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Avoided Greenhouse Gases (GHG) emissions by implementing clean-energy mini-grids in West Africa: calculation and carbon market opportunities.

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DECLARATION

I, Oumar TINE, hereby declare that this thesis represents my personal work, realised to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

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ABSTRACT

Since the Industrial Revolution, the anthropogenic greenhouse gases emissions have notably increased. With their ability to trap heat and their important level of concentrations, the greenhouse gases are the source of the global warming, which leads to the climate change. In order to reduce the atmospheric concentrations of the GHGs, it appears important to cut the emissions from the main sources as the power sector which depends on the burning of fossil fuels for heat and electricity production.

The set of emissions limit to keep the global temperature increase under 2ºC, has forced the main polluters to reduce their emissions or to buy carbon credits. Therefore the implementation of CDM projects that avoid GHGs emissions in developing countries can offset the emissions from developed countries. With a low electrification rate in West Africa, the development of CDM projects as clean energy mini-grids can help to tackle the energy issue while it could also represent an important opportunity in the carbon market.

The work carried out in this study is a calculation of the avoided emissions for three renewable energy based mini-grids, located in Senegal, using the Gold Standard methodology. In addition the opportunity from the carbon market is assessed based on the minimum carbon price set by UNGC.

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Thanks and praises to ALLAH, peace upon his blessed prophet Muhammad.

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	Alternative Current
AFOLU	Agriculture, Forestry and Other Land Use
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CDP	Carbon Disclosure Project
CER	Certified Emission Reduction
DC	Direct Current
ECOWAS	Economic Community of West African States
ECREEE	ECOWAS Center for Renewable Energy and Energy Efficiency
EEA	European Environment Agency
GHG	Greenhouse Gas
GMI	Global Methane Initiative
GWP	Global Warming Potential
IEA	International Energy Agency
IPCC	International Panel for Climate Change
IPCC-AR	IPCC Assessment Report
kVA	Kilo Volt Ampere
kWp	Kilo Watt Peak
LCA	Life Cycle Assessment
LULUCF	Land Use and Land Use Change and Forestry
MAC	Minimum Abatement Cost
MSL	Minimum Service Level
NMHC	Nonmethane Hydrocarbon
NREL	National Renewable Energy Laboratory

PV	Photovoltaic
RCP	Representative Concentration Pathway
RET	Renewable Energy Technologies
RF	Radiative Forcing
SRES	Special Report on Emissions Scenarios
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention for Climate Change
UNGC	United Nations Global Compact

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INTRODUCTION

One of the main challenge the world is facing in this 21st century is the climate change. The industrialization already established in developed countries and growing in developing countries coupled to the growth of the world population make this climate change issue more difficult to address. Across the globe the pollution of water, land and air is a major problem for all the communities and countries. This pollution comes from several and diverse sources and touch all the sectors of human activities. Water pollution is due to the deliberate or accidental introduction of dangerous and harmful foreign substances or chemicals to water. These substances come from industries wastes, sewage, pesticides and fertilizers from agricultural runoff... Garbage from households and industrial waste are the main sources of land pollution causing the degradation of soils.

The air has a defined chemical composition, it is made up of oxygen, nitrogen, water vapor and inert gases; and its pollution occurs when external elements are added to it. This pollution comes from the release of harmful chemicals into the atmosphere mainly through the burning of fuels.

The present-day atmosphere is quite different from the natural atmosphere that existed before the Industrial Revolution, in terms of chemical composition. If the natural atmosphere is considered to be "clean", then this means that clean air cannot be found anywhere in today's atmosphere. (Daly, et al., 2007)

Particles released from burning fuels can take the form of soot made of millions of very tiny elements floating in the air. The presence in the atmosphere of dangerous gases, such as carbon monoxide, nitrogen oxides and chemical vapors is another kind of air pollution. Once they are in the air these elements react with other gases, creating then smog and acid rain. One of the most dangerous form of air pollution is the greenhouse gases, such as carbon dioxide and sulfur dioxide, warming the earth through the greenhouse effect. The greenhouse effect is a physical property of the atmosphere. When the solar radiation passes through the atmosphere a part of it will reach the earth and warm it, then the warmed earth will release heat in form of infrared radiation. Many gases present in the atmosphere have the capacity to trap this infrared radiation, these gases are called greenhouse gases. They absorb a part of the infrared radiation and reject it back to the earth. This natural process is called greenhouse effect, it keeps the earth temperature at an average level vital for the development of life and the survival of the species.

Total anthropogenic GHG emissions have continued to increase over 1970 to 2010 with larger absolute decadal increases toward the end of this period. Annual anthropogenic GHG emissions have increased by 10 $GtCO_{2eq}$ between 2000 and 2010, with this increase directly coming from energy supply (47 %), industry (30 %), transport (11 %) and buildings (3 %) sectors. Since 2000, GHG emissions have been growing in all sectors, except AFOLU (Agriculture, forestry and land use). Of the 49 (±4.5) $GtCO_{2eq}$ emissions in 2010, 35 % (17 $GtCO_{2eq}$) of GHG emissions were released in the energy supply sector, 24 % (12 $GtCO_{2eq}$, net emissions) in AFOLU, 21 % (10 $GtCO_{2eq}$) in industry, 14 % (7.0 $GtCO_{2eq}$) in transport and 6.4 % (3.2 $GtCO_{2eq}$) in buildings. (IPCC, 2014)

As the energy supply sector has the largest share of greenhouse gases emission, the use of renewable energy resources to meet the needs can decrease significantly this emission.

In Sub-Saharan Africa the electrification rate is still very low particularly in the rural areas, while the demand of energy is increasing with the fast growing population. Therefore the implementation of clean energy mini-grids for small communities in rural or remote areas can help the countries to satisfy their energy demand. The clean energy mini-grids projects in West Africa could take benefits from the carbon market by fulfilling the conditions of the clean development mechanism (CDM) for small scale projects or of those of the voluntary carbon market. Those projects can earn carbon credits or certified emission reduction (CER) credits that are saleable to countries and entities having an emission-limitation commitment.

The objective of this study is to apply a calculation method of the avoided greenhouse gases emissions to small scale power generation systems supplying off-grid communities in West Africa and to assess the economical benefits of such emission reduction regarding the carbon market. This study will be a tool for policymakers to assess clean energy mini-grids projects in term of emissions reduction and carbon market opportunities.

The work carried out in the thesis is divided into four chapters:

- In the first chapter the existing literature is reviewed regarding the objective mentioned above
- The second chapter is a description of the main greenhouse gases reported by the United Nations Framework Convention on Climate Change (UNFCCC)
- In the third chapter, the methodology to calculate the avoided emissions of mini-grids is described in details including a description of the carbon market concept.
- The fourth chapter represents the case studies where results are analyzed and discussed.

A general conclusion closes the study with a short discussion on perspectives followed by some recommendations.

Chapter I. LITERATURE REVIEW

The power sector has the largest share in terms of global greenhouse gas emissions. In that share the power systems depending on fossil fuels are responsible of almost the total emissions. As an illustration the largest lifecycle GHG emissions are associated with the combustion of coal. Lifecycle assessments showed a range of 675 – 1689 gCO_{2eq}/kWh electricity for fossil fuel compared to 18 – 180 gCO_{2eq}/kWh for PV (IPCC, 2014). However technologies improvement, carbon capture and storage and the use of renewable energy technologies for heat and power generation can help to reduce significantly the emissions.

Weiser (2007) reviewed and compared the results of greenhouse gas (GHG) emission life-cycle analyses. His research focused on fossil energy technologies, nuclear and renewable energy technologies (RETs), as well as carbon capture and storage (CCS) and energy storage systems. He analyzed up- and downstream processes and their associated GHG emissions in order to avoid underestimation of GHG emissions resulting from electricity generation of the various fuel options. However the study did not take into account an economic analysis to assess the possible benefits that might be earned from replacing one technology by another. As a conclusion from the results, the introduction of advanced fossil fuel technologies can lead to an improvement of life-cycle GHG emissions but a substitution with RETs has a better significant impact.

Amponsah et al. (2014) reviewed 79 studies on a Life Cycle Assessment (LCA) of renewable energy technologies for electricity and heat generation focusing on greenhouse gases emission. Their study demonstrated the variability of existing LCA studies in tracking GHG emissions from renewable technologies and showed the significant change in the mean GHG emission within a technology from one study to another. A comparison of the results with the GHG estimates by fossil fuel indicated that the life cycle GHG emissions are higher in the conventional sources than in the renewable sources with the exception of nuclear-based power plants. However out of the environmental aspect the study did not consider the economic impacts that such assessment might provide.

Bauer et al. (2015) carried out a research on energy systems from a greenhouse gas emissions perspective. The study gave the greenhouse gas emission factors of the different fossil fuels used in the sector and the full-chain GHG emissions average of both renewable and conventional energy systems. A comparison based on the results has shown that most of the pollutants from the conventional system are emitted during the operation phase while for the renewable resources emissions appear during the manufacturing and the decommissioning phases. Moreover the study recalls the importance of considering the energy mix in the life cycle assessment of GHG emissions and gave the example of GHG emissions from Swiss electricity mix. In addition to the study of the current situation predictions are made based on trend in the power plants technologies improvement and the possibility of emissions reduction using carbon capture and storage techniques. However this study did not consider the economic aspect related to the impact of the emission or the reduction of the greenhouse gases, also systems using bio-energy are not studied and discussed.

Pallav Purohit and Axel Michaelowa (2006) carried out a study which assesses the maximum theoretical as well as the realistically achievable clean development mechanism (CDM) potential of solar photovoltaic pumps in India. According to their work, the mitigation costs of 24–242€ per ton CO_2 at current certified emission reduction (CER[1]) prices of less than 15€, SPV pump projects are not viable. However, substitution of diesel pumps could be made viable by a relatively limited subsidy. Nevertheless their study treated just an element that could be part of a mini-grid, therefore studying the CDM potential of solar photovoltaic in case of mini-grids, where there are more final consumers and more emission reduction, could be more beneficial.

Varun Ravi Prakash and I.K. Bhat (2012) carried out a research on small hydropower schemes in India, in their work they attempted to develop a life cycle GHG emissions correlations for three different types of hydropower plants (run-of

[1] Certified Emission Reductions (CERs) are a type of emissions unit (or carbon credits) issued by the Clean Development Mechanism (CDM) Executive Board for emission reductions achieved by CDM projects and verified by a DOE (Designated Operational Entity) under the rules of the Kyoto Protocol.

river, canal based and dam-toe). They found out from the correlations that the GHG emission (g-CO_{2eq}/kWh_e) decreases with the increase of capacity for all type of small hydropower schemes. GHG emission also depends upon head and the value of GHG emissions increases or decreases with head depending upon the type of SHP scheme. However an economic analysis is not included in their study, and the advantages of implementing such hydropower plants in term of economic opportunities, from the emission reduction, are not known.

Britta Reimers et al (2014) carried out a complete emissions life cycle assessment of offshore wind farms. They stated that offshore sites offer significantly better wind conditions compared to onshore. Therefore, the demand for raw materials and the related environmental impacts increase due to technically more demanding wind energy converters and additional components (e.g. substructure) for the balance of plant. They found out that all parameters related to the energy yield have a distinctive impact on the specific GHG emissions, whereas the distance to shore and the water depth affect the results marginally. As a conclusion, in comparison with onshore wind farms, utilizing the given improvement potentials GHG emissions of electricity from offshore and onshore wind farms are comparable. However in this study also there was no economic analysis to evaluate the carbon market opportunities by implementing offshore wind farms.

Proops et al.(1996) carried out a research in which they examined, in UK, the lifecycle implications of eight forms of electricity generations for the emission of three air pollutants, CO_2, SO_2 and NO_x. The assessment of the different power plants was based on three phases of the stations lifecycle: construction, operation and decommissioning. Using an input-output analysis the total pollutants emitted was calculated for each technology. The results showed that all the eight electricity generations compared to 'old coal' technology allows significant emission reduction. Moreover it shows that the emissions of pollutants from renewable based power plants occur mostly during construction and decommissioning, therefore implementation of clean energy power systems can reduce significantly those emissions. In order to understand the characteristics of power generation systems from the perspective of global warming.

Hiroki Hondo (2005) analyzed the life cycle of greenhouse gas emission from nine different systems based on fossil fuels but also on renewable energies. To calculate the emission per kilowatt hour Hondo combined the process-based analysis and the input-output analysis on the entire life cycle. However the study is limited to Japan case and an economic analysis was not carried out to assess the impact of the emissions out of the environmental aspect.

Sabin G.H Guendehou and Epiphane D. Ahlonsou (2003) carried out a critical analysis on greenhouse gas inventories in the Western African region. They found out that there were many issues in GHG emission assessment methodologies, data availability and reliability, furthermore there was a lack of technical capacity for the elaboration of greenhouse gas inventories in all countries of the region.

Annabel Yadoo and Heather (2012) Cruickshank studied the role for low carbon electrification technologies in poverty reduction and climate change strategies. They carried out their research focusing on clean energy mini-grids with three different case studies. They found out that biomass gasifiers or micro-hydro plants are the most suitable options for rural electrification. They are able to provide AC current daily, at a lower levelised cost and give the possibility to increase the capacity to supply more users in case of demand increase. Christian Breyer et al (2015) developed a methodology to calculate greenhouse gas emissions for specific representative PV applications in distinct regions. Dividing the net present value of the PV applications by the total GHG emissions they obtained what they called avoided emissions net present cost. The results of the different case studies show that PV applications ranging from small PV systems in rural off-grid regions up to large scale PV power plants and commercial PV rooftop systems show financial benefits for avoided GHG emissions, with the example of the Sub-Saharan Africa case showing very high potential.

Shreya H. Dave (2009) carried out a complete lifecycle assessment of off-grid lighting application, comparing kerosene and solar lanterns. Dave found out that transition from the conventional use of kerosene combustion to solar-based lighting is not always sustainable. However the solar-based lighting presents many advantages. By using it family can avoid indoor air pollution and additional cost related to health problems. Moreover the price of kerosene is not fixed and might be unaffordable for some people in least developing countries which are not oil producers. O. M. Longe, F.I. Oluwajobi and F. Omowole, (2013) described in their study the current energy status in Sub-Saharan Africa. The paper showed the difficulty for governments to meet the energy demand by extending the grid to connect communities in remote areas. Therefore it appears that clean energy mini-grids, in an economic perspective, represent the best solution to solve the energy access issue. In addition to the economic benefits of their implementation, the clean energy mini-grids will help to curb the emissions of greenhouse gases and other pollutants related to power generation and distribution.

Donald MacKenzie (2009) analyzed the development of carbon markets. In his research he described the market status, the actions undertaken to bring an harmony to facilitate the trade. The study analyses the possibility of establishing a standard in emission rights and discusses the orientations in term carbon market policy. It describes the two main species of carbon markets: cap and trade; and project-based.

Chapter II. GREENHOUSE GASES

II.1 Greenhouse Effect

Greenhouse gases are a group of compound with the ability to trap heat in the atmosphere. Therefore they keep the earth's temperature at an average level thus allowing life to develop on it. These gases are the main cause of the greenhouse effect. The latter is defined as the infrared radiative effect of all infrared-absorbing constituents in the atmosphere. Greenhouse gases, clouds, and (to a small extent) aerosols absorb terrestrial radiation emitted by the Earth's surface and elsewhere in the atmosphere. These substances emit infrared radiation in all directions. (IPCC, 2013)

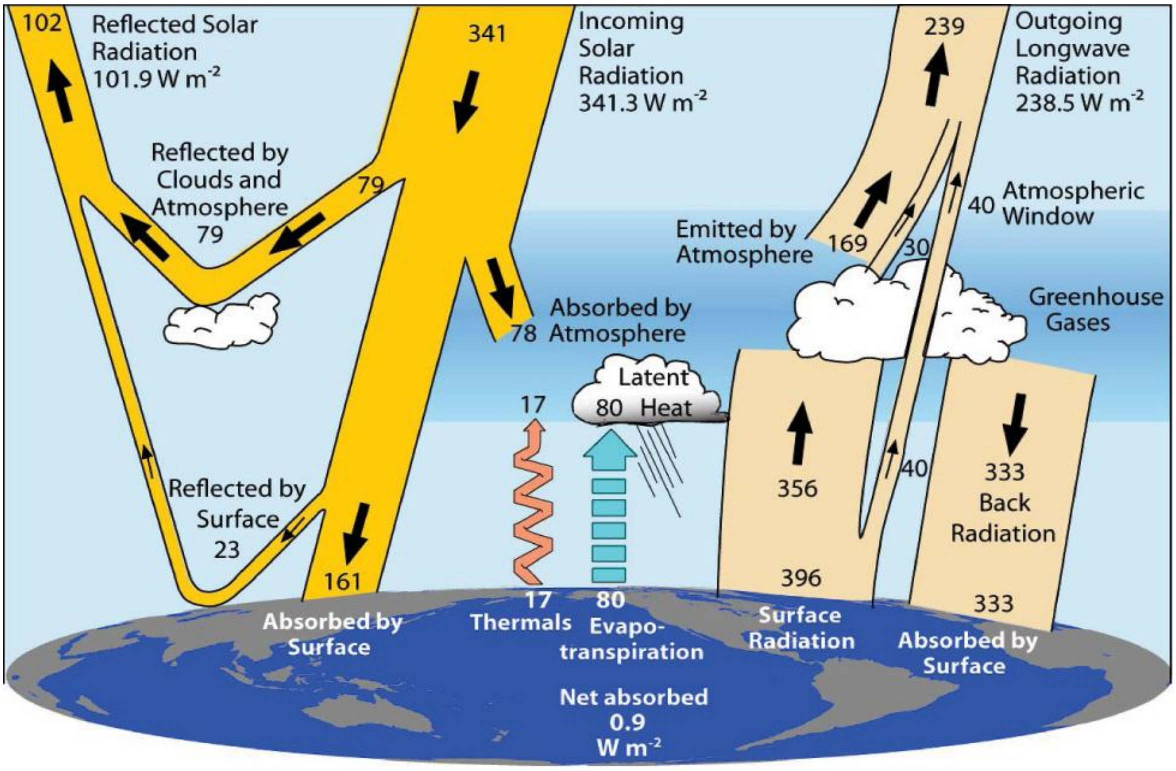

Figure II-1 Earth energy flows and greenhouse effect

The figure II.1 shows how the absorption of solar radiation is balanced by the emission of infra-red radiation through the greenhouse effect.

