Estimation of Greenhouse Gases Emissions from on Grid Electricity Generation and Residential Sectors in Rwandabetween 1990 and 2015

Jean Baptiste GAHIMANO

College of Sciences and Technology

School of Sciences

Master of Atmospheric and Climate Sciences

August 2018

Estimation of Greenhouse GasesEmissions from on Grid Electricity Generation and Residential Sectors in Rwanda between 1990 and 2015

Jean Baptiste GAHIMANO

Reg .Number:217290876

A dissertation submitted in partial fulfilment of the requirements for the degree of

MASTER OF ATMOSPHERIC AND CLIMATE SCIENCES

In The College of Sciences and Technology

Supervisor**: Prof. Bonfils SAFARI**

Co-Supervisor: **Innocent NKURIKIYIMFURA & Alphonse MUTABAZI**

August 2018

Declaration

I declare that this Dissertation contains my own work except where specifically acknowledged

Jean Baptiste GAHIMANO

Reg No.: 217290876

Signature: ....

Date: ....……..

Acknowledgements

I hereby acknowledge that the research presented has been reached and finished with the help and participation of different people to whom I offer special thanks.

I wish to express my gratitude to almighty God, who always protected me and gave me both the strength and this great chance of doing master's studies at UR-CST.

In particular, I forward my thanks to my supervisors:Prof. Bonfils SAFARI and Mr. NKURIKIYIMFURA Innocent, both from the department of physics at UR-CST, and MUTABAZI Alphonse from REMAfor his guidance for selecting the research topic. I sincerely acknowledge them for their time spent analyzing my suggestions, they supervised and guided me in compiling this GHG inventory and their suggestions and insights were of great assistance in improving the quality and presentation of my work.

I wish also to express my highest consideration to my parents, friends and my colleagues at the University of Rwanda for their thoughtful feedback and assistance throughout my degree who contributed morally and financially.

Much appreciation to the entire administration of University of Rwanda and I am grateful to thank Rwanda Education Board (REB) for their scholarship and support.

May God bless you all!

Abstract

This thesis deals with energy consumption and GHG emissions from energy industries and other sectors in Rwanda. It wasaimed to inventory GHG emitted by energy sector and to recalculate GHG emissions estimates of the previous national communications carried in Rwanda case of energy sector. We wished also to identify the relevant sources of GHG emissions across on grid electricity generation and residential sectors and quantifying uncertainty assessment, key category and providing GHG emissions estimate from on grid electricity generation and residential energy sectors.

The inventory was done using IPCC method and 2006 IPCC Guidelines which allowed the assessment of greenhouse gas emissions in Rwanda. During the assessment, 1990 was the base year while 2015 was the inventory year. We used Tier 1 approach and default emission factor values provided by 2006 IPCC guidelines.

Resulting from the analysis, the trends show an average increase of 2.06**%**in total GHG emissions in Rwanda from combined on grid electricity generation and residential sector and were estimated at 455.247Gg CO2eq since 1990 and 781.928 Gg CO2eq in 2015. GHG emissions from on grid electricity generation had a low emission increment of 1.28 % if compare to that of residential activities which was 9.21%. The emissions were 144.214 Gg CO2eqfor on grid electricity generation and 637.713 Gg CO2eq residential activities in 2015.

Uncertainty analysis shows that level uncertainty ranged between ± 6.63 % and ± 9.25% while trends uncertainties were in the range between ± 21.45 % and ± 21.82 %.Energy industry and other energy sectors are identified as key categories while CO_2 from liquid fuel and NH_4, N_2O from biomass are identified as key gas for this inventory.

This work recommends other interested researchers in Rwanda to carry out researches on country emission factors insome cases to improve the accuracy of emission factors used to calculate emissions from a variety of sources.

Keywords: **GHG inventory; Energy sector; IPCC inventory software, IPCC Guidelines;Rwanda.**

List of symbols and acronyms

CH_4 Methane

CCIOU Climate Change and International Obligations Unit

CO_2 Carbon Dioxide

CO_2 eq. Carbon Dioxide equivalence

GHG Greenhouse Gas

Gg Gigagram

GGCRS Green Growth and Climate Resilience Strategy

IPCC Intergovernmental Panel on Climate Change

INC Initial National Communication

TJ Tera-Joule

UNFCCC United Nations Framework Convention on Climate Change

UN United Nation

UR -CST University of Rwanda -Collage of Science and Technology

MININFRA Ministry of Infrastructure

NAPA National Adaptation Programme of Action

N_2O Nitrous Oxide

REMA Rwanda Environmental Management Authority

SNC Second National Communication

Table of contents

List of figures

List of tables

CHAPTER1. GENERAL INTRODUCTION

1.1. Background

This thesis presents the GHG emissions for Rwanda for the period 1990 to 2015. The GHG inventory was clustered for one sector namely the energy sector in particular, on grid electricity generation and residential sectors. The emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) were considered. Based on 2006 IPCC Guidelines for National Greenhouse Gas Inventories, those three GHG emissions named above were computed through the 2006 IPCC Inventory Software and emissions are estimated following the methodological choice. Once the inventory estimates are complete, the next step is to perform an uncertainty analysis and key category analysis.

This inventory has been done through collaboration of director of climate change from REMA and one academic staff who participated in the compilation of the TNC. This was helpful for this thesis with those experts. Its aim was to inventory GHG emitted by energy sector and to recalculate emissions estimated of the previous national communications (INC and SNC) carried in Rwanda for this sector by using 2006 IPCC Guidelines. To achieve the above purpose, we were wished to identify the relevant sources of GHG emissions across on grid electricity generation and residential sectors after data collection from relevant organizations and public institutions. We have also an objective of quantifying uncertainty assessment, identifying key category and providing GHG emissions estimate from on grid electricity generation and residential energy sectors in Rwanda.

1.2. Area of Study

Rwanda is a small and landlocked country in Africa and is located in the Eastern and Central African Region and it shares the borders with Burundi in the south, Uganda in the north, Tanzania in the east and the Democratic Republic of Congo in the west. It is located within the equatorial belt; lies between 1°04’ and 2°51' south latitude, and between 28°45' and 31°15' east longitude. Its average annual temperature is between 16°C and 20°C with not too much irregular Rainfall and temperate climate [1]. Rwanda has total area of 26,338 km^2 where land occupying 24,666 km^2 and the rest is occupied by water [2].

1.3. Problem statement

Over the last 15 years, Rwanda faced power crises because of the sharp increase in demand for electrification and power within a low investment plan in energy. This result to severe electricity rationing and long daily power cuts across the country with a huge negative impact on businesses that seem to be poor utility challenges. From 2004, the Government of Rwanda made an effort that intended to generate on-grid electricity by using thermal power plants. Those implemented power plant consume liquid fuel such as diesel oil and residual fuel oil [3].

During that period also, the biomass energy was mainly exploited in form of firewood and charcoal for cooking purposes by households or some industries[4].

It was estimated that about 85% of total energy consumed in Rwanda is covered by biomass and a great part of it is covered by residential activities [5].The use of biomass and petroleum fuels released direct greenhouses gases mainly dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) that are major contributors to global warming and global climate change. Facing such challenges, Rwanda has taken actions to reduce biomass and fossil fuel energy consumption to mitigate GHG emissions[6].

