubroeck, R. Heijungs, A. Zamagni, M. Brand, and E. Benetto, "Attributional & Consequential Life Cycle Assessment : Definitions , Conceptual Characteristics and Modelling Restrictions," Sustainability, pp. 1–47, 2021, doi: https://doi.org/ 10.3390/su13137386. [20] E. Chambile, N. Ijumba, B. Mkandawire, and J. de D. Hakizimana, "Data on the life cycle carbon emission in Kenyan, Rwandan, and Tanzanian grid electricity generation and transmission systems," Data Br. J., vol. 40, 2022, doi: https://doi.org/10.1016/j.dib.2021.107692. [21] Rwanda Energy Group, "Rwanda Least Cost Power Development Plan (LCPDP) 2019 – 2040," Kigali, 2019. [Online]. Available: https://www.reg.rw/fileadmin/user_upload/LCPDP_REPORT_June_2019.pdf. [22] Eastern Africa Power Pool, "Eastern Africa Power Pool Regional Master Plan Volume II: Data Report," Addis Ababa, Ethiopia, 2014. [Online]. Available: http://www.ea-energianalyse.dk/reports/1332/1332_eapp_master_plan_2014_volume_2_data_report.pdf. [23] United Republic of Tanzania, "Power System Master Plan 2016 Update," Dodoma, 2016. [Online]. Available: https://www.infoafrica.it/wp-content/uploads/2017/02/Power-System- Master-Plan-PSMP-2016-Update.pdf.

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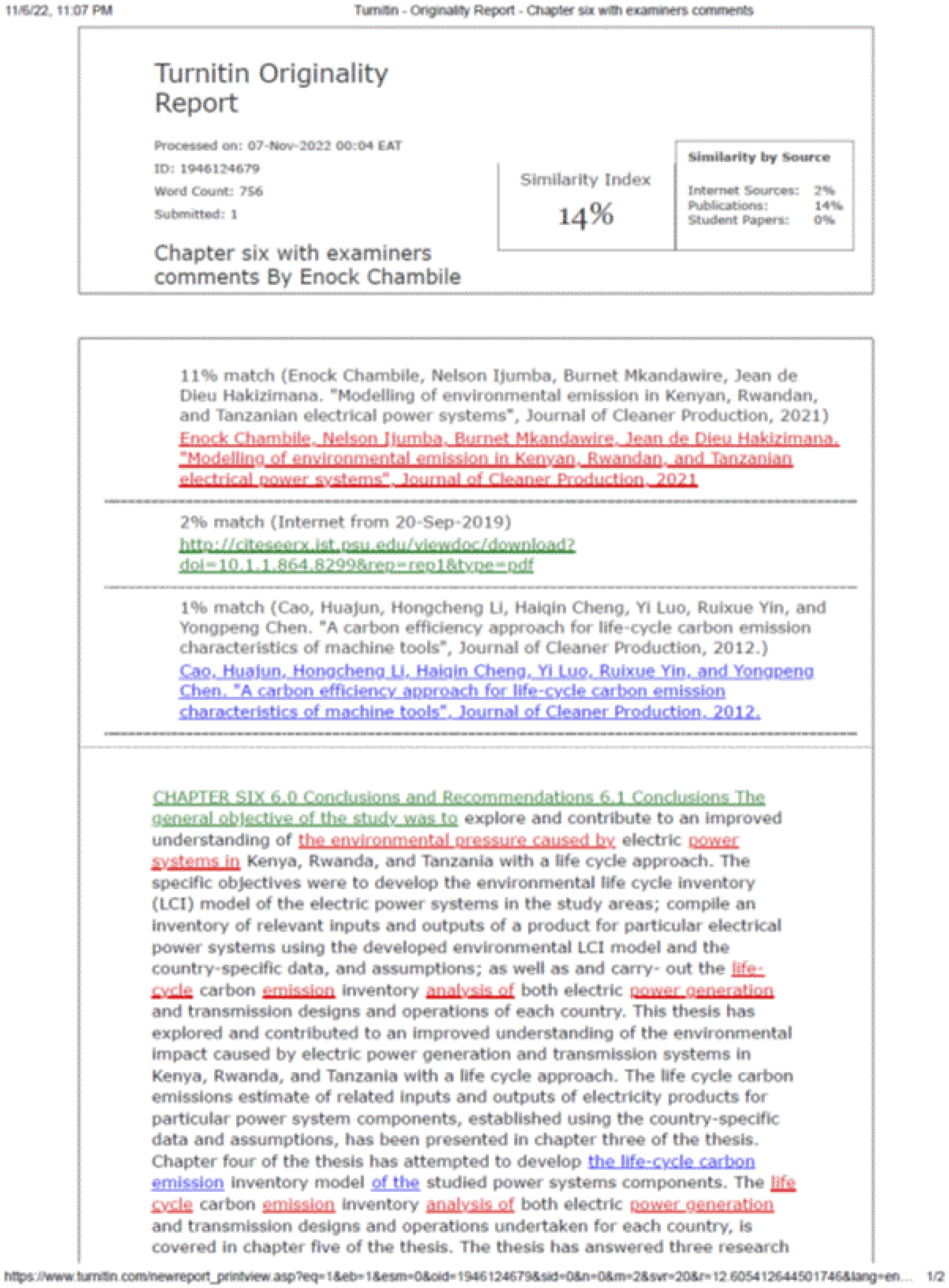

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CHAPTER SIX 6.0 Conclusions and Recommendations 6.1 Conclusions The general objective of the study was to explore and contribute to an improved understanding of the environmental pressure caused by electric power systems in Kenya, Rwanda, and Tanzania with a life cycle approach. The specific objectives were to develop the environmental life cycle inventory (LCI) model of the electric power systems in the study areas; compile an inventory of relevant inputs and outputs of a product for particular electrical power systems using the developed environmental LCI model and the country-specific data, and assumptions; as well as and carry- out the life-cycle carbon emission inventory analysis of both electric power generation and transmission designs and operations of each country. This thesis has explored and contributed to an improved understanding of the environmental impact caused by electric power generation and transmission systems in Kenya, Rwanda, and Tanzania with a life cycle approach. The life cycle carbon emissions estimate of related inputs and outputs of electricity products for particular power system components, established using the country-specific data and assumptions, has been presented in chapter three of the thesis. Chapter four of the thesis has attempted to develop the life-cycle carbon emission inventory model of the studied power systems components. The life cycle carbon emission inventory analysis of both electric power generation and transmission designs and operations undertaken for each country, is covered in chapter five of the thesis. The thesis has answered three research