The greenhouse effect is a natural phenomenon that insulates the Earth's atmosphere from the cold of the space. Without the atmosphere and its physical properties as the greenhouse effect, the Earth's temperature would be around -18ºC instead of the actual 15ºC. However due to high emissions of carbon dioxide and other GHG gases from human activities, the atmosphere absorbs more heat and increases the global temperature.

That enhanced greenhouse effect is due to anthropogenic greenhouse emissions coming from different human activities. The carbon-dioxide emissions come mainly from fossil fuel combustion. The methane emission is a result of the organic decay of waste landfills. It is also produced during the production and transport of fossil fuels. Livestock and agricultural practices contribute also to methane emissions moreover they are the main source of nitrous oxide emissions as well. The fluorinated gases are totally anthropogenic, their emissions are the result of different human activities. They involve mainly in cooling systems, aluminum production, electricity distribution equipments and are the most dangerous greenhouse gases with the highest global warming potential.

There are several gases present in the atmosphere able to absorb heat. They can be produced by natural processes or human activities. Those greenhouse gases represent less than 1% of the atmosphere, for that reason they are called trace gases. Their levels in the atmosphere depend on a balance between the sources of emissions and their sinks, which respectively, produce and destroy the gases in different natural processes. However human activities introduced new sources, interfere with the sinks and therefore affect the GHGs levels. The increase of GHGs levels creates an enhanced greenhouse effect thus affecting the earth's temperature and provoke climate change. The consequences of the climate change are dramatic, it causes drought and the melting of the ice in the poles thus the sea level increases and many nether lands are threaten. Furthermore the direct and indirect consequences cannot be entirely measured. Most of the greenhouse gases present in the atmosphere naturally occur (e.g. : water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)) while the others are produced only by human activities, particularly in industrial processes (e.g. fluorinated gases).

Water vapor is the most abundant GHG in the atmosphere, representing two-thirds of the natural greenhouse gas effect. Its level in the atmosphere depends on meteorological conditions and temperatures. It is part of a hydrological cycle between oceans, lands and atmosphere. As human activities do not add water to that closed system of evaporation, condensation and precipitation, it is therefore not counted in the international greenhouse gases inventories. The rest of the greenhouse gases are trace gases with various concentrations and atmospheric lifetime. The figure II.2 represents the range of concentrations of atmospheric trace gases.

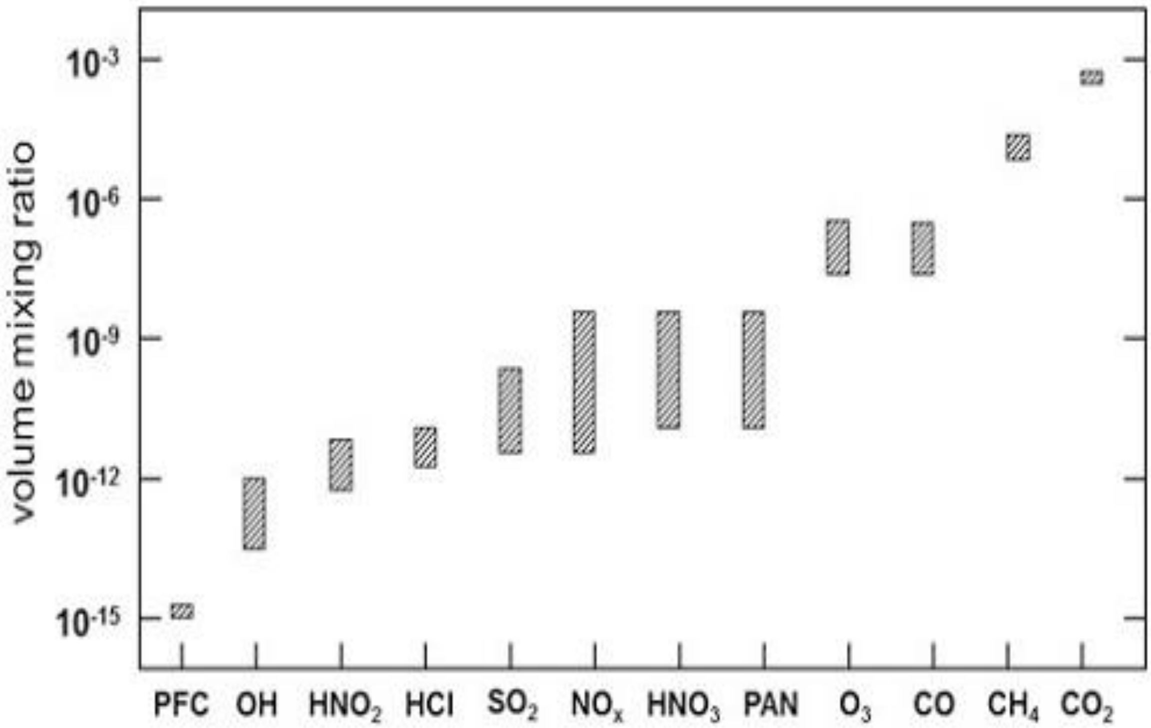

Figure II-2 Trace gases concentrations (Schlager, et al., 2012)

The figure II.2 shows that among the trace gases, the carbon dioxide (CO_2) has the highest concentration. Therefore it is used as a reference unit to express the global warming potential (GWP) of all other greenhouse gases, thus they are usually given in carbon dioxide equivalent (CO_2-eq) in term of global warming impact.

Atmospheric concentrations of several important greenhouse gases have increased significantly since large-scale industrialization began around 200 years ago. (IPCC, 2007)

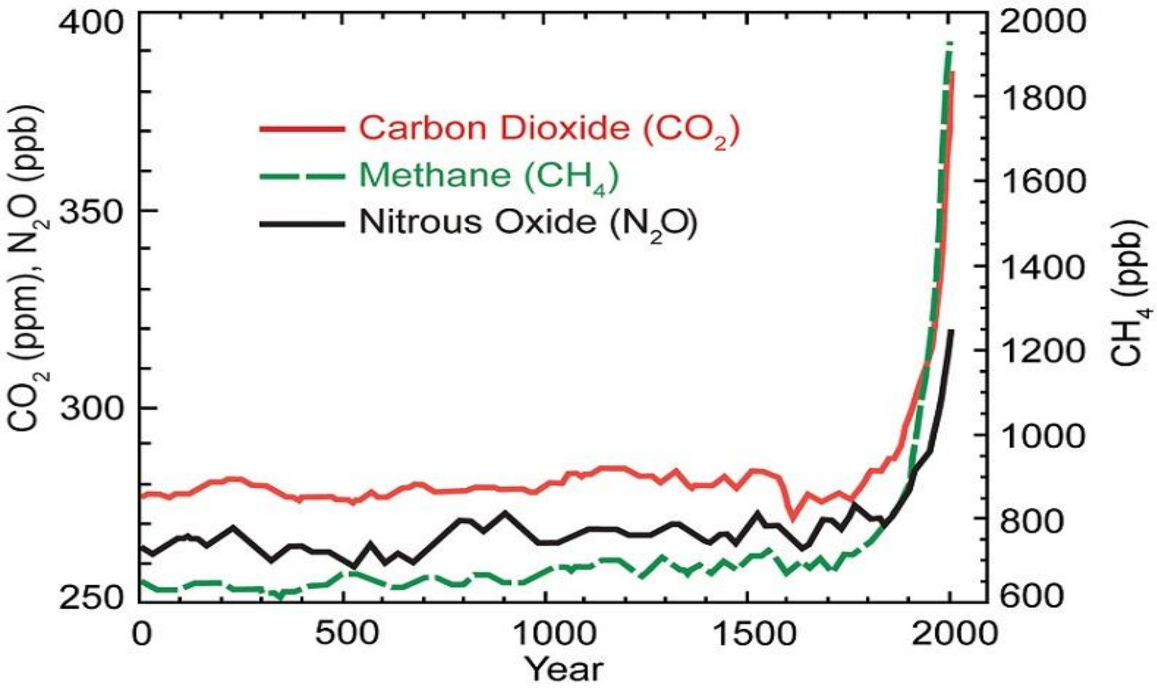

Figure II-3 Atmospheric concentrations of some greenhouse gases over the past 2000 years. (IPCC, 2007)

The result of the industrialization is the consumption of huge amount of energy which is mainly drawn from fossil fuels as they have an important energy potential. Also the advent of electricity participated significantly to the notable increase of the fossil fuels exploitation. Moreover the population growth engenders a constant increase in the global energy demand thus more and more fossil fuels are burnt to meet that demand. These facts explain the abrupt increase of concentrations on the figure II.3.

Fossil fuel combustion converts carbon that had been stored deep in the Earth to carbon dioxide that enters the atmosphere. Clearing land for agriculture converts carbon stored in soils and plants to carbon dioxide. Even though the most important greenhouse gases occur naturally and are important for life on Earth, burning fossil fuels and other human activities have caused a large increase in their concentrations. (Doll, et al., 2011)

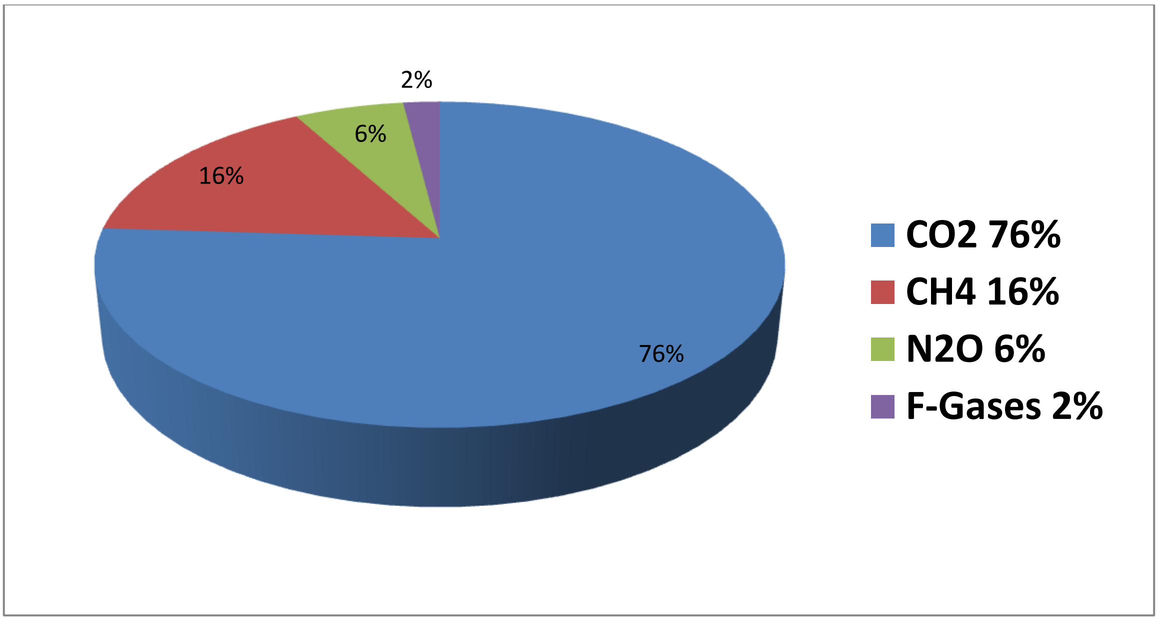

Figure II-4 Anthropogenic GHG Emissions share by Groups of Gases in 2010 (IPCC, 2014)

In the figure II.4 it appears that carbon dioxide is the principal greenhouse gas with the share of 76%, therefore it represents the main target for policymakers in order to tackle the climate change issue. However methane and nitrous oxide with their smaller amount are more dangerous than carbon dioxide and need to be reduced by cutting the anthropogenic emissions.

II.2 Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) is the principal contributor to the enhanced greenhouse gas effect and represents the second contributor to the natural greenhouse gas effect after water vapor. The observations of its concentrations started in Hawaii in 1958 at the Mauna Loa Observatory where high quality measurements were carried out.

Each year billions of tonnes of carbon dioxide are exchanged between the earth, the oceans and the atmosphere through a natural process. In fact there is a finite quantity of carbon dioxide on Earth moving in a complex process between the three mentioned elements. However change in the balance are due to human activities, which is causing an increasing concentration of carbon dioxide in the atmosphere dangerously. The actual value of the concentration is more than 40% greater than the pre-industrial value which was about 280 parts per million (ppm) and it is higher than at any time during the past 650,000 years. The information were obtained by drilling the ice in Antarctica and checking the composition of the air bubbles from different Earth's era, trapped in the ice core.

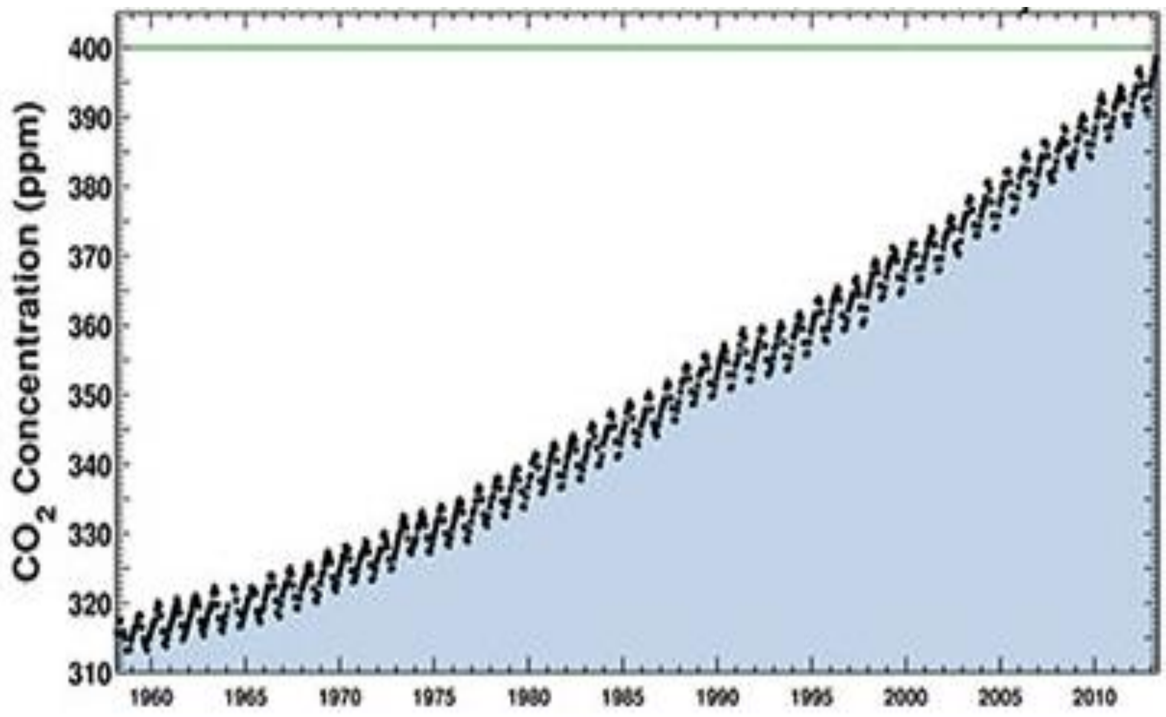

Figure II-5 Carbon dioxide concentration (Source: Scripts Institution of Oceanography)

The annual cycle observed on the figure II.5 represents the annual cycle of plant respiration. In the Northern Hemisphere CO_2 concentrations increase during Winter and Fall and decrease during Spring and Summer. The reversed process also takes place in the Southern Hemisphere at a less extend and disappears in the Equator region. It corresponds to the growth and death of the vegetations in a year.

The time taken for atmospheric CO_2 to adjust to changes in sources or sinks is of order 50 to 200 years, determined mainly by the slow exchange of carbon between surface waters and deeper layers of the ocean, consequently CO_2 emitted into the atmosphere today will influence the atmospheric concentration of CO_2 for centuries into the future. (IPCC, 1990)

II.2.1 Source of carbon dioxide (CO_2) emission

Carbon dioxide is produced through natural processes as respiration and decomposition and also by human activities. The anthropogenic CO_2 is emitted principally by the combustion of fossil fuels mainly in the power and industrial sectors. In addition the natural gas systems, the production of metals and cement represent also a non negligible source of carbon dioxide emissions.

Over 7,500 large CO_2 emission sources (above 0.1 $MtCO_2$/yr) have been identified. These sources are distributed geographically around the world but four clusters of emissions can be observed: in North America (the Midwest and the eastern freeboard of the USA), North West Europe, South East Asia (eastern coast) and Southern Asia (the Indian sub-continent). (IPCC, 2005). This pattern shows that the share of the African continent in the global carbon dioxide emissions is very low. In fact the African share of the cumulative historical carbon dioxide emission is less than 10%.

CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78 % of the total GHG emission increase from 1970 to 2010, with a similar percentage contribution for the period 2000 – 2010 (high confidence). Fossil fuel-related CO_2 emissions reached 32 (±2.7) $GtCO_2$/yr, in 2010, and grew further by about 3% between 2010 and 2011 and by about 1 – 2 % between 2011 and 2012. Of the 49 (±4.5) $GtCO_{2eq}$/yr in total anthropogenic GHG emissions in 2010, CO_2 remains the major anthropogenic GHG accounting for 76% (38±3.8 $GtCO_2$/yr) of total anthropogenic GHG emissions in 2010. (IPCC, 2014)

Furthermore land use and deforestation are a significant source of carbon dioxide emissions. The vegetation absorbs carbon dioxide from the air during its growth and part of that CO_2 is stored in the plants and in the soils. This process is therefore a biological carbon capture and sequestration. However forestry activities and change in land use can either remove the carbon dioxide from the atmosphere or release it in it. Thus plants can act as sink or source of carbon dioxide. Therefore in regions where large areas of vegetation are cleared, to develop agriculture or to build facilities and settlements, the land use, the land use change and forestry (LULUCF) can be an important source of carbon dioxide emission.