Understanding the dynamics of energy consumption and associated with greenhouse gas emissions at regional level will be critical for achieving mitigation targets and a low carbon economy. However, it needs considerable knowledge to guide this process since in some studies, they consider amount of energy consumption to estimate associated emissions on energy statistics rather than direct measurements, which contributes to the uncertainty and inconsistency of GHG accounts. Reducing the uncertainty requires the inventory of energy consumption and associated GHG emissions in specific regions and sectors.This will remove the gap between knowledge of how emissions are generated to improve expertise in accessing and analyzing multiple data sources which is also considered to be important as well.Inventories in Rwanda are done for the purpose of reporting to the UNFCCC and may not correspond to actual public research levels therefore different researches have to be gathered in different ways based on new scientific insights. In Rwanda, the INC and the SNC inventories have been carried across different inventory sectors by using 1996 IPCC Guidelines and their best practices. Therefore, the main research problem was to carry out a recalculation of previous GHG inventories for energy sector from 1990 to 2015 by using 2006 IPCC Guidelines and to evaluate how the past and current trends in energy consumption represented byon grid electricity generation and residential activities developed over time in Rwanda.

1.4. Objectives of this study

The main purpose of this thesis was to inventory GHG emitted by energy sector and to recalculate emissions estimated of the previous national communications (INC and SNC) carried in Rwanda for this sector by using 2006 IPCC Guidelines. The overall objective of the studies was to increase understanding of GHG emissions related to both on grid electricity generation and residential sectors since these two sectors are considerably large and encompass many aspects in Rwanda which would leads to a fairly well understanding of the energy consumption and GHG emission behavior.

Specific objectives

In order to achieve the above purpose of this study, the following objectives are conducted:

i. Identify the relevant sources of GHG emissions across on grid electricity generation and residential sectors,
ii. Collect data of energy consumption from relevant organizations and public institutions,
iii. Quantify uncertainty assessment,
iv. Identify key category,
v. Gather GHG emissions estimate fromon grid electricity generation and residential energy sectors in Rwanda.

1.5. Significance of this study

This work is intended to identifying GHG emission sources and related emission estimates known as GHG inventory. Itgives an understanding of the actual trends and picture in GHG emissions from on grid electricity generation and residential both sub-categories of energy sector in Rwanda.

Its outcomes may help decision and policy makers to analyze and design mitigation plans and strategies to reduce the GHG emissions in the atmosphere. It comes also as framework of filling the gap of lack of gathered scientific documents on GHG inventories in Rwanda. Itinforms also the Rwandan GHG emission profile and provides information that may be helpful to manage climate risk.

1.6. Organization of this Study

This research is based on compiling an inventory of GHG emissions from grid electricity generation and residential energy sectors in Rwanda within 1990 and 2015 as base year and inventory year respectively.

It is structured within five chapters:

The first chapter introduces giving the background on energy consumption and GHG emission related to energy sector in particular on grid electricity generation and residential both sub-categories of energy sector in Rwanda, the studied problems and the objectives of this study are also given in this chapter. The second chapter reviews the literature related to this research. The material and methods used to achieve our objectives are described in the third chapter. The results of our inventory and discussion are developed in the fourth chapter while the fifth chapter concludes this study and it also gives recommendations.

CHAPTER 2. LITERATURE REVIEW

2.1. Greenhouse gases background

2.1.1. Definition

Compound gases that trap heat (long-wave radiation) in the atmosphere are defined as GHG. The mainly known heat trapping gases are carbon dioxide, methane, nitrous oxide, and the fluorinated gases. When they are present in the atmosphere, they make the Earth's surface warmer.

According to IPCC, global climate of the earth is determined by natural and of human origin factors within the sun as main driver of weather and climate. The earth's surface warms up during the day and cools down at night, releasing the heat in the form of infrared radiation (IR) into space. Before all IR can escape out the space, they are trapped by GHG present in the atmosphere. The absorption of those radiations by GHG makes it possible to keep this planet warm. Therefore, GHG is taken as one among factors that affect climate [7].

Among human activity that release GHG, there is combustion of biomass and fossil fuels such as diesel oil, residual fuel, liquid petroleum gas and other fossil fuel[8].

Since the signing of the Kyoto protocol in 1997, global efforts on reducinganthropogenic activity that impact climate change state that GHG emissions have been rapidly increasing [9].

2.2.Greenhouse effects and Global warming

Climate system is mainly influenced by changes in the concentration of different gases in the atmosphere, which affect the earth's absorption of radiation. Naturally, earth absorbs and reflects incoming solar radiation and longer wavelength terrestrial radiation is emitted back into space. A portion of the outgoing terrestrial radiation energy is absorbed by gases in the atmosphere and warms the earth's surface and atmosphere, creating what is known as the "Greenhouse effect" [10].

Anthropogenic GHG emissions released into the atmosphere change global average atmospheric concentrations and enhance the greenhouse effect by causing the rise in atmospheric temperatures. The rise in global average temperatures is known "Global Warming" and this affects climate patterns all over the world because the increase in global surface temperature thus, climate change is occurring and can be viewed through extreme weather, sea levels rise and natural disasters related to climate [11].

2.2. Background Information to Greenhouse Gases Inventory

2.2.1. Definition

GHG inventory can be defined as estimates of all emissions and removals of greenhouse gases from given sources or sinks from a defined region in a specific period of time. However, GHG inventory needs methods and guidelines[12].

The inventory should cover four sectors as indicated by the 2006 IPCC guidelines such as Energy, Industrial Processes and Product Use (IPPU), Agriculture, Forestry and Other Land Use (AFOLU) and Waste sectors [13].

2.2.2. GHG inventory methods and guidelines

The GHG emission estimates have to be compiled in accordance withtwo setsof IPCC guidelines on methodologies for GHG inventories estimation and further IPCC elaborated Good Practice Guidance and Uncertainty Management in national GHG inventories; IPCC 2000 as reference. This with guidance on good practice in 2000 and another guidance for land use, land-use change and forestry in 2003[14].

Methods to be used are developed in those guidelines. strictly, those guidelines are intended to ensure that the GHG emission estimates were transparent, accurate, complete, consistent and comparable through time and comparable with other inventories compiled in other countries of the same national circumstances[15].

GHG inventory make sense when estimates are based on parameters associated with emission rates[12].Under the United Nation, IPCC Inventory Software has been developed. The software aimed to implement Tier1 and Tier2 IPCC methodologies in the 2006 IPCC Guidelines for National GHG Inventories used in the preparation of national GHG inventories according to 2006 IPCC Guidelines either for hall inventories or for separate sectors. It is an essential tool for Parties of non Annex I of UNFCCC that have limited data resources without their own inventory systems and it can be used by those Parties, trainers and trainees in national GHG inventory compilation[16].

2.3. GHG National inventory in accordance with IPCC and UNFCCC

The United Nations Framework Convention on Climate Change (UNFCCC) is a global threat considered as international agreement which came into force in1994 with an aim of stabilizing the amount of GHG emitted in the atmosphere by human activities in order to prevent their harmful climate change. Before this convention, IPCC was established by United Nation in 1988. After two years, IPCC proved that anthropogenic activities contribute more to climate change. The proved IPCC result has been taken into account by UNFCCC[13].

Countries that are parties of the convention have to report their GHG emissions regularly to UNFCCC as an international agreement requirement for climate change. However, Annex I countries use GHG reporting to prove their emission reduction commitments such as Kyoto Protocol while non-Annex I countries use GHG reporting as a key to gain climate funding and to inform international negotiations and support policy decisions [17].That inventory report is required to be prepared in accordance with the reporting guidelines accepted by the UNFCCC which describe the methods used for estimating GHG concentrations[13].

2.4. History of Rwanda to UNFCCC and other international agreementfor climate change

The UNFCCC was one of three conventions adopted at Rio Earth Summit in the 1992. Rwanda participated in that Conventions and signed as Non-Annex I Parties to UNFCCC agreement in 1998 as its commitment to fight against climate change. The first report was titled as Initial National Communication (INC)and it was submitted to the UNFCCC in 2005. That national communication reports, it focuses on mitigation strategy, the low carbon policy and an updated emissions inventory [18].The National Adaptation Programme of Action (NAPA) was completed in 2006 and Climate Change and International Obligations Unit (CCIOU) was established in 2009 within REMA to coordinate carbon market activities [19].