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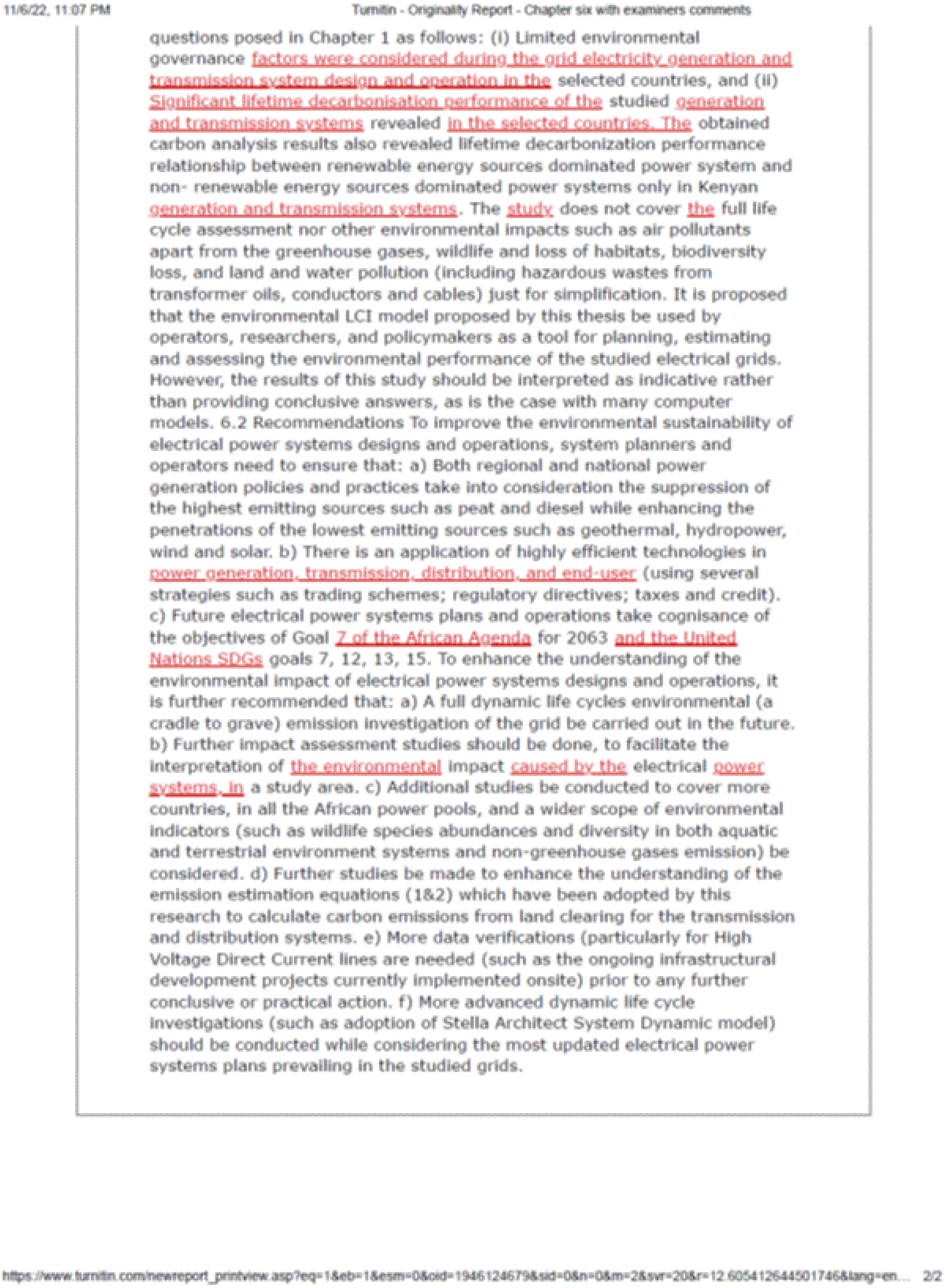

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questions posed in Chapter 1 as follows: (i) Limited environmental governance factors were considered during the grid electricity generation and transmission system design and operation in the selected countries, and (ii) Significant lifetime decarbonisation performance of the studied generation and transmission systems revealed in the selected countries. The obtained carbon analysis results also revealed lifetime decarbonization performance relationship between renewable energy sources dominated power system and non- renewable energy sources dominated power systems only in Kenyan generation and transmission systems. The study does not cover the full life cycle assessment nor other environmental impacts such as air pollutants apart from the greenhouse gases, wildlife and loss of habitats, biodiversity loss, and land and water pollution (including hazardous wastes from transformer oils, conductors and cables) just for simplification. It is proposed that the environmental LCI model proposed by this thesis be used by operators, researchers, and policymakers as a tool for planning, estimating and assessing the environmental performance of the studied electrical grids. However, the results of this study should be interpreted as indicative rather than providing conclusive answers, as is the case with many computer models. 6.2 Recommendations To improve the environmental sustainability of electrical power systems designs and operations, system planners and operators need to ensure that: a) Both regional and national power generation policies and practices take into consideration the suppression of the highest emitting sources such as peat and diesel while enhancing the penetrations of the lowest emitting sources such as geothermal, hydropower, wind and solar. b) There is an application of highly efficient technologies in power generation, transmission, distribution, and end-user (using several strategies such as trading schemes; regulatory directives; taxes and credit). c) Future electrical power systems plans and operations take cognisance of the objectives of Goal 7 of the African Agenda for 2063 and the United Nations SDGs goals 7, 12, 13, 15. To enhance the understanding of the environmental impact of electrical power systems designs and operations, it is further recommended that: a) A full dynamic life cycles environmental (a cradle to grave) emission investigation of the grid be carried out in the future. b) Further impact assessment studies should be done, to facilitate the interpretation of the environmental impact caused by the electrical power systems, in a study area. c) Additional studies be conducted to cover more countries, in all the African power pools, and a wider scope of environmental indicators (such as wildlife species abundances and diversity in both aquatic and terrestrial environment systems and non-greenhouse gases emission) be considered. d) Further studies be made to enhance the understanding of the emission estimation equations (1&2) which have been adopted by this research to calculate carbon emissions from land clearing for the transmission and distribution systems. e) More data verifications (particularly for High Voltage Direct Current lines are needed (such as the ongoing infrastructural development projects currently implemented onsite) prior to any further conclusive or practical action. f) More advanced dynamic life cycle investigations (such as adoption of Stella Architect System Dynamic model) should be conducted while considering the most updated electrical power systems plans prevailing in the studied grids.