Natural sources (figure II.6) of carbon dioxide emission regroup ocean-atmosphere exchange, plant, animal and micro organisms respiration and decomposition. The dissolved carbon dioxide within the oceans is released into the air at the surface of the water, it represents 42.84% of the total natural sources. The emissions from the organisms come from respiration and decomposition where the carbon dioxide is a by-product of the energy production and the breakdown of dead organic material. Together they account for 57.12% of the total natural sources.

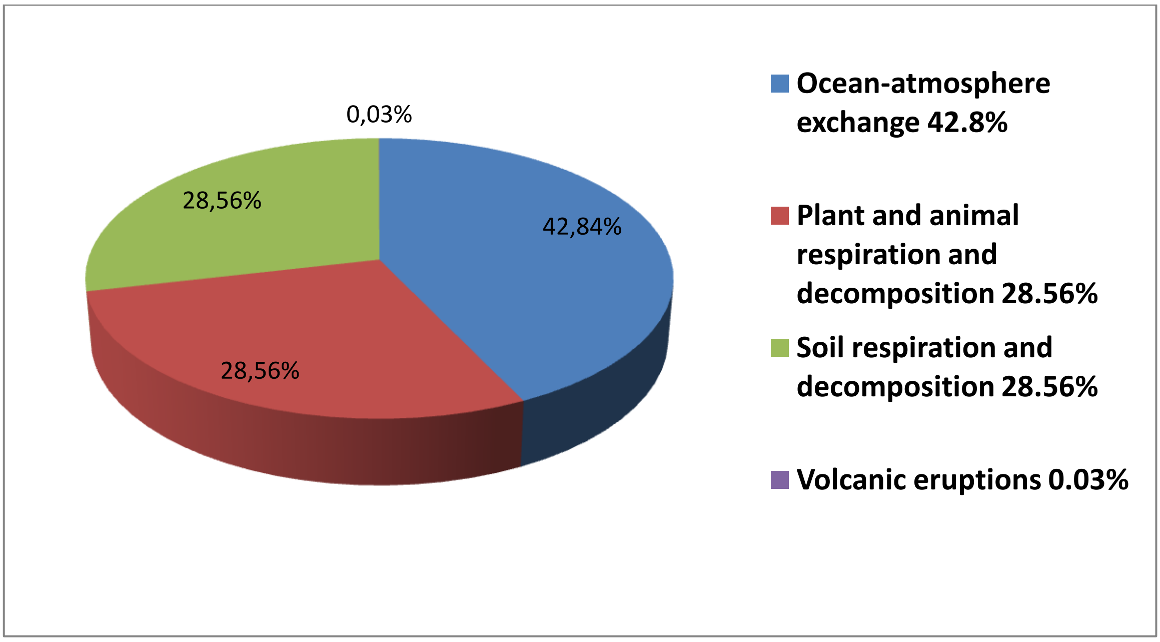

Figure II-6 Natural sources of CO_2 (IPCC, 2007)

The burning of fossil fuels is the main anthropogenic source of carbon dioxide emissions. It represents 87% of the total manmade CO_2 emissions, it is followed by the land use changes and the industrial processes with respectively 9% and 4% of the total carbon dioxide emissions.

Emissions coming from fossil fuels combustion are dominated by the electricity and heat sector where important amount of coal are mainly used to for heat and power generation. The usage of gasoline, diesel and kerosene to power vehicles, trains, ships and planes made the transportation sector the second largest source of anthropogenic source of carbon dioxide emissions. The industrial sector which consist of different activities as mining, manufacturing and building, is the third largest source of human-produced carbon dioxide emissions as shown in figure II.7

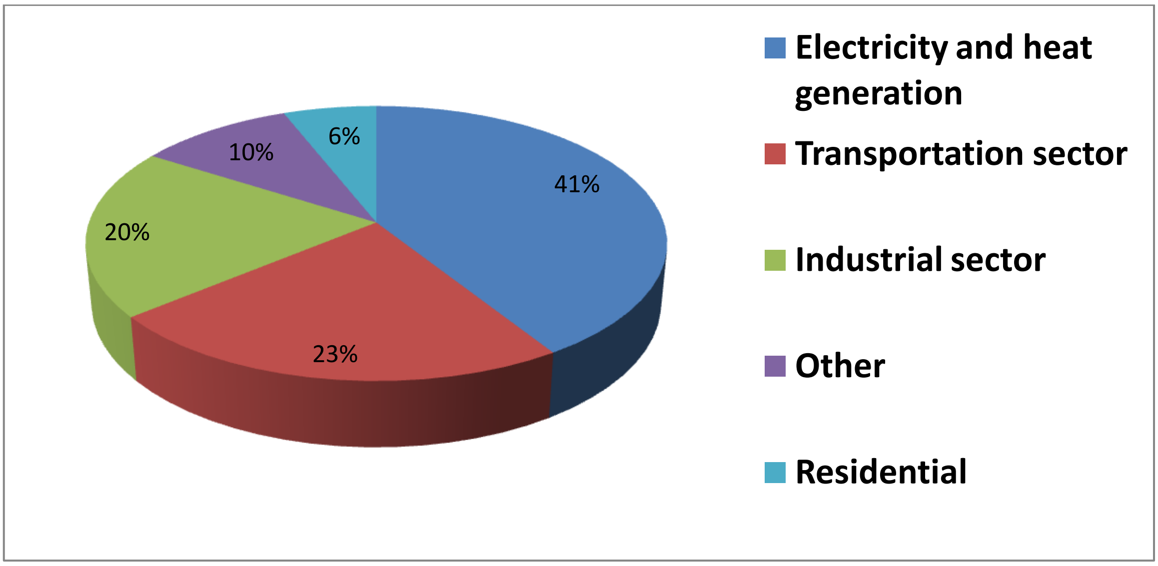

Figure II-7 CO_2 emissions from fossil fuel combustion (Source: IEA)

Land use changes are a substantial source of carbon dioxide emissions globally, accounting for 9% of human carbon dioxide emissions and contributed 3.3 billion tonnes of carbon dioxide emissions in 2011. (Le Quéré, et al., 2012)

Fossil fuels are often used to produce chemicals and petrochemical products like ammonia and hydrogen thus emitting carbon dioxide in the process. Some other products as lubricants, plastics and solvents are derived from petroleum. These products release more carbon dioxide as they evaporate, dissolve, or wear out during their lifetime.

II.2.2 Trend in carbon dioxide (CO_2) concentration

The future concentrations of CO_2 in the atmosphere depends mainly on emission rates from fuel combustion, land use and the behavior of the sinks. To predict the future atmospheric concentrations many scenarios have been developed by scientists and researchers. The projections (figure II.8) in the Special Report on

Emissions Scenarios (SRES) from the Intergovernmental Panel on Climate Change (IPCC) shows an increase of the greenhouse gases emissions in almost all cases. For the atmospheric concentration of carbon dioxide (CO_2) in the year 2100, the IPCC projects a level between 540 and 970 parts per million (ppm).

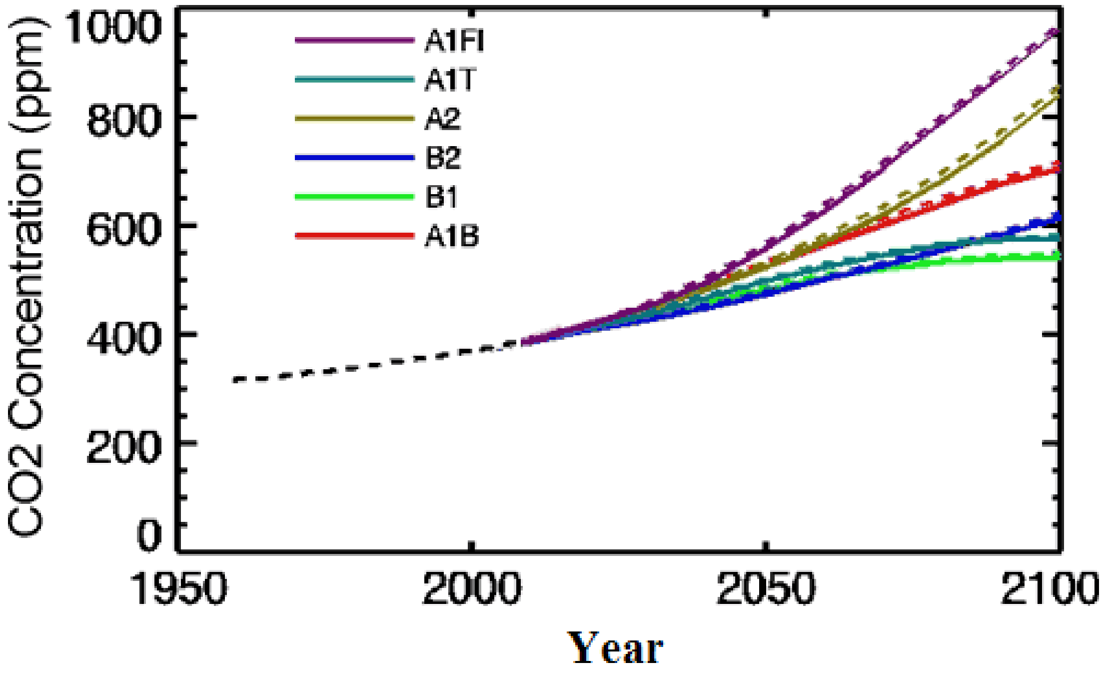

Figure II-8 Projected CO_2 concentrations (Source: IPCC SRES)

Scenario A1F1 assumes high global economic growth and continued heavy reliance on fossil fuels for the remainder of the century. Scenario B1 assumes a major move away from fossil fuels toward alternative and renewable energy as the century progresses. Scenario A2 is a middling scenario, with less even economic growth and some adoption of alternative and renewable energy sources as the century unfolds. (Cook, 2016) The black dashed line represents the carbon dioxide concentrations as observed at Mauna Loa from 1958 to 2008.

II.3 Methane (CH_4)

Methane (CH_4) is a hydrocarbon, it represents the primary component of natural gas and is a widespread fuel. It is the most abundant reactive trace gas in the atmosphere and the second-most important greenhouse gas for the enhanced greenhouse effect after the carbon dioxide gas. Its chemical properties made it a potent greenhouse gas contributing significantly to climate change. Thus compared to carbon dioxide, the global warming potential of methane is 28 times higher. Methane represents 16% of the total anthropogenic greenhouse gas emissions.

The global atmospheric concentration of methane has increased from a pre-industrial value of about 715 ppb to 1732 ppb in the early 1990s, and was 1774 ppb in 2005. The atmospheric concentration of methane in 2005 exceeds by far the natural range of the last 650,000 years (320 to 790 ppb) as determined from ice cores. Growth rates have declined since the early 1990s, consistent with total emissions (sum of anthropogenic and natural sources) being nearly constant during this period. (IPCC, 2007)

The global annual mean concentration of methane was 1803 ± 2 part per billion (ppb) in 2011 and it contributes to some 20% of the greenhouse gas effect. Methane is emitted from both natural and anthropogenic sources. From the natural source, it s primarily produced by anaerobic processes as the decomposition of organic matter. In addition the human-induced emissions come mainly from land use change, livestock and fossil fuel related processes.

The methane's short atmospheric lifetime of twelve (12) years combined to its relative potency compared to carbon dioxide makes efforts to reduce its emissions more attractive in order to tackle the climate change issue. The figure II.9 representing the annual average methane levels shows clearly the important increase in atmospheric concentration of methane. However the rate of increase had declined between 1999 and 2006 and rapidly soars from 2007.

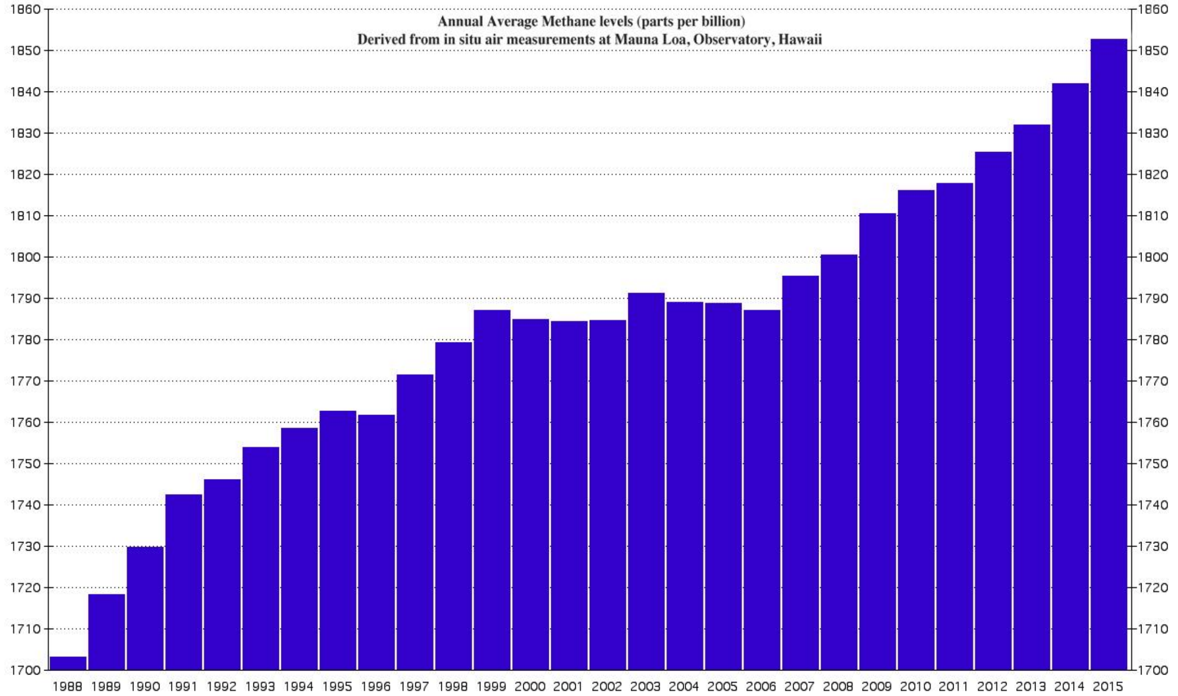

Figure II-9 Annual average methane levels (Source: NOAA)

II.3.1 Sources of methane (CH_4) emissions

Methane is mainly produced by bacteria feeding on organic material in anaerobic environments. However various natural and human influenced or created sources are also behind the methane emissions.

There is very high level of confidence that the atmospheric methane (CH_4) increase during the Industrial Era is caused by anthropogenic activities. The massive increase in the number of ruminants, the emissions from fossil fuel extraction and use, the expansion of rice paddy agriculture and the emissions from landfills and waste are the dominant anthropogenic CH_4 sources. Total anthropogenic sources contribute at present between 50 and 65% of the total CH_4. (IPCC, 2013)

Methane is produced naturally by forest fires, permafrost, wild animals, rivers, lakes and wetlands. But more than half of the methane entering the atmosphere comes from human activities. According to the Global Methane Initiative, anthropogenic sources worldwide include the digestive process of ruminant animals (29 percent), oil and gas systems (20 percent), landfills (11 percent), rice paddies (10 percent, with other agricultural production at 7 percent), wastewater (9 percent), coal mining (6 percent) and manure from farmed animals (4 percent). (Motavalli, 2015)

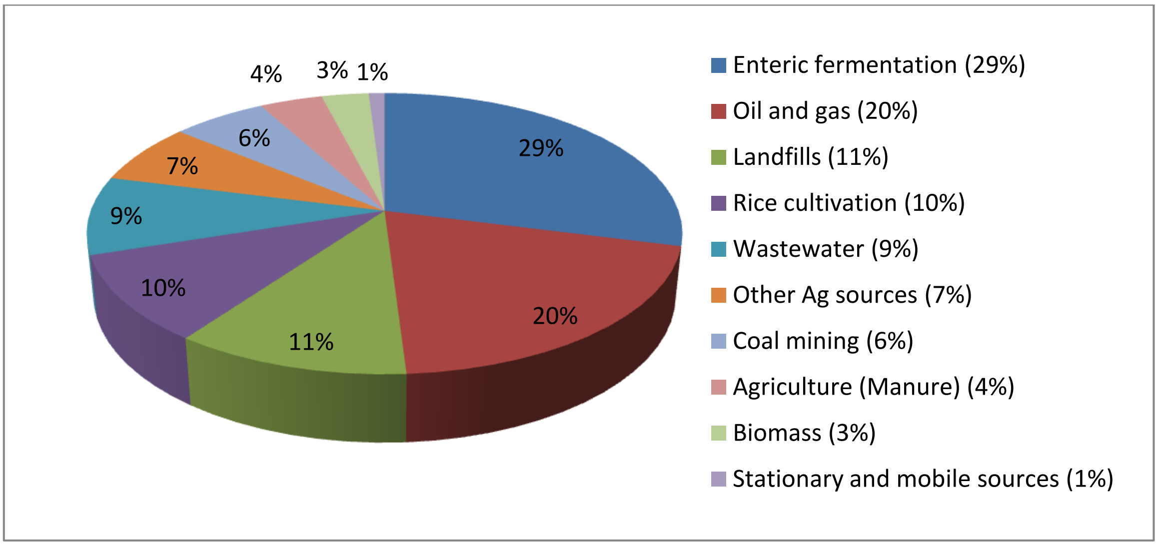

Figure II-10 Estimated Global Anthropogenic Methane Emissions by Source, 2010 (Source: GMI)

The microbial fermentation occurring in animals stomachs converts feed into products that can be digested and utilized by the animals. This process, named enteric fermentation, is characterized by the production of methane as a by-product later released by the animals via flatus. The emissions from oil and gas systems are due to losses occurring during the production, processing, storage, transmission, and distribution; it represent the second most important anthropogenic source of emission. Among the main manmade emission sources are landfills and rice cultivation where the methane is emitted when organic matter decomposes under anaerobic conditions. The coal mining is also a source of emission as the trapped methane is released during operations.