The government of Rwanda also at the highest political level recognizes the environmental degradation and climate by protecting and enhancing biodiversity and ecosystem services and reduction in fuel wood demand pressure on the forest resources, different strategies such as achievement of sustainable land use and water resource management and reduced vulnerability to climate change have been provided by the Green Growth and Climate Resilience Strategy (GGCRS) that helps the country to become a climate resilient, low carbon economy by 2050 [20].

2.5. Energy sector description in Rwanda

2.5.1. Energy sector overview

In Rwanda, energy sector is based on Electricity, Biomass, Gas and Petroleum. The energy consumption is dominated by biomass where approximately 86% of primary energy comes from biomass, in the form of fire wood (57%) and charcoal (23%), together with smaller amounts of crop residues and peat (6%).; petroleum products 11% and electricity 3% of which 56% come from the hydroelectric plants and 44% from thermal power plants[5].

Following the energy policy in Rwanda and considering energy use broadly, the main consumers are households (91%), which mainly use energy in the form of traditional fuels such as wood, followed by the transport sector (4%), industry (3%), and public services (2%). Households are also the dominant consumers of electricity (51%), the bulk of which demand is primarily used for lighting. The industrial sector (42%) is the second largest consumer of energy, which mainly comes from motor drivers and lighting. Public sector consumption of electricity (6%) is mainly for powering public buildings, street lighting and water pumping[21].

2.5.2. on-grid electricity generation and residential sectors in Rwanda

In this century, Rwanda faced power crises because of the sharp increase in demand for electrification and power within a low investment plan in energy. This result to severe electricity rationing and long daily power cuts across the country with a huge negative impact on businesses that seem to be poor utility challenges. However, the Government of Rwanda made an effort that intended to generate on-grid electricity by using thermal power plants. The thermal power plants consume energy fuel such as diesel oil and residual fuel oil for the purpose of electricity generation [3].

Residential energy consumption in Rwanda covers biomass used for cooking and boiling, but it also concerns power generation to a less extent. The resources of biomass are exploited in form of wood, charcoal or agricultural residues. Residential energy covers also combustion of kerosene and liquid petroleum[4].

CHAPTER 3. METHODOLOGY

3.1. Introduction

Currently, the Republic of Rwanda does not have its own developed methodology for estimating national GHG emissions and removals. Thus, non Annex I guidelines of the UNFCCC and IPCC methodology have been used in this inventory which covers the main anthropogenic direct GHG sources (CO_2, CH_4 and N_2O) from energy sector in Rwanda and they are calculated as CO_2 equivalence.

This work is based on twosub-categories of energy category: on-grid electricity generation and residual sectors that participate more in GHG emission in Rwanda. The inventory estimates are calculated depending to the UNFCCC reporting requirements in accordance with the 2006 IPCC guidelines for national GHG inventories and default emission factors are used following Tier 1 approach to establish emissions for the energy sectors. However, methodologies proved in the Revised 1996 IPCC Guidelines and 2000 IPCC Good Practice Guidance and Uncertainty Management for National Greenhouse Gas Inventories are taken into account in this study.

3.1.1. Inventory preparation

GHG inventory was compiled by using IPCC Inventory SoftwareVersion 2.54 and all human activities input to energy were covered in this inventory including energy industries: ***on-grid electricity generation***as considered sub-sector and other sectors: ***residential sub-sector***. The software is designed to access activity data specification, emission factor assignment, emission calculations, producing emission reports and data management.

3.2. IPCC Inventory Software

The new version GHG Inventory Software has been developed by IPCC National Greenhouse Gas Inventories Programme and its Technical Support Unit located at IGES in Hayama, Japan. This software aimed to implement Tier1 and Tier2 IPCC methodologies in the 2006 IPCC Guidelines for National GHG Inventories used in the preparation of national GHG inventories according to 2006 IPCC Guidelines either for hall inventories or for separate sectors. It is an essential tool for Parties of non Annex I of UNFCCC that have limited data resources without their own inventory systems and it can be used by those Parties, trainers and trainees in national GHG inventory compilation.

Software approach is basically based on enabling to fill out activity and emission factor data into the 2006 IPCC Guidelines category worksheets. It can also support many other functions related to database administration such as Quality Control, data export / import as well as data reporting as described by the figure bellow [16]

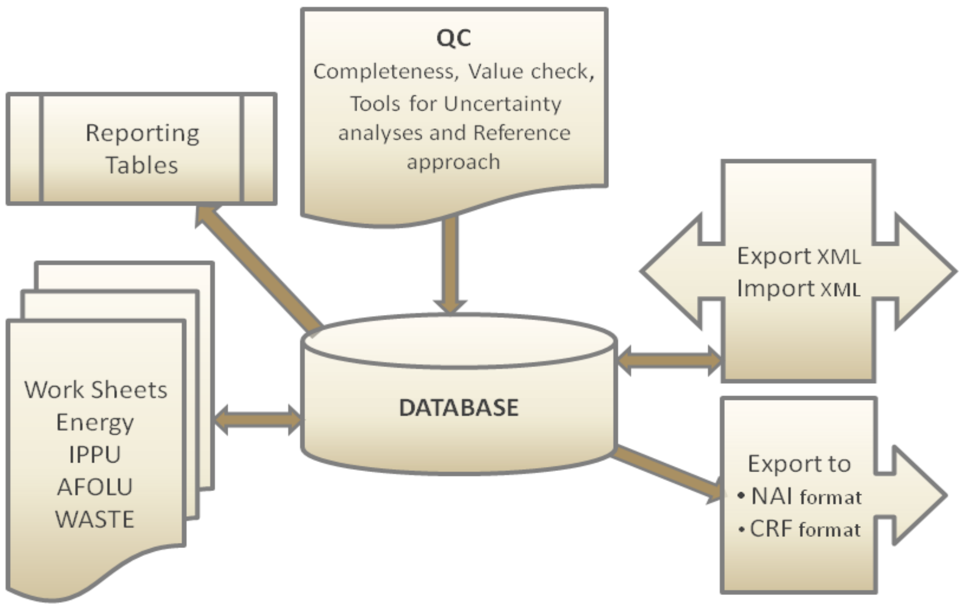

Figure 1. IPCC InventoryBasic software modules

3.3. Methodology for GHG inventory

3.3.1. Data collection

Rwanda has established a data collection strategy and existed data were used. Data collection activity is time series consistency, establish and maintain good verificationto minimize errors and inconsistencies in the inventory estimates.

In this study, data used to compile this inventory were collected from various sources including the Ministry of natural resources, Ministry of trade and industry, the Ministry of Infrastructure, the Ministry of Finance and Economic Planning; in addition of various public institutions such as Rwanda Development Board, Rwanda Standard Board, Rwanda Energy Group, Rwanda Natural Resources Authority, Rwanda Environmental Management Authority and Rwanda Revenue Authority.

3.3.2. Estimation of emissions

GHG emissions from energy industries are generally calculated by multiplying the fuel combustion by the corresponding emission factors and default values for emission factors provided in the IPCC 2006 guidelines were used with their respective uncertainty ranges.

Fuel consumption data in mass or volume units has first converted into the energy content of these fuels.

The product of activity data (fuel consumed) and emission factors (mass of carbon dioxide emitted per unit of fuel consumed) estimate GHG emitted by human activity and it is represented by this basic equation:

$$Emission = AD \bullet EF$$

Equation (1)

WithAD: activity data

EF: Emission factor

The basic method Tier 1 is used instead of Tier 2 and Tier 3 that are higher tiers demanding in terms of complexity and data requirements. Here default emission factors for energy sector provided by 2006 IPCC Guidelines were used.