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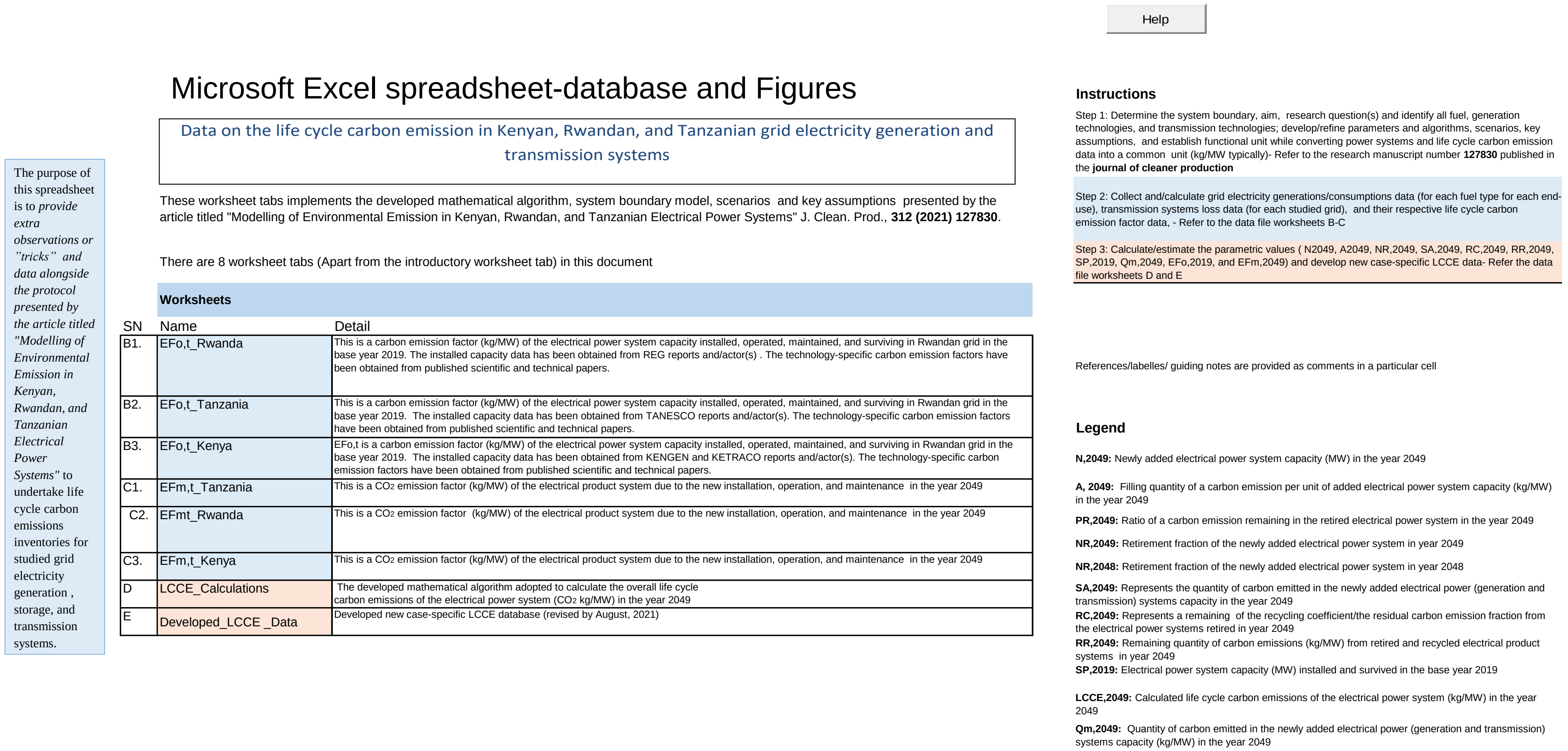
Appendix 6.0 LCCEI Excel worksheets

Appendix 6.1 LCCEI Excel worksheet (A. Introduction)



Microsoft Excel spreadsheet-database and Figures

Data on the life cycle carbon emission in Kenyan, Rwandan, and Tanzanian grid electricity generation and transmission systems

The purpose of this spreadsheet is to *provide extra observations or "tricks" and data alongside the protocol presented by the article titled "Modelling of Environmental Emission in Kenyan, Rwandan, and Tanzanian Electrical Power Systems"* to undertake life cycle carbon emissions inventories for studied grid electricity generation , storage, and transmission systems.

These worksheet tabs implements the developed mathematical algorithm, system boundary model, scenarios and key assumptions presented by the article titled "Modelling of Environmental Emission in Kenyan, Rwandan, and Tanzanian Electrical Power Systems" J. Clean. Prod., **312 (2021) 127830**.

There are 8 worksheet tabs (Apart from the introductory worksheet tab) in this document

Worksheets

SN	Name	Detail
B1.	EFo,t_Rwanda	This is a carbon emission factor (kg/MW) of the electrical power system capacity installed, operated, maintained, and surviving in Rwandan grid in the base year 2019. The installed capacity data has been obtained from REG reports and/actor(s) . The technology-specific carbon emission factors have been obtained from published scientific and technical papers.
B2.	EFo,t_Tanzania	This is a carbon emission factor (kg/MW) of the electrical power system capacity installed, operated, maintained, and surviving in Rwandan grid in the base year 2019. The installed capacity data has been obtained from TANESCO reports and/actor(s). The technology-specific carbon emission factors have been obtained from published scientific and technical papers.
B3.	EFo,t_Kenya	EFo,t is a carbon emission factor (kg/MW) of the electrical power system capacity installed, operated, maintained, and surviving in Rwandan grid in the base year 2019. The installed capacity data has been obtained from KENGEN and KETRACO reports and/actor(s). The technology-specific carbon emission factors have been obtained from published scientific and technical papers.
C1.	EFm,t_Tanzania	This is a CO_2 emission factor (kg/MW) of the electrical product system due to the new installation, operation, and maintenance in the year 2049
C2.	EFmt_Rwanda	This is a CO_2 emission factor (kg/MW) of the electrical product system due to the new installation, operation, and maintenance in the year 2049
C3.	EFm,t_Kenya	This is a CO_2 emission factor (kg/MW) of the electrical product system due to the new installation, operation, and maintenance in the year 2049
D	LCCE_Calculations	The developed mathematical algorithm adopted to calculate the overall life cycle carbon emissions of the electrical power system (CO_2 kg/MW) in the year 2049
E	Developed_LCCE _Data	Developed new case-specific LCCE database (revised by August, 2021)

Instructions

Step 1: Determine the system boundary, aim, research question(s) and identify all fuel, generation technologies, and transmission technologies; develop/refine parameters and algorithms, scenarios, key assumptions, and establish functional unit while converting power systems and life cycle carbon emission data into a common unit (kg/MW typically)- Refer to the research manuscript number **127830** published in the **journal of cleaner production**

Step 2: Collect and/calculate grid electricity generations/consumptions data (for each fuel type for each end-use), transmission systems loss data (for each studied grid), and their respective life cycle carbon emission factor data, - Refer to the data file worksheets B-C

Step 3: Calculate/estimate the parametric values (N2049, A2049, NR,2049, SA,2049, RC,2049, RR,2049, SP,2019, Qm,2049, EFo,2019, and EFm,2049) and develop new case-specific LCCE data- Refer the data file worksheets D and E

References/labelles/ guiding notes are provided as comments in a particular cell

Legend

N,2049: Newly added electrical power system capacity (MW) in the year 2049

A, 2049: Filling quantity of a carbon emission per unit of added electrical power system capacity (kg/MW) in the year 2049

PR,2049: Ratio of a carbon emission remaining in the retired electrical power system in the year 2049

NR,2049: Retirement fraction of the newly added electrical power system in year 2049