Moreover biomass burning in tropical and sub tropical regions is thought to be a significant source of atmospheric CH_4, with estimates of global emission rates ranging from 20 to 80Tg CH_4 per year. (IPCC, 1990)

II.3.2 Trend in methane (CH_4) concentration

In its Fifth Assessment Report (AR5) Working Goup 1, "Climate Change 2013: The Physical Science Basis, Intergovernmental Panel on Climate Change (IPCC) presents projections of future atmospheric concentration of greenhouse gases, based on four scenarios or Representative Concentration Pathways (RCP) as shown in figure II.11.

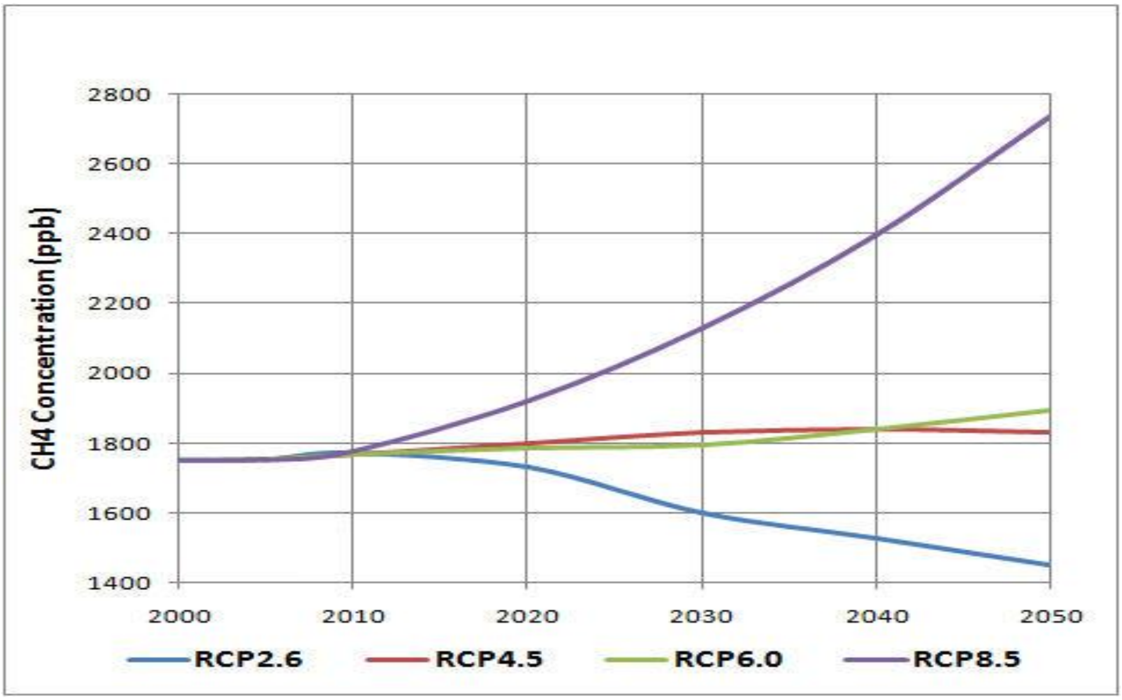

Figure II-11 RCP Scenarios for methane (Source: IPCC)

- RCP2.6 is a strong mitigation scenario.
- RCP4.5 is a mitigation scenario where radiative forcing is stabilized before 2100.
- RCP6.0 is a slower mitigation scenario where radiative forcing is stabilized after 2100.
- RCP8.5 is an extreme emissions scenario where greenhouse gas emisions rate increases.

The trend in CH_4 and emissions are largely due to differences in the assumed climate policy along with differences in model assumption. Emissions of CH_4 show a rapidly increasing trend for the RCP8.5 (no climate policy and high population). For RCP6 and RCP4.5, CH_4 emissions are more-or-less stable throughout the century, while for RCP2.6, these emissions are reduced by around 40%. The low emission trajectories for CH_4 are a net result of low cost emission options for some sources (e.g. from energy production and transport), and a limited reduction for others (e.g. from livestock). (Van Vuuren, et al., 2011)

Even though the RCPs represent a set of development in methane emissions they are not absolute bounds. However they can help policymakers to adopt and implement measures to prevent possible future issues related to atmospheric concentrations of methane. Moreover unexpected event and new development in projections techniques may change the different trajectories and force to quickly adapt and to find new solutions.

II.4 Nitrous oxide (N_2O)

Nitrous oxide is a chemical compound mostly known for its anaesthetic effect in surgery and euphoric effect when inhaled. At high temperatures it is also an effective oxidizer used to increase the output power of engines. However when nitrous oxide (N_2O) is released in the atmosphere it reacts with the oxygen (O) molecules to form nitric oxide (NO) which in turn reacts with the ozone. Therefore nitrous oxide is part of a natural process which regulates the concentration of ozone in the atmosphere.

Before the Industrial Revolution, the atmospheric concentration of nitrous oxide stayed in a safe range of levels because of natural sinks. But for a long time now human activities have been creating emissions much more rapidly than the Earth can remove them. Nitrous oxide levels are now higher today than at any other time during the last 800,000 years. (Schilt, et al., 2010)

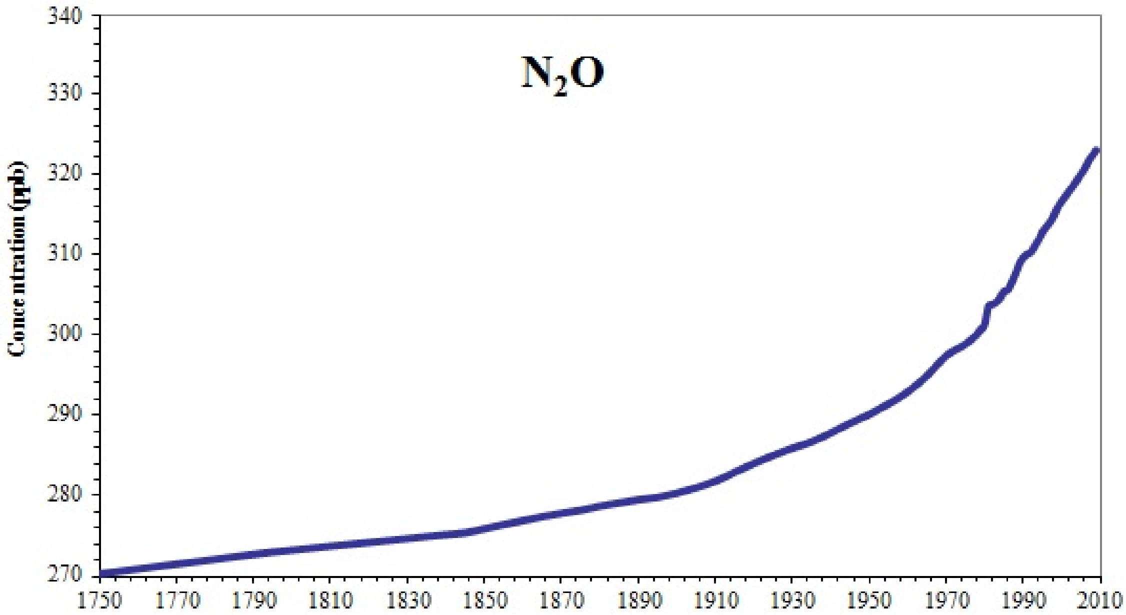

Figure II-12 Nitrous oxide concentration evolution (Source: EEA)

Nitrous oxide (N_2O) in 2011 has a surface concentration 19% above its 1750 level while its atmospheric concentration was 324.2 ppb (324.0 to 324.4) and has increased by 20% since 1750. (IPCC, 2013) The figure II.12 represents its concentration's evolution since 1750.

An increase in emissions of N_2O will cause the depletion of the ozone layer. Furthermore the nitrous oxide molecule has the ability to trap heat and act as greenhouse gas. Then in addition to the negative impact it can have on the ozone layer, nitrous oxide participates to the enhanced greenhouse effect with a global warming potential of 265 higher than the one of carbon dioxide (CO_2) and methane (CH_4).

Nitrous oxide is emitted by both natural and human sources. Anthropogenic emissions represent around 30 to 45% of the present-day global total, and are mostly from agricultural and soil sources and fossil-fuel activities. Natural emissions come mostly from microbial activity in the soil. The main sink for N_2O is through photolysis and oxidation reactions in the stratosphere, leading to an estimated lifetime of 131 ± 10 years. (IPCC, 2013)

II.4.1 Sources of nitrous oxide (N_2O) emissions

The main emissions of nitrous oxide from natural sources come from the Earth's soil and the oceans as shown in the figure II.13.

Soils under natural vegetation are an important source of nitrous oxide, accounting for 60% of all naturally produced emissions. Other natural sources include the oceans (35%) and atmospheric chemical reactions (5%). (IPCC, 2007)

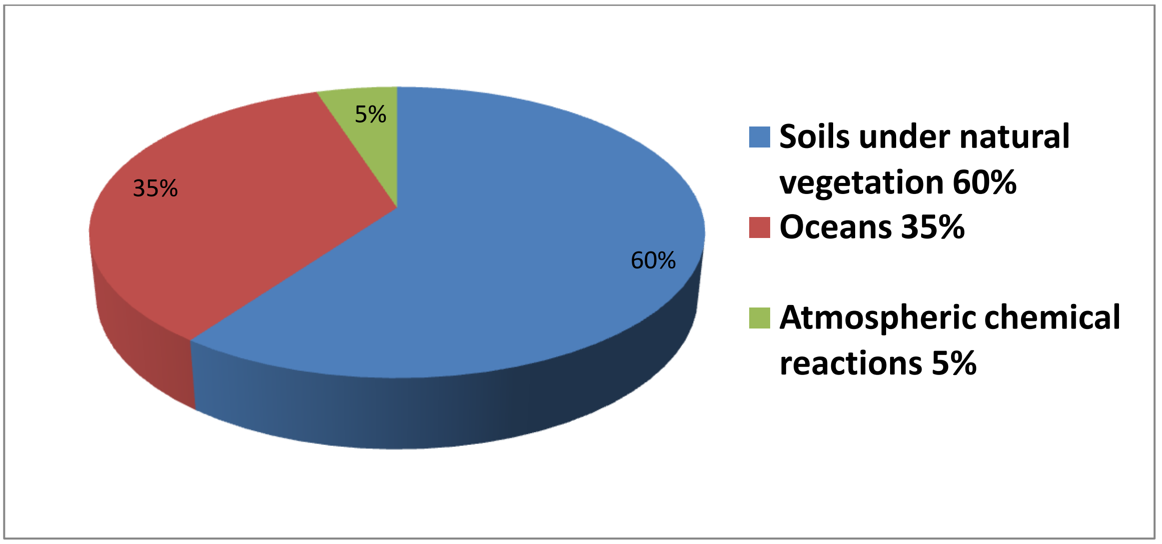

Figure II-13 Natural sources of nitrous oxide (IPCC, 2007)

Nitrous oxide from soils is emitted by microbes breaking down nitrogen under natural vegetation. The high availability of nutrient combined to high level of moisture in tropical and riparian rainforests soils made those regions important contributors to nitrous oxide emissions. Thus 6.6 million tonnes of N_2O are released each year in those areas.

The 35% share of emission from the oceans correspond to 3.8 million tonnes of nitrous oxide produced by bacteria in the parts of the water where oxygen levels are very low. The nitrous oxide is a by-product of the microbial denitrification occurring in sinking particles under the anaerobic conditions necessary for the process to take place.

The 5% amount of emission coming from the atmospheric chemical reactions are due mainly to the oxidation of ammonia which is naturally released into the atmosphere by different sources as oceans, manure or plants remains.
The oxidization of ammonia from natural sources creates 600,000 tonnes of nitrous oxide per year. (IPCC, 2007)

The human-induced emissions of nitrous oxide in the figure II.14, regroup several sources, where the biggest quantity are released by the agricultural activities, representing 67% of total emission. The agriculture is followed by the fossil fuel combustion and industrial processes with 10% on a par with emissions from biomass burning. Atmospheric deposition and human sewage complete the total human-induced emissions of N_2O, with respectively 9% and 3% of the total emission.

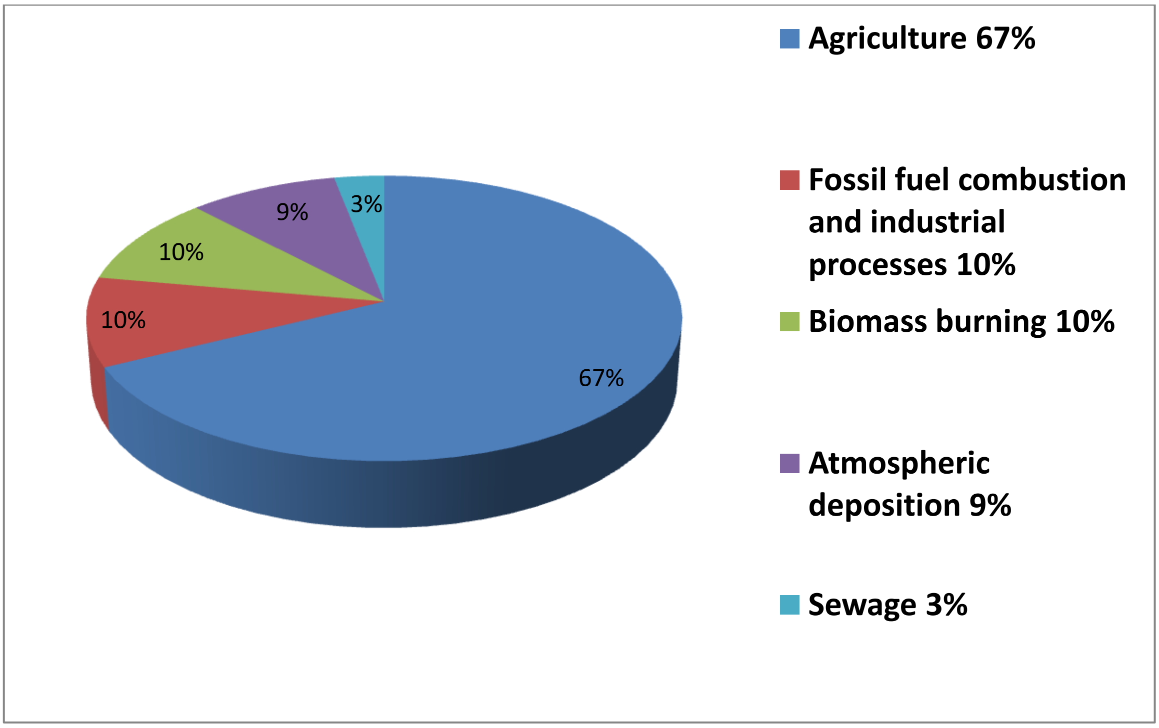

Figure II-14 Human sources of N_2O (IPCC, 2007)

The nitrous oxide emissions from agriculture come, in one hand, directly from the soils and the livestock manure, in the other hand the emissions come indirectly from the use of synthetic fertilizers.

The combustion of fossil fuels and biomass is a significant source of nitrous oxide emission also, as part of the nitrogen in the fuels and the biomass is oxidized when released into the air.

The oxidization of nitrogen compounds during the production of nitric and adipic acid results in the creation of nitrous oxide and represents the main source of emission of N_2O from industrial processes.

Moreover several human activities cause the release of nitrogen compounds into the atmosphere which represent a non-negligible source of nitrous oxide as they fall back on the surface and involve in the nitrification and denitrification processes occurring into the soils.

Finally the storage of wastewater for its treatment create an ideal environment for nitrous oxide emission as bacteria break down organic materials in nitrification and denitrification processes.

II.4.2 Trend in nitrous oxide (N_2O) concentration

Nitrous oxide (N_2O) emissions are projected to increase from increased anthropogenic nitrogen production. It is thus likely that N_2O emissions from soils will increase due to the increased demand for feed/food and the reliance of agriculture on nitrogen fertilisers. (IPCC, 2013)

The IPCC-AR5 has adopted a series of four representative concentration pathways (RCPs) as examples of a range of scenarios of internally consistent future projections of the major greenhouse gas emissions. (Van Vuuren, et al., 2011) The projections show an increase in nitrous oxide concentrations for the four scenarios. An additional study of Eric Davidson confirms the trend with few differences in the rate of increase.