3.4. Source categories

3.4.1. Energy industry sectoras source category

The Rwandan energy industry is mainly based on electricity generation from thermal power plants. In 2015, the total installed electricity capacity is 160 MW , of which 60% comes from hydrological resources along with other indigenous sources and less than 40% comes from residual fuel and diesel-powered generators [22].

Table 1: Thermal power plant in Rwanda

power plant	MW insitalled	commissioned	Fuel
Jabana I	7.8	2004	Residual
Jabana II	20	2009	Residual
Gatsata	4.77	2004	Residual
Aggreko I Gikondo	10	2005	Diesel
Aggreko I Mukungwa	5	2006	Diesel

Source:[23]

In this thesis, GHG emissions from on electricity generation are based on estimated according to 2006 IPCC guidelines.

Source categories description

In this inventory, energy industries source category considered was the main activity electricity generation (1.A1.a.i) which match to the main activity electricity and heat source categories of the 2006 IPCC guidelines.

Electricitygeneration

The emitted GHG from electricity generation in Rwanda is considered in this work with great issues for on-grid electricity generation mainly from the private companies that feed in the grid under the Power Purchase Agreement scheme. However, electricity for those industries is generated by liquid fuels (residual fuels and Gas/diesel oils) combustion in thermal generators.

3.4.2. Other sectors as source category

The other energy sector in Rwanda is based on imported liquid fuel such kerosene, LPG and biomass.Biomass is mainly exploited in form of firewood and charcoal for cooking purposes by households or some industries and about 85% of total energy consumed in Rwanda is covered by biomass where a great part of it is covered by residential activities [5]. The use of those fuel and biomass release direct greenhouses gases mainlyCO_2, CH_4, N_2O.

Source categories description

In this inventory, for the other sectors source category we have considered Residential activities (1.A.4.b) as sub-category of interest.

Residential activities

In this study, GHG emissions arising from others sectors source activities consist of emissions produced from combustion activities in household as a residential sector. It includes combustion of and biomass (including wood, charcoal and other biogas fuel) for lighting and cooking activities as described in the IPCC 2006 guidelines.

3.4. Methodological issues

According to 2006 IPCC guidelines, in this work we have estimated GHG emissions from energy industries mainly on grid electricity generation and residential by multiplying the fuel combustion by the corresponding emission factors [24].

However, Fuel consumed data in mass or volume units has first converted into the energy content of these fuels by using the methodology described in the energy statistics manual[25].

Due to lack of sufficient country-specific data, Tier 1 methodology and default values for emission factors are mainly applied for all the fuels in accordance with the methodologies and good practices detailed in the volume two to the 2006 IPCC guidelines.

3.4.1. Data sources

According to the 2006 IPCC revised guidelines; data collection is a fundamental part of inventory preparation. The main activity data in energy sector are typically the amounts of combusted fuels, their characteristics and the combustion technologies as well. While the amounts of fuels combusted would be sufficient to perform tier 1, fuel characteristics and combustion technologies are mandatory to perform tier 2 and tier 3. In this inventory, an effort was made to collect data on one parameter which is the amounts of fuels combusted. However, higher tier was not implemented due to the lack of national emission factors. Data on combusted liquid fuels have to be collected in volume units (litters) and converted in mass units (Gg) using their respective densities and finally into TJ[26].

The activity data (AD) comprised of the fuel used for electricity generation and residential sectors which is presented in **Table 2**.

The activity data was provided in terms of Gg and then we have converted them into TJ using default Net Calorific values found inside the IPCC Inventory software.

3.5. Uncertainty and time series consistency

Uncertainty is thelack of knowledge of the true value of a variable that can be described as a probability density function which characterize the range and likelihood of possible values. Uncertainty estimates are an essential element of a complete inventory of greenhouse gas emissions and they are associated with both annual estimates of emissions, and emission trends over time as proved in chapter 3, volume1 of the 2006 IPCC Guidelines.

The purpose of the uncertainty analysis for the emission inventory is to quantify uncertainty in the unknown fixed value of total emissions. Various causes of uncertainty can be quantified by statistical means. However, 95 percent confidence interval of the emissions estimates for individual categories energy sector and for the whole inventory is basically evaluated to quantify uncertainty. Confidence interval is a range that may safely be declared to be consistent with observed data. The 95 percent confidence interval is enclosed by the 2.5th and 97.5th percentiles of the PDF[27].

In this inventory, the uncertainty was estimated by mode Version 2.54 IPCC software and tier 1 methodology was used while default values for emission factor uncertainties were used in combination with uncertainties of collected data.

3.6. Key category analysis

The key category concept helps us to identify the categories that have a significant influence on a country's total energy inventory of greenhouse gases in terms of the absolute level of emissions, the trend in emissions and both level and trend assessments were performed based on the IPCC 2006 guidance for a period of 10 years from 2006 taken as a base year to 2015. However, in Rwanda GHG inventory already exists, therefore the key categories were identified quantitatively from the previous estimates [28].

3.6.1. Methodological approaches to identify key categories

Beside on greenhouse gas inventory, approach 1 level assessment has been used to identify the categories whose level has a significant effect on total national energy sector emissions. Here, data available are twenty five years and key categories are identified using a determined cumulative emissions threshold.

Approach 1 to identify key categories assesses the influence of various categories of sources on the level, and possibly the trend, of the total greenhouse gas inventory.

Both level and trend assessment for identifying key categories and key gases are conducted in this inventory by using IPCC Software a mode Version 2.54.

Level assessment

The level assessment should be performed for the base year of the inventory and for the latest inventory year (year t). Any category that meets the threshold for the base year or the most recent year should be identified as key.

The contribution of each source category to the total national inventory level is calculated according to the following equation:

Key category level assessment $= |sourcecategoryestimate \ / \ totalcontribution|$

$$L_{x,t}=\frac{|E_{x,t}|}{\sum_y |E_{y,t}|}$$

Equation (2)

Where:

$L_{x,t}$= level assessment for source x in latest inventory year (year t).

$|E_{x,t}|$ = absolute value of emission estimate of source category x in year t

$\sum_y |E_{y,t}|$= total contribution, which is the sum of the absolute values of emissions inyear t calculated using the aggregation level chosen by the country for key category analysis.

According to the above equation, key categories are those that, when summed together in descending order of magnitude, add up to 95 percent of the sum of all$L_{x,t}$.

Trend assessment

The trend assessment is used to identify categories that may not be large enough to be identified by the level assessment, but whose trend is significantly different from the trend of the overall inventory and it can be calculated according to this equation:

Trend assessment (approach 1)

$$T_{x,t} = \frac{|E_{x,0}|}{\sum_y |E_{y,0}|} \times \left| \left[\frac{(E_{x,t} - E_{x,o})}{|E_{x,0}|} \right] - \left[\frac{(\sum_y E_{y,t} - \sum_y E_{y,0})}{|\sum_y E_{y,0}|} \right] \right|$$

Equation (3)

Where:

$T_{x,t}$: Trend assessment of source category x in year t as compared to the base year (year 0)

$|E_{x,0}|$: Absolute value of emission estimate of source category x in year 0

$E_{x,t}$ and $E_{x,o}$ are real values of estimates of source category x in years t and 0, respectively

$\sum_y E_{y,t}$ and $\sum_{\square} \square_{\square,0}$ are total inventory estimates in years t and 0, respectively.

The trend of category refers to the change in the source category emissions over time, computed by subtracting the base year (year 0) estimate for source category x from the latest inventory year (year t) estimate and dividing by the absolute value of the base year estimate.