NR,2048: Retirement fraction of the newly added electrical power system in year 2048

SA,2049: Represents the quantity of carbon emitted in the newly added electrical power (generation and transmission) systems capacity in the year 2049

RC,2049: Represents a remaining of the recycling coefficient/the residual carbon emission fraction from the electrical power systems retired in year 2049

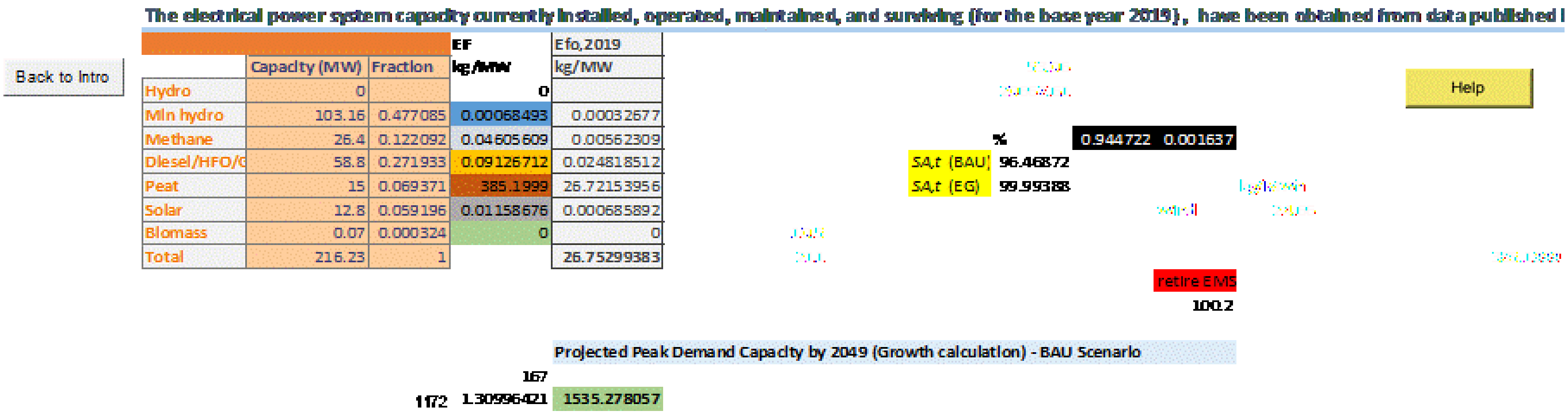
RR,2049: Remaining quantity of carbon emissions (kg/MW) from retired and recycled electrical product systems in year 2049

SP,2019: Electrical power system capacity (MW) installed and survived in the base year 2019

LCCE,2049: Calculated life cycle carbon emissions of the electrical power system (kg/MW) in the year 2049

Qm,2049: Quantity of carbon emitted in the newly added electrical power (generation and transmission) systems capacity (kg/MW) in the year 2049

Appendix 6.2 LCCEI Excel worksheet (B1. EFo,$_{2019}$_Rwanda)



The electrical power system capacity currently installed, operated, maintained, and surviving (for the base year 2019), have been obtained from data published I

	Capacity (MW)	Fraction	EF kg/MW	Efo,2019 kg/MW
Hydro	0		0	
Min hydro	103.16	0.477085	0.00068493	0.00032677
Methane	26.4	0.122092	0.04605609	0.00562309
Diesel/HFO/C	58.8	0.271933	0.09126712	0.024818512
Peat	15	0.069371	385.1999	26.7215396
Solar	12.8	0.059196	0.01158676	0.000685892
Biomass	0.07	0.000324	0	0
Total	216.23	1		26.75299383

% 0.944722 0.001637

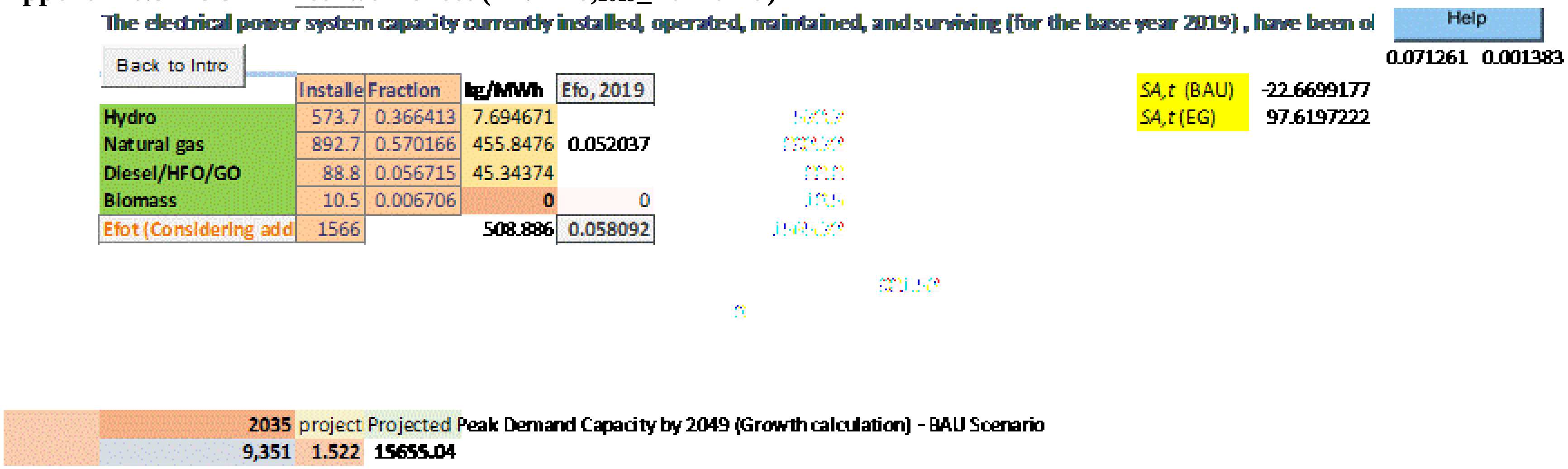
SA,t (BAU)	96.46872
SA,t (EG)	99.99388

retire EMS
100.2

Projected Peak Demand Capacity by 2049 (Growth calculation) - BAU Scenario

167
1172 1.30996421 1535.278057

Appendix 6.3 LCCEI Excel worksheet (B2. EFo,$_{2019}$_Tanzania)



The electrical power system capacity currently installed, operated, maintained, and surviving (for the base year 2019) , have been ol

0.071261 0.001383

	Installe	Fraction	kg/MWh	Efo, 2019	
Hydro	573.7	0.366413	7.694671		573.7
Natural gas	892.7	0.570166	455.8476	0.052037	892.72
Diesel/HFO/GO	88.8	0.056715	45.34374		88.8
Biomass	10.5	0.006706	0	0	10.5
Efot (Considering add	1566		508.886	0.058092	1565.72