The RCPs of the IPCC-AR5 are reasonable projections of a range of scenarios, from little new mitigation to very aggressive goals in all sectors and in dietary preferences. There is no silver bullet for stabilization of atmospheric N_2O. Rather, meeting this challenge will require simultaneous large improvements in agricultural efficiencies, diet modification, and other sector emission reductions. (Davidson, 2012)

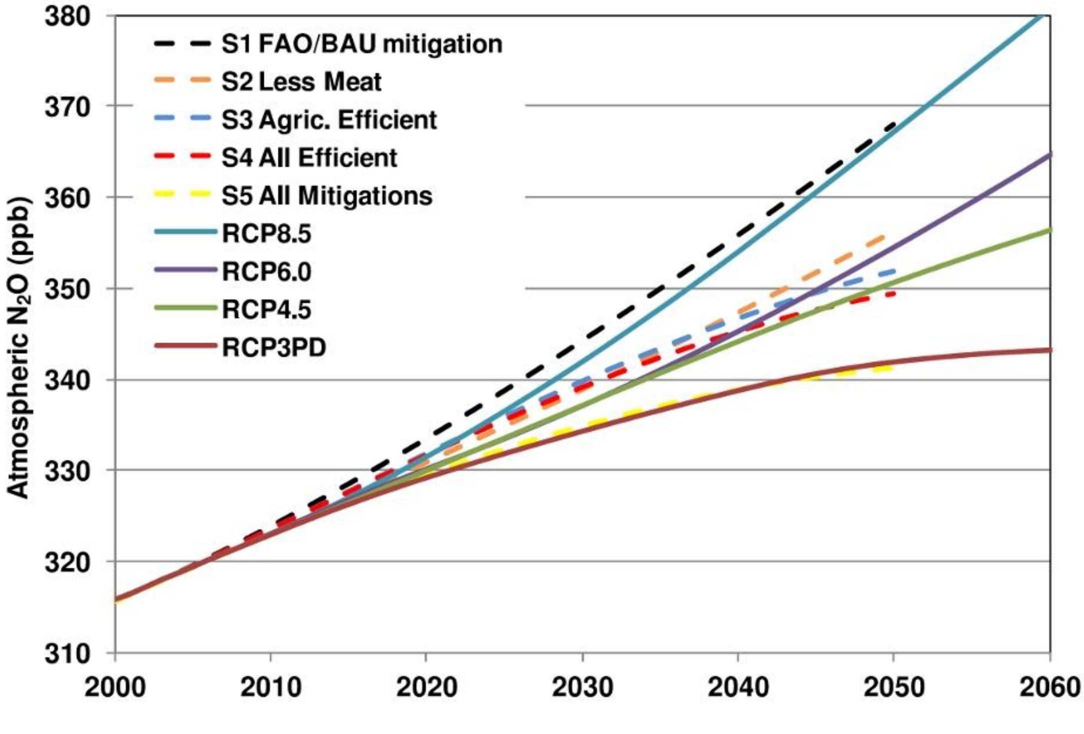

Figure II-15 Concentrations projections for nitrous oxide (N_2O) (Davidson, 2012)

The figure II.15 represents the projected atmospheric nitrous oxide concentrations for the four RCPs and the five scenarios Eric studied. Scenario S1 represents “business-as-usual” nitrous oxide emissions. S2 is the mitigation where average meat consumption per person in the developed world in 2030 is half that in 1980. S3 is the mitigation where agricultural nitrous oxide emissions are cut by half by 2050. S4 combines the agricultural mitigation with the one where industrial, transport, and vegetation burning nitrous oxide emissions are cut by half by 2050. S5 combines all three mitigations. (Davidson, 2012)

II.5 Fluorinated gases

The fluorinated gases are the only greenhouse gases that are not produced naturally. They are manmade gases, emitted by different anthropogenic sources through many processes. Their lifetime can reach thousands of years and some of them are more than thousand times more effective than carbon dioxide in term of infrared and heat capture. As an example, the sulfur hexafluoride (SF_6) has a global warming potential of 23500 over 100 years and a lifetime of 3200 years.

Human emissions have caused atmospheric levels to increase from near zero in 1750 to 89 parts per trillion (ppt) for hydrofluorocarbons (HFCs) and 6.7 ppt for hexafluoride (SF_6) in 2009. Perfluorocarbons (PFCs) levels have increased from 34.7 ppt in pre-industrial times to 82 ppt in 2009. (Montzka, et al., 2011) Global annual mean SF_6 in 2011 was 7.29 ppt, increasing by 1.65 ppt since 2005. SF_6 has a lifetime of 3200 years, so its emissions accumulate in the atmosphere and can be estimated directly from its observed rate of increase. Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) all continue to increase relatively rapidly, but their contributions to radiative forcing are less than 1% of the total by well-mixed GHGs (IPCC, 2013) The figure II.16 shows the fluorinated gases evolution from 1980 to 2010.

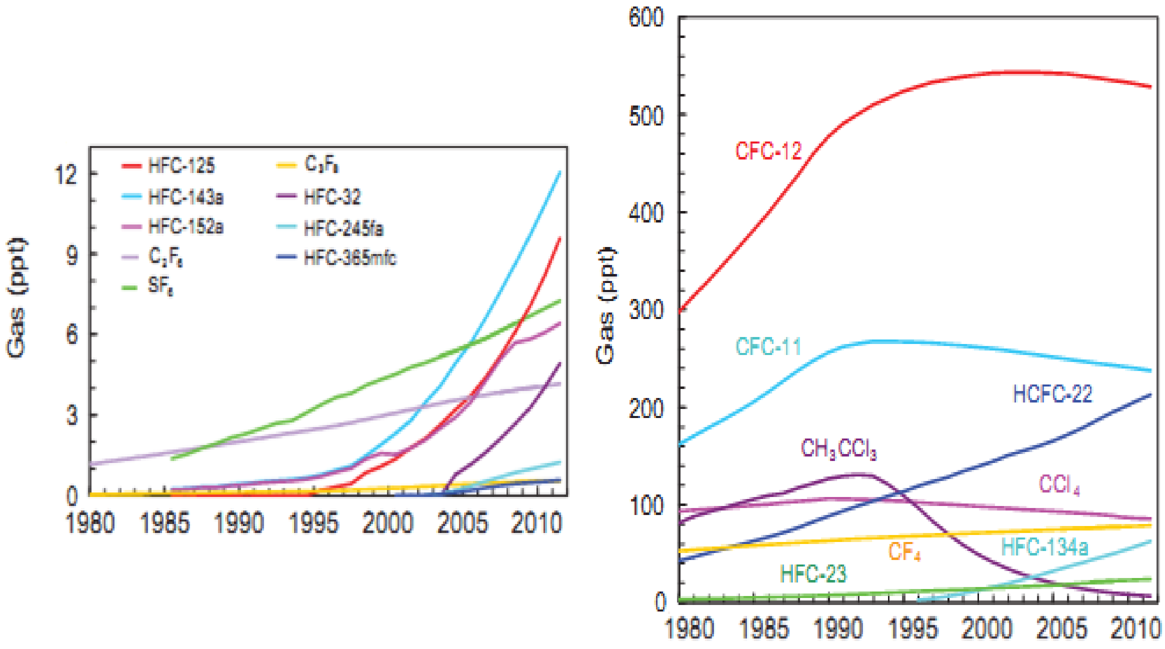

Figure II-16 Halogen gases global averaged concentrations evolution (IPCC, 2013)

II.5.1 Sources of fluorinated gases

The fluorinated gases are produced by human activities. They are used in refrigeration, air conditioning, aerosols cans and foams (table II.1). Some are used in electronics industries and the others are emitted during the manufacture of metals as aluminum. Moreover in addition to their ability to trap heat the chlorofluorocarbons (CFCs) can deplete the ozone layer thus having double negative impact.

Hydrofluorocarbons (HFCs) are mostly used in refrigerators and air conditioners as a coolant but over time they start to leak out slowly, substantial amount can be released per year due the important number of commercial refrigerators. The most important sources of HFCs are air-conditioners used in vehicles. Mobile air-conditioners (MAC) used in cars and other vehicles are the systems that are responsible for the largest amount of HFC emissions. This is a combination of there being a large amount of these devices installed in vehicles around the world (80% of passenger cars and commercial vehicles). (Velders, et al., 2009) HFCs are also used in foams as blowing agents and are released into the atmosphere at any time between the manufacturing and the disposal of the products. They are produced by aerosols as well, where they are used as propellants to spray out pressurized contents.

Table II-1 HFCs sources (United Nations Environment Programme, 2012)

HFC use	Percentage
Refrigeration and air-conditioning	79%
Foams	11%
Aerosols	5%
Other (fire protection, solvents, etc.)	5%

Perfluorocarbons are mostly produced during the manufacturing of semiconductors and aluminium.

The aluminium industry produces 12000 tonnes of CF_4 (PFC-14) and 900 tonnes of C_2F_6 (PFC-116) annually, making it the largest source of PFC emissions. C_2F_6 is also used directly as an etchant and cleaner in semiconductor manufacturing. The portion of the gas that does not react with the materials during the process is usually released into the atmosphere. C_2F_6 emissions from this industry creates 1800 tonnes annually. (Worton, et al., 2007)

The sulfur hexafluoride come mainly from the power sector where it is used in the equipments dedicated to the transmission and distribution of electricity.
SF_6 is another significant source of fluorinated gas emissions. This gas is mainly used by the electric power industry as an insulator and arc interrupter. The other important source of SF_6 emissions is from its use as a cover gas in magnesium production. Total SF_6 emissions equal 7160 tonnes annually. (Worton, et al., 2007)

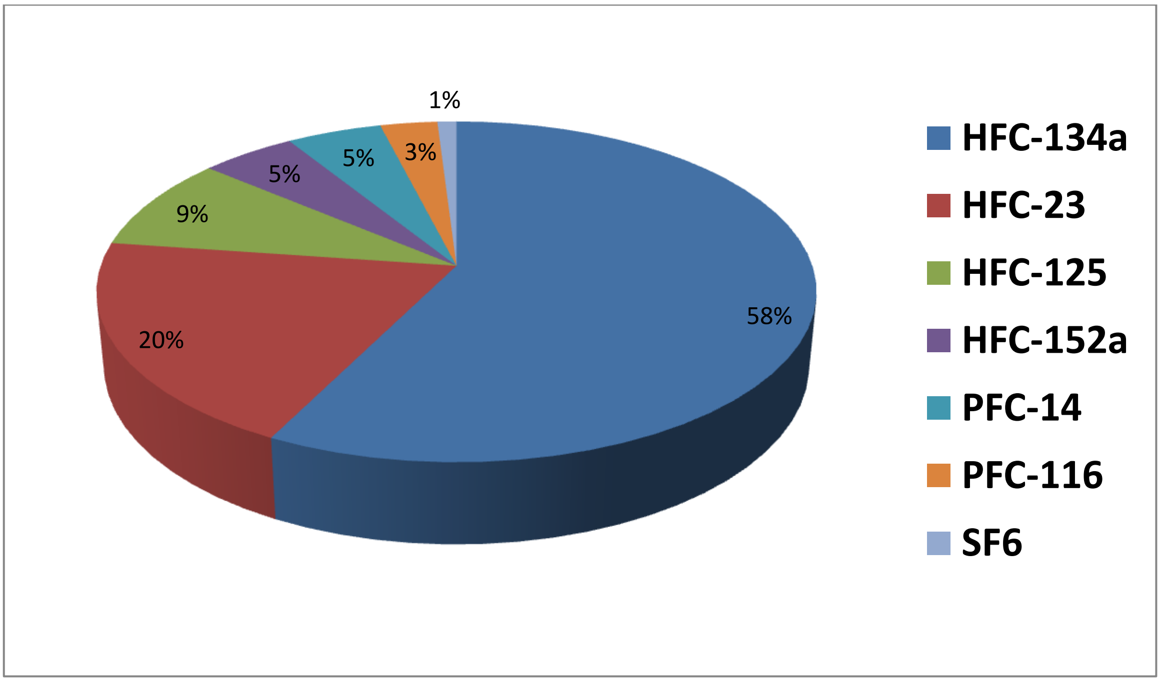

Figure II-17 Human sources of fluorinated gases (Source: UNEP[2])

The figure II.17 represents the shares of some fluorinated gases, with the most important amounts for the hydrofluorocarbons.

[2] The 2010 Assessment of the Scientific Assessment Panel, United Nations Environment Programme (UNEP)

II.5.2 Trend in fluorinated gases concentrations

It is certain that the global mean abundances of major chlorofluoro-carbons (CFCs) are decreasing and HCFCs are increasing. Atmospheric burdens of major CFCs and some halons have decreased since 2005. HCFCs, which are transitional substitutes for CFCs, continue to increase, but the spatial distribution of their emissions is changing. (IPCC, 2013) The trends are described by the curves in the figure II.18.

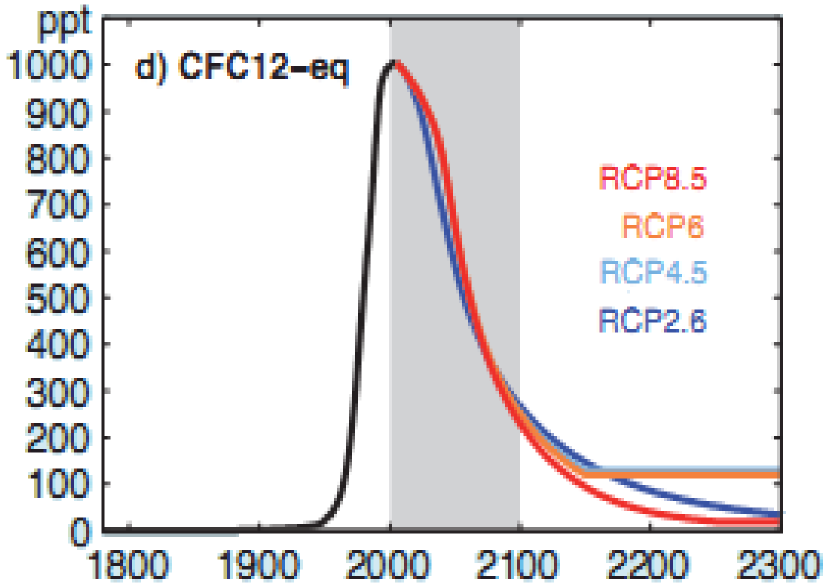

Figure II-18 CFC 12-eq concentrations scenarios (IPCC, 2013)

CFC12-eq is an aggregate of the chlorofluorocarbons controlled under the Montreal Protocol. The equivalent concentrations are derived so as to equal the aggregate forcing of the represented forcing agents.

II.6 Global Warming Potential

II.6.1 Definition and concept

The necessity to assess and to compare the impact of different greenhouse gases over a certain period of time led to the development and the adoption of metrics as Global Warming Potential (GWP) to solve the issue. The GWP is a metric tool that facilitates the trade-off between emissions of different greenhouse gases. Therefore policymakers have a simple mean to understand the relative abilities, of a given greenhouse gas, to affect the climate through the radiative forcing that it can cause. It helps to compare the amount of heat trapped by a certain mass of gas to the amount of heat trapped by the same mass of carbon dioxide and was presented in the First IPCC Assessment in 1990.

The Global Warming Potential is a measure of the relative, globally-averaged warming effect arising from the emissions of a particular greenhouse gas.

- It is a relative measure in that it expresses the warming effect compared to that of a reference gas (or 'molecule').
- It is a global measure in that it is derived from the globally- and annually-averaged net radiative fluxes at the tropopause[3], and thus describes the effects on the whole surface-troposphere system.
- It is a time-integrated measure of warming over a specified time horizon, taking account of the change with time of the species concentration. (IPCC, 1992)

The Global Warming Potential (GWP) of the emissions of a greenhouse gas was defined in IPCC (1990) as the time-integrated change in radiative forcing due to the instantaneous release of 1kg of a trace gas expressed relative to that from the release of 1kg of CO_2.

Calculation of the GWP for a particular species requires specification of the following:

- the radiative forcing both of the reference gas and of the species, per unit mass or concentration change;
- the time horizon over which the forcings have to be integrated;
- the atmospheric lifetime both of the species and of the reference gas;

[3] Boundary between the stratosphere and the troposphere

- the pathway of chemical breakdown of the species and the extent to which it gives rise to other greenhouse species, e.g., O_3 production from CH_4, NO_x, CO and NMHCs;
- the present and future chemical state of the atmosphere, i.e., levels of the background concentrations of various species throughout the troposphere;
  the present and future physical state of the atmosphere, i.e., values of meteorological variables throughout the troposphere (e.g., temperature profile, cloud properties). (IPCC, 1992)

The GWP is given by the following expression:

$$GWP = \frac{\int_0^n a_i c_i d_t}{\int_0^n a_{CO_2} c_{CO_2} d_t}$$

where a_i is the instantaneous radiative forcing due to a unit increase in the concentration of trace gas, i. c_i is concentration of the trace gas, i, remaining at time, t, after its release and n is the number of years over which the calculation is performed. The figure II.19 shows the relative lifetime of some greenhouse gases after a pulse emission.

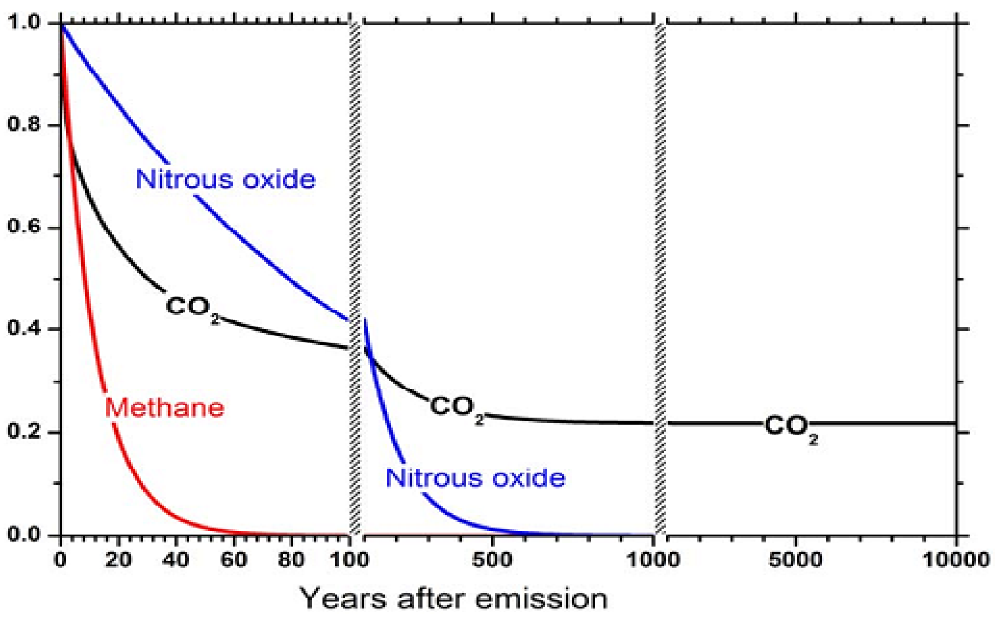

Figure II-19 Comparison of fractions of three different greenhouse gases remaining in the atmosphere as a function of time after a pulse emission. (Manning, et al., 2009)

The radiative forcing is the most important element for the calculation of the Global Warming Potential as it represents the parameter measured to assess the impact of the emissions of the selected greenhouse gas. It depends on the absorption of infrared radiation by the greenhouse gas and the spectral location of its absorbing wavelengths.