The total trend refers to the change in the total inventory emissions over time, computed by subtracting the base year (year 0) estimate for the total inventory from the latest year (year t) estimate and dividing by the absolute value of the base year estimate.

CHAPTER 4. RESULTS AND DISCUSSION

4.1. Greenhouse gas emissionsin energy sector

The total in GHG emissions during the period 1990 to 2015, by sub-sector are presented in **Table 3**.

The energy production release GHG emission in constant increasing rate but it starts to change rate in 2005 to 2015.

4.2. GHG emissions trends for energy sector

The total GHG emission growth from 1990 to 2015 was averaged to2.06% from combined on grid electricity generation and residential sector which were estimated at 455.247Gg CO2eq in 1990 to 781.928 Gg CO2eq in 2015.

As shown by **Figure2**, the general rising trend can be explained by the change in increase demand for electricity and biomass as a cooking fuel in households and industries.

In 1994, GHG emissions decrease, this can be justified by low imports of petroleum products during the 1994 Genocide of the Tutsi that happened in Rwanda.

In 2005, we have observed one of highest change in energy requirement (12.29%), this may be due to high energy demand and introduction of purchased of diesel powered generator plants in Rwanda. However, year 2008 showed a drop change in GHG emissions (7.11%), this happened due to the switch off of some private rental power plants.

The year 2015 shows a significant drop from its previous year 2014. This was influenced by different clean development mechanism introduced in Rwanda for emissions reduction purposes and a shift from fuels energy usage to renewable energy sources.

4.2. GHG emissions per inventory categories of Energy sector

4.2.1. Energy Industries

For the energy industriescategory, this study focused to on grid electricity production. The total GHG emission growth from 2005 to 2015 was 1.28% annually rate.

Figure3 showed thegeneral rising trend that can be explained by the change in lifestyle and increased demand for electricity in households and industries within Energy sector.

In 2008, it was observed a drop change in GHG emissions and may be due to switch of somepurchased diesel powered generatorof some private rental power plants in Rwanda while the research showed that oil imports increased from about 2.5% in 2000 to above 5.5% by 2012.

4.2.2. Energy Other Sectors

GHG emissions from Residential which was main contributor of Energy Other Sectors increased by an annually rate of 9.21% from 1990 to 2015 with GHG emissions of 455.24 Gg CO_2-eq and 637.71 Gg CO_2-eq respectively.

From the analysis of **Figure4, t**he year 1994 shows a significant drop from its previous years may be because of the 1994 genocide of the Tutsi that happened in Rwanda for that period, while the rising in level of the trend may due to a high demand of energy fuel such as biomass and power crisis related to increase growth of Rwandan economy.

4.3. GHG emissions per type of fuel for energy production

4.3.1. GHG emissions from liquid fuel

This inventory considered diesel oil, residual fuel, kerosene and liquid petroleum gas as energy fuels that contribute to total GHG emissions.

The general trendsshowed by **Figure 5** were consistence in three GHG gases and showed a great change since 2004. This may be related to the use of residual fuel by thermal power plants introduced in Rwanda from that time except for the year 2008. The main reason for this drop may likely be the temporal closing of some thermal power plants that use oil fuels.

4.3.2. GHG emissions from biomass

This inventory considered wood and charcoal as energy fuels that contribute to total GHG emissions. It showed an increasing trend form 6284.109Gg CO2eq in 1990 to 9011.738Gg CO2eq in 2015.

Figure 6 showed a continuous increased rate trend may be due to charcoal production that released methane especially in the traditional open.

4.5. Uncertainty and time series assessment

In this inventory, uncertainty and time series assessments were conducted using the Tier 1 methodology in accordance with the 2006 IPCC guidelines and good practices. We have taken1990 as the base year, level and trend uncertainty were estimated using the 2006 IPCC software. Level estimates ranged between± 6.63 % and ± 9.25% while trends uncertainties were in the range between ± 21.45 % and ± 21.82 %as demonstrated by **Table 4**.

Table 4showed that for some years, uncertainties are relatively high. The main reason for high uncertainties could be the data gaps, the use of default emission factors and in some cases estimates were based on extrapolated data, assumptions, and approximation methodologies.

4.6. Key categories

Based on level analysis, two source categories were identified (Table 5) as the main contributors to total direct GHG emissions in Rwanda for this energy inventory between 1990 and 2015, while 4 source categories were identified based on the trend analysis.

As it could be seen from the **Table 5**, identified key categories are energy industry where on grid electricity is taken into consideration and other sectors represented residential activities during this Energy GHG inventory.

CHAPTER 5. CONCLUSION AND RECOMMENDATION

5.1.Conclusion

In this inventory, GHG emissions from energy industries (case of on grid electricity generation) andenergy sectors (case of residential activities) were estimated for a period between 1990 and 2015. Estimates on GHG were produced on a sub-sectoral basis by considering direct GHG including CO_2, CH_4 and N_2O. The estimation of GHG emissions was determined as well and they are and expressed in CO_2 equivalent. Estimates of the key sources and uncertainty level were provided. Default emission factors provided by IPCC 2006 Revised Guidelines were used. The key category analysis was conducted both for sources and GHG gases according to IPCC 2006 guidelines.

The trends in GHG emissions from energy sector in Rwanda were analyzed from 1990 to 2015. The determined emissions were found to be in the descending order of CO_2, N_2O and CH_4.

The result from analysis showed that on grid electricity generation has lower emissions if compared residential activities. Total emissionsenergy inventory, in terms of GHG emissions in carbon equivalent, amount to emissions 455.246Gg CO_2eq from 1990 to781.928Gg CO_2eq in 2015.

The overall inventory showed that GHG emissions raised by 2.06% in total GHG emissions in Rwanda. The level uncertainties were between ± 6.63 % and ± 9.25% while trends uncertainties were in the range between ± 21.45 % and ± 21.82 %.

The result from IPCC inventory software shows that energy industry and other sectors are identified as key categories while CO_2 from liquid fuel and NH_4, N_2O from biomass are identified as key gas for this inventory.

5.2.Recommendation

There is a need for further research on the emission of greenhouse gases emissions inventory for CO_2, N_2O and CH_4 emitted from other energy sub-categories such as manufacturing industries and transport to establish its current status in Rwanda.

Further research is needed in some cases to improve the accuracy of emission factors used to calculate emissions from a variety of sources. Therefore, there is a need of developing Rwanda specific emission factors in order to shift from default emissions factors within Tier 1 to Tier2 during the coming GHG inventories.

Finally, we recommend other interested researchers to carry research on GHG emissions (CO_2, N_2O and CH_4) in Rwanda in relation with their contribution to global warming and climate change and possible effect of backup offgrid.