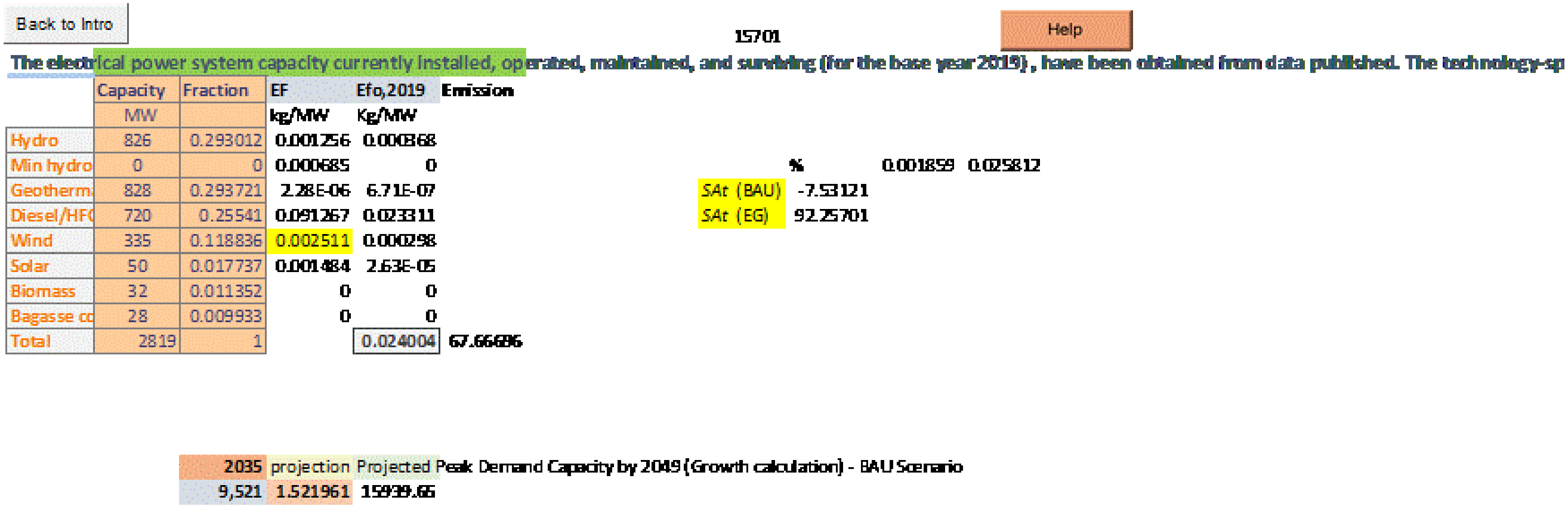
881.52

0

SA,t (BAU)	-22.6699177
SA,t (EG)	97.6197222

	2035	project	Projected	Peak Demand Capacity by 2049 (Growth calculation) - BAU Scenario
	9,351	1.522	15655.04	

Appendix 6.4 LCCEI Excel worksheet (B3. EFo,$_{2019}$_Kenya)



15701

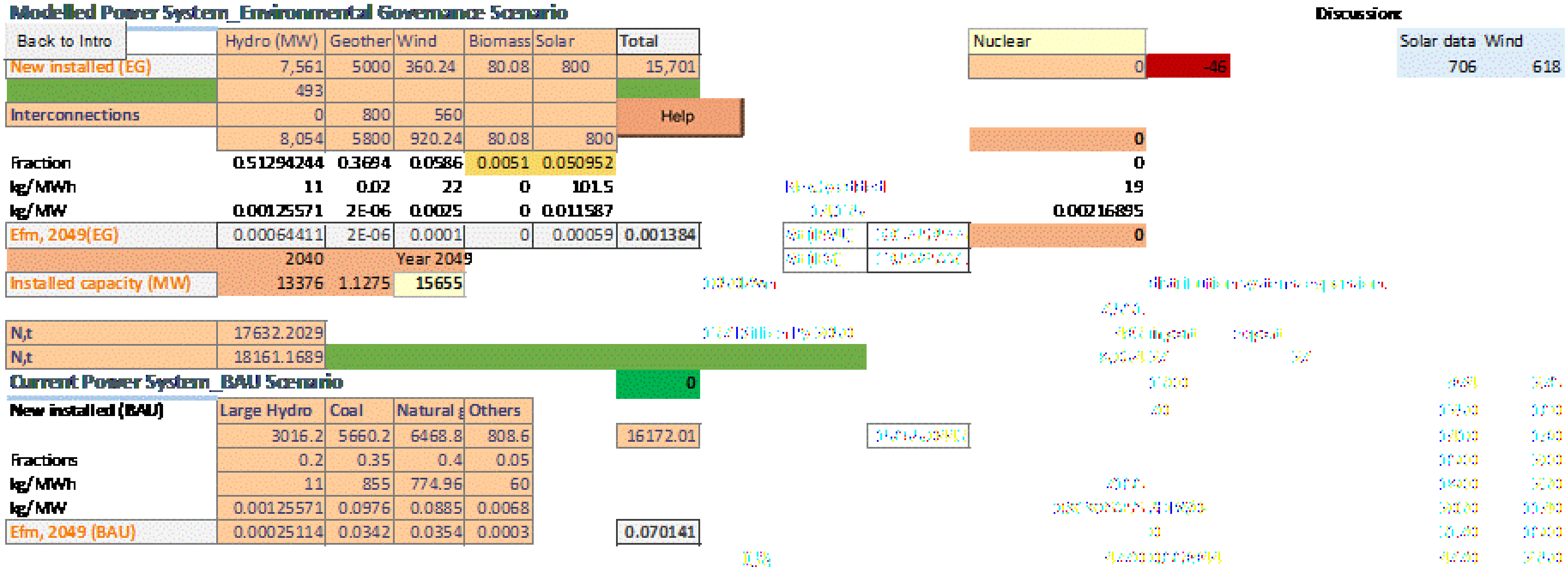
The electrical power system capacity currently installed, operated, maintained, and surviving (for the base year 2019) , have been obtained from data published. The technology-sp

	Capacity	Fraction	EF	Efo,2019	Emission
	MW		kg/MW	Kg/MW	
Hydro	826	0.293012	0.001256	0.000368	
Min hydro	0	0	0.000685	0	
Geotherm	828	0.293721	2.28E-06	6.71E-07	
Diesel/HFO	720	0.25541	0.091267	0.023311	
Wind	335	0.118836	0.002511	0.000298	
Solar	50	0.017737	0.001484	2.63E-05	
Biomass	32	0.011352	0	0	
Bagasse co	28	0.009933	0	0	
Total	2819	1		0.024004	67.66696

	%	0.001859	0.025812
SAt (BAU)	-7.53121		
SAt (EG)	92.25701		

2035	projection	Projected Peak Demand Capacity by 2049 (Growth calculation) - BAU Scenario
9,521	1.521961	15939.65

Appendix 6.5 LCCEI Excel worksheet (C1. EFm, $_{2049}$_Tanzania)