II.6.2 Radiative forcing

The radiative forcing is defined as the change in the net vertical irradiance (expressed in watts per square metre; W/m^2) at the tropopause due to an internal or external change in the forcing of the climate system, such as a change in the concentration of CO_2 or other greenhouse gases.

Alternative definitions of RF have been developed, each with its own advantages and limitations. The instantaneous RF refers to an instantaneous change in net (down minus up) radiative flux (shortwave plus longwave; in $W.m^{-2}$) due to an imposed change. This forcing is usually defined in terms of flux changes at the top of the atmosphere (TOA) or at the climatological tropopause, with the latter being a better indicator of the global mean surface temperature response in cases when they differ. (IPCC, 2013) When radiative forcing from a factor or group of factors is evaluated as positive, the energy of the Earth-atmosphere system will ultimately increase, leading to a warming of the system. In contrast, for a negative radiative forcing, the energy will ultimately decrease, leading to a cooling of the system. (IPCC, 2007)

The radiative forcing capacity (RF) is the amount of energy per unit area, absorbed by the greenhouse gas. The IPCC (1990) presented simplified formulas to calculate the radiative forcings from Wigley (1987) with coefficients of Hansen *et al.* (1988) and later they were improved by Myhre *et al.* (1998).

In the table II-2 are given the formulas to compute the radiative forcing of some specific greenhouse gases.

Table II-2 Expressions used to calculate the radiative forcing of different greenhouse gases

TRACE GAS	RADIATIVE FORCING APPROXIMATION GIVEN IN $W.m^{-2}$
Carbon dioxide	$\Delta F = 5.35 \ln(C/C_o)$
Methane	$\Delta F = 0.036(\sqrt{M} - \sqrt{M_o}) - [f(M, N_o) - f(M_o, N_o)]$
Nitrous oxide	$\Delta F = 0.12(\sqrt{N} - \sqrt{N_o}) - [f(M_o, N) - f(M_o, N_o)]$
CFC-11	$\Delta F = 0.22(X - X_o)$
CFC-12	$\Delta F = 0.28(Y - Y_o)$
Other CFCs, HCFCs and HFCs	$\Delta F = A(Z - Z_o)$

Where $f(M, N) = 0.47 \ln[1 + 2.01 \times 10^{-5}(MN)^{0.75} + 5.31 \times 10^{-15} M(MN)^{1.52}]$

C_0 = 278 ppmv, M_0 = 772 ppbv, and N_0=270 ppbv are the pre-industrial concentrations of carbon dioxide, methane and nitrous oxide respectively. X_o, Y_o and Z_o represent also the pre-industrial concentration of the above fluorinated gases. A is based on forcing relative to CFC-11 given in the IPCC's first assessment report published in 1990.

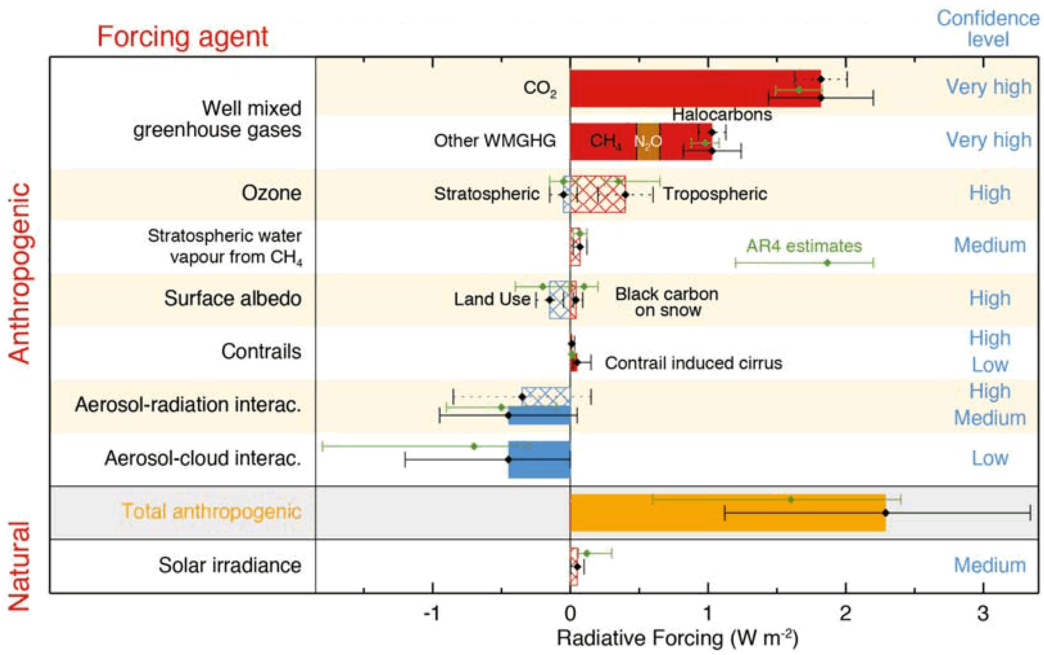

Figure II-20 Radiative forcing of climate between 1750 and 2011 (IPCC, 2013)

The figure II-20 shows how the anthropogenic radiative forcing has increased significantly since the industrial revolution, thus affecting the climate durably with a global average temperature increase.

The relation between the temperature and the radiative forcing is given by the following relation:

$$\boldsymbol{\Delta T = \lambda \Delta F}$$

Where λ is the climate sensitivity parameter, with units in $K/(W/m^2)$, and ΔF is the radiative forcing. A typical value of λ is 0.8 $K/(W/m^2)$ when the carbon dioxide concentration is doubled.

The table II-3 gives the global warming potential values of the greenhouse gases mentioned in this chapter. They are retrieved from the IPCC fifth assessment report (AR5) of the year 2014.

Table II-3 Global warming potential (GWP) values relative to CO_2

Industrial designation or common name	Chemical formula	GWP values for 100-year time horizon
Carbon dioxide	CO_2	1
Methane	CH_4	28
Nitrous oxide	N_2O	265
CFC-11	CCl_3F	4660
CFC-12	CCl_2F_2	10200
HFC-23	CHF_3	12400
HFC-125	CHF_2CF_3	3170
HFC-134a	CH_2FCF_3	1300
HFC-152a	CH_3CHF_2	138
PFC-14	CF_4	6630
PFC-116	C_2F_4	11100
Sulfur hexafluoride	SF_6	23500

Chapter III. CARBON TRADE AND THE AVOIDED EMISSIONS CALCULATION FOR MINI-GRIDS

III.1 The Concept of Carbon Trading

An increased concentration of the greenhouse gases in the atmosphere, led the world leaders to adopt measures that will help to curb the emissions. In fact, to limit the global warming at 2ºC (critical threshold) it is necessary to stabilize the atmospheric GHGs concentration at around 450 part per million volume. Thus at the 1992 Earth Summit in Rio de Janeiro, 166 countries signed the United Nations Framework Convention on Climate Change (UNFCCC). In the convention they agreed in the need to set a limit for the global greenhouse gases emissions in order to reduce the impact of the anthropogenic GHGs emissions on the climate system before the damages reach an irreversible point. In their endeavor to tackle the climate change issue, carbon trade has become one of the most important policy instrument created to address the problem. Thus in 1997 the Kyoto Protocol was signed and the carbon trade concept was set up.

During the negotiations on the Kyoto Protocol under the UNFCCC, the USA – in addition to objecting to significant cuts in greenhouse gas emissions – insisted on the trading of carbon allocations being a key element of the international climate treaty. And while the USA never ratified the Kyoto Protocol, the legacy of its negotiating position has made carbon trading the central pillar of international climate policy. (Jutta, et al., 2010)

Kyoto set up a system of emissions limits for a basket of six GHGs for developed countries, mechanisms for those developed countries to trade their emissions limits, and mechanisms for developed countries to offset their emissions by financing emissions reductions in developing countries. While the Kyoto Protocol itself has led to a very small number of trades directly among countries, the European Union and a variety of other jurisdictions have since pursued emissions trading to reduce their regional GHG emissions. Carbon markets are now the largest class of environmental or emissions trading markets in the world in terms of both volume and market value, by a very wide margin. (Richard, et al., 2012)

The two main components of the carbon trade concept are the carbon cap-and-trade and the carbon offsetting schemes. The emission reduction is only possible by putting a limit on emissions, which is called the cap. Therefore the offsetting and the trading are mechanisms used to developed a carbon market with a significant potential, particularly for developing countries.

III.1.1 Carbon cap and trade

The carbon cap and trade concept is based on a overall legal limit on emissions set by authorities in a country within a given period of time. Then a certain number of emissions permits become available for the polluters which in the circumstances can trade them. Thus entities emitting less than their allowances have the possibility to sell their permits to entities which are not able to reduce their emissions. Under the UNFCCC, countries and regions are obliged to respect a limit of emissions in order to keep the global warming below 2ºC, hence a cap is fixed and it determined the number of emissions permits issued within a country or region.
The permit in a carbon trading scheme is considered equivalent to one tonne of carbon dioxide equivalent (CO_{2e}). Such permits presuppose that the global warming potential of the other greenhouse gases can be calculated and converted to a multiple of the value that was assigned to carbon dioxide, which is one. (Jutta, et al., 2010)

The trading scheme is related to the marginal abatement cost (MAC) which is the cost needed to reduce the emission by an additional unit. Therefore the increase of the abatement induces an increase of the marginal abatement cost. Thus the more the target of emission reduction is high, the more the cost increase. As long as the cost of permits is higher than the abatement cost, polluters will continue to carry out the emission reduction instead of purchasing permits. The cap and trade market encompasses the borders as the greenhouses gases are well mixed gases and also the global concentration reduction does not depend specifically on the emission reduction of a certain location. This aspect increases the opportunity of permits trade and tends to globalize the carbon market.

The trade component of this model is only a useful tool to manage the cost of emission reduction, it has no tangible impact on the reduction itself. Therefore setting a global carbon cap is the most important component, which however is a very complex process as it requires a certain consensus, involving the main polluters. In that perspective industrialized countries took collectively and voluntarily, from the Kyoto protocol, 95 per cent of the emissions for which they are responsible. The Kyoto Protocol was adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005 whereas the first commitment period started on 1 January 2008.

In the Kyoto Protocol, permits allocated to industrialized countries with emissions targets are called Assigned Amount Units (AAUs). Trading of AAUs is allowed between countries that have been issued them under the Kyoto Protocol. Other entities cannot trade these AAUs. (Jutta, et al., 2010) AAUs are permits or pollution units allocated to GHGs emitters under the cap and trade frame.

An important aspect in the carbon cap and trade scheme is the monitoring, which ensures that the limit (cap) set is respected by the entities concerned. Even if entities ensure the report of their own emissions, independent control are carried out. In order to avoid the fraud in the reports from the polluters, authorities generally use emission factors and the quantity of fuel purchased, instead of direct measurement, to assess the emissions.

The economical benefit behind the cap and trade scheme is given by Jutta (2010). In his illustrative description, two companies are covered by an emissions cap, each emitting three units of a greenhouse gas. A government regulation limits greenhouse gas emissions from six units to four, thereby setting an overall cap of four units. Each company is given two permits. Company A finds that it would cost € 5 to reduce its emissions by one unit but company B finds that the equivalent reduction would cost them € 11. The total cost for both companies would therefore be € 5 + € 11 = € 16. If company A were to reduce its emissions by two units instead of just one, however, and company B does not reduce its emissions at all, the cost would only be € 5 + € 5 = € 10 for the same volume of reduction. By selling a permit to company B for € 10, company A recovers the expenses for making both the emissions reduction it would have had to make to comply with the regulation as well as the cost of the extra reduction made to trade with company B. By buying a permit from company A, company B saves € 1 compared to making its own reductions.

Carbon markets represent an important money potential and are expanding as climate change is seen as a serious issue worldwide. However as any economic market they are not immune to volatility and speculations. Thus its value keeps fluctuating because it depends on different parameters related to emissions trading schemes.

Seen as a whole, the world of carbon trading was characterized by two opposite trend in 2015: volumes continued to contract and prices continued to increase. Traded volume dropped by 19 percent, from 7.6 Gt CO_2 worth of transactions in 2014 to 6.2 Gt in 2015. The overall turnover increased 9 percent from €44.3 to €48.4 billion. (Thomson Reuters, 2016)

III.1.2 Carbon offset

A carbon offset is a reduction in emissions of carbon dioxide or greenhouse gases made in order to compensate for or to offset an emission made elsewhere. (Goodward, et al., 2010)

Offsets are typically achieved through financial support of projects that reduce the emission of greenhouse gases in the short- or long-term. The most common project type is renewable energy. (Environment Protection Authority Victoria, 2010)

The carbon offset scheme has been always a part of the carbon cap and trade schemes. Two instruments developed at the Kyoto protocol ensure officially the control and the implementation of carbon offsets. The first instrument is the Clean Development Mechanism (CDM) which regulates carbon offsets projects set up in countries without an emission reduction compliance, mainly the developing countries. The second instrument is the Joined Implementation (JI) which is an mechanism with the same purpose as the CDM, however it is destined to offsets projects located in countries with an emission target and eventually with a transitional economy.

It exists two kinds of carbon market under this scheme. In one hand is the compliance market which is under the Kyoto compliant mechanism, in the other hand is the voluntary market which is not ruled by a mandatory system and is set outside of the United Nations (UN) framework, it is supervised by officious bodies committed to tackle climate change issues with voluntary actions from companies, governments and citizens sometimes without any legal obligation to achieve a reduction target. However the compliance and voluntary offset markets follow the same concept and have targeted the same outcomes. The projects in both markets are based almost on the same principles, they use the same tools, mechanisms and procedures to calculate the amount of credits an offset project can generate.
In 2014, voluntary demand for carbon offsets grew 14% to 87 million tonne of carbon dioxide equivalent ($MtCO_{2eq}$) transacted. Though this volume represents only a fraction of 1% of total global emissions in 2014, it is almost one-tenth of all offset demand. (Hamrick, et al., 2015)

A key point in the carbon offset scheme is to know what would have happened in the absence of the offset project. Therefore it is necessary to calculate or to assess the amount of greenhouse gases emissions avoided by implementing an offset project. Then appears the positive impact and the efficiency of the mechanism in addressing the emissions reduction challenge. In that perspective Dan Welch (2007) declared: 'Offset credits are an imaginary commodity based on subtracting what you hope will happen from what you claim would have happened.' Credits are pollution units which represent emission reductions due to the implementation of a carbon offset projects. Credits from carbon offsets projects can be traded and used by entities to respect their commitment toward the Kyoto protocol only if the credits are issued by the CDM board under the UNFCCC regulatory framework.

III.2 Avoided Emissions Calculation Method for Mini-grids

The calculation method used in this thesis is the CDM Gold Standard methodology. It respects the conditions of the Clean Development Mechanism (CDM) as it takes into account the parameters and the criteria related to the calculation of the avoided emissions set under the CDM scheme. Among the criteria and the parameters are the project size, the use of renewable energy resources and a baseline scenario based on the use of fossil fuel energy. The methodology addresses the suppressed demand of off-grid communities with small-scale power systems projects based on renewable energy resources.

III.2.1 Suppressed demand

One of the advantages in implementing clean energy mini-grids is in their ability to avoid greenhouse gases emissions during their operating time as they are environmental friendly. Therefore the governments under the United Nations Framework Convention for Climate Change decided to support the projects helping to address what is called the suppressed demand through the Clean Development Mechanism. The concept of suppressed demand was developed to make attractive the projects activities as there are almost no CERs generated without it.

The suppressed demand is defined as a “Scenario where future anthropogenic emissions by sources are projected to rise above current levels, due to the specific circumstances of the host Party”. (UNFCC, 2015) It means that in the absence of the CDM project emissions would have increased. Those circumstances can be a lack or an insufficient access to modern and low carbon emissions energy infrastructure.

Unmet latent demand for basic services is termed “suppressed demand”. Suppressed demand occurs where minimum service levels are unavailable or only available to an inadequate level. For example, households without electricity, those that are dependent on biomass for cooking or those who do not have access to adequate amounts of potable water. (Marina, et al., 2013)

In the case of off-grid communities, the suppressed demand is assessed by considering the default emission factors from high emission sources of energy such as diesel generators or fossil fuel power plants. Thus the total emission is calculated by multiplying the emission factor with the total energy consumed that ensures a defined baseline service level. The setting of the baseline involves two important concepts which are the income effect and the price effect. In fact both of them have an impact on the energy consumption, therefore it is necessary to take them into account when elaborating a baseline scenario.

III.2.2 The concept of mini-grids

Mini-grids are decentralized systems supplying local customers usually in remote and rural areas. In this study the mini-grids refer to off-grid systems which are not connected to the main national grid, the power is generated on-site using renewable energy resources which in some cases are associated to a fossil fuel based generator.