ADDENDUM

Addendum 1: Tables

Table 4: Fuel consumed for energy sector in Rwanda between 1990 and 2015 (TJ)

Activity (TJ)	Period	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
	Liquid Fuel	**527**	**361**	**378**	**426**	**168**	**180**	**207**	**307**	**342**	**331**	**306**	**531**	**592**
	Biomass	**56108**	**57887**	**58451**	**59006**	**59551**	**60083**	**60598**	**61095**	**61571**	**62021**	**62442**	**62830**	**62809**
Activity (TJ)	**Period**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
	Liquid Fuel	**747**	**774**	**1577**	**2093**	**2033**	**1426**	**1845**	**1960**	**2302**	**2532**	**2938**	**2923**	**2356**
	Biomass	**64699**	**67282**	**65628**	**68046**	**68953**	**69022**	**69091**	**70868**	**72691**	**74560**	**76478**	**78445**	**80462**

Table 5: GHG emissions from on grid electricity generation and residential subsectors of energy sector between 1990 and 2015 (Gg CO2 eq)

IPCC Categories	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**
Energy	**455.3**	**456.4**	**461.1**	**468**	**452.5**	**456.42**	**461**	**470.7**	**475.3**
Electricity Generation	NO	NO	NO	NO	NO	NO	NO	NO	NO
Residential	455.2	456.4	461.1	467.9	452.5	456.42	461	470.7	475.3
IPCC Categories	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
Energy	**476.4**	**476**	**493.1**	**506.3**	**531.3**	**534.68**	**609.6**	**666.8**	**669.3**
Electricity Generation	NO	NO	NO	NO	NO	0.008	33.65	91.72	95.94
Residential	476.4	476	493.1	506.3	531.3	534.67	576	575.1	573.4
IPCC Categories	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	
Energy	**624.8**	**658.9**	**680.2**	**720**	**751.6**	**795.79**	**809.8**	**781.9**	
Electricity Generation	58.03	104.1	105.1	129.5	142.7	178.6	182.6	144.2	
Residential	566.8	554.8	575	590.5	608.9	617.15	627.2	637.7	

NO: Not Occurring

Table 6: Estimated national inventory quantitative uncertainties

Period		**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Indicator	**Uncertainty in total inventory ± (%)**	**-**	**6.81**	**6.63**	**6.95**	**7.01**	**7.07**	**7.13**	**7.19**	**7.25**	**7.3**	**7.39**	**7.4**	**7.39**
	Trend uncertainty ± (%)	**21.8**	**21.8**	**22.01**	**21.77**	**21.82**	**21.81**	**21.79**	**21.76**	**21.71**	**21.72**	**21.71**	**21.65**	**21.73**
Period		**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Indicator	**Uncertainty in total inventory ± (%)**	**7.62**	**7.92**	**7.73**	**8.02**	**8.12**	**8.13**	**8.14**	**8.35**	**8.56**	**8.76**	**9.02**	**9.25**	**9.48**
	Trend uncertainty ± (%)	**21.7**	**21.7**	**21.61**	**21.54**	**21.56**	**21.68**	**21.59**	**21.58**	**21.52**	**21.49**	**21.44**	**21.45**	**21.56**

Table 7: key source categories and related key gases in Rwanda between 2006 and 2015

Key Categories by source/sink	Type of fuels	Key gases	Level Analysis	Trend Analysis	GHG Emissions (CO2 eq) for the year 2015
Energy industry	**Liquid fuels**	**CO_2**		**X**	**143.17**
Other sector	**Biomass**	**CH_4**	**X**	**X**	**506.91**
	Liquid fuels	**CO_2**		**X**	**30.89**
	Biomass	**N_2O**	**X**	**X**	**99.77**

Addendum 2: Figures

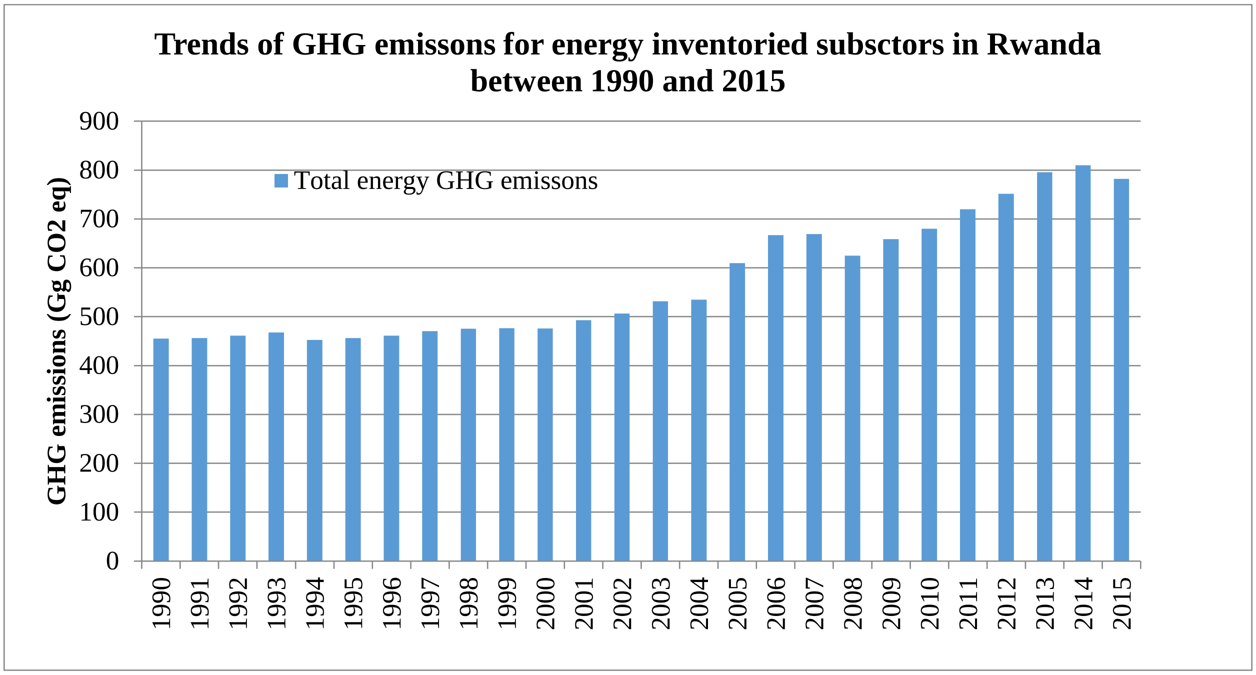

Figure 2: Total GHG emissions from energy sector in Rwanda between 1990 and 2015

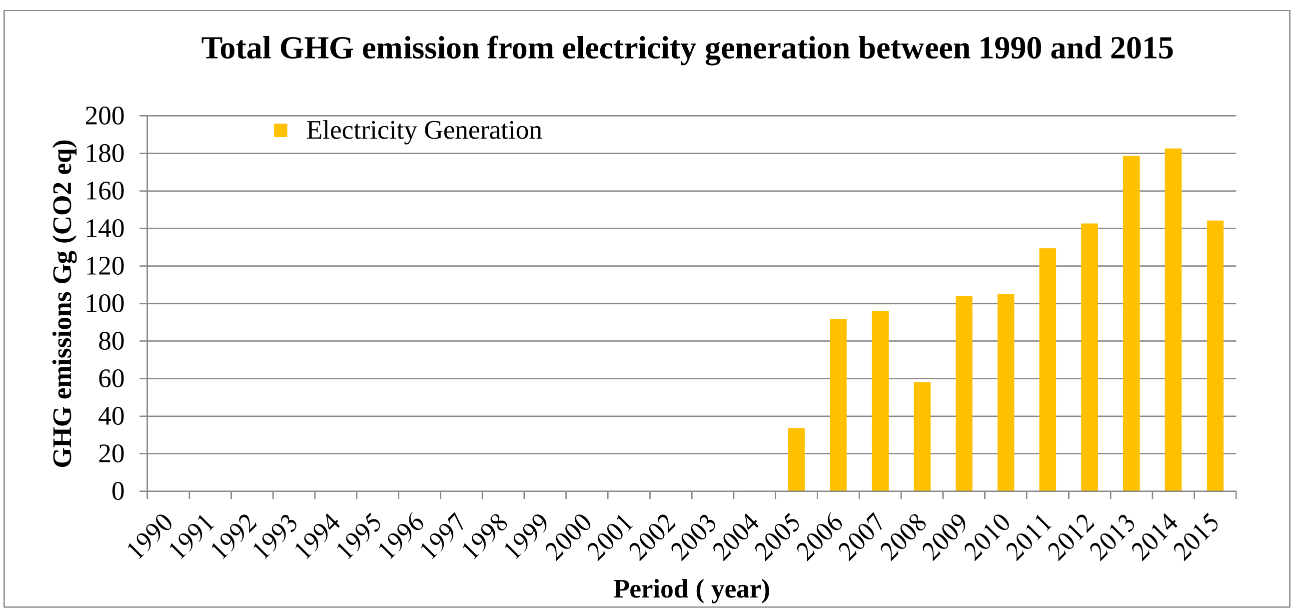

Figure 3: GHG emissions from on grid electricity generation in Rwanda between 1990 and 2015