Modelled Power System_Environmental Governance Scenario

Back to Intro	Hydro (MW)	Geother	Wind	Biomass	Solar	Total
New installed (EG)	7,561	5000	360.24	80.08	800	15,701
	493					
Interconnections	0	800	560			Help
	8,054	5800	920.24	80.08	800	
Fraction	0.51294244	0.3694	0.0586	0.0051	0.050952	
kg/MWh	11	0.02	22	0	101.5	
kg/MW	0.00125571	2E-06	0.0025	0	0.011587	
Efm, 2049(EG)	0.00064411	2E-06	0.0001	0	0.00059	0.001384
	2040		Year 2049			
Installed capacity (MW)	13376	1.1275	15655			

Nuclear	
0	-46
0	
0	
19	
0.00216895	
0	

Discussions

Solar data	Wind
706	618

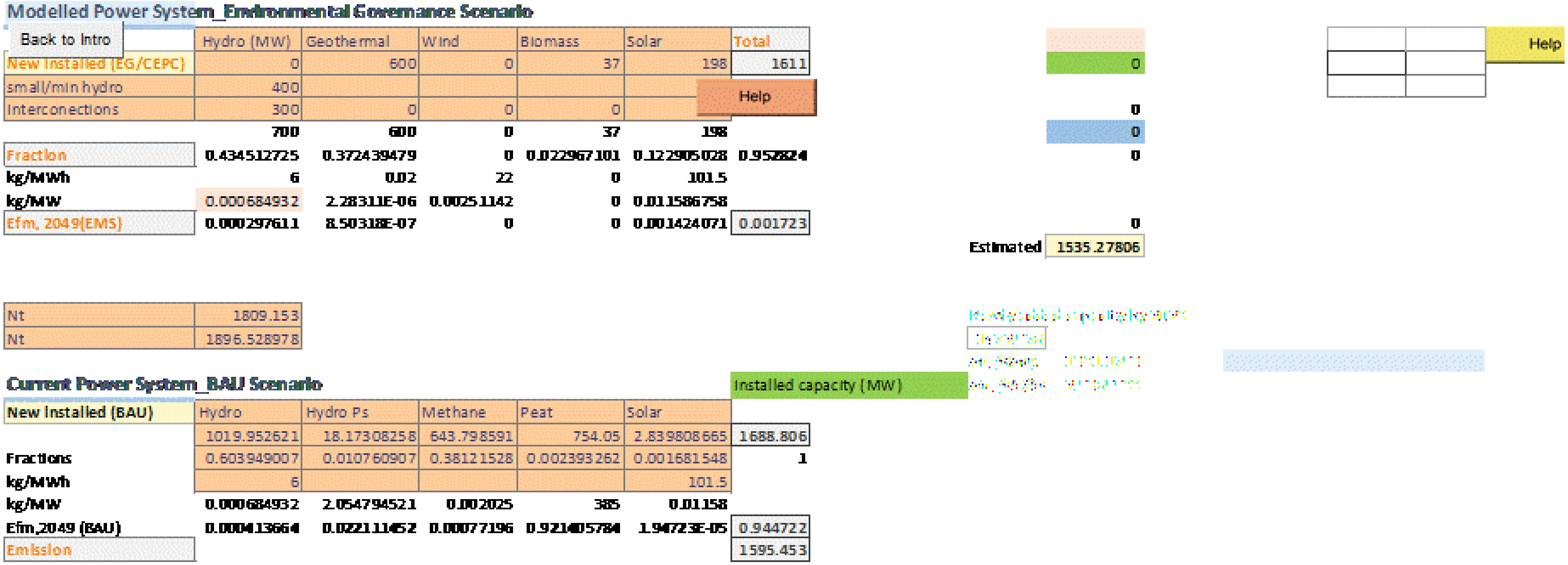
N,t	17632.2029
N,t	18161.1689

Current Power System_BAU Scenario

0

New installed (BAU)	Large Hydro	Coal	Natural g	Others	
	3016.2	5660.2	6468.8	808.6	16172.01
Fractions	0.2	0.35	0.4	0.05	
kg/MWh	11	855	774.96	60	
kg/MW	0.00125571	0.0976	0.0885	0.0068	
Efm, 2049 (BAU)	0.00025114	0.0342	0.0354	0.0003	0.070141

Appendix 6.6 LCCEI Excel worksheet (C2. EFm, $_{2049}$_Rwanda)



Modelled Power System_Environmental Governance Scenario

	Hydro (MW)	Geothermal	Wind	Biomass	Solar	Total
New Installed (EG/CEPC)	0	600	0	37	198	1611
small/min hydro	400					
Interconections	300	0	0	0		
	700	600	0	37	198	
Fraction	0.434512725	0.372439479	0	0.022967101	0.122905028	0.952824
kg/MWh	6	0.02	22	0	101.5	
kg/MW	0.000684932	2.28311E-06	0.0025114 2	0	0.011586758	
Efm, 2049(EMS)	0.000297611	8.50318E-07	0	0	0.001424071	0.001723