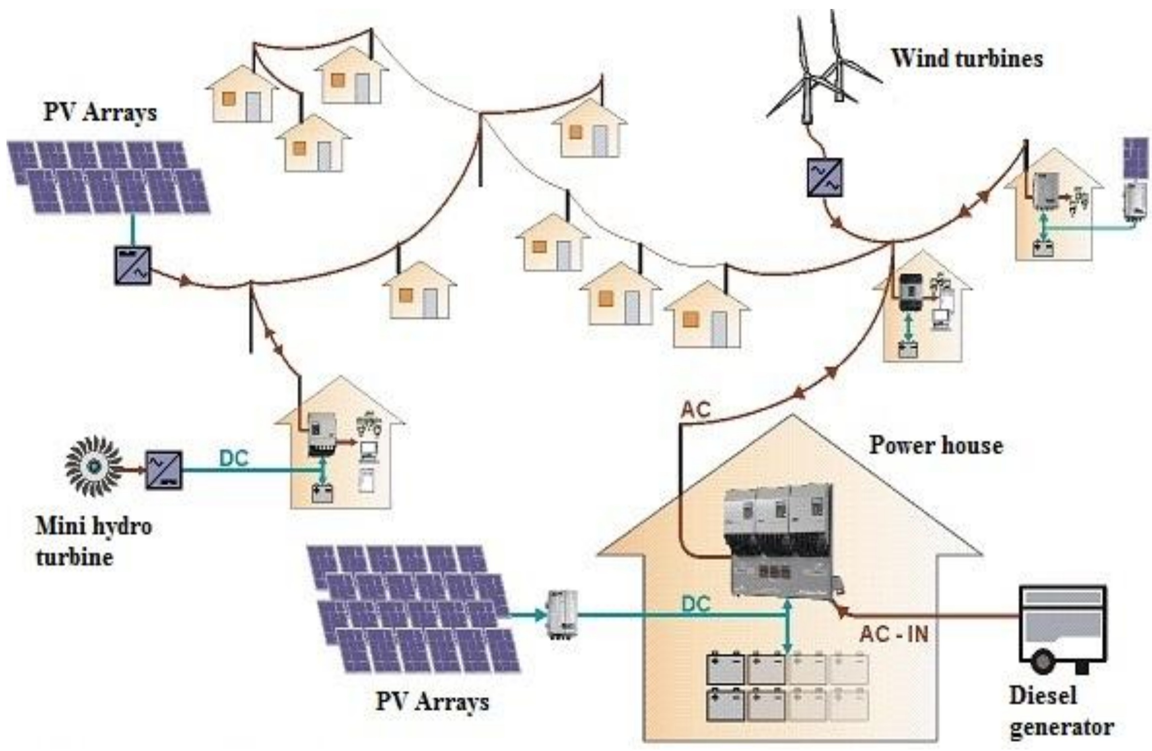

Figure III-1 Mini-grid

Mini grids are also called isolated grids or micro grids, they regroup a number of small scale power generators interconnected and often associated to an energy storage system which supply electricity to a community through a small distribution network as illustrated in figure III.1.

Those small scale power generation technologies have capacities typically in the range of 3 kW to 10,000 kW and are used to provide an alternative to or an enhancement of the traditional electric power system. (NASIR, et al., 2013)

III.2.3 CDM Gold Standard methodology

The methodology is applicable to renewable energy based electrification or energization activities for communities that do not have access to the national or regional grid or for communities which have less than 50% grid availability. The maximum emission reduction per project under the scheme, must be equal or less than 10000 t CO_2/year. The renewable energy sources eligible for this methodology are limited to solar, hydro, wind, renewable biomass and biogas. However a back-up power generation from fossil fuel based power generation systems is allowed. Even though the methodology is limited to small scale projects, it is not applicable to portable electricity systems, such as batteries and LED lanterns. (Morten, et al., 2013) The most important point of the methodology is the setting of a baseline scenario representing the situation in the absence of the project.

III.2.3.1 Baseline

According to the UNFCCC under the CDM methodology the standardized baseline is a baseline established for a Party or a group of Parties to facilitate the calculation of emission reduction and removals and/or the determination of additionality for CDM project activities.

The diagram III.2 shows how after the clean energy based mini-grid project implementation, rural communities are supplied with electricity and greenhouse gases emissions are avoided.

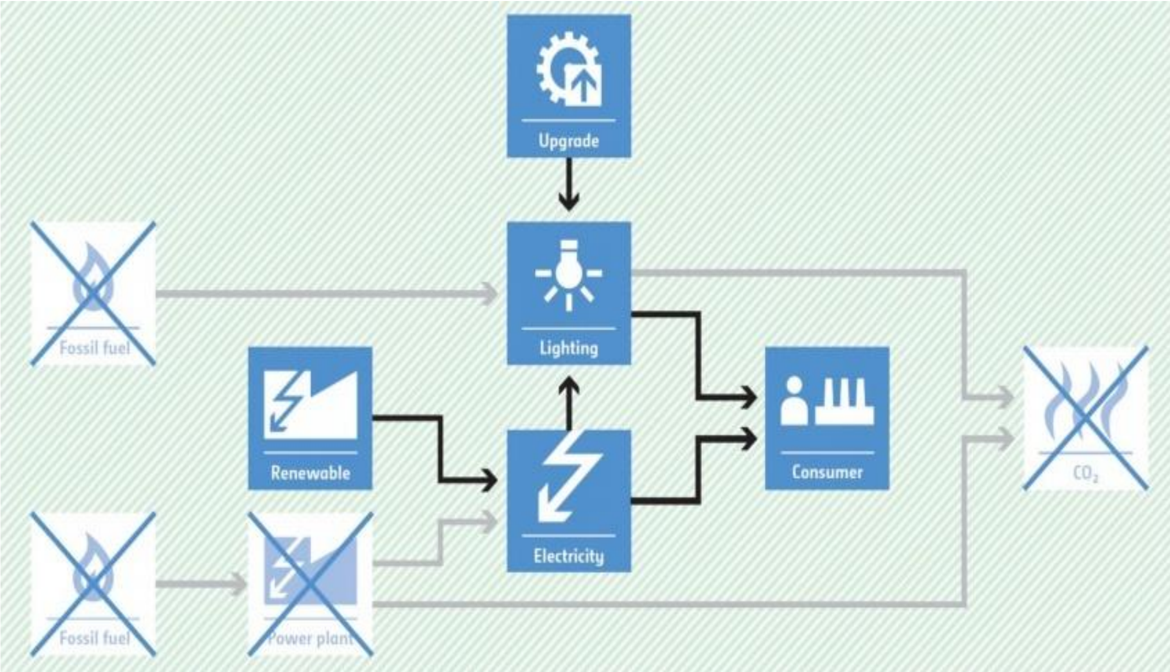

Figure III-2 Baseline and project scenario (UNFCC, 2015)

The baseline involve two parameters: the baseline emissions and the baseline service level.

- **Baseline service level**

The baseline service level is based on the setting of a Minimum Service Level for each consumer group supplied with electricity (table III.1). It represents the basic amount of electricity needed per day by the consumer and is expressed in kilo-watt hour per day (kWh/day).

Table III-1 Gold standard default MSL (The Gold Standard Foundation, 2013)

Consumer group	Default MSL (kWh/day)
Household (hh)	**3.0**
Health center (hc)	**8.6**
Dispensary (d)	**4.1**
School (s)	**10.0**
Kindergarten (k)	**4.4**
Public administration (pa)	**4.4**
Trading place (tp)	**11.0**

The total MSL is given by the following equation:

$$\boldsymbol{MSL_{ec,y} = (MSL_{ec,hh,y} \times n_{hh}) + (MSL_{ec,hc,y} \times n_{hc}) + (MSL_{ec,d,y} \times n_d) + (MSL_{ec,s,y} \times n_s) + (MSL_{ec,k,y} \times n_k) + (MSL_{ec,pa,y} \times n_{pa}) + (MSL_{ec,tp,y} \times n_{tp}) + (MSL_{ec,xx,y} \times n_{xx})}$$

$$\boldsymbol{MSL_{ec,y} = \sum (MSL_{ec,i,y} \times n_i)}$$

Where: $MSL_{ec,i,y}$ represents the Minimum Service Level in energy consumption (ec) in kWh for a consumer group (i) in a year (y) and n is the number of units in the consumer group.

- **Baseline emissions**

Under the Gold standard methodology, the baseline emissions are defined as the sum of the MSL for all connected consumers multiplied by an appropriate emission factor. Diesel generators are defined as the default baseline measure to deliver the MSL for all eligible consumer groups. However grid emission factor can also be used to calculate the emissions.

The emission factor (EF) of a diesel generator system is 1.3 $kgCO_{2e}/kWh$[4], while the grid emission factor depends on the location where the project is implemented and can be retrieved from the International Energy Agency (IEA) database.

Thus the baseline emissions for an electricity generation system is given by:

$$\boldsymbol{BE_Y = MIN(E_{d,y} \div MSL_{ec,y}; 1) \times ((MSL_{ec,y} \times EF))}$$

Where: BE_y is the baseline emissions in tCO_2 ; EF is the emission factor ; $E_{d,y}$ is the renewable electricity in kWh delivered (d) in a year (y) ; $MIN(E_{d,y} \div MSL_{ec,y};1)$ if $E_{d,y} \geq MSL_{ec,y}$ the ($MSL_{ec,y}$) is the maximum electricity consumption in kWh which can be credited else the $E_{d,y}$ is credited.

[4] CDM Small-scale Methodology AMS I.F, table I.F.1

III.2.3.2 Emission reduction

The emission reduction is calculated by subtracting the project emissions and the leakage emissions from the baseline emission. However project emissions are considered to be zero tonnes CO_2 each year (PE_y=0) for renewable biomass, wind and solar. However for hydropower and biogas, the project emissions have to be considered.

$$\boldsymbol{ER_y = BE_y - PE_y - LE_y}$$

Where: ER_y Emission reductions (tCO_2) during one year (y)

BE_y Baseline emissions (tCO_2) in a year (y)

PE_y Project emissions (tCO_2) in a year (y)

LE_y Leakage emissions (tCO_2) in a year (y)

Leakage is to be considered if non-eligible consumers (e.g hotel, petrol station) are connected to the mini-grid.

Chapter IV. CASE STUDIES IN WEST AFRICA (SENEGAL)

IV.1 ECOWAS Electricity Access Overview

The West African region regroups fifteen countries under a regional institution named ECOWAS (Economic Community of West African States).
The 15 ECOWAS Member States cover a diversity of demographic, socio-economic, and social contexts, each of which impacts energy demand and supply throughout the region. (ECOWAS, 2014)

One of the main challenge the region is facing is the access to energy particularly the modern energy services as electricity. To meet their energy demand, population still depend on the use of traditional biomass with low efficiency energy conversion instruments and important pollutants emissions. According to the International Energy Agency (IEA) in 2011, sub-Saharan Africa accounted for almost half (47.6%) of all people without access to electricity. Even though the electrification rate is very low in the region, there are important disparities within the regional community and within countries.

Figure IV-1 ECOWAS members

The data from the International Energy Agency shows the situation, with a very low electrification rate in Sierra Leone, where only 5% of the population have access to electricity, while in Cabo Verde the electrification rate reaches 94% (table IV.1). But the main issue consist in the rural electrification, most of the countries in the region have difficulties to supply electricity to remote communities as the cost of a grid extension is very high and not beneficial for the power utilities.

Table IV-1 ECOWAS member states electrification rate (IEA, 2014)

Countries	National electrification rate	Urban electrification rate	Rural electrification rate
Benin	**28%**	**55%**	**6%**
Burkina Faso	**16%**	**54%**	**2%**
Cabo Verde	**94%**	**100%**	**84%**
Côte d'Ivoire	**26%**	**42%**	**8%**
Gambia	**35%**	**60%**	**2%**
Ghana	**72%**	**90%**	**52%**
Guinea	**12%**	**28%**	**3%**
Guinea-Bissau	**20%**	**37%**	**6%**
Liberia	**2%**	**3%**	**0%**
Mali	**27%**	**55%**	**12%**
Niger	**14%**	**62%**	**4%**
Nigeria	**45%**	**55%**	**35%**
Senegal	**55%**	**90%**	**28%**
Sierra Leone	**5%**	**11%**	**1%**
Togo	**27%**	**35%**	**21%**

In order to address the energy access issue, ECOWAS created the ECOWAS Center for Renewable Energy and Energy Efficiency (ECREEE) through which it promotes the use of renewable energy resources to meet the increasing energy demand. Thus in order to reduce the energy gap particularly in rural and peri-urban areas, clean energy mini-grids projects are developed and implemented throughout the region as shown in the table IV.2.

Mini-grids are a tool to provide cost-effective, reliable electricity service to populations not served by the current grid infrastructure. Mini-grids can be developed around a number of business models and power generation options, and are increasingly incorporating renewable generators. (ECOWAS, 2014)

Table IV-2 Renewable and Hybrid Mini-Grid Projects in ECOWAS, July 2014 (Source: ECREEE)

Benin	-
Burkina Faso	The Ministry of Energy's Electrification Development Fund has financed 3 hybrid PV-diesel projects, each with an installed capacity of 15 kWp.
Cabo Verde	Two projects, Monte Trigo (PV-diesel) and Vale da Custa (PV-wind-diesel), have a combined capacity of 50 kW.
Côte d'Ivoire	-
Gambia	A 350 kW wind park.
Ghana	-
Guinea	Two operational hydropower mini-grids.
Guinea-Bissau	-
Liberia	The 60 kW micro-hydro mini-grid, which came online in 2013, is operated and managed by the village of Yandohun.
Mali	The Malian Agency for the Development of Household Energy and Rural Electrification has developed a successful Public-Private-Partnership model in which private operators apply for Rural Electrification Authorizations and financial support from the Rural Electrification Fund. twenty-one hybrid PV-diesel projects (totalling 2.1 MW) exist in Mali.
Niger	-
Nigeria	Several renewable mini-grids exist, including a 4 kW PV mini-grid system in the isolated community of Ofetebe, which now has approximately 4 hours of electricity per day.
Senegal	The Senegalese Agency for Rural Electrification has installed 107 mini-grids, totalling 1 MW of installed PV capacity.
Sierra Leone	A hybrid hydro-PV mini-grid supplies the community of River Number 2.
Togo	-

Note: "-" indicates data are not available

IV.2 Case Study 1: Ndiba (Hybrid PV/Diesel System)

IV.2.1 Data[5]

Ndiba is a village in the region of Kaolack in Senegal. Its geographic coordinates are:

- Latitude 13º46'0" N
- Longitude 15º33'0" W

The different groups of consumers and their specific number are given in the table IV.3.

Table IV-3 Consumers in Ndiba

Consumer group	Number
Household (hh)	**34**
Health center (hc)	**0**
Dispensary (d)	**1**
School (s)	**1**
Kindergarten (k)	**0**
Public administration (pa)	**1**
Trading place (tp)	**1**

The mini-grid generation system consists of a PV array connected to a battery bank and a diesel generator is used as a back-up source. The DC current from the PV modules is converted to AC current by 3 inverters before it is injected into the local grid. While 3 other inverters ensure the conversion from DC to AC (vice versa) of the current coming from the battery bank and going to it during the discharging and charging phase.

The PV array has a power peak of 5.850 kWp. It generates 9673 kWh per year, representing 64% of the total energy generated (15199 kWh, $E_{d,y}$) by the system.

[5] Source: CERER

The diesel generator produces the 36% remaining, which corresponds to 5526 kWh per year and releases 4.942 tCO_2/year (PE_y).

As there is no non-eligible consumers connected to the grid, the leakage emission (LE_y) is null.

IV.2.2 Results

The results of the calculation are given in the table IV.4.

Table IV-4 Results from Gold Standard calculation tool C.S 1

Consumer group	Number	Total MSL for each consumer group (kWh)	BE(tCO_2/year) based on MSL
Household (hh)	**34**	**37230**	**48.28**
Health center (hc)	**0**	**0**	**0**
Dispensary (d)	**1**	**1497**	**1.95**
School (s)	**1**	**3650**	**4.75**
Kindergarten (k)	**0**	**0**	**0**
Public administration (pa)	**1**	**1606**	**2.09**
Trading place (tp)	**1**	**4015**	**5.22**
Total		**47998**	**62.29**

$$BE_Y = MIN\left(E_{d,y} \div MSL_{ec,y}; 1\right) \times \left(\left(MSL_{ec,y} \times EF\right)\right)$$

$E_{d,y}$ = 15199 kWh ; $MSL_{ec,y}$ = 47998 kWh ; EF = 1.3 $kgCO_2$/kWh

$$BE_Y = 18\ tCO_2/year$$

$$ER_y = BE_y - PE_y - LE_y$$

BE_y = 18 tCO_2/year ; PE_y = 4.942 tCO_2/year ; LE_y = 0

$$ER_y = 13\ tCO_2/year$$

IV.3 Case study 2: Sine Moussa Abdou (Hybrid PV/Wind/Diesel System)

IV.3.1 Data[6]

Sine Moussa Abdou is a village in the region of Thies in Senegal, with around 900 inhabitants. Its geographic coordinates are:

- Latitude 15°10'57" N
- Longitude 16°44'44" W

The table IV.5 gives the group of consumers and their specific corresponding number.

Table IV-5 Consumers in Sine Moussa Abdou

Consumer group	Number
Household (hh)	**96**
Health center (hc)	**0**
Dispensary (d)	**1**
School (s)	**1**
Kindergarten (k)	**0**
Public administration (pa)	**1**
Trading place (tp)	**1**

The mini-grid generation system consists of a PV array of 5 kWp, a wind turbine of 5kW connected to a battery bank of 24 elements of 2500 Ah/2V. 3 inverters convert the DC current to AC and a generator of 11 kVA is used as a back-up. The diesel generator produces 313.01 kWh per year distributed between the months of March, September and November. With a diesel emission factor of 1.3 $kgCO_2/kWh$, it emits 0.407 tCO_2/year (PE_y).

As there are no non-eligible consumers the leakage emissions (LE_y) are null.

[6] Source: CERER

IV.3.2 Results

The results of the calculation are given in the table IV.6.