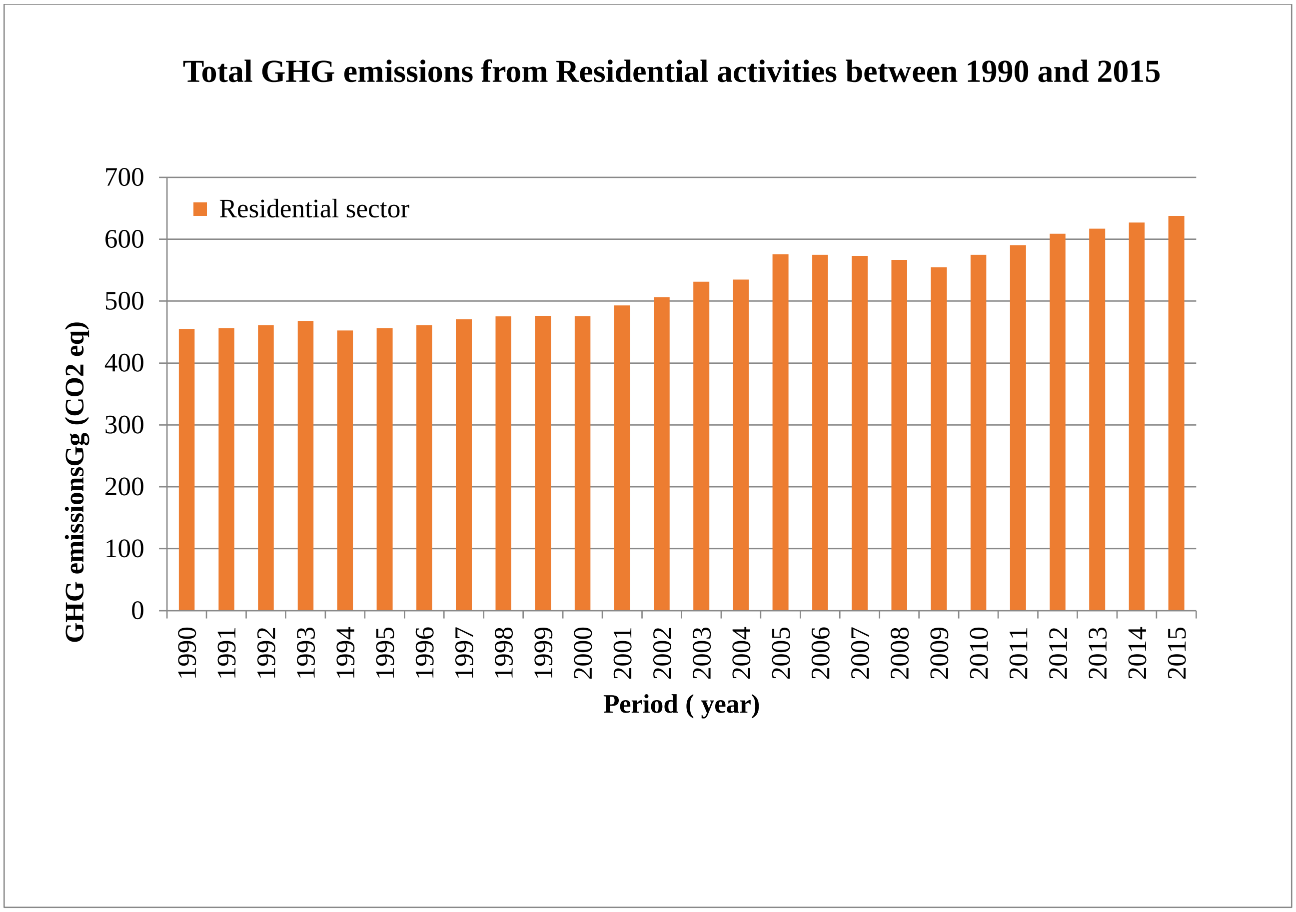

Figure 4: GHG emissions from residential activities between 1990 and 2015

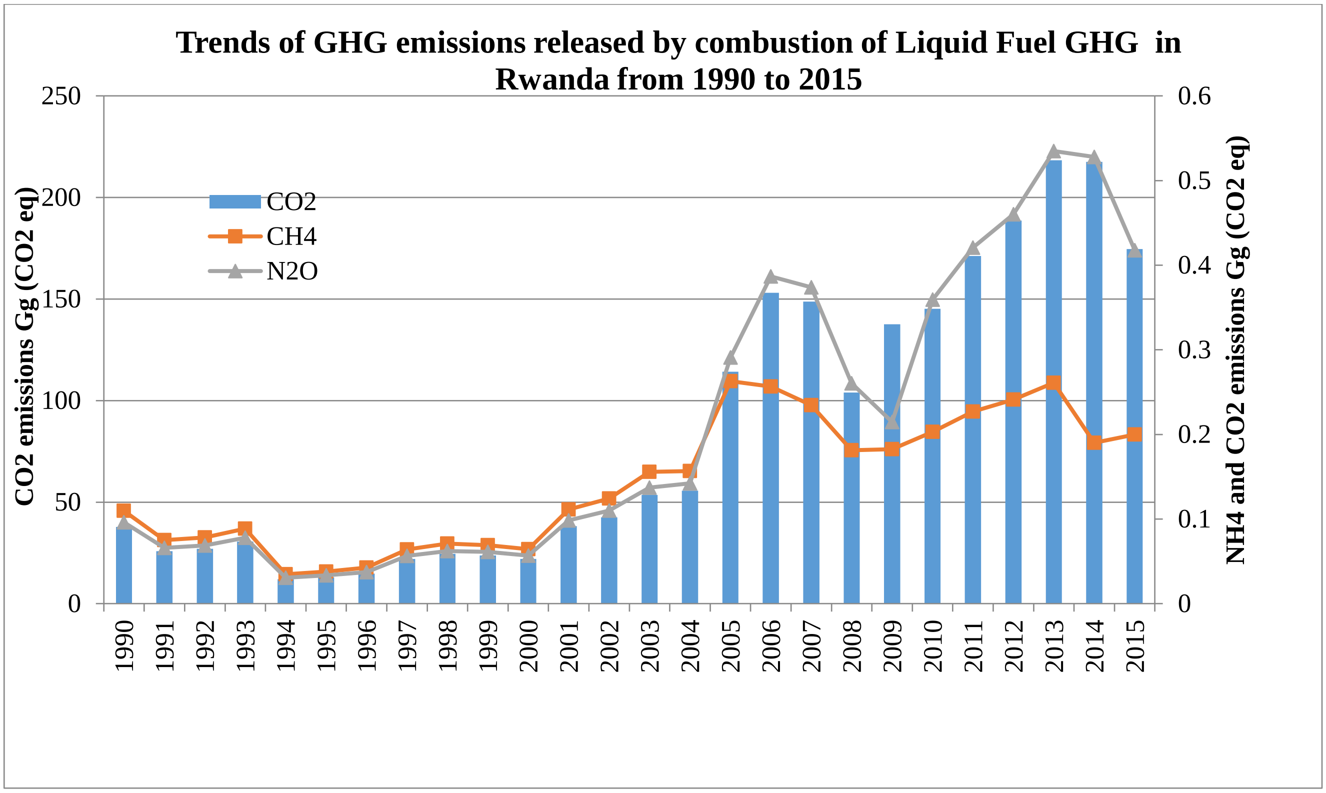

Figure 5: Trends of various GHG gases from liquid fuel in Rwanda between 1990 and 2015