0

0

0

0

0

Estimated 1535.27806

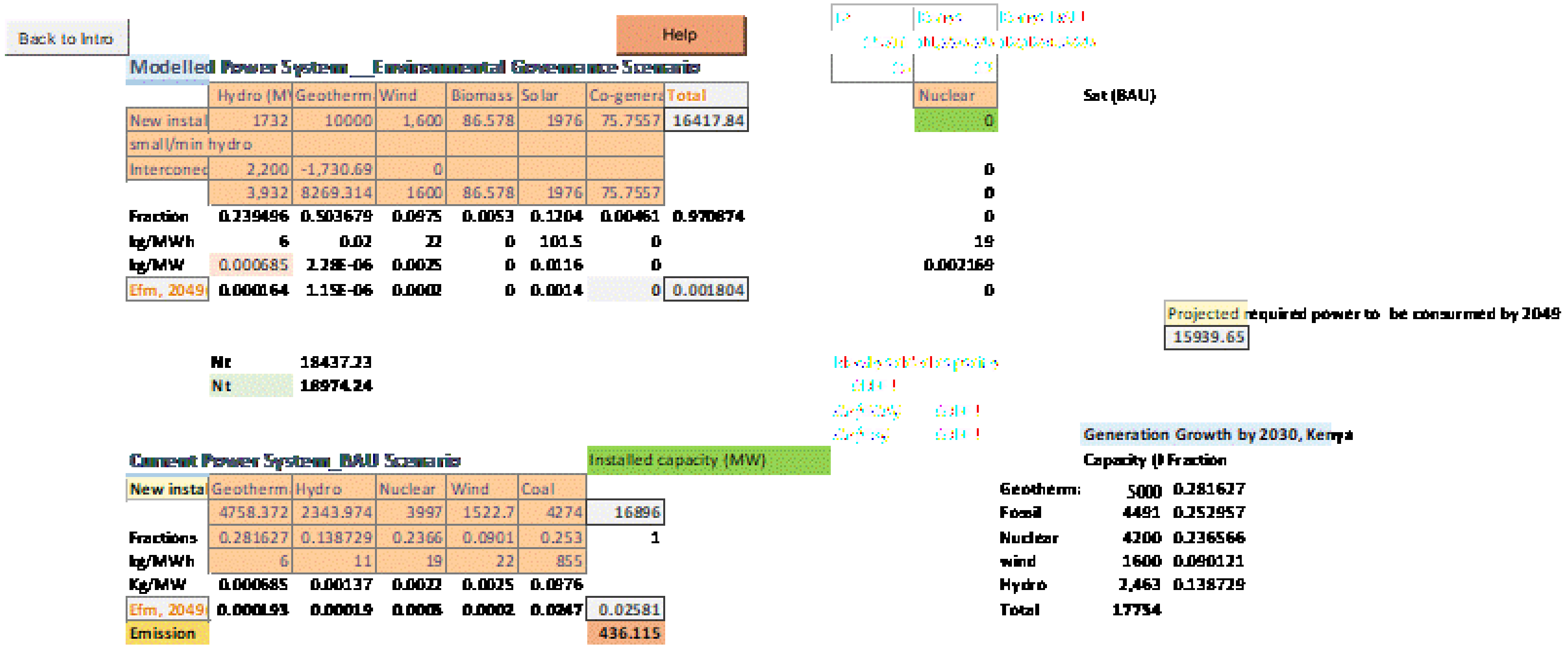
Nt	1809.153
Nt	1896.528978

Current Power System_BAU Scenario

Installed capacity (MW)

New Installed (BAU)	Hydro	Hydro Ps	Methane	Peat	Solar	
	1019.952621	18.17308258	643.798591	754.05	2.839808665	1688.806
Fractions	0.603949007	0.010760907	0.38121528	0.002393262	0.001681548	1
kg/MWh	6				101.5	
kg/MW	0.000684932	2.054794521	0.002025	385	0.01158	
Efm,2049 (BAU)	0.000413664	0.022111452	0.00077196	0.921405784	1.94723E-05	0.944722
Emission						1595.453

Appendix 6.7 LCCEI Excel worksheet (C3. EFm, $_{2049}$_Kenya)



Modelled Power System__Environmental Governance Scenario

	Hydro (M	Geotherm	Wind	Biomass	Solar	Co-genera	Total	Nuclear
New instal	1732	10000	1,600	86.578	1976	75.7557	16417.84	0
small/min hydro								
Interconec	2,200	-1,730.69	0					0
	3,932	8269.314	1600	86.578	1976	75.7557		0
Fraction	0.239496	0.503679	0.0975	0.0053	0.1204	0.00461	0.970874	0
kg/MWh	6	0.02	22	0	101.5	0		19
kg/MW	0.000685	2.28E-06	0.0025	0	0.0116	0		0.002169
Efm, 2049	0.000164	1.15E-06	0.0002	0	0.0014	0	0.001804	0

Sat (BAU)

Projected required power to be consumed by 2049

15939.65

Nt	18437.23
Nt	18974.24

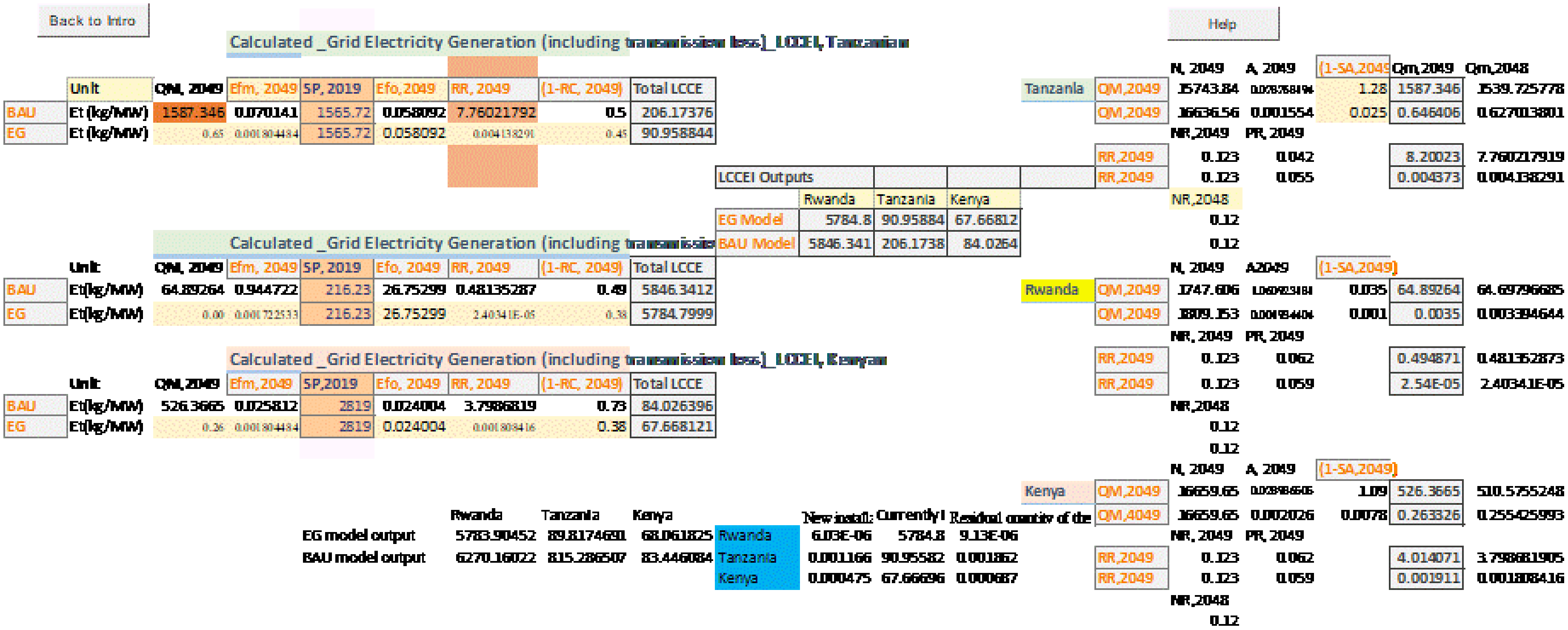
Current Power System_BAU Scenario

New instal	Geotherm	Hydro	Nuclear	Wind	Coal	Installed capacity (MW)
	4758.372	2343.974	3997	1522.7	4274	16896
Fractions	0.281627	0.138729	0.2366	0.0901	0.253	1
kg/MWh	6	11	19	22	855	
Kg/MW	0.000685	0.00137	0.0022	0.0025	0.0976	
Efm, 2049	0.000193	0.00019	0.0006	0.0002	0.0247	0.02581
Emission						436.115

Generation Growth by 2030, Kenya

	Capacity (I	Fraction
Geotherm:	5000	0.281627
Fossil	4491	0.252957
Nuclear	4200	0.236566
wind	1600	0.090121
Hydro	2,463	0.138729
Total	17754	