Table IV-6 Results from Gold Standard calculation tool C.S 2

Consumer group	Number	Total MSL for each consumer group (kWh)	BE(tCO_2/year) based on MSL
Household (hh)	**96**	**105120**	**136.32**
Health center (hc)	**0**	**0**	**0**
Dispensary (d)	**1**	**1497**	**1.95**
School (s)	**1**	**3650**	**4.75**
Kindergarten (k)	**0**	**0**	**0**
Public administration (pa)	**1**	**1606**	**2.09**
Trading place (tp)	**1**	**4015**	**5.22**
Total		**115888**	**151**

$$\boldsymbol{BE_Y = MIN\left(E_{d,y} \div MSL_{ec,y}; 1\right) \times \left(\left(MSL_{ec,y} \times EF\right)\right)}$$

C = 10 kW ; $MSL_{ec,y}$ = 115888 kWh ; EF = 1.3 $kgCO_2$/kWh

$$\boldsymbol{BE_Y = 26\ tCO_2/year}$$

$$\boldsymbol{ER_y = BE_y - PE_y - LE_y}$$

BE_y = 26 tCO_2/year ; PE_y = 0.407 tCO_2/year ; LE_y = 0

$$\boldsymbol{ER_y = 26\ tCO_2/year}$$

IV.4 Case Study 3: Kalom (Biomass power plant)

IV.4.1 Data

Kalom is a village in the region of Fatick in Senegal, with around 1300 inhabitants. Its geographic coordinates are:

- Latitude 14º32'0'' N
- Longitude 16º25'0'' W

The table IV.7 gives the number of consumers of the locality, distributed in different groups.

Table IV-7 Consumers in Kalom

Consumer group	Number
Household (hh)	**115**
Health center (hc)	**1**
Dispensary (d)	**0**
School (s)	**1**
Kindergarten (k)	**0**
Public administration (pa)	**1**
Trading place (tp)	**1**

The village is not connected to the national grid, its energy supply is ensured by only a biomass based power plant of 32 kW using 15% of its capacity. The plant burns peanut husks and millet stems to produce continuously electricity. Therefore the project emissions (PE_y) are not taken into account as the carbon dioxide emitted through the combustion of biomass fuel is in a closed cycle of the plants life.

No non-eligible consumers are recorded and connected to the mini-grids, therefore leakage emissions (LE_y) are null.

IV.4.2 Results

The calculation of the avoided emissions based on the Gold Standard methodology gives the following results in the table IV.8:

Table IV-8 Results from Gold Standard calculation tool C.S 3

Consumer group	Number	Total MSL for each consumer group (kWh)	BE(tCO_2/year) based on MSL
Household (hh)	**115**	**125925**	**163.3**
Health center (hc)	**1**	**3139**	**4.08**
Dispensary (d)	**0**	**0**	**0**
School (s)	**1**	**3650**	**4.75**
Kindergarten (k)	**0**	**0**	**0**
Public administration (pa)	**1**	**1606**	**2.09**
Trading place (tp)	**1**	**4015**	**5.22**
Total		**138335**	**180**

$$BE_Y = MIN(E_{d,y} \div MSL_{ec,y}; 1) \times \left((MSL_{ec,y} \times EF)\right)$$

C = 32 kW ; $MSL_{ec,y}$ = 138335 kWh ; EF = 1.3 $kgCO_2$/kWh

$$BE_Y = 55\ tCO_2/year$$

$$ER_y = BE_y - PE_y - LE_y$$

BE_y = 55 tCO_2/year ; PE_y = 0 tCO_2/year ; LE_y = 0

$$ER_y = 55\ tCO_2/year$$

IV.5 Carbon market opportunities

On April 22, 2016, the United Nations Global Compact (UNGC) called for a minimum internal carbon price level of US$100/tCO2e by 2020 in order to be consistent with a 1.5–2°C pathway. (World Bank & ECOFYS, 2016) Thus, based on the UNGC minimum price, as the systems last for 25 years, the minimum possible benefits from the carbon market for the three projects are given in the table IV.9.

Table IV-9 Projects outcomes

Projects	Capital cost	Total avoided emissions over 25 years	Benefits	Percentage over the capital cost
Ndiba	**-**	**325 tCO_2**	**32500 USD**	**-**
Kalom	**245283 USD**	**1375 tCO_2**	**137500 USD**	**56.05%**
Sine Moussa Abdou	**40638 USD**	**650 tCO_2**	**65000 USD**	**159.94%**

Regarding the capital cost and the minimum carbon price from the UNGC, the benefits from implementing clean energy mini-grids represent an important incentive for the projects. However a comparison of the benefits to the net present cost of the project, which take into account the operation and maintenance, the replacement and the fuel cost, will decrease significantly the percentage as the purchase of fuel increase the cost and the emissions from the diesel generator reduce the avoided emissions and the financial benefits. Furthermore the entities are not yet compelled to apply the minimum price. According to the World Bank, the corporate carbon price range reported to CDP in 2015 spans from US$1/$tCO_2$e to US$357/tCO_2e, thus the uncertainties on the projects carbon benefits are significant.

IV.6 Discussion

The calculated quantity of avoided emissions from the three clean mini-grids shows that the developing countries have a small carbon footprints. Even though the concept of 'suppressed demand' tries to take into account the fact that their per-capita emissions would be much higher if they had better access to electricity, the baseline scenario based on their electricity consumption has proven that rural communities have very low carbon dioxide emissions. The results from the biomass based mini-grids in Kalom shows that it is better to implement projects totally based on renewable sources in order to obtain significant avoided emissions. However depending on the location and the availability of the renewable energy resources, a back-up generator using fossil fuel is necessarily used, thus the projects will release a certain quantity of pollutants and reduce its CER credits.

The Gold Standard calculation methodology is well elaborated as it takes into account all the consumer groups characterizing the off-grid communities and their basic electricity needs. Therefore the results obtained are satisfactory. However credits are accorded only to the projects with a total energy consumption equal or less than the minimum service level consumption given in the methodology. Therefore in the case the electricity consumed is higher than the MSL consumption, the baseline emissions will not reflect the real avoided quantity of emissions. Moreover the projects emissions are considered as null when the energy source is biomass, solar or wind, while the studies carried out by the NREL shows that wind and solar PV power plants produce respectively 10 gCO_2e/kWh and 40 gCO_2e/kWh mainly during the manufacturing process of the components and the installation of the plants.

The minimum carbon price proposed by the UNGC could be an important lever to boost the implementation of CDM projects, however without any compelling policy, prices fluctuate and become very low as the demand for CER decrease. Therefore clean energy mini-grids projects owners tend to find financial mechanism other than the CDM in order to reduce their capital cost and to make their projects viable.

CONCLUSION

With the climate change the world is facing probably its most important challenge. The greenhouse gases are the main factors of this climate change as they affect the global average temperature by trapping the heat released by the earth. The most abundant greenhouse gas is the carbon dioxide. The balance between the natural sink and source maintained the carbon dioxide concentration at almost an constant level, however since the Industrial Revolution, the anthropogenic emissions increased the atmospheric concentration till it reaches a dangerous level which threaten the whole ecosystem as temperatures increase and the climate started to change. There are other greenhouse gases having a higher potential in term of long wave radiation absorption compared to the carbon dioxide, but fortunately their atmospheric concentration is lower. Methane is the second most abundant greenhouse gas representing 16% of the GHGs, it has a global warming potential of 28. As the increase of atmospheric concentration of the carbon dioxide, the atmospheric concentration of methane has also increased due to anthropogenic emissions. In term of atmospheric concentration, the methane is followed by the nitrous oxide representing 6% of the GHGs with a global warming potential of 265. The atmospheric concentration of the nitrous oxide has also increased due to human activities but at a lower extent compared to the atmospheric concentration of carbon dioxide and methane. While the carbon dioxide, the methane and the nitrous oxide are also naturally produced, the fluorinated gases are totally anthropogenic and have very high global warming potentials, however their atmospheric concentrations are low and they represent 2% of the GHGs. With the concept of global warming potential, the greenhouse gases can be expressed in term of carbon dioxide equivalent, therefore the total emissions are given in CO_{2eq} (CO_2 equivalent).

In 2010, 49 (±4.5) $GtCO_{2eq}/yr$ of greenhouse gases were emitted, carbon dioxide accounted for 76% (38±3.8 $GtCO_2/yr$) of that total anthropogenic GHG emissions. Most of the carbon dioxide emissions come from the power and heat sector with the burning of fossil fuels. Therefore it appears important to reduce the emissions from the sector by using clean, reliable and renewable energies to ensure the heat and power production.

The low electrification rate in West African countries, particularly in rural areas has led the authorities to find sustainable solutions to address the energy access issue. In most cases, extending the grid to supply remote communities represent an important cost for the power utilities, therefore the implementation of mini-grids is the most adequate solution for many rural areas. As the governments are committed to tackle the energy access problem and also the GHGs emissions, the implementation of clean energy mini-grids will help to address sustainably both issues by ensuring electricity supply and avoiding GHGs emissions. In the ECOWAS region, ECREEE has listed many renewable based projects, with 107 mini-grids implemented in Senegal. The calculation of the avoided emissions of three of those mini-grids shows that the quantity of emissions avoided are very small compared to the giga tonnes of GHGs globally emitted each year. As an example, the calculation for the biomass based mini-grids installed in Kalom with a capacity of 32 kW gives only 55 tCO_2/year as avoided emissions and it has the biggest quantity of avoided emissions among the three case studies. However by implementing many more clean energy mini-grids, it will be possible to obtain significant amount of avoided emissions. Furthermore the carbon market represent an important opportunity for renewable based projects when they obtain CERs through the clean development mechanism or VERs through the voluntary market. The case studies of Ndiba and Kalom shows that the minimum benefit with the UNGC carbon price, represents more than 50% of the projects capital costs. However the deflation affects the development of CDM projects as carbon prices are not fixed.

Most of the demand for CERs from the CDM comes from the European Union Emissions Trading Scheme, which is the largest carbon market. In July 2012, the market price for CERs fell to new record low of €2.67 a tonne, a drop in price of about 70% in a year. Analysts attributed the low CER price to lower prices for European Union emissions allowances, oversupply of EU emissions allowances and the slowing European economy. (Chestney, 2012)

Therefore it appears necessary to find alternative mechanisms to support the development of clean energy mini-grids. The governments commitment to reduce the dependence on fossil fuels is one of the main means to promote and finance the clean energy mini-grids in the absence of the clean development mechanism and the deflation in the carbon market.

As recommendations:

- The clean energy mini-grids projects owners should take into account the future electricity demand as the access to electricity improves the households economic situation.
- Mini-grids could be integrated to ensure a reliable power supply.
- In order to avoid totally the emissions, the mini-grids should be based only on renewable energy sources.
- As the Gold Standard methodology is applied to small scale projects, the emissions due to the manufacturing and installation of renewable power plants are not taken into account. However when the avoided emissions concern an important number of mini-grids under the same project, the emissions from renewable energies should not be neglected as they are real and could represent an important quantity.
- In addition to the carbon market, the projects owners should find alternative mechanisms to finance their mini-grids projects as the fluctuation of the carbon price makes the market not totally reliable.

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APPENDICES

Case studies results with the Gold Standard calculation tool.

Energy Generation System:	NDIBA
ERy = Emissions Reduction in a year (t CO_2) View Formula	13
PEy = Project Emission in a year (t CO_2) View Formula	5
LEy = Leakage Emission in a year (t CO_2) View Formula	0
NEC = Non Eligible Consumers in a year (kWh)	0
BEy = Baseline Emission in a year (t CO_2) View Formula	18

Input data must be inserted in the light red cells
Pre-defined data is provided in the white cells
Calculations are presented in the black cells

END

Consumer group (CG)	Default MSL for each consumer group (kWh) per day	Default MSL for each consumer group (kWh) in a year	Default BE for each consumer group (t CO_2) in a year	Number of the specific consumer group (n)	Total MSL for each consumer group (kWh)
Household (hh)	3.0	1,095	1.42	34	37,230
Health Center (hc)	8.6	3,139	4.08	0	0
Dispensary (d)	4.1	1,497	1.95	1	1,497
School (s)	10.0	3,650	4.75	1	3,650
Kindergarten (k)	4.4	1,606	2.09	0	0
Public Administration (	4.4	1,606	2.09	1	1,606
Trading Place (tp)	11.0	4,015	5.22	1	4,015

Add new CG line | Delete line

Total MSLec,y (kWh/year) View Formula	47,998
Baseline Emissions based on MSL (t CO_2/year)	62

Method A: The electricity delivered is based on the installed capacity and and an availability factor.

IC = Installed capacity (W or Wp)	
AF = Availability factor (%)	

Method B: The electricity delivered is based on actual monitoring at generation-level and a default transmission and distribution losses' (TDL) factor

Emy = Electricity monitored in a year (in *kWh/year*)	15,199
TDL = Transmission and distribution losses' factor (%)	10.0%
Edy = Electricity delivered in a year (in *kWh/year*) View Formula	13,679

Choose method:
○ Method A
◉ Method B

Energy Generation System:	Sine Moussa Abdou
ERy = Emissions Reduction in a year (t CO_2) View Formula	26
PEy = Project Emission in a year (t CO_2) View Formula	0
LEy = Leakage Emission in a year (t CO_2) View Formula	0
NEC = Non Eligible Consumers in a year (kWh)	0
BEy = Baseline Emission in a year (t CO_2) View Formula	26

Input data must be inserted in the light red cells
Pre-defined data is provided in the white cells
Calculations are presented in the black cells

END

Consumer group (CG)	Default MSL for each consumer group (kWh) per day	Default MSL for each consumer group (kWh) in a year	Default BE for each consumer group (t CO_2) in a year	Number of the specific consumer group (n)	Total MSL for each consumer group (kWh)
Household (hh)	3.0	1,095	1.42	96	105,120
Health Center (hc)	8.6	3,139	4.08	0	0
Dispensary (d)	4.1	1,497	1.95	1	1,497
School (s)	10.0	3,650	4.75	1	3,650
Kindergarten (k)	4.4	1,606	2.09	0	0
Public Administration (|	4.4	1,606	2.09	1	1,606
Trading Place (tp)	11.0	4,015	5.22	1	4,015

Add new CG line | Delete line

Total MSLec,y (kWh/year) View Formula	115,888
Baseline Emissions based on MSL (t CO_2/year)	151

Method A: The electricity delivered is based on the installed capacity and and an availability factor.

IC = Installed capacity (W or Wp)	10,000
AF = Availability factor (%)	22.8%

Method B: The electricity delivered is based on actual monitoring at generation-level and a default transmission and distribution losses' (TDL) factor

Emy = Electricity monitored in a year (in *kWh/year*)	
TDL = Transmission and distribution losses' factor (%)	10.0%
Edy = Electricity delivered in a year (in *kWh/year*) View Formula	19,973

Choose metho
◉ Method A
○ Method B

Energy Generation System:	Kalom
ERy = Emissions Reduction in a year (t CO_2)	55
PEy = Project Emission in a year (t CO_2)	0
LEy = Leakage Emission in a year (t CO_2)	0
NEC = Non Eligible Consumers in a year (kWh)	0
BEy = Baseline Emission in a year (t CO_2)	55

Input data must be inserted in the light red cells
Pre-defined data is provided in the white cells
Calculations are presented in the black cells

END

Consumer group (CG)	Default MSL for each consumer group (kWh) per day	Default MSL for each consum group (kWh) in a year	Default BE for each consume group (t CO_2) in a year	Number of the specific consumer group (n)	Total MSL for each consumer group (kWh)
Household (hh)	3.0	1,095	1.42	115	125,925
Health Center (hc)	8.6	3,139	4.08	1	3,139
Dispensary (d)	4.1	1,497	1.95	0	0
School (s)	10.0	3,650	4.75	1	3,650
Kindergarten (k)	4.4	1,606	2.09	0	0
Public Administration (|	4.4	1,606	2.09	1	1,606
Trading Place (tp)	11.0	4,015	5.22	1	4,015

Add new CG line   Delete line

Total MSLec,y (kWh/year)	138,335
Baseline Emissions based on MSL (t CO_2/year)	180

Method A: The electricity delivered is based on the installed capacity and and an availability factor.

IC = Installed capacity (W or Wp)	32,000
AF = Availability factor (%)	15.0%

Method B: The electricity delivered is based on actual monitoring at generation-level and a default transmission and distribution losses' (TDL) factor

Emy = Electricity monitored in a year (in *kWh/year*)	
TDL = Transmission and distribution losses' factor (%)	10.0%
Edy = Electricity delivered in a year (in *kWh/year*)	42,048

Choose metho
- (●) Method A
- ( ) Method B

SUMMARY

Regarding the climate change issue and the low electrification rate in West Africa, mainly in rural areas, the implementation of clean energy mini-grids will allow to avoid future greenhouse gases emissions while solving the electricity access problem. In this master thesis the avoided emissions of greenhouse gases were calculated using the Gold Standard calculation tool for three mini-grids. In comparison to the giga tonnes of global emissions, the results obtained show that a mini-grid only avoid a small quantity of GHGs. Thus to avoid important quantity of future emissions, it is necessary to implement many more mini-grids projects preferably based on renewable energy resources only. However with the minimum carbon price from the UNGC, the carbon market can represent an important source of incentive for clean energy mini-grids projects as it was observed after the calculations.

RESUME

Au regard du problème que représentent le changement climatique et le faible taux d'électrification en Afrique de l'Ouest, principalement dans les zones rurales, l'implémentation de mini-centrales à énergie propre permettra d'éviter les futures émissions de gaz à effet de serre tout en résolvant le problème d'accès à l'électricité. Dans cette thèse de master, les émissions de gaz à effet de serre évitées ont été calculées en utilisant la feuille de calcul du Gold Standard pour trois mini-centrales. En comparaison aux giga tonnes d'émissions globales, les résultats obtenus montrent qu'une mini-centrale ne permet d'éviter qu'une petite quantité d'émission de gaz à effet de serre. Ainsi pour éviter des quantités conséquentes de futures émissions, il faut nécessairement installer beaucoup plus de mini-centrales basées de préférence seulement sur les énergies renouvelables. Néanmoins avec le prix minimum de carbone fixé par le UNGC, le marché carbone peut représenter une importante source de subvention pour les projets de mini-centrales à énergie propre comme il a été observé après les calculs.