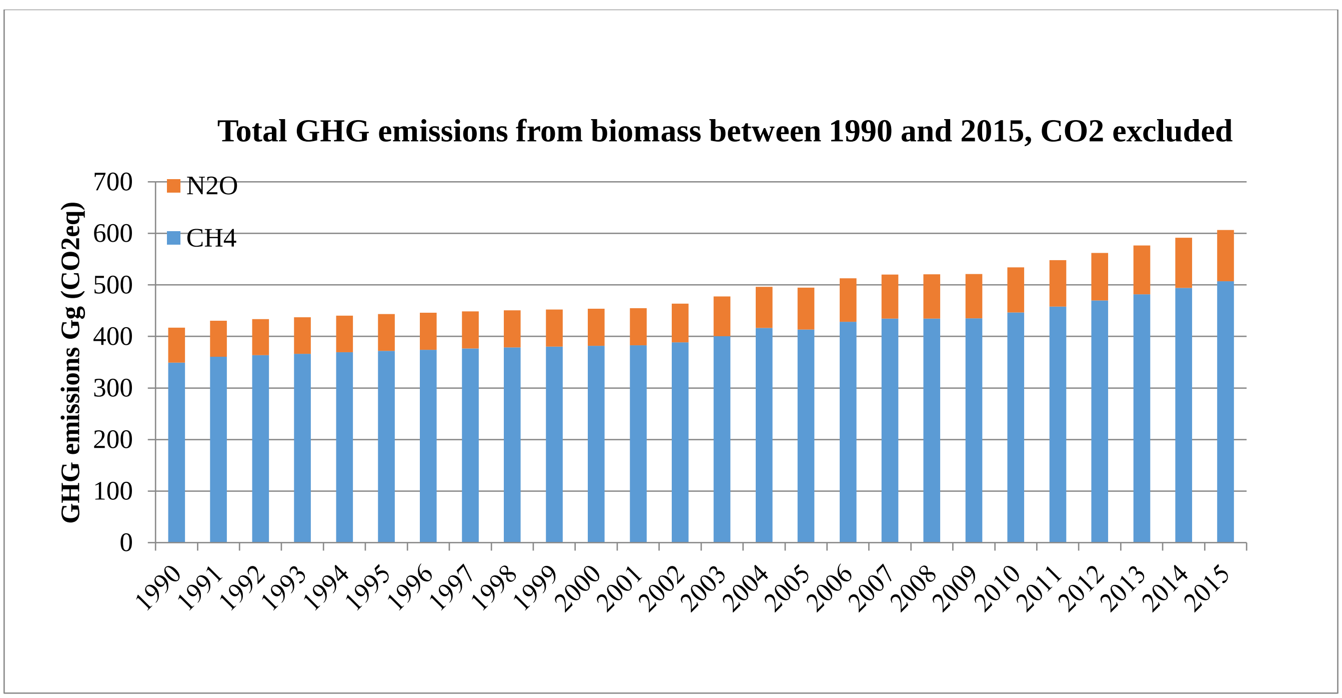

Figure 6: Trends of various GHG gases from biomass in Rwanda between 1990 and 2015

References

[1] K. Mikova, E. Makupa, and J. Kayumba, "Effect of Climate Change on Crop Production in Rwanda," *Earth Sci.*, vol. 4, no. 3, pp. 120–128, 2015.

[2] Mohammed Haggag, Jean Kalisa, and Ahmad Abdeldayem, "Projections of precipitation, air temperature and potential evapotranspiration in Rwanda under changing climate conditions," *African J. Environ. Sci. Technol.*, vol. 10, no. 1, pp. 18–33, 2016.

[3] T. Vision, "CHAPTER 8 : ENERGY RESOURCES," vol. 2020, no. Ror, pp. 1–17, 2007.

[4] S. Mubera, N. Jules, and N. Uwitonze, "Fundamentals of Renewable Energy and Applications Energy Sector Development in Sub Saharan Africa : Case Study of Rwanda," vol. 8, no. 1, pp. 1–6, 2018.

[5] S. National *et al.*, "(u.n.f.c.c.c)," 2012.

[6] T. Report, G. Lund, and F. Information, "Rwanda - State of Environment and Outlook Report 2015," no. June, 2016.

[7] IPCC, "ipcc_far_wg_I_full_report.pdf." Press Syndicate of University of Cambridge, Briitain, 1990.

[8] S. Report, O. F. The, I. Panel, and O. N. C. Change, *Managing the risks of extreme events and disasters to advance climate change adaptation*. 2012.

[9] B. Anthropogenic, "Understanding the energy consumption and Greenhouse Gas emissions and the implication for achieving climate change mitigation targets," 1997.

[10] S. Stiebert, "Greenhouse gas emissions," no. March, 2013.

[11] K. J. Hagen and J. L. Thompson, "Frederick County Greenhouse Gas Emissions Inventory Report," no. August, 2010.

[12] T. Krug and I. T. F. I. Co-chair, "GHG Inventories : Their Importance to Monitor Progress in Climate Change Mitigation," no. March, 2015.

[13] G. Gas and E. Inventories, "National Inventory Report Sweden 2017," 2017.

[14] I. Conventions, "2), 4), 2 6). .," no. February 2005, pp. 1997–2000, 2007.

[15] N. C. Accounting, "National Greenhouse Gas Inventory Report 2014," 2015.

[16] S. Republic, "IPCC Inventory Software," vol. 2017, no. June, 2017.

[17] R. D. Cóndor, *Monitoring and Assessment of Greenhouse Gas Emissions and Mitigation Potential in Agriculture (MAGHG)*. 2013.

[18] M. Cole and J. Dyszynski, "Baseline Report," no. February, 2011.

[19] E. Development and F. Population, “Rwanda INDCs - November 2015 - Page 1 of 24,” no. November, pp. 1–24, 2015.

[20] K. Provisional, “Consideration of funding proposals – Addendum XV Funding proposal package for FP073,” no. March, 2018.

[21] M. Faq, “GREENHOUSE GAS INVENTORY,” 2011.

[22] J. D. D. Uwisengeyimana, A. Teke, and T. Ibrikci, “Current Overview of Renewable Energy Resources in Rwanda,” vol. 5, no. 6, pp. 92–97, 2016.

[23] E. R. Profile, “Emissions reduction profile,” no. June, 2013.

[24] T. Simmons, “Co2 Emissions From Stationary Combustion of Fossil Fuels,” *IPPC Good Pract. Guid. Uncertain. Manag. Natl. Greenh. Gas Invent.*, pp. 15–40, 2000.

[25] C. Mandil, “Energy Statistics–Manual,” *Int. Energy Agency, Paris, Fr.*, pp. 1–196, 2005.

[26] J. Goodwin, M. Woodfield, M. Ibnoaf, M. Koch, and H. Yan, “Approaches to Data Collection,” *2006 IPCC Guidel. Natl. Greenh. Gas Invent. Vol. 1 Gen. Guid. Report.*, pp. 1–19, 2009.

[27] F. Study, O. N. Indian, and B. Public, “Chapter 3,” no. 2002, pp. 29–42, 2007.

[28] A. Herold, S. Monni, E. Lin, and C. P. Meyer, “Methodological Choice and Identification of Key Categories,” *2006 IPCC Guidel. Natl. Greenh. Gas Invent. Vol. 1 Gen. Guid. Report.*, p. 30, 2006.