Appendix 6.8 LCCEI Excel worksheet (D1. LCCEI_Calculations)



Calculated _Grid Electricity Generation (including transmission loss)_LCCEI, Tanzanian

	Unit	QM, 2049	Efm, 2049	SP, 2019	Efo,2049	RR, 2049	(1-RC, 2049)	Total LCCE
BAU	Et (kg/MW)	1587.346	0.070141	1565.72	0.058092	7.76021792	0.5	206.17376
EG	Et (kg/MW)	0.65	0.001804434	1565.72	0.058092	0.004138291	0.45	90.958844

Calculated _Grid Electricity Generation (including transmissio

	Unit	QM, 2049	Efm, 2049	SP, 2019	Efo, 2049	RR, 2049	(1-RC, 2049)	Total LCCE
BAU	Et(kg/MW)	64.89264	0.944722	216.23	26.75299	0.48135287	0.49	5846.3412
EG	Et(kg/MW)	0.00	0.001722533	216.23	26.75299	2.40341E-05	0.38	5784.7999

Calculated _Grid Electricity Generation (including transmission loss)_LCCEI, Kenyan

	Unit	QM,2049	Efm,2049	SP,2019	Efo, 2049	RR, 2049	(1-RC, 2049)	Total LCCE
BAU	Et(kg/MW)	526.3665	0.025812	2819	0.024004	3.7986819	0.73	84.026396
EG	Et(kg/MW)	0.26	0.001804434	2819	0.024004	0.001808416	0.38	67.668121

LCCEI Outputs			
	Rwanda	Tanzania	Kenya
EG Model	5784.8	90.95884	67.66812
BAU Model	5846.341	206.1738	84.0264

		N, 2049	A, 2049	(1-SA,2049	Qm,2049	Qm,2048
Tanzania	QM,2049	15743.84	0.078768194	1.28	1587.346	1539.725778
	QM,2049	16636.56	0.001554	0.025	0.646406	0.627013801
		NR,2049	PR, 2049			
	RR,2049	0.123	0.042		8.20023	7.760217919
	RR,2049	0.123	0.055		0.004373	0.004138291
		NR,2048				
		0.12				
		0.12				

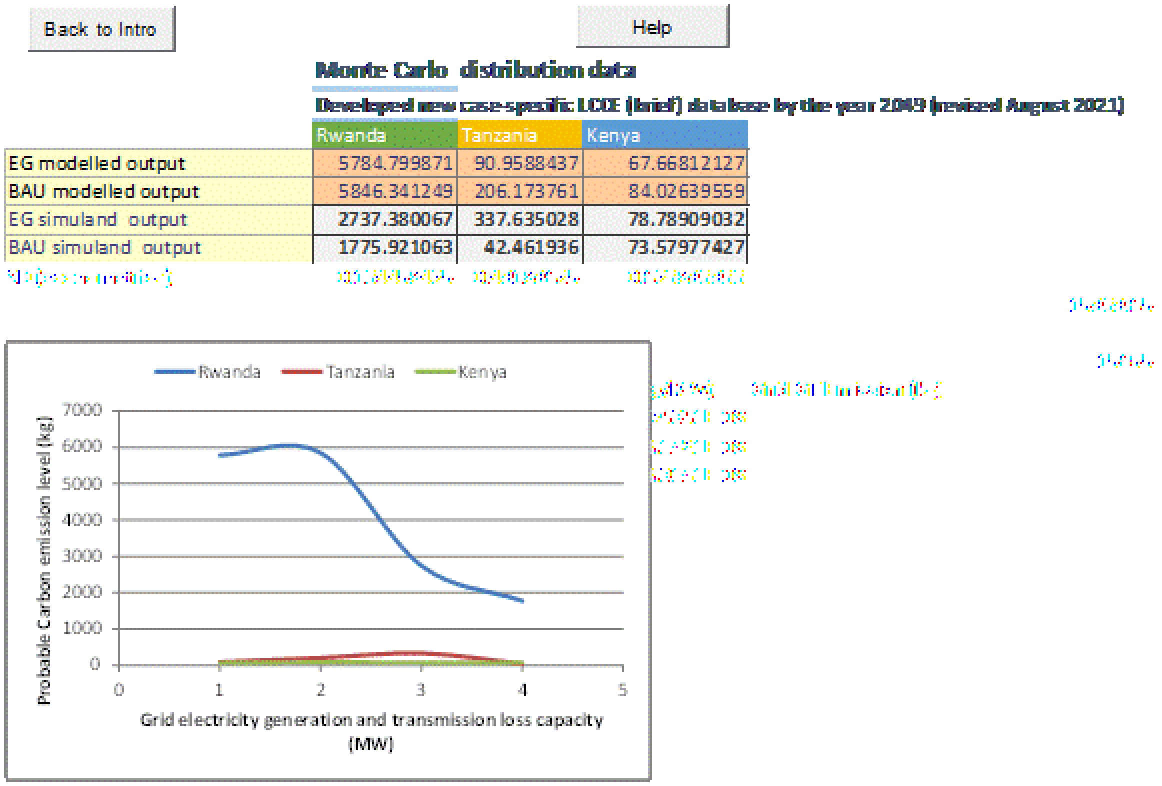
		N, 2049	A2049	(1-SA,2049)		
Rwanda	QM,2049	1747.606	1.060923184	0.035	64.89264	64.69796685
	QM,2049	1809.153	0.001984404	0.001	0.0035	0.003394644
		NR, 2049	PR, 2049			
	RR,2049	0.123	0.062		0.494871	0.481352873
	RR,2049	0.123	0.059		2.54E-05	2.40341E-05
		NR,2048				
		0.12				
		0.12				

		N, 2049	A, 2049	(1-SA,2049)		
Kenya	QM,2049	16659.65	0.028984606	1.09	526.3665	510.5755248
	QM,4049	16659.65	0.002026	0.0078	0.263326	0.255425993
		NR, 2049	PR, 2049			
	RR,2049	0.123	0.062		4.014071	3.798681905
	RR,2049	0.123	0.059		0.001911	0.001808416
		NR,2048				
		0.12				

	Rwanda	Tanzania	Kenya
EG model output	5783.90452	89.8174691	68.061825
BAU model output	6270.16022	815.286507	83.446084

	New install:	Currently I	Residual quantity of the
Rwanda	6.03E-06	5784.8	9.13E-06
Tanzania	0.001166	90.95582	0.001862
Kenya	0.000475	67.66696	0.000687

Appendix 6.9 LCCEI Excel worksheet (E1. Developed LCCE data)



Monte Carlo distribution data

Developed new case-specific LCCE (brief) database by the year 2049 (revised August 2021)

	Rwanda	Tanzania	Kenya
EG modelled output	5784.799871	90.9588437	67.66812127
BAU modelled output	5846.341249	206.173761	84.02639559
EG simuland output	**2737.380067**	**337.635028**	**78.78909032**
BAU simuland output	**1775.921063**	**42.461936**	**73.57977427**